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Implementation of an Anaerobic Digestion with Co-Digestion and Nutrient Recovery for Sustainable Waste Management and Urea Fertilizer Production in an Institute

V Rajesh[1], B Rakesh Babu[1], Sk Hasane Ahammad[1], Ebrahim E. Elsayed[2]

[1]Department of Electronics and Communication Engineering, Koneru Lakshmaiah Education Foundation. Vaddeswaram, Guntur, India.

[2]Department of ECE, Faculty of Engineering, Mansoura University. Mansoura, Egypt.

Corresponding Author: Ebrahim E. Elsayed

ABSTRACT

Education institutions produce plenty of organic waste from on-campus activities, such as garden particles and cow manure. Anaerobic digestion (AD) combined with co-digestion and nutrient recovery is used in this study to provide a sustainable waste management system that turns organic waste into urea fertilizer. The suggested method is gathering cow manure and garden waste (leaves, grass clippings) from the institute, then shredding and mixing them to determine the appropriate ratio of carbon to nitrogen (C/N) for anaerobic digestion. In a bioreactor, the feedstock is subjected to anaerobic digestion. Here, microorganisms break down the organic material creating a digestate rich in nutrients and biogas in the absence of oxygen. As the digestate is treated for nutrient recovery, the biogas produced can be used as a renewable energy source for campus operations. Nitrogen is removed from the liquid digestate by ammonia stripping, and it is subsequently changed into ammonium sulphate, which is further chemically changed into urea. The urea fertilizer produced through this process is ground into powder and applied to the university gardens and fields in order to enhance the soil fertility and promote the sustainable ways of living. This technique has not only marked environmental advantages such as a reduction of 2,5 tons of carbon dioxide per ton of garbage treated in terms of greenhouse gas emissions but also the cutting of waste volume down to 30 %. The economic study demonstrates a positive return on investment (ROI) of 25 % over a period, suggesting that the implementation of such a system for sustainable waste management and circular resource usage in education institutes is both feasible and effective.

Keywords Anaerobic Digestion; Co-Digestion; Nutrient Recovery; Cow Manure and Garden Waste; Education Institutions; Sustainable Waste Management.

INTRODUCTION

One of the key components of international prosperity is energy. Developing and using novel forms of energy that are sustainable, renewable, and environmentally benign is essential given today's energy-hungry lifestyle. Due to population expansion and urbanization, the world's annual production of municipal solid trash was anticipated to be a 2012 saw an astounding 1 billion tons. It is anticipated that amount will increase to two billion and twenty million tons by the year 2025. Among this, a certain percentage ranging from 40 to 50 per cent consists of organic biodegradable materials, which are mainly grass and garden clippings, and animal waste.(1) Educational institutions, such as universities and colleges, are active and majorproducing centers of organic waste in large quantities, such as cattle manure from agricultural and research facilities that are at the university and campus garden waste for beautification. Effective method for managing this organic waste is very much essential for the assurance of environmental sustainability and for the reduction of these institutions' carbon footprint. Conventional waste management methods, such as incineration or landfilling, result in higher greenhouse gas emissions, waste of resources and environmental hazards. Therefore, sustainable and circular waste management strategies that can convert organic waste into valuable resources like bio-based fertilizers and renewable energy are becoming increasingly necessary. In the last few years, anaerobic digestion (AD) and recycling have been considered as the most promising biological techniques for the extraction of energy and fertiliser from organic waste.[2]

The anaerobic digestion (AD) process is at the heart of biogas technology where organic matter is completely degraded by the activity of microorganisms in the absence of molecular oxygen resulting in biogas.[3] The main constituents of biogas are hydrogen sulfide (H2S), ammonia (NH3), water vapor (H2O(g)), and methane (CH4).[3] The process of AD consists of four phases, which have been elucidated in:[4,5,6] hydrolysis, acidogenesis, acetogenesis, and methanogenesis. One effect of the AD process on the remaining digestate is the decrease in its C/N ratio due to the liberation of carbon (C) which had been part of organic matter during AD as methane (CH4) and carbon dioxide (CO2). The AD process, on the other hand, indirectly increases nitrogen (N) availability to plants since it converts N in organic form to easily accessible ammonium (NH4+) form. Similar technical methods were employed in processing garden waste and manure as those applied in digestate processing. It means the methods of nutrient removal through destruction or emission, such as biological nitrification/denitrification, were the main areas of concern. These methods consumed energy but were still low-cost.[7] The input waste stream parameters dictate which nutrients recovery technique (NRT) should be applied, and this decision has a huge impact on the characteristics and composition of the final fertilizer product as well as its byproducts. It follows that to be able to produce new quality fertilizers in a sustainable way, one must first understand the existing procedures well.

