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Biogas Generation and Nutrient Recycling from Sugarcane Distillery Residues through Anaerobic Digestion

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***Abstract*— Press mud and raw spent wash or vinasse, are the two main high strength organic wastes from the sugarcane sector that anaerobic digestion is known to be an efficient and sustainable method of treating. Due to their significant organic loading and improper disposal techniques, these by-products are handled independently and pose a major environmental risk. In order to evaluate current trends in biogas generation and nutrient recovery, the origin, properties, and biomethane potential of both press mud and raw spent wash were investigated in this study. Methane generation has been observed to range from around 0.24 L/g volatile solids in the case of press mud to 0.45–0.55 Nm³ per kilogram of COD removed for spent wash, despite a satisfactory removal efficiency of COD ranging from 65% to 85%. Depending on the mixing ratio, co-digestion of these wastes boosts methane generation by 12–59%, improves biodegradability, optimizes the carbon–nitrogen balance, and lessens inhibitory effects. In order to assist and strengthen circular economy activities, this article also evaluated how anaerobic digestion fits into the operations of a sugarcane distillery. Reusing press mud and Biomethanated Spent Wash (BMSW) as organic fertilizers greatly increases crop output while lowering the quantity of chemical fertilizers used. While yields increased by about 5% for BMSW and 15% for press mud, field observations showed a decrease in the amount of DAP and urea utilized. In summary, the results have demonstrated that anaerobic digestion combined with agricultural reuse creates a regenerative cycle that increases the economic feasibility and environmental sustainability of sugarcane-based biorefineries by converting waste into renewable energy and biofertilizers.**

***Index Terms*— Anaerobic Digestion, Press Mud, Raw Spent Wash, Methane Yield, Co-digestion.**

I. INTRODUCTION

For ages, anaerobic digestion has been used to produce biogas. Anaerobic digestion produces biogas, which was used to heat bathwater as early as the 10th century in Assyria and the 16th century in Persia, according to historical documents. Jan Baptista van Helmont first noticed that decomposing organic waste in lakes created a combustible gas in the 17th century. Methane was discovered to be the main constituent of this gas by Sir Humphry Davy in 1808.

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Anaerobic digestion systems first appeared in South Asia in the 18th century, and as technology continued to evolve, they progressively made their way to Europe. It was not until around 1930 that a clear scientific explanation of how organic matter breaks down to produce biogas was developed [1]. Anaerobic digestion is a naturally occurring biochemical process in which microorganisms break down organic waste without oxygen to produce flammable biogas [2]. The process starts with hydrolysis, which reduces complex substrates like proteins, lipids, and carbohydrates to simpler ones. During the acidogenesis step, these materials undergo further change into various acids and gases.

The volatile fatty acids are further broken down into acetate, hydrogen, and carbon dioxide during the acetogenesis phase [3]. Methanogenic archaea transform these intermediate products into methane in the last stage, called methanogenesis, resulting in approximately the majority of the biogas produced [5][6][7].

A. Process Flow for the Generation of Press Mud and Raw Spent Wash in the Sugarcane Industry

Bagasse is a fibrous by-product that is left over after the sugarcane stalks are crushed to get the juice. In addition to being useful as fuel, this residue can be used as a renewable feedstock to produce bioethanol. The main intermediary used in the production of both sugar and alcohol is the extracted juice. Press mud is created when some of this liquid is used to make sugar, where contaminants are eliminated. This nutrient-rich by-product is used as a substrate for anaerobic digestion and as a soil supplement to improve fertility [4]. Molasses is a secondary by-product of the fermentation of another portion of the juice. The integrated biorefinery cycle is subsequently completed by processing the molasses further to generate alcohol, primarily ethanol. The integrated biorefinery cycle is completed by further processing the molasses into alcohol, primarily ethanol. This integrated technique demonstrates the adaptability of sugarcane since it provides energy and industrial chemicals in addition to organic byproducts that increase agricultural output and environmental sustainability. Below Fig. 1 shows the generation process of Press Mud (PM) and Raw Spent Wash (RSW) from sugarcane.

