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Energimyndighetens titel på projektet – svenska
Maximera biogasproduktionen med efterbehandlingstillämpningar

Energimyndighetens titel på projektet – engelska
Maximizing residual biogas recovery with post-treatment application

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Nyckelord
Post-treatment, anaerobic digestion, methane, biogas, digestate

Förord

This report presents the findings of a systematic review and meta-analysis on the impact of post-treatment strategies on methane recovery from digestate. The study was conducted to assess the efficiency of different post-treatment methods and their potential to enhance biogas production, contributing to the advancement of anaerobic digestion technologies.

The research was carried out in accordance with established methodological guidelines, ensuring a comprehensive and unbiased evaluation of existing literature. The results provide valuable insights for researchers, policymakers, and industry stakeholders, supporting informed decision-making in the field of renewable energy and waste management.

Innehållsförteckning

Sammanfattning

Anaerobic digestion (AD) is a promising technology for waste valorization and renewable energy generation. However, a substantial fraction of the energy potential remains in the digestate, limiting methane (CH_4) recovery and overall process efficiency. This study employs a systematic review and meta-analysis to assess the effectiveness of post-treatment strategies in enhancing CH_4 yield from digestate derived from various feedstocks. The analysis reveals that post-treatment efficiency is strongly influenced by feedstock composition, with sewage sludge and agricultural residues being the most studied substrates. Among post-treatment methods, physical (e.g., thermal hydrolysis, ultrasonication) and biological (e.g., enzymatic hydrolysis) strategies demonstrated the highest CH_4 yield improvements (>330 NmL/g VS), whereas chemical and physicochemical treatments resulted in lower methane recoveries (<220 NmL/g VS) due to potential microbial inhibition. The findings highlight the need for integrated post-treatment approaches and comprehensive techno-economic evaluations to facilitate large-scale implementation and optimize biogas production.

Summary

Anaerobic digestion (AD) is a sustainable process that combines waste management, nutrient recycling, and clean energy production. However, a significant portion of the feedstock's energetic potential remains untapped in the digestate, leading to suboptimal methane (CH_4) recovery and reduced process efficiency. This project aims to evaluate the effect of post-treatments on digested materials from various feedstocks, as well as their cost-efficiency, through a systematic review and meta-analysis. The results will provide valuable insights for researchers, enabling them to optimize post-treatment research. Moreover, industry stakeholders, including equipment producers and technology developers, will be able to apply the project's findings to develop more effective and commercially viable solutions. The increased methane recovery achieved through efficient post-treatments will contribute to the expansion of renewable energy generation and assist in meeting global decarbonization targets.

Inledning/bakgrund

The increasing global energy demand of 46% by 2060, and the need to expand the share of renewable energy to 65% by 2050 to contain global warming, highlights the crucial role of improving renewable energy production. In order to achieve that, one promising approach is the development of AD, a sustainable and circular process which combines waste management, clean energy production and nutrient recycling. In AD, organic biomasses are degraded in digesters in the absence of O_2, generating biogas (mainly composed of CH_4 and CO_2) and residual undigested material called digestate. The produced biogas can be used for electricity and heat production or upgraded into vehicle fuel and even liquefied to be used as fuel for maritime transport. Digestate, on the other hand, can be used for soil enhancement and fertilization. However, a significant portion of the energetic potential contained in the feedstock remains in the digestate. It is estimated that only 43-70% of biomass is degraded during AD of various feedstocks, such as manure, agricultural residues, sewage sludge and food waste. The remaining material is a mixture of recalcitrant compounds that are hardly digested and biodegradable organic matter, which remained in the reactor for a period shorter than the nominal retention time. The incomplete degradation of feedstocks also leads to challenges such as higher digestate production per GWh (resulting in higher digestate transportation cost and emissions), gas emissions during storage and high nutrient and carbon content, which increases digestate processing requirements for land application. Post-digesters can slightly improve organic matter removal, but even then, 23%-50% of the methane potential is still lost. The application of post-treatments has been shown to increase degradation of the recalcitrant materials which are not converted even in the post-digester, maximizing the recovery of methane from the available feedstocks and therefore the overall efficiency of the process. Preliminary analysis conducted by our research group shows that ammonia stripping post-treatment can improve methane recovery by up to 215% from digested material from reactors fed with sewage sludge. Additionally alkaline post-treatment has proven to be effective in recovering methane from digestate sourced from manure fed reactors. A meta-analysis performed with literature data on the effect of different post-treatments in digested material coming from various feedstocks could help light the way to a more efficient methane recovery. The results would show where more effort is needed (e.g. least studied types of feedstock and reactor configurations) and which post-treatments are the most efficient and least costly for each situation.