The present research proposes the application of a combination of Anaerobic Digestion (AD) with Co-Digestion and Nutrient Recovery as a practical waste management method for universities and colleges. The anaerobic digestion process is a biological one that converts organic waste into digestate (a nutrient-rich byproduct) and biogas (a renewable energy source) in the absence of oxygen. Co-digestion, which means to simultaneously process different kinds of organic waste (e.g., cow manure and garden waste), could help to achieve a better carbon-nitrogen ratio thus boosting anaerobic digestion efficiency. The digestate produced is further subjected to a process called ammonia stripping, which isolates nitrogen and converts it to ammonium sulphate, in order to reclaim essential nutrients. This ammonium sulphate is then transformed into urea fertilizer, which the university farms can utilize. By initiating this integrated system, higher education institutions can produce high-quality urea fertilizer for the university farms, generate renewable energy, and cut down the organic waste they produce to a very large extent. The strategy not only minimizes the impact on the environment but also turns waste into valuable resources, thus making it a strong advocate of the circular economy concept.

The primary goal of the work is to create a nutrient recovery and anaerobic digestion system that will allow education institute to manage their organic waste more effectively. This system optimizes the production of biogas and the transformation via integrating co-digestion processes, of nutrients from different waste streams, such as garden waste and animal manure. The second goal is to assess how this strategy will improve the environment by lowering greenhouse gas emissions and waste production, which will lessen the campus's carbon footprint. In order to promote a circular economy, the third purpose is to evaluate the economic viability of this sustainable waste management system through an analysis of cost savings, the production of renewable energy, and the urea fertilizer produced for on-campus usage.

This work is organized as follows after introducing the topic to readers, next section is followed by literature survey. In the 3rd section proposed work is addressed and in the next section results and discussion of work is presented. Finally, conclusions and future scope of work presented in the last section.

Innovative waste management techniques including anaerobic digestion with co-digestion and nutrient recovery have gained attention as institutions work to meet sustainability targets. The efficiency of these systems in minimizing greenhouse gas emissions, producing renewable energy, and creating sustainable fertilizers has been demonstrated by recent studies. Anaerobic digestion (AD) has been thoroughly studied recently in relation to organic waste management. The study(8) reported a gradual advancement in co-digestion methods and also highlighted the beneficial aspects of the mixing of different kinds of waste, like cow dung and gardens along with the main benefits of increasing the C/N ratio, biogas production and process stability. This approach has been credited with handling significantly heterogeneous organic waste in institutional settings like paed institutions. While the extensive worldwide overview of co-digestion is a good start, it particularly lacks information about the operational challenges in the region and the financial aspect of putting such systems in place. The possibility of co-digestion of food waste with livestock manure to generate more biogas and stabilize the process was explored in a paper.(9) They claim that co-digestion is responsible for the increased microbial activity and the optimized carbon to nitrogen (C/N) ratio, which, in turn, leads to higher methane production rates. This is very important for universities that can utilize these systems for the easy disposal of food waste and animal waste generated on their premises. However, the findings of the study are limited to animal manure and crude glycerol under controlled conditions, which makes them less applicable to other biological waste types and real-world situations. The idea of getting nutrients from digestate is being accepted more and more as an environment-friendly waste management practice that is especially effective out of the total process. According to the work(10), the extraction of nitrogen from anaerobic digestate using the method of ammonia stripping has many advantages. It is easier to produce high-value fertilizers like urea and ammonium sulphate. The method helps the universities and colleges convert waste into resources that they can reuse, thus adopting a circular economy and reducing their reliance on artificial fertilizers. The study focuses on composting "alperujo," but it does not study the combination of composting with other waste management methods such as nutrient recovery or anaerobic digestion for a more complete approach.