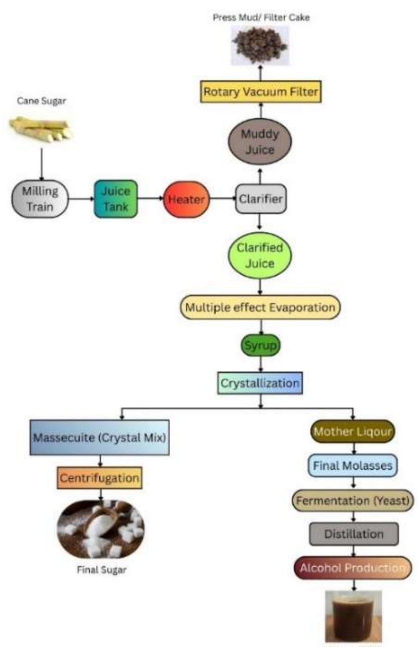

Figure 1. Generation process of Press mud and RSW from Sugarcane

II. Raw Spent Wash (VINASSE)

The wastewater generated by molasses-based distilleries, known as raw spent wash (RSW), has a very high organic burden, with COD levels usually ranging from 80,000 to 1,50,000 mg/L and BOD levels approaching 96,000 mg/L. Melanoidin pigments give it a dark brown hue. Polysaccharides, lignin, proteins, suspended particles, and a variety of micronutrients are present in this effluent, which is typically acidic (pH 3.8–5.5) and released at high temperatures. Anaerobic digestion can eliminate up to 85% of the COD from RSW during treatment, according to several studies [8][9].

A. Production Process of Vinasse from Sugarcane

The fibrous waste left over after sugarcane juice is extracted is called bagasse, and it is utilized extensively as a raw material in the production of paper and biogas, as well as a fuel in boilers [10]. Fibers, waxes, and suspended particles are among the contaminants found in freshly extracted cane juice. Lime-sulphitation, a treatment method that involves adding lime and sulfur compounds to correct the pH and produce clarified juice, eliminates these non-sugar components [11]. The cleared, sugar-rich juice with sucrose, glucose, and fructose is mixed with yeast (Saccharomyces cerevisiae) to initiate anaerobic fermentation, which produces carbon dioxide and ethanol from the sugars [11]. It is also possible to capture and purify the CO2 that is generated during this process for a variety of uses [12]. The liquid produced from fermentation is typically referred to as "beer" and has an ethanol content of about 8–12%. To extract ethanol from water and solids, this mixture is distilled or purified to produce crude ethanol [13]. Molecular sieves are used to further remove moisture and increase the purity to more than 99%, resulting in fuel-grade ethanol, since ethanol and water form an azeotropic combination at about 95% purity. After that, the final product is transported and kept in tanks for use in fuel blending, beverage production, or other industries. As a solid fibrous waste, bagasse can also be used in cogeneration systems or as a substrate for the production of biogas [10]. Although vinasse, the liquid residue left over after distillation, is rich in nutrients and organic matter and can be used to produce biogas or biomethane, its vast volume and disposal issues also raise serious environmental concerns [13].

B. Characteristics of Raw Spent Wash

The COD and BOD measurements of raw wasted wash show that it has remarkably high quantities of organic materials. The Chemical Oxygen Demand (COD) is very high, usually ranging from 80,000 to 1,58,000 mg/L. The amount of oxygen needed to chemically oxidize both organic and inorganic substances is represented by COD. Large concentrations of both biodegradable and non-biodegradable organic materials are indicated by elevated COD values [5]. A significant amount of decomposable organic matter is indicated by Biochemical Oxygen Demand (BOD) levels, which normally range from 35,000 to 96,000 mg/L and, in some studies, even higher [6]. A popular indicator of biodegradability is the BOD-to-COD ratio; values of 0.5 or higher indicate high biodegradability. However, BOD/COD ratios frequently range from 0.4 to 0.6, indicating that although the wastewater is somewhat biodegradable, certain refractory chemicals are still present [5].