Genomförande

This systematic review and meta-analysis followed Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) guidelines and focused on literature covering the application of digestate in biogas production. The search was conducted in the Web of Science database using the query 'TS=(digestate AND (biogas OR methane OR biomethane))', restricted to articles in English published between 1945 and 2023. This initial search yielded 2,417 results.

I. Screening criteria

The screening involved a three-stage process with strict inclusion criteria: Digestate Mention: Articles without direct mention of digestate, including relevant synonyms, were excluded. Post-treatment: Articles were excluded if they did not discuss post-treatment processes for digestate. Biogas Production: Studies were included only if biogas production from digestate was clearly stated, regardless of whether data were presented in text or graphical format. Review articles were excluded to focus on primary research.

II. Data extraction eligible

Articles were indexed with a unique identifier. Data extraction followed a standardized protocol, with each article evaluated for specific categories, as outlined in the data extraction table. Entries were normalized (e.g., consistent terminology for substrates such as "pig manure") to streamline data aggregation and analysis. Units were recorded in full metric notation (e.g., "60 mL/g VS" or "8% (w/w)").

For graphical data, WebPlotDigitizer (https://automeris.io/) was used to retrieve numerical values. Where chemical composition data were present but did not align with existing table columns, new columns were added to ensure comprehensive data collection.

Resultat

The study evaluated the impact of different post-treatment strategies on CH_4 yield from digestate, considering its organic fractions: liquid, solid, and total. The majority of the studies focused on the total fraction of the digestate (42%), followed by the solid fraction (34%) and the liquid fraction (24%) (Figure 1).

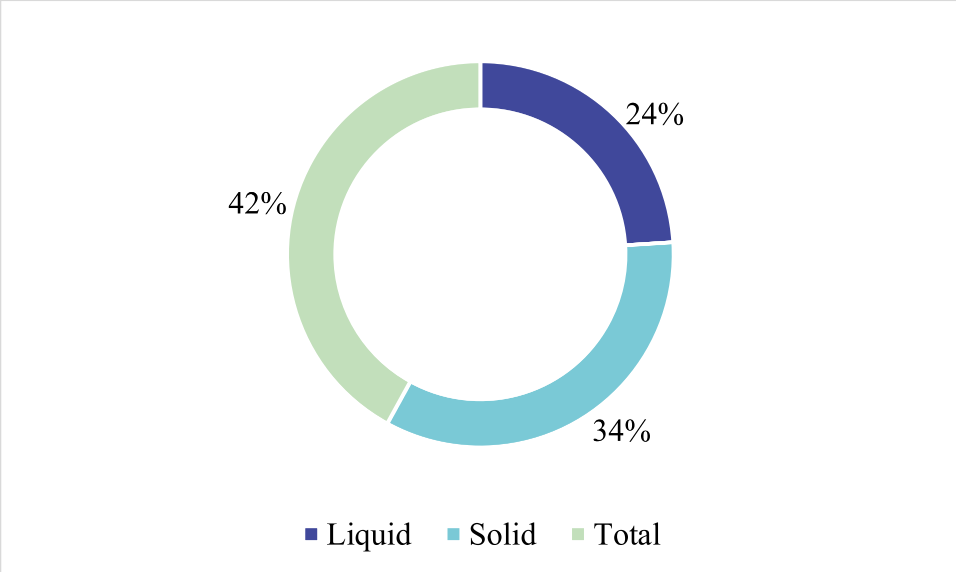

Figure 1. Distribution of the organic fraction of the digestate (i.e., solid, liquid, and total) (%) based on data from the systematic review.

Regarding feedstock distribution, sewage sludge was the most studied substrate (37%), followed by agricultural biomass (31%) (Figure 2).