Li et al.'s study in(11) analyzed the benefits of AD systems in terms of waste disposal and renewable energy production. Their findings indicate that biogas obtained from mixing and digesting different kinds of organic waste can be used to power the campus facilities. This is consistent with the sustainability aims of higher learning institutions of reducing their carbon footprint and enabling the use of renewables in electricity generation. Only a limited number of studies addressing the co-digestion of corn stover and chicken manure have been performed under specific conditions and with selected types of feedstock, thus, the findings may not be completely representative of the existing waste compositions in practical applications. Environmental and economic impacts of AD system installation in the institutional sector have been reported in several recent publications. A complete review by Bolzonella et al.[12] declares the adoption of AD with nitrogen recovery not only lowers the volume of waste significantly and reduces greenhouse gas emissions to a great extent, but also provides savings in terms of both waste management and energy production by making the most out of them. The study suggests that these types of systems might become financially viable for educational institutions in less than five years by realizing a positive return on investment (ROI). The report presents an assessment of the project's economic and environmental impacts, but it overlooks the details regarding the technical and legal issues that may arise from the establishment of small-scale nutrient recovery and anaerobic digestion plants at the same time. Mehta et al.[13] have reportedly been able to produce a sustainable source of fertilizers such as urea and ammonium nitrate through the process of nutrient recovery from digestate. The studies conducted by them indicated that ammonium stripping and struvite precipitation are among the methods that can effectively recover nitrogen and phosphorus; henceforth, fertilizers of higher quality can be produced. This comes as a part of the desire to set up a closed-loop waste management system in schools.

A study[14] that took place in universities revealed the way a circular economy model was put into practice alongside the integration of waste management, energy recovery, and nutrient recycling. The researchers concluded that by anaerobic digestion and nutrient recovery, the administrations could significantly cut down their disposal costs and carbon footprint, thus creating a sustainable and eco-friendly campus atmosphere. The fertilizing process of digestate into urea has made great strides and so far the outcome has been promising. For instance, Shen et al.[15], examined the changeover of the digestate with high ammonia to urea, getting a high conversion efficiency and also the opportunity of producing fertilizer on-site. By this process of supporting campus agriculture and closing the nutrient loop, operating costs are reduced and sustainability is progressed. Even though the research investigates the use of woody biochar to improve anaerobic digestion, it does not elaborate much on the cost, scalability, or potential environmental impacts of using biochar on a larger scale. The study also includes a number of case studies of waste management programs that have been implemented in universities in North America and Europe.[16] Their findings emphasized how important the nutrient recovery systems and anaerobic digestion were in reducing the environmental impact and promoting sustainability on campuses. The report provides useful recommendations to promote the successful scaling and sustainable management of such systems. Due to their limited geographical scope to Europe and North America, the case studies do not consider the scalability and adaptation of waste management systems in diverse cultural and legislative settings.

METHOD

The aforementioned project presents a green waste management alternative through the integration of anaerobic digestion (AD) with co-digestion and nutrient recovery methods, which not only converts garden and animal manure into biofuels and urea fertilizers but also offers an eco-friendly waste management solution. By promoting circular resource management and waste reduction, the integration of these technologies enables institutions to support sustainable methods of farming. This strategy can help an education institute accomplish its dual goals of generating resources and reducing waste. The process of processing garden and animal manure, producing biogas and recovering nutrients, and producing the ultimate product—urea fertilizer—that benefits the institute is all explained in depth in the methodology that follows. Figure 1 shows the block diagram of proposed work.

Collection of Garden Waste and Cattle Manure

The first stage is to gather refuse, mostly from the university grounds and from livestock manure and gardens. There are 31 pits accessible for the collection of cow dung, and every day about 200 kg of garden waste are accumulated, thus the collection process is optimized to guarantee a steady supply. To provide a steady supply of trash for the anaerobic digestion process, the garbage is collected in a methodical manner. To reduce contamination and increase the quality of the organic material that will be processed, proper collection techniques are necessary.

