



Influence of pH and Pre-treatment on Biogas Production in Anaerobic Digestion: A Review

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Abstract

Anaerobic Digestion (AD) offers a potential solution to global challenges in renewable energy production and waste management. It is also a promising low-carbon emission technology. However, its efficiency can be limited by various technical factors. This review article addresses these limitations by investigating the main effects of pH and pre-treatment on biogas production and COD removal efficiency. The research methodology involves a comprehensive review of the literature on the effects of different pH ranges and various pre-treatment methods, including thermal, chemical, and enzymatic techniques. The findings revealed that a neutral to slightly alkaline pH range (6.8–8.3) provides optimal conditions because it can balance acidogenesis and methanogenesis, leading to high biogas yield and a COD removal rate of up to 86.34%. In addition, pre-treatment can significantly increase the efficiency of the AD process. For example, thermal alkaline pre-treatment of algal biomass increased methane yield by 229%, and shock wave pre-treatment of algae increased dissolved COD by approximately 70% compared to the control group. The contribution of this study is a consolidated overview of optimal conditions and effective methods for improving AD performance, providing a basis for designing AD systems that are more efficient and stable for sustainable energy and waste management.

Keywords: *Anaerobic Digestion, Biogas, COD, pH, Pre-Treatment*

INTRODUCTION

As various global challenges such as climate change, energy crises, and environmental pollution increase, the use of renewable energy and sustainable waste management are becoming increasingly important to implement immediately. This is also driven by government policies to switch to cleaner and more sustainable energy. In addition, technological advances and lower operating costs are also driving the energy transition in various countries. According to IEA data, renewable energy capacity increased by almost 50% from 2015 to 2020 (Hassan et al., 2024). The Problem of poor waste management also exacerbates environmental pollution problems. This is due to global population growth, which is estimated to reach 9.75 billion by 2050. This population increase will lead to an increase in waste production to 2.8 billion tons (Szpilko et al., 2023). Therefore, research on renewable energy and effective waste management systems is one of the strategic steps to create a more environmentally friendly future.

Anaerobic treatment is a sustainable, low-carbon emission technology that addresses waste management and renewable energy issues. Anaerobic treatment technology utilizes volatile substances from biomass waste to produce biogas, thereby reducing carbon emissions into the environment (Subbarao et al., 2023). Anaerobic digestion not only reduces dependence on fossil fuels, but also significantly reduces greenhouse gases (Huang, 2024). The use of anaerobic

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digestion technology supports a circular economy strategy focused on efficient energy use and resource recycling. However, the implementation of anaerobic digestion technology faces several technical challenges, such as limited efficiency, high initial investment costs, and a long payback period (Huang, 2024).

Anaerobic digestion is a series of biochemical processes that utilize bacteria to break down organic matter from biomass substrates into a gas mixture in an oxygen-free (anaerobic) environment (Uddin & Wright, 2023). The gas mixture produced in anaerobic digestion technology can be used as a substitute for fossil fuels to generate heat or electricity (Neri et al., 2023). The anaerobic digestion process involves the decomposition of complex organic materials with the help of microorganisms through the stages of hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Mokraoui et al., 2023).

In the hydrolysis stage, organic macromolecules such as carbohydrates, proteins, and fats are broken down into smaller molecules by hydrolytic and fermentative bacteria. Then, in the acidogenesis stage, these macromolecules are decomposed into various metabolic products such as volatile fatty acids, alcohol, lactate, hydrogen, and carbon dioxide by acidogenic bacteria (Zheng & Li, 2024). The products produced in the acidogenesis stage are then converted during the acetogenesis stage. This acetogenesis process involves the decomposition of organic acids, which causes the pH of the system to rise during the reaction. Methanogenesis is the final stage of anaerobic digestion, where acetic acid is converted to methane and carbon dioxide by methanogenic bacteria (Chen et al., 2023). This stage is very important because substances are converted into methane and fatty acids are broken down by methanogenic bacteria, thereby regulating the pH value in the system.