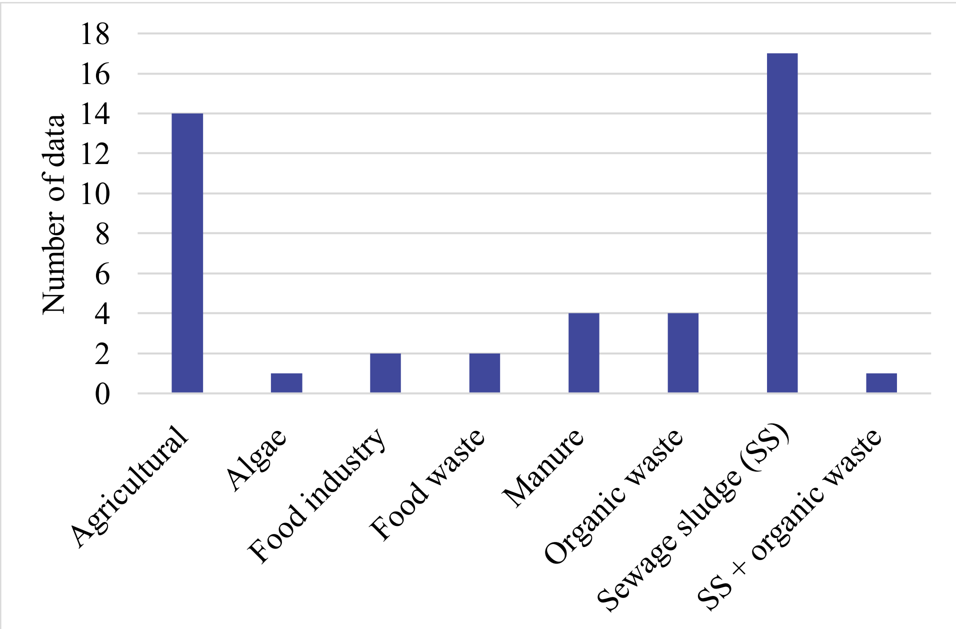

Figure 2. Proportion of different digestate sources analyzed in the systematic review.

From a geographical perspective, Italy and China accounted for the highest number of studies (n = 8 each), followed by the United Kingdom (n = 4), Germany (n = 3), and France (n = 3) (Figure 3).

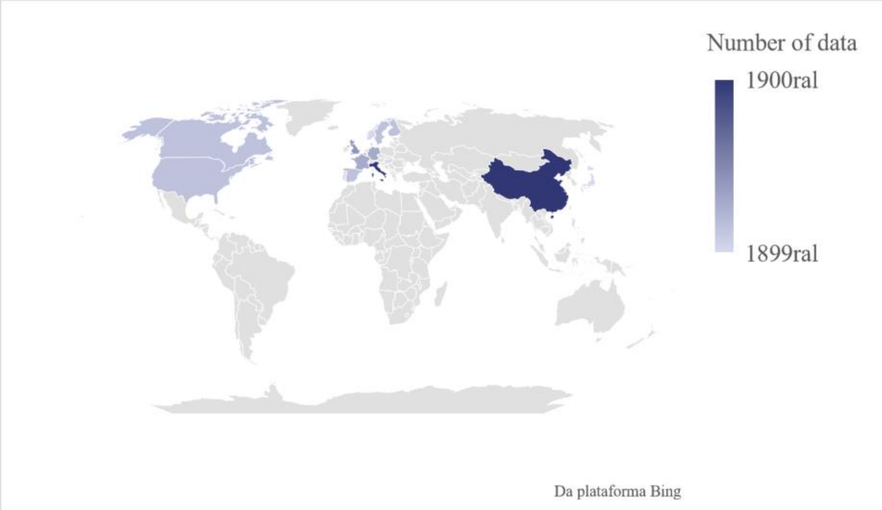

Figure 3. Geographical distribution of studies applying post-treatment to digestate in the systematic review.

Post-treatments were categorized into four main types: physical, chemical, biological, and physico-chemical. Physical post-treatments accounted for approximately 60% of the studies (Figure 4). However, among all strategies, physical and biological post-treatments exhibited the highest improvements in CH_4 yield.

Physical post-treatments, such as thermal hydrolysis and ultrasonication, led to the highest average CH_4 production, exceeding 370 NmL/g volatile solids (VS). Similarly, biological post-treatments achieved an average CH_4 yield of approximately 330 NmL/g VS, with more stable performance across different feedstocks.