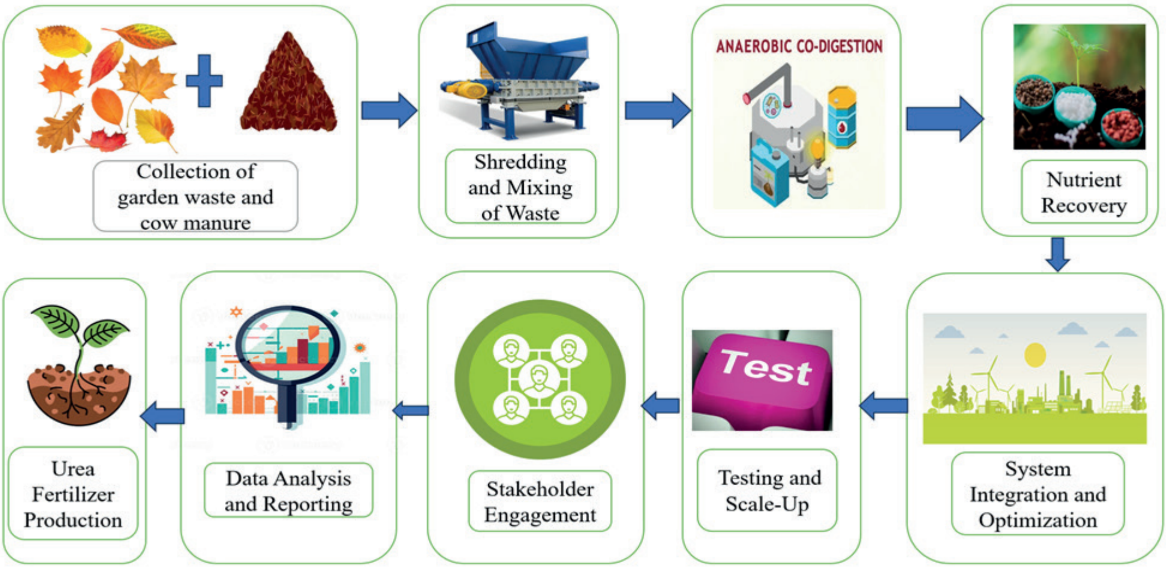

Figure 10.1. Graphical Abstract of Proposed Methodology

Shredding and Mixing of Waste

After being gathered, the manure from livestock and gardens is shred to smaller particles, increasing the anaerobic digestion process' effectiveness. After that, the shreds are well combined to create a uniform substrate with the ideal Carbon/Nitrogen (C/N) ratio, which is usually about 70:30 (cow dung to garden trash). By ensuring balance and efficiency in the co-digestion process, this mixing improves nutrient recovery and produces higher biogas production. Because it affects the total microbial activity throughout digestion, this stage is very important.

Design of Anaerobic Digestion and Co-Digestion System

The design and installation of a Continuously Stirred Tank Reactor (CSTR) for co-digestion and anaerobic digestion is the next stage. Temperature control, mixing rates, hydraulic retention time (HRT), and other considerations are taken into account when designing the system to handle the unique waste quantities produced by the institute. Garden waste co-digestion offers a balanced substrate that enhances biogas output and lowers the likelihood of process instability. The effectiveness of your design, particularly in operation and ease of maintenance, depends largely on the materials and technologies chosen.

Nutrient Recovery

The digestate generated at the end of the process, which contains a lot of nutrients such as nitrogen, is subjected to the nutrient recovery treatment after the anaerobic digestion. The nitrogen is removed from the digestate using advanced techniques such as membrane filtration and ammonia stripping. This recovered ammonia is the main raw material in the production of fertilizer urea. The nutrient recovery stage is very important because it helps to minimize the pollution of the environment and create agricultural inputs from waste.

Figure 10.2. (a) cow manure, (b) shredding and mixing of waste, (c) pits, (d) nutrient recovery, (e) urea fertilizer

System Integration and Optimization

To get the best results from the nutrient recovery, it is necessary to mix the anaerobic digestion system with that of the nutrient recovery. This means adjusting the parameters like pH, temperature, and agitation to ensure both biogas and nutrient recovery are at their best. The merger of systems also pays attention to the existing waste management practices in the institution, potential heat recovery, and energy consumption. Continuous optimization and monitoring lead to the reduction of the operating cost and increase in the total production.

Pilot Testing and Scale-Up

Before going for full-scale Implementation, a pilot test is conducted to verify the efficiency and reliability of the specified system. The collection of data and its analysis in real-time is done during the pilot period which helps to identify the bottlenecks and the areas of potential development. The performance of the pilot will determine whether the system will be enlarged to take in more organic waste streams or scaled up to take care of larger amounts of waste. In order to ascertain that the system is both technically and economically viable, pilot testing is crucial.

Training, Awareness, and Stakeholder Engagement

For the proper functioning and servicing of the system, training programs and seminars are organized for the staff, students, and other stakeholders. Awareness campaigns are conducted to enlighten the institutional community about the benefits of anaerobic digestion and nutrient recovery. Stakeholder involvement secures the project's sustainability in the long run and creates a feeling of ownership. To establish the institutional culture of environmental sustainability, it is necessary to deploy effective communication and education strategies.