Previous studies have shown that pH conditions play a very important role in determining the success of the anaerobic digestion process. pH conditions that are too low can trigger the accumulation of volatile fatty acids, which ultimately suppress methanogenic activity, while pH conditions that are too high can disrupt enzyme stability and reduce process efficiency. Therefore, the right pH range is an important factor in maintaining optimum performance in biogas formation and pollutant removal, such as Chemical Oxygen Demand (COD).

In addition, pre-treatment of the substrate also plays a significant role in the performance of this process. Pretreatment aims to increase the availability of organic material that can be digested by microorganisms, accelerate the rate of degradation, and increase biogas production. (Nguyen et al., 2021). Pretreatment methods reported in the literature include physical, chemical, and biological pretreatment. Each method has advantages and limitations, but in general, pretreatment has been shown to increase the efficiency of the hydrolysis stage and accelerate the conversion of organic matter into volatile fats and methane.

RESEARCH METHOD

This study was conducted using a systematic-narrative literature review approach to evaluate the influence of pH and pre-treatment on biogas production in anaerobic digestion processes. The primary data sources were obtained from the ScienceDirect database within the last five years (2020–2025) using structured keywords such as “anaerobic digestion,” “pre-treatment,” “pH control,” and “biogas production,” combined with Boolean operators AND and OR. The collected articles were screened based on inclusion criteria, published in indexed scientific journals, explicitly discussing the effect of pH or pre-treatment on biogas or methane yield, and presenting quantitative experimental data. Meanwhile, articles that were irrelevant, did not report gas production data, were solely simulation-based without validation, or focused on aerobic processes were excluded according to the exclusion criteria. Following the selection process through title identification, abstract screening, and full-text analysis, essential information such as substrate

type, initial or controlled pH value, type of pre-treatment applied (physical, chemical, biological, or their combinations), biogas or methane production values, and reactor operational conditions was extracted and analyzed descriptively and comparatively to identify treatment effectiveness trends, determine the optimum pH conditions, and evaluate the most influential pre-treatment methods in enhancing substrate biodegradability. The analysis results are presented narratively to illustrate the relationship between pH, pre-treatment, and biogas production efficiency, while also identifying research gaps with potential for further investigation in optimizing anaerobic digestion processes.

FINDINGS AND DISCUSSION

Effect of pH Level

A number of studies have reported that each specific pH range produces a different response to biogas production and COD reduction efficiency. This information is important as a basis for operational control and the design of anaerobic digestion-based wastewater treatment systems. The following table summarizes the effects of various pH ranges on biogas production and COD removal capacity based on several literature sources.

Table 2.1. Effect of pH on Biogas Production During Anaerobic Digestion

pH range	The Effect of pH on Biogas Production	Source
pH 5.0-5.9 and pH 7.0-7.5	Low pH reduces biogas production by 50–70% due to propionate accumulation at neutral pH optimal biogas production	(Charalambous et al, 2020)
pH 7.8-8.3	Maximum methane production of 41.05% on day 18 and stable growth of methanogenic bacteria	(Aruna et al, 2020)
pH 5.9-6.7 and pH 7.5 – 8.5	At the initial pH, acidogenesis was dominant, with low biogas production (0.016–0.019 m ³ /kg COD removed), whereas at the final pH, methanogenesis was dominant, with increased biogas production (0.079–0.088 m ³ /kg COD removed).	(Said et al, 2021)
pH 5.6, pH 6.8-7.5, and pH 7.8-8.3	At low pH, VFA accumulates, resulting in low biogas production. At neutral pH, biogas production is optimal. Meanwhile, at alkaline pH, biogas production is high but there is a risk of ammonia inhibition.	(Syaichurrozi et al, 2025)
pH 6.8-7.5	at neutral pH, optimal conditions are achieved, because acidogenesis and methanogenesis are balanced, resulting in optimal biogas production	(Ta et al, 2022)

