iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 14 **Issue:** V **Month of publication:** May 2026

DOI: https://doi.org/10.22214/ijraset.2026.83329

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue V May 2026- Available at www.ijraset.com

Enhancing Biogas Production from Sugarcane Waste and Vegetable Waste through Optimized Co-digestion and Catalytic Intervention: A Review

Rasita R. Kamble[1], Prof. Kiran M. Kangle[2]
[1]*M.Tech Environmental Engineering, KIT College of Engineering, Kolhapur, Maharashtra, India*
[2]*Professor, Department of Civil/Environmental Engineering, KIT College of Engineering, Kolhapur, Maharashtra, India*

Abstract: Anaerobic digestion (AD) is a proven and sustainable technology for converting organic waste in the form of biogas. However, mono-digestion of agro-industrial or municipal organic wastes often results in low methane yield, process instability, and inhibition due to nutrient imbalance and rapid acidification. To overcome these challenges, anaerobic co-digestion has gained significant attention as it improves substrate synergy and enhances microbial activity. Vegetable waste is a major problem in India. Huge quantity of waste is generated from market. Also, Sugarcane industrial residue generated in large quantities waste, its included sugarcane press mud, sugarcane bagasse, vinasse, sugarcane wastewater are promising substrates for co-digestion with vegetable waste. In this paper we focus on sugarcane Press mud waste with vegetable waste. Previous studies have demonstrated that an optimized substrate ratio plays a critical role in improving digestion performance. In recent years, catalytic intervention using metallic additives and nano-particles has emerged as an advanced strategy to further enhance anaerobic digestion by accelerating hydrolysis, improving electron transfer, and stimulating methanogenic activity. This review critically examines existing literature on anaerobic co-digestion of sugarcane waste and vegetable waste with optimized substrate ratios, and the role of metallic and nano-catalysts in improving methane yield and process stability. Research gaps related to catalyst dosage, nano-toxicity, and large-scale applicability are also highlighted to guide future experimental investigations.
Keywords: Anaerobic digestion, co-digestion, sugarcane press mud, vegetable waste, nano-catalysts, methane yield/

I. INTRODUCTION

The rapid depletion of fossil fuel reserves and the growing concern over climate change have intensified global efforts to develop renewable and sustainable energy sources. Among various renewable energy technologies, anaerobic digestion (AD) has emerged as an effective method for converting organic waste into biogas while simultaneously addressing waste management challenges [1]. Biogas production through anaerobic digestion not only provides a clean energy source but also reduces greenhouse gas emissions and produces nutrient-rich digestate suitable for agricultural applications [2]. India generates large quantities of biodegradable waste from both agro-industrial and municipal sources. The sugar industry alone produces significant amounts of sugarcane press mud, a solid residue obtained during sugar clarification processes [3]. Press mud is rich in organic matter, minerals, and trace elements but exhibits limited biodegradability due to its fibrous and lignocellulosic nature [4]. Mono-digestion of sugarcane press mud often results in slow degradation rates and lower methane yield [5].

Similarly, vegetable waste constitutes a major fraction of municipal solid waste generated from households, markets, and food processing units [6]. Vegetable waste is highly biodegradable and rich in carbohydrates and moisture; however, its mono-digestion leads to rapid acidification, accumulation of volatile fatty acids (VFAs), and pH reduction, which inhibits methanogenic microorganisms [7,8]. Anaerobic co-digestion has been widely recognized as a practical solution to overcome the limitations associated with mono-digestion of individual substrates [9]. Co-digestion improves nutrient balance, enhances microbial diversity, and increases system stability [10]. Several researchers have investigated the co-digestion of agro-industrial residues with municipal organic waste and reported significant improvements in biogas production and methane content [11–13].

Substrate mixing ratio is a key parameter governing co-digestion performance. Hitesh and Priya [14] conducted a systematic study on anaerobic co-digestion of sugarcane press mud and vegetable waste and reported that a mixing ratio of 30:70 (press mud: Vegetable waste) resulted in maximum biogas yield and stable digestion performance. This improvement was attributed to balanced C/N ratio, enhanced moisture content, and improved microbial activity. Similar observations were reported by Singh et al. [15] and Kumar et al. [16], emphasizing the importance of optimized substrate ratios.

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In recent years, advanced enhancement techniques such as catalytic intervention have been explored to further improve anaerobic digestion efficiency. Metallic additives including iron, nickel, cobalt, and trace metals are known to play a crucial role in enzymatic reactions and methanogenic pathways [17,18]. Furthermore, nano-particles have attracted considerable attention due to their high surface area, enhanced reactivity, and ability to accelerate microbial electron transfer processes [19,20]. Studies have shown that nano-metal oxides can significantly increase methane yield and reduce digestion lag phase [21].