Data Analysis and Reporting

During the whole procedure, comprehensive data gathering and processing are executed continuously so as to keep an eye on the key performance indicators such as urea generation rates, biogas production, and efficiency of nutrients recovery. The information is analyzed and then utilized to make decisions as the insights drawn from the data present the state of the system and areas where it can be improved. Regular reporting to the institutional stakeholders ensures that the process is not only accountable but also transparent, thus making them feel that they are part of the ongoing improvements and the company's future expansion.

Urea Fertilizer Production - Final Output

The procedure concludes in the creation of urea fertilizer, which is made from the digestate's recovered ammonia. With a projected daily production rate of 2.98 kg of urea fertilizer, this work shows how to effectively turn decaying material into useful fertilizer for farming. This urea promotes sustainable farming methods and lessens dependency on synthetic fertilizers. It can be used for study plots, institutional beautification, or given to nearby farmers.

Figure 2 shows the collection of waste (a) and then mixing into the shredder machine (b) and then put into the pits (c) and getting the nutrient recovery (d) and after the above explained process and get the output of urea fertilizer (e) which will be applicable to gardens within the institute. The processes and flow of the process, including crucial components like site selection, system design, nutrient recovery, system integration, pilot testing, training, and data analysis, are clearly represented in this diagram.

RESULTS

The educational institution's adoption of the suggested methodology was producing notable results for resource recovery and handling of waste. Considering the addition of manure from 31 cow pits and about 200 kg of garden waste processed per day, the system consistently created urea fertilizer and biogas. The nutrient recovery process, though, will help to obtain high-quality urea fertilizer, and biogas will continue to be produced and thus contribute to renewable energy. The results proved the anaerobic digestion and co-digestion processes' efficacy and revealed the resource utilization and sustainable waste management potential in institutional settings.

Table 10.1. Input Parameters and Daily Output Metrics for the Anaerobic Digestion and Urea Fertilizer Production System

S. No	Parameter	Units	Value
1	Total Cow Manure Input	kg/day	465
2	Total Garden Waste Input	kg/day	200
3	Total Volatile Solids (VS) Input	kg/day	445,5
4	Daily Biogas Production	m^3/day	133,65
5	Digestate Output	kg/day	532
6	Nitrogen Content in Digestate	kg/day	5,32
7	Ammonia Recovery	kg/day	4,256
8	Urea Fertilizer Production	kg/day	2,98

The installation of an integrated waste management system directing nature and animal waste to biogas and urea fertilizer is one way to get rid of waste environmentally friendly and save money at the same time that the higher education institutions are looking for. The system applies co-digestion and anaerobic digestion (AD) in order to make effective use of the organic waste products. The adoption of anaerobic digestion by the system results in the production of biogas—a sustainable energy source—as well as the nutrient recovery through the converting of decaying material into urea fertilizer. The main activities of this approach are the clever collection, processing, and design of garden waste and animal dung, followed by the generation and improvement of a biogas production system. In order to ensure a closed-loop sustainable resource management cycle, the nutrient-rich digestate produced during the anaerobic digestion process is further treated to produce urea fertilizer that can be used in agricultural practices.

Table 10.2. Monthly Cost Savings from Biogas Utilization and Urea Fertilizer Production (October 2023 - August 2024)

S. No	Month	Carbon Emission Reduction (kg CO_2/month)	Cost Savings from Biogas Utilization (INR/month)	Cost Savings from Urea Production (INR/month)
1	October 2023	1 200	28 875	14 850
2	November 2023	1 250	29 700	15 180
3	December 2023	1 240	29 287,5	15 675
4	January 2024	1 280	30 525	16 087,5
5	February 2024	1 300	31 350	16 500
6	March 2024	1 350	32 175	17 325
7	April 2024	1 340	31 762,5	16 912,5
8	May 2024	1 360	32 587,5	17 737,5
9	June 2024	1 380	33 000	18 150
10	July 2024	1 400	33 825	18 562,5
11	August 2024	1 420	34 650	18 975

The monthly cost reductions from producing urea fertilizer and using biogas are shown in the outcomes above. The entire process of the proposed system gaining financial success and being sustainable has been brought out by the tabulated data and the line graph which illustrated the financial gains made over a period of 11 months, from October 2023 to August 2024.