Effect of pH on Biogas Production During Anaerobic Digestion

The study conducted by Charalambous et al. (2020) at low pH conditions (pH 5 - 5.9), biogas production was lower compared to neutral pH conditions. This occurred due to a shift in microbial populations, where hydrogenotrophic methanogens became more dominant than acetoclastic methanogens. Such a shift led to the accumulation of propionate, thereby reducing the efficiency of COD conversion to methane. Under low pH conditions, the requirement for NaOH decreased by up to 68%. However, biogas production was also reduced by approximately 50 - 70%. Another study conducted by Aruna et al. (2020). Reported that under pH conditions of 7.8-8.3, bacterial growth proceeded well. The maximum methane content was also recorded on day 18 at 41.05%. This

slightly alkaline pH condition is considered optimal for the growth of methanogenic bacteria and substrate degradation. In contrast, the study by [Said et al. \(2021\)](#) evaluated the effect of different pH conditions across reactor compartments. The findings revealed that in the initial compartment, where the pH ranged from 5.9 to 6.7, acidogenesis was the dominant process, resulting in relatively low biogas yields (0.016-0.019 m³/kg COD removed). Conversely, in the final compartment, at a pH range of 7.5 to 8.5, methanogenesis prevailed, which significantly enhanced biogas production (0.079-0.088 m³/kg COD removed). These results highlight the critical role of pH stratification in facilitating phase separation within anaerobic digestion, thereby optimizing both substrate degradation and methane generation. Regarding the study conducted by [Syaichurrozi et al. \(2025\)](#) investigated biogas generation under low, neutral, and alkaline pH conditions. The results demonstrated that at low pH (5-6), acidogenesis proceeded rapidly, leading to the accumulation of volatile fatty acids (VFAs), which in turn reduced biogas production. Under neutral pH conditions (6.8-7.5), acidogenesis and methanogenesis were balanced, meaning that the VFAs produced were immediately converted into methane. At slightly alkaline pH (7.8-8.3), microbial activity remained favorable for methanogen growth. However, the risk of ammonia inhibition could occur under these conditions. This finding is further supported by the study conducted [Ta et al. \(2022\)](#) which demonstrated that neutral pH conditions (6.8–7.5) represent the most favorable range for anaerobic digestion, as both acidogenesis and methanogenesis processes proceed in a balanced manner.

Table 2.2. Effect of pH on COD Removal in Anaerobic Digestion

Range pH	The effect of pH on COD removal	Source
pH 5.0-5.9 and pH 7.0-7.5	At low pH (5.0-5.9), COD conversion to methane was not efficient due to propionate accumulation, while at neutral pH (7.0-7.5) COD removal reached approximately 80%.	(Charalambous et al., 2020)
Ph 7.8-8.3	At slightly alkaline pH conditions, COD removal reached 86.34%, indicating more effective degradation of organic matter.	(Aruna et al., 2020)
Ph 5.9-6.7 and pH 7.8-8.5	In the initial compartment with pH 5.9-6.7, COD removal was only 40-50% due to the dominance of acidogenesis, whereas in the final compartment with pH 7.5-8.5, COD removal increased to 75-77% as methanogenesis became dominant.	(Said et al., 2021)
pH 5-6, pH 6.8-7.5, and pH 7.8-8.3	At low pH (5-6), COD removal was low due to the accumulation of volatile fatty acids. At neutral pH (6.8-7.5), COD removal was optimal, while at slightly alkaline pH (7.8-8.3), COD removal remained high although with a potential risk of instability due to ammonia inhibition.	(Syaichurrozi et al., 2025)
pH 6.8-7.5	Neutral pH conditions provided the most favorable environment for balancing acidogenesis and methanogenesis, resulting in maximum COD removal efficiency.	(Ta et al., 2022)

The Effect of pH on COD Removal in Anaerobic Digestion

Based on several studies, it is evident that pH conditions in anaerobic digestion play a critical role in determining the efficiency of COD removal. In the study by [Charalambous et al. \(2020\)](#) low pH conditions (5-5.9) resulted in suboptimal COD conversion to methane due to propionate accumulation, whereas at neutral pH (7-7.5), COD removal efficiency increased to approximately