Despite these advancements, comprehensive reviews integrating optimized co-digestion strategies with catalytic enhancement, particularly for sugarcane press mud and vegetable waste, remain limited. Therefore, this review aims to critically analyse existing literature on anaerobic co-digestion of agro-industrial and municipal organic waste, optimized substrate ratios, and catalytic intervention strategies to provide a strong scientific foundation for future experimental and scale-up studies.

Sugarcane-based industries generate several biodegradable residues including bagasse, vinasse, molasses, wastewater, and press mud, all of which possess significant potential for renewable energy generation through anaerobic digestion [22–25]. Previous investigations demonstrated that pretreatment methods and reactor design significantly influence methane yield and digestion kinetics of lignocellulosic sugarcane residues [23,27,42]. Co-digestion approaches involving sugarcane residues with cattle manure, sewage sludge, and other organic substrates have also shown improved process stability and enhanced methane productivity due to synergistic nutrient balancing [26,30,37–40]. Furthermore, recent techno-economic evaluations suggest that biogas generation from sugar industry waste can contribute substantially to sustainable waste management and circular bioeconomy development [31,53,54].

II. CHARACTERISTICS OF SUGARCANE PRESS MUD AND VEGETABLE WASTE

Sugarcane press mud is characterized by high total solids (60–70%), volatile solids content, and significant concentrations of calcium, phosphorus, and trace metals [3,4]. However, its high lignocellulosic fraction limits microbial accessibility under anaerobic conditions [5].

Vegetable waste contains easily degradable organic compounds such as carbohydrates and proteins, high moisture content, and low lignin levels [6,7]. Although these properties Favor rapid hydrolysis, they also lead to VFA accumulation and pH instability during mono-digestion [8].

In addition to its high organic content, sugarcane press mud contains fibrous lignocellulosic components that reduce biodegradability under anaerobic conditions unless pretreatment strategies are applied [22,23,42]. Studies on vinasse and sugarcane bagasse have demonstrated that substrate composition, moisture content, and carbon-to-nitrogen ratio strongly influence digestion efficiency and methane recovery [24,39]. Similarly, vegetable waste possesses high biodegradability but may rapidly acidify the digestion medium because of excessive volatile fatty acid accumulation [7,64]. Therefore, co-digestion of press mud and vegetable waste offers complementary physicochemical properties suitable for stable anaerobic digestion

The complementary characteristics of these substrates make them ideal candidates for anaerobic co-digestion.

III. OPTIMIZED CO-DIGESTION AND SUBSTRATE RATIO SELECTION

Several studies have demonstrated that substrate ratio significantly affects biogas yield and digestion stability [9,10]. Hitesh and Priya [14] identified a 30:70 ratio of sugarcane press mud to vegetable waste as optimal for enhanced methane production. The improved performance was linked to balanced nutrient availability and reduced inhibitory effects.

Supporting studies have reported similar trends, confirming that higher proportions of vegetable waste improve hydrolysis, while press mud contributes buffering capacity and essential trace elements [15,16].

Several studies have demonstrated that substrate ratio significantly affects methane yield, buffering capacity, microbial stability, and volatile fatty acid accumulation during anaerobic co-digestion [9,10,32]. Hitesh and Priya [14] identified a 30:70 ratio of sugarcane press mud to vegetable waste as optimal for enhanced methane production. The improved performance was linked to balanced nutrient availability, improved moisture content, and reduction of inhibitory compounds.

Supporting investigations on co-digestion of sugarcane bagasse with manure and agro-industrial residues also reported enhanced methane production and process stability under optimized substrate combinations [26,37–40]. Research by Angelidaki et al. [32] and Batstone et al. [33] further emphasized the importance of biomethane potential assessment and kinetic modelling for evaluating substrate compatibility in anaerobic digestion systems. Additionally, optimization of operational parameters such as organic loading rate, hydraulic retention time, and mixing intensity plays a critical role in achieving stable digestion performance [35,46].

IV. CATALYTIC INTERVENTION IN ANAEROBIC DIGESTION

Metallic additives such as Fe, Ni, and Co act as essential cofactors for enzymes involved in methanogenesis [17]. Nano-particles further enhance digestion by improving interspecies electron transfer and accelerating hydrolysis [19–21]. Iron oxide nano-particles, in particular, have been reported to increase methane yield by up to 30% under optimized conditions [21].