In contrast, chemical and physicochemical post-treatments resulted in significantly lower CH_4 yields, with averages of 213 and 189 NmL/g VS, respectively.

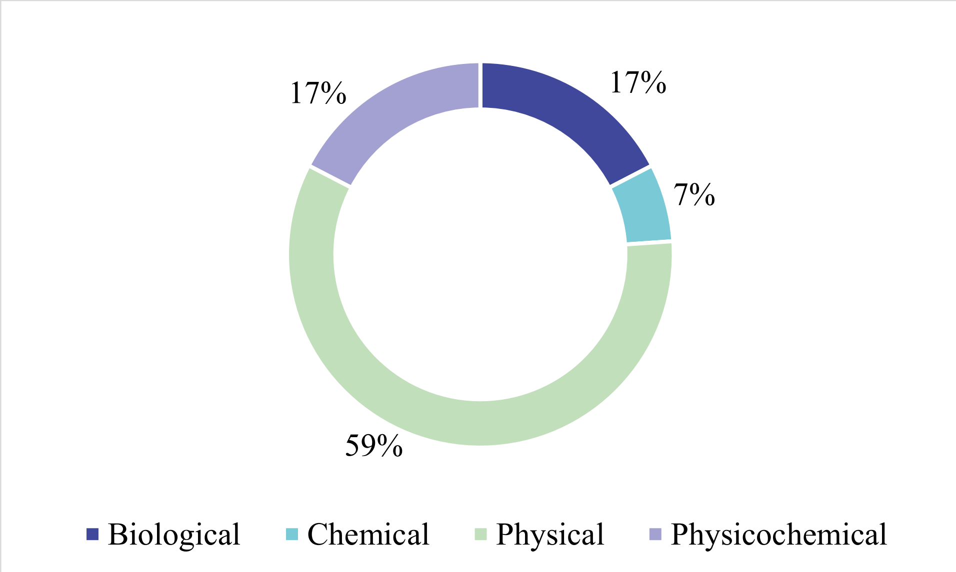

Figure 4. Categories of post-treatments applied to digestate in the systematic review.

Diskussion

The preference for investigating the total fraction can be attributed to economic and operational factors. Separating digestate into solid and liquid phases requires additional processing steps, increasing costs and technical complexity (Schnürer & Jarvis, 2018). The solid fraction often retains a higher concentration of biodegradable organics, making it an attractive target for post-treatment enhancement.

The biochemical composition of sewage sludge and agricultural residues significantly influences CH_4 yield, as sewage sludge contains high microbial content, and agricultural residues may have recalcitrant lignocellulosic structures. The high contribution of Italy and China to the dataset aligns with their policies promoting biogas production and waste valorization.

The disparity in performance between post-treatment strategies underscores the importance of selecting approaches that balance organic matter solubilization with microbial compatibility. Physical treatments, such as thermal hydrolysis and ultrasonication, enhance cell disruption and solubilization of organic matter, improving microbial accessibility (Carrère et al., 2016). Similarly, biological treatments, often based on enzymatic hydrolysis or microbial strategies, selectively degrade complex polymers into more bioavailable substrates, enhancing subsequent AD efficiency (Zhang et al., 2022).

In contrast, the lower CH_4 yields observed for chemical and physicochemical post-treatments suggest potential inhibitory effects on microbial activity. One possible explanation is the formation of inhibitory compounds such as recalcitrant lignin derivatives, refractory organics, or ammonia accumulation, which can suppress microbial activity (Ko et al., 2015). Moreover, excessive chemical dosing can lead to pH imbalances, negatively impacting methanogenic archaea (Kumar et al., 2019).

PublikationslistaSlutrapporten ska I förekommande fall innehålla en publikationslista och, där så är möjligt, annat relevant material från projektet.

- There is a manuscript in preparation entitled "Maximizing additional methane production through post-treatment application" that will be submitted in April/May to the journal Renewable Energy.
- The article “Methane yield response to pretreatment is dependent on substrate chemical composition: a meta-analysis on anaerobic digestion systems” was published in Scientific Reports in January 2024.
- The article “Magnetic nanoparticles for eliminating endocrine-disrupting compounds in water treatment – a quantitative systematic analysis” was published in Frontiers in Environmental Science in November 2024.

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Bilagor

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