C. Biogas Generation from Raw Spent Wash

The effectiveness of anaerobic digestion and the resulting biogas production from raw waste wash has been assessed in several experiments. The effectiveness of the OPUR treatment system, which uses anaerobic digestion to treat distillery effluent under Indian climatic conditions, was investigated in one such study by Manoj Wagh et al. [15], the main findings demonstrated a removal effectiveness of roughly 65–72% when the Chemical Oxygen Demand (COD) decreased from approximately 140,000 to nearly 38,500 mg L^{-1}. The BOD decreased by around 80–85%, from 70,000 mg L^{-1} to over 13,000 mg L^{-1}. In addition, TDS was reduced by almost 75%, from 100,000 mg L^{-1} to 25,000 mg L^{-1}. In this context, the rate of biogas production was between 0.45 and 0.55 Nm^3 per kilogram of COD eliminated [7]. The anaerobic digestion of waste wash in the Shakarganj Sugar Mills biogas power plant has been studied by Abdullah et al. [8], Their findings showed that 20.34 million m^3 of biogas were produced from 0.5 million m^3 of spent wash generated in a single year (from October to September). 55,760 m^3 of biogas was generated daily on average from 1,394 m^3 of spent wash. With an 81% removal efficiency, COD reduced from the maximum value of 95,000 mg/L to 18,000 mg/L during the biogas generating process. Additionally, 83% of BOD and 44% of TDS have been eliminated using the technology [8]. Anun Salaeh, Khaliyah Sania, and colleagues [9]. investigated utilising a SAB reactor to recover biogas from high-strength distillery waste wash. According to their results, methane production was maximum and inhibition was lowest at an S/I ratio of 1:4. The success rate of COD elimination was 85.4%. The specific methane yield was 299.0 ± 13.5 mL CH_4/g COD eliminated, and the average daily methane production was 22.2 ± 0.9 L/day [9]. In an experimental investigation, R. Shyam Sundar, R. Saravanan, and colleagues [10] used anaerobic digestion to produce and upgrade biogas from distillery waste wash[10].

III. PRESS MUD

When sugarcane juice is clarified, press mud, also called filter cake, is produced. It has a high percentage of organic matter, lignocellulosic chemicals, waxes, proteins, and minerals in addition to 60–85% moisture. Codigesting it with carbon-rich materials can enhance its carbon-to-nitrogen (C/N) ratio, which typically ranges from 9 to 14. [11][12][13].

A. Production Process of Press Mud in Cane Sugar Mill

In the process of milling, bagasse, a fibrous byproduct, is separated while sugarcane is crushed to obtain the juice. In boilers, bagasse is frequently burned to produce steam and electricity [14]. The extracted juice is gathered in a juice tank and heated to coagulate contaminants and deactivate enzymes that cause sugar inversion in order to increase clarity [15]. To allow the contaminants to settle, the juice is heated and then treated with clarifying chemicals like lime in a clarifier. The liquid is divided into two streams by this process: transparent juice, which undergoes additional processing to facilitate the crystallization of sugar [15].Muddy juice has suspended particles and non-sugar substances. The solid by-product that remains after this muddy juice is sent through a rotary vacuum filter to extract sucrose-rich juice is known as press mud, or filter cake. Press mud can be used to produce biogas and compost because of its high organic wax and nutritional content [14]. After being transferred from the milling area to the boiler unit, bagasse is burned to generate steam. Steam powers turbines that produce electricity in addition to heating sugar mill juice and evaporation processes [16].

B. Characteristics of Press Mud

Press mud's biodegradability and anaerobic digestion performance are significantly impacted by its highly varied fundamental properties. The range of total solids (TS) is from 27.7% to 47.85%. Volatile solids (VS), which indicate the amount of organic content in press mud, also differ significantly amongst samples, ranging from 18.65% to 80.8% [11]. Lignocellulosic composition: hemicellulose typically comprises up 10% of the lignocellulosic material, with documented values as high as 27.1%, whereas cellulose normally makes up 11–12%. Lignin is found in modest amounts, typically ranging from 9% to 14%, with a peak value of 17.4%. [11][12]. The carbon-to-nitrogen (C/N) ratio, which ranges from 9 to 14, is generally low and indicates nitrogen-rich material that, if digested alone, could cause ammonia inhibition. One substrate, however, exhibits a greater C/N ratio of 26:1, which is nearer the ideal range [13].