Metallic additives such as iron (Fe), nickel (Ni), and cobalt (Co) act as essential cofactors for enzymes involved in methanogenesis and electron transport pathways [17,18]. Trace metals improve microbial metabolism and support syntrophic interactions among anaerobic microorganisms [61]. Nano-particles have gained increasing attention because of their high surface area, catalytic activity, and ability to accelerate direct interspecies electron transfer (DIET) [19,20,62,63].

Iron oxide nanoparticles, biochar-assisted systems, and conductive materials have been reported to significantly improve methane production, reduce lag phase duration, and enhance volatile solids degradation [21,44,45]. Studies have demonstrated that conductive additives stimulate microbial electron transfer mechanisms, thereby improving overall digestion efficiency [61–63]. However, catalyst concentration must be carefully controlled because excessive nanoparticle dosage may inhibit microbial communities and negatively affect digestion stability [19,20].

SR.NO.	Substrate Combination	Optimized Ratio	Catalyst/Additive	Methane Yield Improvement	Major Findings	Reference
1	Sugarcane press mud + vegetable waste	30:70	No catalyst	Stable methane production	Improved C/N ratio and digestion stability	[14]
2	Sugarcane bagasse + cattle manure	50:50	No catalyst	Enhanced biogas yield	Better nutrient balance and hydrolysis	[26]
3	Agro-industrial waste co-digestion	Variable	Iron (Fe) additives	Increased methane yield	Improved enzymatic activity and methanogenesis	[17]
4	Sugarcane residues	Variable	Iron oxide nanoparticles	Up to 30% methane enhancement	Accelerated electron transfer and reduced lag phase	[21]
5	Sugarcane waste digestion	Variable	Iron-based catalysts	Improved methane productivity	Enhanced microbial activity	[45]
6	Sugarcane residues Vinasse	Variable	Biochar	Increased digestion efficiency	Enhanced DIET mechanism and process stability	[44]

V. RESEARCH GAPS AND FUTURE SCOPE

Despite promising laboratory-scale results, several challenges remain in the application of catalyst enhancement in anaerobic digestion systems. One of the key research gaps is the lack of precise understanding of the optimal catalyst dosage [19] and particle size require to achieve maximum efficiency. Without causing inhibition.

Additionally, the long-term toxicity and environmental impact of nanoparticles used as catalyst are not yet fully understood, raising concern about their sustainability and safe application. [20]

Another important limitation is the difficulty in the recovery and reuse of catalysts, which affects the economics feasibility of the process. Furthermost, most studies have been conducted at laboratory scale, and there is insufficient data on the performance and stability of such system is continuous and large-scale digesters.

Despite promising laboratory-scale outcomes, several technical and operational challenges remain in catalyst-assisted anaerobic digestion systems. One major research gap involves determining the optimal dosage, particle size, and long-term stability of nano-catalysts required for maximum methane enhancement without microbial inhibition [19,20]. Additionally, the environmental fate, toxicity, and recovery of nanoparticles after digestion remain insufficiently investigated.

Most existing studies have focused on batch-scale experiments, whereas limited information is available regarding continuous reactor operation, scale-up feasibility, and industrial implementation [27,31]. Advanced kinetic modelling approaches such as ADM1 have been proposed for process optimization and prediction of digestion performance under varying operational conditions [33]. Future investigations should also evaluate reactor configurations including UASB systems and thermophilic digestion technologies for large-scale biogas production [47,50].

Furthermore, integration of pretreatment techniques, conductive catalysts, and optimized co-digestion strategies may improve substrate biodegradability and methane recovery [42–45]. Techno-economic analysis, lifecycle assessment, and policy support are equally important for commercial deployment of biogas technologies in agro-industrial sectors [53–57].

Therefore, future research should focus on integrating optimized substrate with controlled catalyst enhancement strategies, while also addressing scalability, environmental safety, and cost- effectiveness to enable practical implementation.

VI. CONCLUSION

Anaerobic co-digestion of sugarcane press mud and vegetable waste under optimized conditions offers a sustainable pathway for renewable energy generation. The 30:70 substrate ratio has been widely reported as optimal, and catalytic intervention presents a promising approach to further enhance methane yield and process stability. This review provides a comprehensive framework for experimental research focused on catalyst-assisted anaerobic digestion.

