Матеріали XXV Міжнародної науково-практичної конференції
«Екологія. Людина. Суспільство»
пам'яті д-ра Дмитра СТЕФАНИШИНА
(12 червня 2025 р., м. Київ, Україна)

Proceedings of the XXV International Science Conference
«Ecology. Human. Society»
dedicated to the memory of Dr. Dmytro STEFANYSHYN
(June 12 2025, Kyiv, Ukraine)

ISSN (Online) 2710-3315
https://doi.org/10.20535/EHS2710-3315.2025.327131

USE OF ARTIFICIAL INTELLIGENCE TOOLS IN ANAEROBIC DIGESTION PROCESSES

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Abstract
Anaerobic digestion (AD) is a process that has found increasing relevance for sustainable waste management and bioenergy production. Nevertheless, microbial interactions and process dynamics make it challenging to maximize and predict biogas production. Recent breakthroughs in artificial intelligence (AI), particularly in artificial neural networks (ANN), have provided new opportunities for solving these problems and drastically enhanced process optimization, predictive capability, as well as perpetual stability. This paper aims to provide a review of recent literature covering the application of AI, specifically Artificial Neural Networks (ANN), integrated with various optimization algorithms, including Genetic Algorithms (GA) and Particle Swarm Optimization (PSO), in anaerobic digestion systems from 2022 to 2024. The results of the evaluation demonstrate that ANN models exhibit a significant improvement over conventional kinetic-based approaches, characterized by lower prediction errors, higher biogas production, and greater robustness.

Keywords: *Anaerobic digestion, Artificial intelligence, Artificial neural networks, Genetic algorithm, Particle swarm optimization, Biogas, Process optimization, Renewable energy.*

Introduction: Anaerobic digestion (AD) is getting more important as an essential sustainable waste management and energy production technology. It is a complex set of microbial processes through which organic matter is transformed into biogas. The intrinsic complexity, nonlinearity, and variability in the anaerobic digestion process make it difficult to predict and optimize continuous, stable, and efficient biogas production. Recently, Artificial intelligence (AI), primarily through the use of artificial neural networks (ANNs), has been recognized as a strong modeling and optimization tool, as it can deal with complex nonlinearities and increase predictive precision. Conventional empirical/kinetic modeling approaches for anaerobic digestion are typically too simplistic to properly capture the complex dynamics. As such, the advent of AI-based methods is a leap, providing flexible, reliable and very accurate predictions models. A systematic review of the recent literature on Artificial intelligence (AI) and, in particular, ANN, Genetic Algorithms (GA), as well as Particle Swarm Optimization (PSO) application for anaerobic digestion.

Methods: This review evaluates the published literature (2022–2024) on applications and performances of various AI methodologies relevant to anaerobic digestion processes with a comprehensive view. That is, the review specifically emphasizes artificial neural nets (ANNs) and a fuse with some other advanced optimization algorithms such Genetic Algorithms (GA) a Particle Swarm Optimization (PSO) The database search was done using Scopus, ScienceDirect and Web of Science via bold keywords "anaerobic digestion", "artificial intelligence", "ANN", "genetic algorithm" and "particle swarm optimization". The major results and methodologies, as well as comparison reviews of related study were summed up to provide an emerged state-of-the-art and limitations of research.

Results: The reviewed literature suggests that ANN models have made significant progress in prediction and optimization for some anaerobic digestion applications. Chen et al. (2022) utilized integrated anaerobic-aerobic bioreactors and artificial neural networks (ANNs) with Bayesian regularization and backpropagation to significantly enhance the efficient removal of chemical oxygen demand (COD) and methane yields [1].

Comparable analyses have demonstrated that when combined with GA and PSO optimization algorithms, ANN-based models (GA-assisted ANNs and PSO-assisted ANNs) exhibit higher prediction accuracy than classical kinetic modeling approaches. For example, Avinash and Mishra (2024) reported that Artificial Neural Networks (ANN) and Adaptive Neuro-Fuzzy Inference Systems (ANFIS) outperform traditional kinetic models, yielding significantly lower root mean square errors (RMSE) and higher correlation coefficients (R^2) in prediction. Avinash & Ramu (2021) and Mougari et al. (2021) demonstrated that the integration of ANN and GA to estimate cumulative methane yield yielded accurate results with low uncertainties, despite a background of high predictive determinism [2, 3].

Moreover, Zaied et al. (2023) used an ANN in the preliminary analysis of biogas yields from palm oil mill effluent (POME) and cattle manure co-digestion, depicting its strength in analyzing multi-variate estimates with high prediction accuracy, particularly in terms of biogas outputs. Hasanpour Seyedlar et al. (2024) used ANN-PSO models for mitigation-based biogas H2S, finding a nearly 50% reduction in sulfure content, ranging from model H2S to H_2S in biogas [4, 5].

Zhan and Zhu (2024) also confirmed their finding that ANN-GA can significantly enhance methane yield by approximately 20.6% with biochar in anaerobic digestion. Below in Picture 1, you can see the pros and cons of AI in AN [6].