C. Biogas Generation from Press Mud

There has been much research done on the production of biogas from press mud. M. A. Rouf, P. K. Bajpai et al. [17]. reported the maximum production at 0.24 L/g of press mud at its solid concentration of 6% in a study to estimate the ideal conditions for producing biogas from press mud using a batch reactor. The ideal C/N ratio for biogas production was determined to be 18, which is greater than the press mud average of 14. Press mud and cane pith in a 1:1 ratio greatly increased biogas production, with methane accounting up around 65% of the resulting biogas [17]. The technological and economic viability of producing biogas from press mud was the subject of a related study by M. A. Rouf, M. S. Islam, et al. [18]. Methane formed about 65% of the biogas that was produced. The overall gas output was 0.18 L/g of press mud, according to the data. The C/N ratio was below the ideal threshold for efficient biomethanation, ranging from 13 to 15. 75–80% of the press mud under study was volatile. Biogas generation in a 150 cft reactor configuration was tracked for solid contents ranging from 6% to 8% [18]. According to a study by Srinivas Kasulla and his fellow researchers [14] introducing trace metals like iron, nickel, and cobalt to press mud enhanced its biogas generation by roughly 20–30%. For every kilogram of organic dry materials, they demonstrated a final methane output of roughly 430–460 L. After digestion, the production of crude biogas from one ton of press mud varied from 82 to 90 m^3, and in a few instances, it approached 100–105 m^3. When press mud was anaerobically digested, the addition of iron produced the highest overall biogas output among the other metal additives. However, the addition of nickel and cobalt triggered the fastest biogas generation on the first day [14].

IV. CO-DIGESTION BENEFITS

Co-digestion is demonstrated to be a successful strategy for boosting anaerobic digestion efficiency by matching these substrates in a complimentary way. By increasing the environment's carbon/nitrogen ratio and nutrition level, this technique creates a more conducive environment for bacteria. Additionally, by lowering the concentration of inhibitors like ammonia and Sulphur containing gases, this procedure enhances the biodegradability of the substrate and aids in the breakdown of more resistant organic materials. As a result of improved control over the pH, alkalinity, and VFA content, the digester operates more steadily and produces more biogas and methane. Co-digestion helps manage several kinds of organic waste and facilitates their disposal. Press mud and raw spent wash are not technically efficient in the sugarcane industry since they are processed differently even if they are processed in the same location. Since both are readily available at one location, processing together is more beneficial for co-digestion. Although co-digestion has been shown to be more efficient than mono-digestion in terms of biodegradability and biogas production, the ideal ratios for creating their combination are yet unknown. Press mud has a greater carbon content, whereas spent wash has a higher nitrogen concentration. Co-digestion helps prevent ammonia toxicity and deficits by preserving carbon/nitrogen ratios. Compared to spent wash, where readily degradable elements speed up the process, lignin in press mud is more difficult to break down. Methane output is reportedly increased by 12–59% when press mud is supplemented with vinasse, bagasse, or vegetable waste. Below, Table I. shows the Co-digestion of Press Mud with various materials.

TABLE I: CO-DIGESTION OF PRESS MUD WITH VARIOUS MATERIALS

Co-digestion material	Conditions	Increased CH4 Yield (%)	References
Vinasse	Press mud and Vinasse in the ratio 50:50	12-13%	[19]
Vegetable Waste	Press mud and vegetable waste in the ratio 30:70	37%	[20]
Abattoir wastewater	Sugarcane Press mud and Abattoir wastewater in a ratio of 80:20	59%	[21]
Distillery wastewater	Press mud and Distillery wastewater in the ratio 1:2	15%	[22]
Food Waste	Sugarcane Press mud and Food waste in the ratio 80:20	22%	[23]

V. CIRCULAR ECONOMY

One example of a circular economy in action is the sugarcane distillery industry, which uses anaerobic digestion to recycle its own wastes into useful goods. Press mud, raw spent wash, and bagasse are converted into methane-rich biogas and a nutrient-rich digestate by microorganisms in anaerobic digesters. The industry's consumption of fossil fuels and emissions can be reduced by burning the biogas to generate power and heat or using it to make biomethane. The digestates are processed and used again on farmland as soil conditioners and biofertilizers in an attempt to improve soil fertility and quality while simultaneously lowering the need for synthetic fertilizer. After these wastes are applied, practical farmers have reported using less synthetic fertilizer. This method contributes to sustainability for a cleaner environment, reduced production costs, and resource recovery by recycling waste materials into energy and agricultural inputs. Finally, the anaerobic digestion of sugarcane distillery effluent enables a regenerative production system that would enable a circular economy where resources and nutrients can be continuously recovered and reused. The main objective of this evaluation study is to, at the very least, assist sugarcane farmers in understanding integrated nutrient management (INM) strategies. By combining synthetic fertilizer input with additional natural elements like press mud and biomethanated spent wash (BMSW) materials, this technique aims to maximise crop requirements. This type of production technique aims to prevent dependence on soil indices, unfavourable soil properties that synthetic fertilizer inputs may cause, and potentially costly sources of environmental danger. The goal of this integrated nutrient and resource recycling solution is to improve the value addition to organic by-products from sugar mills and mills rich in matter and vital nutrients, while also advancing the circular economy. By integrating the organic by-product and recycling the resource into agricultural nutrients for crop and plant productivity and farmer profitability, this forces economic and environmental sustainability aspects to align. Overall, the use of BMSW and press mud press offers sugarcane farmers and environmental protection a number of immediate benefits while promoting the circular economy. These benefits include an immediate decrease in synthetic fertilizers and improvements in soil quality to have the proper soil structure, higher levels of beneficial microorganisms, and increased water-holding capacities. Because of the better soil conditions and crop requirements based on balanced nutrients, there will undoubtedly be a higher possibility for increased crop productivity and performance [24][25][26].

