Optimized hydrodynamic cavitation-based Pretreatment Strategies to enhance residual Biogas Yield from Solid Digestate and Struvite Recovery from Liquid Fraction

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Abstract

Digestate valorisation is essential for improving the sustainability and efficiency of anaerobic digestion systems. This study explores an integrated approach combining hydrodynamic cavitation (HC) pretreatment of the solid fraction with struvite precipitation from the liquid fraction to enhance energy and nutrient recovery. Solid and liquid fractions of digestate were separated and processed independently. HC pretreatment of the solid fraction significantly improved biochemical methane potential (BMP), increasing methane yield by over 95% and reducing the lag phase during anaerobic digestion. Kinetic modeling indicated accelerated biodegradation rates, and the energy output from additional methane production exceeded the input required for cavitation, confirming the process as energy positive. In parallel, the liquid fraction was subjected to struvite precipitation by adjusting pH and dosing magnesium chloride. The precipitate was characterized using X-ray diffraction and scanning electron microscopy, confirming the formation of crystalline struvite with high purity. Nutrient recovery efficiencies exceeded 80% for both ammonium and phosphate. A mass and energy balance revealed that the integrated HC and struvite processes achieved efficient conversion of residual organics into biogas and dissolved nutrients into fertilizer. The results demonstrate a feasible and scalable strategy for digestate valorization, offering a dual benefit of enhanced biomethane recovery and nutrient recycling. This approach contributes to the circular economy and improves the sustainability of biogas plants.

Keywords: Digestate valorization, hydrodynamic cavitation, struvite precipitation, residual biogas enhancement

1. Introduction

Anaerobic digestion generates renewable energy but leaves behind digestate rich in residual organics and nutrients. Effective valorization of this digestate is essential for improving the overall sustainability of biogas plants. Integrating HC pretreatment for solids with struvite recovery from the liquid fraction can thus form a closed-loop valorization scheme: maximize methane from organics while capturing dissolved N and P as fertilizer. In this study, we optimized HC pretreatment conditions for the solid digestate and evaluated the effects on biochemical methane potential (BMP) and kinetics. We also precipitated struvite from the treated liquid fraction and characterized the precipitate by X-ray diffraction and electron microscopy. Finally, we present a mass-and-energy balance to assess overall system efficiency. The results are compared to recent literature to contextualize the benefits of the combined treatment strategy.

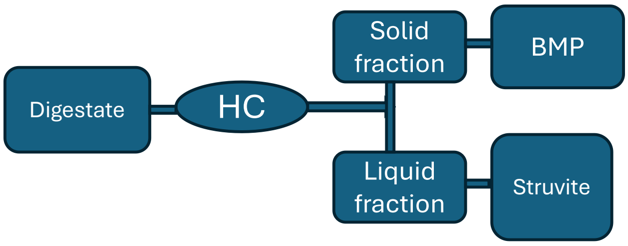

Fig. 1: Objective of the study

2. Materials and Methods

2.1. Sample collection, characterization and HC pretreatment

Fresh digestate was collected from the AD plant situated in Ireland. The primary feedstocks of the AD plant were WWTP Sludge, grass silage and chicken manure. The sample was stored at 4°C to avoid further methanogenesis and methane production. The digestate sample was characterized according to the standard method (APHA 2005) (Table 1).

An HC rig, similar to the one previously reported by *(Islam & Ranade, 2023)*, introducing a vortex-based cavitation device with a nominal capacity of 1.2m^3/h was used for the cavitation pre-treatment of spent wash and vinasse. Samples of pre-treated sludge were collected after different numbers of passes through HC device (20, 50 and 200 passes). All the treated and untreated samples were then characterized and used for the BMP. Struvite was extracted by precipitation method and mixing equimolar Mg with N:P. The molar ratio of N: P was adjusted using $MgCl_2$. The mixing was done in an orbital shaker for 1hr at 200 rpm in room temperature. The formed precipitate was centrifuged for 10 minutes at 3000 rpm, cleaned with deionized water, and dried in a drying oven for 24 hr at 40 °C.