The assessment highlights the remarkable benefits of ANN-based models over classical kinetic approaches, especially when combined with GA and PSO. These AI enablers effectively resolve significant issues, such as accuracy prediction, system stability, and process optimization, to achieve higher biogas output with lower operational risks. However, the applicability of such ANN models can be significantly enhanced by including additional parameters, such as microbial population dynamics, nutrient availability, reactor architecture, and feedstock properties, in addition to operating data [2, 7, 8]. At the same time, real-time self-learning corresponding ANN models that adapt themselves are an open research field with potential. AI-driven hybrid modeling approaches that combine model-based AI and mechanistic models can offer even more robust and universally applicable solutions for the inherent variability of anaerobic digestion. In Picture 2, you can see a SWOT analysis of AI in AD.

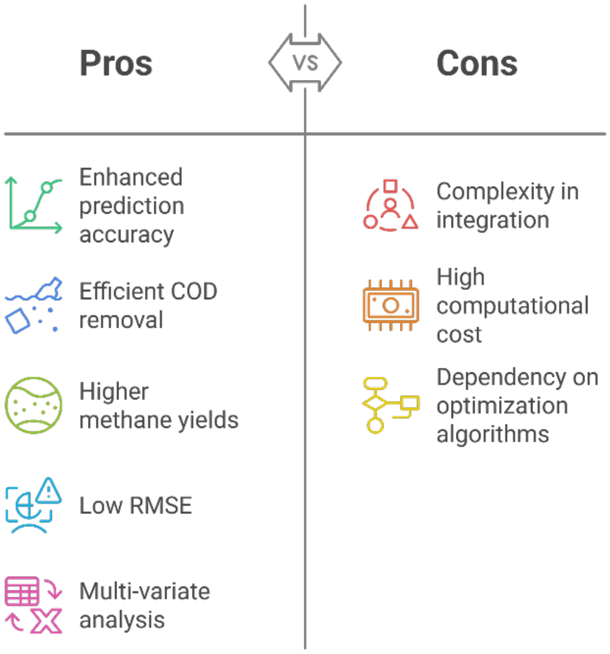

Fig 1. *Pros. And Cons of AI in AN*

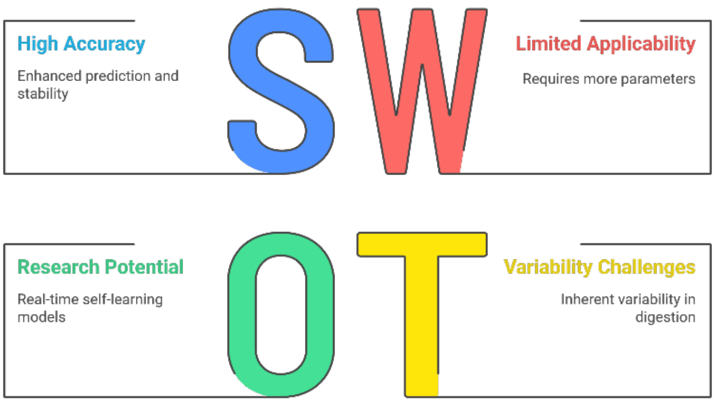

Fig.2. *SWOT analysis of AI in AD*

Conclusions: The integration of AI methodologies, specifically artificial neural networks (ANN) coupled with optimization techniques (genetic algorithms and particle swarm optimization), demonstrates clear superiority over traditional kinetic and empirical models in predicting and optimizing anaerobic digestion processes. These advancements have improved prediction accuracy, enhanced biogas production efficiency, and facilitated effective control of the anaerobic digestion process. Future research directions should prioritize the development of real-time adaptive and hybrid models to further enhance predictive capabilities and operational stability.

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ВИКОРИСТАННЯ ІНСТРУМЕНТІВ ШТУЧНОГО ІНТЕЛЕКТУ В ПРОЦЕСАХ АНАЕРОБНОГО ЗБРОДЖУВАННЯ

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Анотація

Анаеробне зброджування (АБ) - це процес, який набуває все більшої актуальності для сталого управління відходами та виробництва біоенергії. Тим не менш, мікробні взаємодії та динаміка процесу ускладнюють максимізацію та прогнозування виробництва біогазу. Нещодавні прориви в галузі штучного інтелекту (ШІ), зокрема, штучних нейронних мереж (ШНМ), надали нові можливості для вирішення цих проблем і значно покращили оптимізацію процесів, прогнозування, а також стабільність процесу. Метою цієї тези є огляд нещодавньої літератури, що висвітлює застосування ШІ, зокрема штучних нейронних мереж (ШНМ), інтегрованих з різними алгоритмами оптимізації, представленими генетичними алгоритмами (ГА) та оптимізацією рою частинок (PSO), в системах анаеробного зброджування в період з 2022 по 2024 рік. Результати доводять, що ШНМ-моделі демонструють значну перевагу порівняно з традиційними кінетичними підходами зі значно меншими помилками прогнозування, більшим виробництвом біогазу та більшою надійністю.

Ключові слова: анаеробне зброджування, штучний інтелект, штучні нейронні мережі, генетичний алгоритм, оптимізація рою частинок, біогаз, оптимізація процесу, відновлювані джерела енергії.