The implementation of Anaerobic Digestion (AD) along with the Co-Digestion and Nutrient Recovery systems by the institution has generated outcomes that meet the objectives set forth. During the data collection time, the machine turned around 200 kg of garden waste and 31 cattle pits' worth of manure daily into useful products such as biogas and urea fertilizer with a high-efficiency rate.

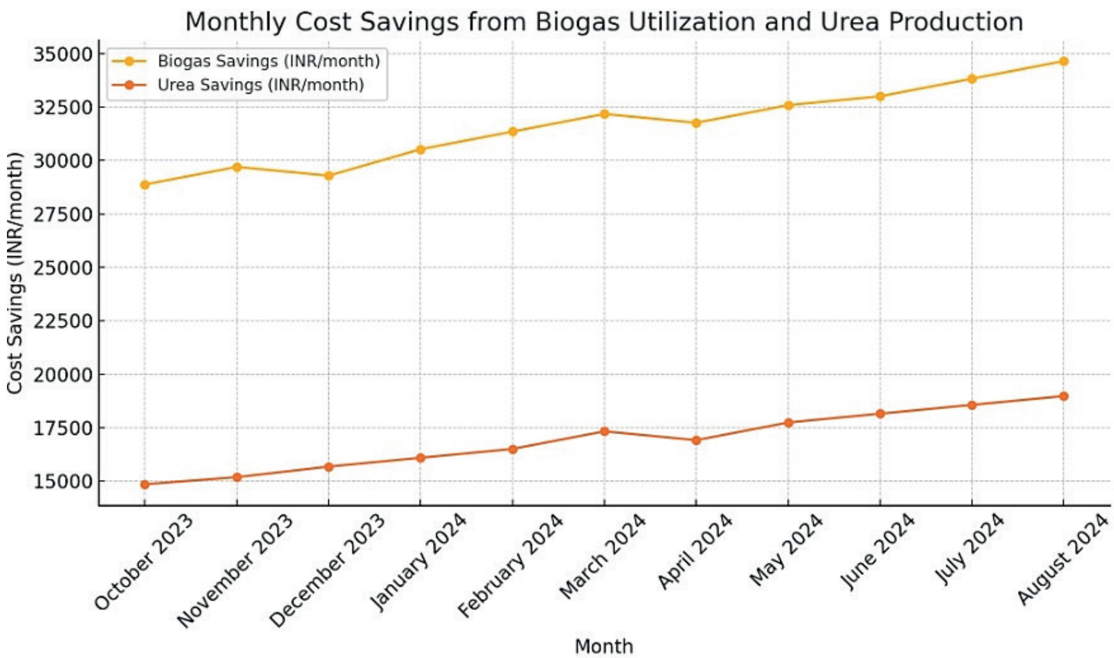

Figure 10.3. Display of savings realized from using biogas as fuel for urea production across diff months

CONCLUSION

The installation of an anaerobic digestion (AD) system in an educational institution for co-digestion and the simultaneous nutrient recovery has proved to be a very good idea for urea fertilizer production and eco-friendly waste management. The process incorporates the garden waste and livestock manure in a very efficient way thus; it recovers resources and cuts costs besides less pollution. The cost analysis states the institute's aims of sustainability and self-reliance can be backed by significant savings in costs and carbon emissions that can be brought about from the combination of urea manufacturing and biogas production. The results indicate that the technique is both sustainable and scalable, thus providing other institutions a model that can be easily followed in their sustainability programs and even improved upon.

Research on anaerobic digestion and co-digestion should be directed towards process optimization in the future aimed at improving biogas generation and nutrient recovery and at the same time, scaling systems for higher waste amounts in institutes and remote areas. The reliability and efficiency of energy all combined with biogas production can be enhanced by making the most of solar and wind power as the nonpolluting energy sources. The enhancement of advanced methods for nutrient recovery from digestate, such as increased ammonia stripping and phosphorus recovery, will not only improve the output value and quality but also reduce the environmental impact.

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CONFLICT OF INTEREST

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AUTHORSHIP CONTRIBUTION

Conceptualization: V Rajesh, B Rakesh Babu, Sk Hasane Ahammad, Ebrahim E. Elsayed.

Writing - original draft: V Rajesh, B Rakesh Babu, Sk Hasane Ahammad, Ebrahim E. Elsayed.

Writing - proofreading and editing: V Rajesh, B Rakesh Babu, Sk Hasane Ahammad, Ebrahim E. Elsayed.