Anaerobic co-digestion of sugarcane press mud and vegetable waste represents a sustainable and environmentally beneficial strategy for renewable energy generation and organic waste management. Optimized substrate combinations, particularly the 30:70 ratio of press mud to vegetable waste, have demonstrated improved methane yield, nutrient balance, and process stability. Recent advancements in catalytic enhancement using metallic additives, nanoparticles, and conductive materials further improve digestion efficiency through accelerated hydrolysis and enhanced electron transfer mechanisms.

Nevertheless, challenges associated with catalyst toxicity, large-scale implementation, process economics, and long-term operational stability still require extensive investigation. Future research should focus on pilot-scale studies, advanced reactor systems, techno-economic assessments, and environmentally safe catalyst recovery methods to support industrial-scale deployment of catalyst-assisted anaerobic digestion technologies.

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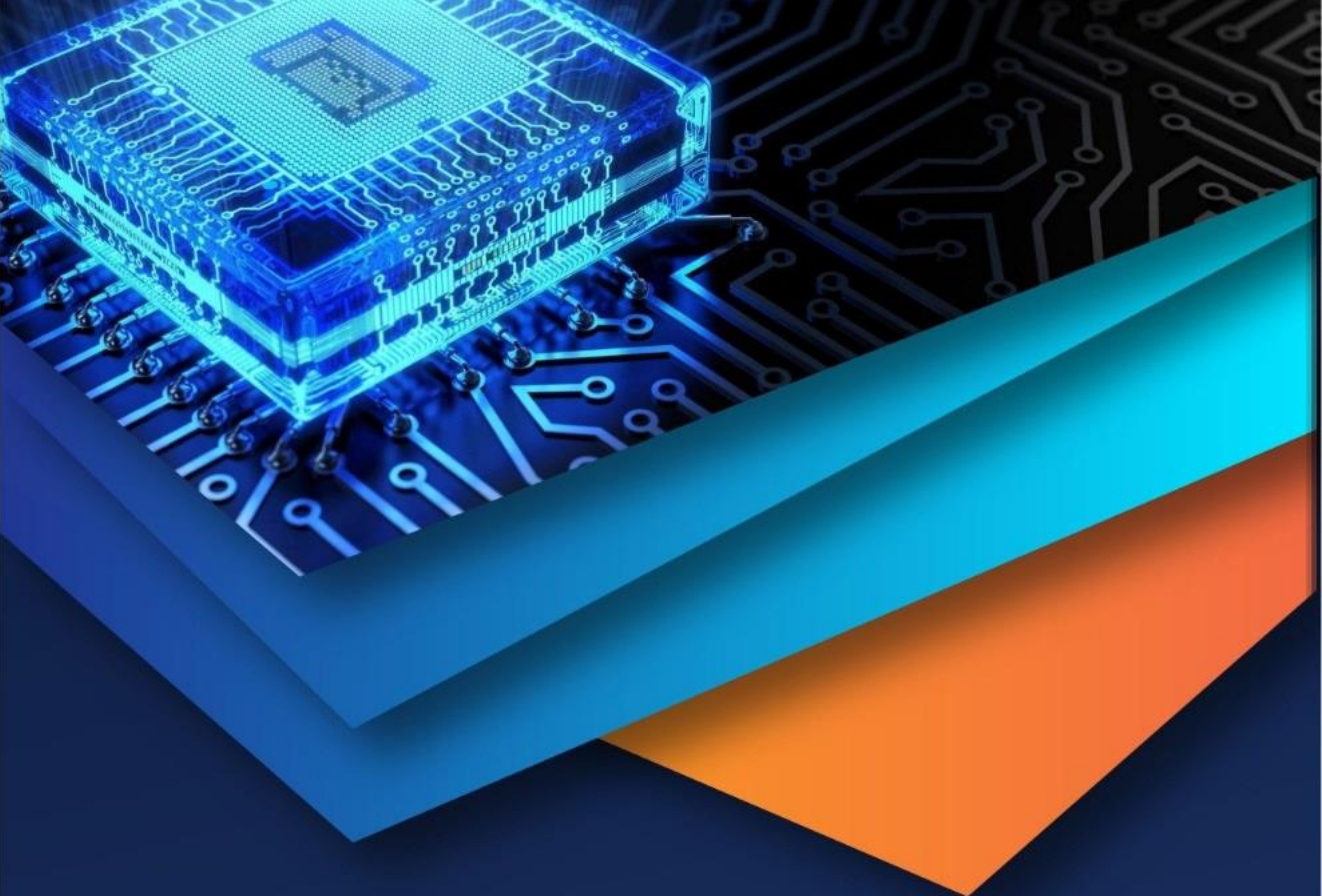

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