A. Analysis of Fertilizer Application with and without Biomethanated Spent Wash.

The importance of biomethanated discarded waste (BMSW) as a source of fertilizer is shown by comparison with traditional sugarcane cultivation. Conventional processing required 200 kg of DAP and 200 kg of urea fertilizer per acre to yield 45 MT. This means that 4.44 kg of DAP fertilizer and 4.44 kg of urea fertilizer are required for every metric ton of cane yield. Depending on the ultimate yield, the improved approach uses about 100 liters of spent wash for every ton of sugarcane, or 4.725 MT of spent wash per acre. With more than 1.89 kg of nitrogen and 0.68 kg of phosphate provided by the waste wash, some chemical fertilizer can be substituted. As a result, a total of just 196.47 kg of DAP fertilizer and 197.27 kg of urea fertilizer are needed. Furthermore, the organic matter in the waste wash makes the soil more fertile, which raises the output by 5% to about 47.25 MT per acre. Effective fertilizer consumption is demonstrated by the decreased fertilizer usage per unit of sugarcane produced per ton, which is roughly 4.16 kg of DAP fertilizer and 4.18 kg of urea fertilizer per ton of sugarcane.

The study's overall conclusions show that using biomethanated waste wash can boost crop yields while lowering the requirement for chemical fertilizers.

B. Analysis of Fertilizer Application with and without Press Mud.

The use of press mud and traditional sugarcane farming to obtain a sustained supply of nutrients is explained in full below. The typical method required 200 kg of DAP and 200 kg of urea per acre of land to produce an estimated 45 tons of sugarcane. For every extra ton of sugarcane, 4.44 kg of DAP and 4.44 kg of urea are consumed. Depending on the crop produced, the enhanced technology uses 40 kg of press mud per ton of sugarcane, or roughly 2.07 metric tons of press mud per acre. Additionally, the press mud produces 5.175 kg of nitrogen and 3.11 kg of phosphorus, which can partially replace the need for artificial fertilizer. As a result, only 184.52 kg of DAP and 194.81 kg of urea per acre of mixed fertilizers are needed. Additionally, the organic component of the press mud improves soil health and increases output by 15% to 51.75 MT per acre. There is a significant push for improved fertilizer use, as evidenced by the fact that only 3.57 kg of DAP fertilizer and 3.76 kg of urea fertilizer are needed per metric ton of sugarcane production. Press mud is more economical and environmentally beneficial than other agricultural practices because it not only increases crop yield but also uses less chemical fertilizer.

V. CONCLUSION

According to the observations, anaerobic digestion of press mud and raw discarded wash appears to be a very effective method of waste recycling by the sugarcane business. With significant biogas outputs, concurrent bioremediation, and COD and BOD reductions, both waste collectors offer a very high potential for bio-methanation. More specifically, co-digestion produces a lot of biogases, balanced nutrients, improved biodegradability, and a stable process. By converting biowaste into nutrient-rich waste, biogas, and biomethane through fermentation in sugarcane distilleries, this method may alleviate the waste management issue and bring the idea of the circular economy to life. Agricultural R&D also contributes to the successful use of waste recycling from biogas facilities. Applying waste wash bioproducts through biomethane technology could boost sugar cane productivity by about 5% while also enhancing soil health and reducing the requirement for pesticides. Similarly, adding press mud lowers the demand for urea and DAP while increasing crop output by roughly 15%. The economic and agricultural benefits of using organic nitrogen from biogas technology are highlighted by the previously mentioned benefits, improved soil health, and careful fertilizer application. As a result, employing biotechnology in a closed-loop system for cane processing enhances sustainable agriculture, optimises resource use, and achieves environmental objectives. These clearly point to a route for a sustainable and regenerative sugarcane fermentation process.

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