Table 1. Characterization of the digestate

Parameters (gm/L)	Digestate
TS	8.99
VS	64.37
COD	101.55
TOC	27.1
C	43.87
H	6.94
N	3.01
S	1.1
TP	0.456
TN	1.35
Ammonia	0.288

2.2 Struvite precipitation and characterization

For struvite precipitation 250 ml beaker was used filled with 100 ml digestate supernatant. The pH was adjusted to 9 with 1 M HCl and 1 M NaOH. Then $MgCl_2$ was added as a Mg source at a molar ratio of 1.2: 1 (Mg: P). The system was kept stirring over night and struvite was recovered through centrifugation and washed three times with deionized water.

3. Results and Discussion

3.1 BMP enhancement

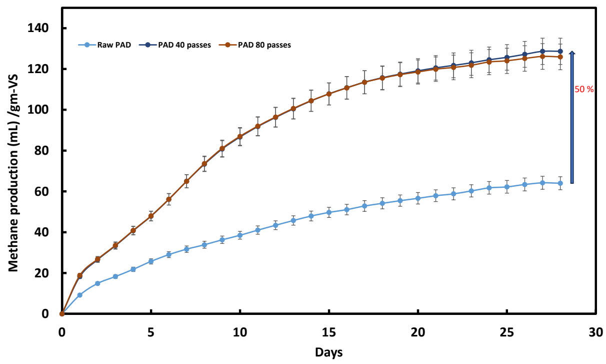

Fig. 2: BMP enhancement using HC pretreatment

Figure 1 shows the cumulative methane production over 30 days for raw primary anaerobic digestate (PAD) and HC-pretreated digestate subjected to 40 and 80 passes. The data clearly demonstrate a significant enhancement in methane yield due to hydrodynamic cavitation (HC) pretreatment. The raw PAD achieved a final methane yield of approximately 65 mL/g-VS, whereas pretreated with 40 passes reached around 125 mL/g-VS, and 80 passes yielded slightly higher at ~130 mL/g-VS. This corresponds to an impressive ~95% increase in methane production for the 80-pass sample compared to the untreated control. In addition to total methane yield, the rate of methane production is substantially accelerated in HC-treated samples. The curves for both 40 and 80 passes show a rapid initial rise, indicating shortened lag phases and enhanced biodegradation kinetics (Repinc et al., 2022). The diminishing difference between 40 and 80 passes suggests diminishing returns beyond 40 passes, implying that 40 passes may represent an optimal trade-off between performance and energy input (Islam & Ranade, 2024).

3.2 Struvite precipitation

XRD analysis was performed on the precipitate obtained from anaerobic digestate and the diffraction data were collected across a 2θ value of 6° to 90°, to determine the crystalline phases present. The XRD pattern shows the characteristic peak close to that of the struvite pattern standard (Standard XRD data for struvite: PDF# 01-077-2303). However, some impurities are present in the recovered precipitate. Furthermore, the morphological analysis reveals the presence of well-formed, faceted crystals exhibiting a predominantly prismatic to cuboidal morphology, which is characteristic of struvite ($MgNH_4PO_4 \cdot 6H_2O$). The crystals appear as elongated rectangular prisms and equant cubic blocks, suggesting controlled crystal growth under stable supersaturation conditions. This morphological regularity aligns with previous reports of struvite precipitation under optimized pH and ionic strength (Đurđević et al., 2020).

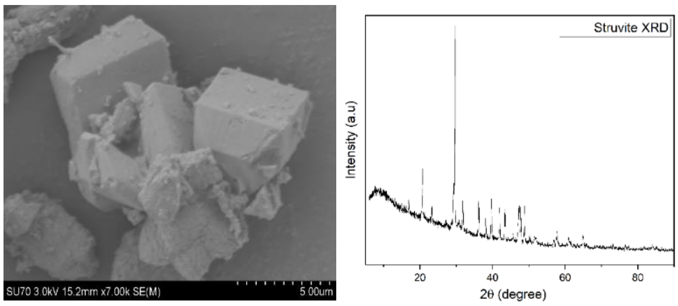

Fig. 3: SEM and XRD of struvite precipitation from digestate

4. Conclusion

Hydrodynamic cavitation pretreatment significantly enhanced the methane yield and biodegradation rate of anaerobic digestate, while reducing the lag phase. Struvite precipitation effectively recovered over 80% of nitrogen and phosphorus from the liquid fraction as high-purity crystals. Together, these integrated processes offer a sustainable and energy-efficient approach for complete digestate valorization.

References

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