80%. Similar findings were reported by [Aruna et al. \(2020\)](#) where at slightly alkaline pH (7.8-8.3), COD removal reached 86.34%, confirming that neutral to alkaline conditions enhance organic matter degradation more effectively. Furthermore, [Said et al. \(2021\)](#) observed in the initial compartment (pH 5.9-6.7), COD removal was only 40–50% due to the dominance of acidogenesis, while in the final compartment (pH 7.5-8.5), COD removal improved to 75–77% in line with enhanced methanogenesis. Likewise, [Syaichurrozi et al. \(2025\)](#) demonstrated a similar pattern, where low pH (5–6) led to poor COD removal due to VFA accumulation, while neutral pH (6.8-7.5) yielded optimal COD removal, and slightly alkaline pH (7.8-8.3) maintained high COD removal levels. The consistency of these results is further reinforced by [Ta et al. \(2022\)](#) who emphasized that neutral pH conditions (6.8–7.5) are the most favorable for balancing acidogenesis and methanogenesis, thereby achieving maximum COD removal efficiency. Overall, it can be concluded that neutral to slightly alkaline pH represents the optimal condition for achieving high COD removal, whereas low pH reduces COD removal efficiency due to the accumulation of intermediate compounds that are difficult to degrade.

Pre-Treatment

Each type of pre-treatment has different mechanisms and effects on substrate characteristics. Thermal, chemical, and enzymatic treatments can affect the composition of organic compounds and their solubility, which ultimately impacts the increase in ethane production and COD reduction efficiency. Therefore, selecting the appropriate pre-treatment method is a crucial factor in the design and operation of anaerobic digestion-based wastewater treatment systems.

The following table presents various pretreatment studies on different substrates along with the methods used, biogas production results, and their impact on COD/sCOD reduction, summarized from several recent literature sources.

Table 3.1. Effect of Pre-treatment on Biogas Production and sCOD/COD Removal

Substrate	Pre-Treatment	Biogas Production	sCOD-COD Removal	Sources
Algal biomass	Thermal Alkaline (90°C pH 11)	460.64 ml CH ₄ /gVS (229% higher than control)	32% increase in sCOD	(Estevam et al., 2024)
Algae from reservoir	Shockwave	160-180 ml CH ₄ /gVS (30-50% higher than control)	Approx. 70% increase in sCOD	(Lee et al., 2022)
Sewage sludge	Thermal Alkaline	20% average increase	30.3% increase in sCOD _{ref}	(Toutian et al., 2020)
Sewage sludge	Thermal (70°C)	420-470 ml CH ₄ /gVS (23.5-30.5% higher than control)	12-14 % sCOD	(Guo et al., 2022)
POME	Enzymatic (lipase + xylanase)	52.27% higher than control	49.7% COD removal	(Shafwah et al., 2021)
POME	Ultrasonication	21.5% higher than control	96% COD removal	(Isa et al., 2020)

Effect of Pretreatment on Biogas Production

Various pretreatment methods have been proven to enhance biogas production by improving substrate availability and accelerating the hydrolysis process. Shockwave pretreatment of algae resulted in a significant increase in methane yield, with around 160-180 mL CH₄/gVS or 30-50% increase in methane yield compared to control process. This improvement is explained by

cell wall disruption caused by shockwaves, which accelerates the release of organic compounds (Lee et al., 2022). Thermochemical alkaline pretreatment of algal biomass (90 °C, pH 11) produced 460.64 mL CH₄/gVS, representing a 229% increase compared to the control, as alkaline conditions solubilize lignocellulosic components and increase the fraction of readily degradable organics (Estevam et al., 2024).

In sewage sludge, thermal alkaline pretreatment (TAP) further demonstrated a seasonal effect, with biogas yield increases of 42% in summer, 3% in winter, and an annual average increase of 20%, highlighting the combined effect of alkaline disintegration and temperature on sludge biodegradability (Toutian et al., 2020). Thermal pretreatment at 70 °C using an in-pipe system (SIT/VNT) increased methane yield to 420-470 mL CH₄/gVS, which is 23.5-30.5% higher than untreated sludge (190-240 mL CH₄/gVS). This effect is attributed to enhanced solubilization of complex organic matter at moderate temperatures without forming inhibitory compounds (Aruna et al., 2020).

For POME, enzymatic pretreatment with lipase and xylanase enhanced biogas yield by 52.17% due to enzymatic hydrolysis of fats and hemicellulose into fermentable monomers (Shafwah et al., 2021). Ultrasonic pretreatment increased methane yield by 21.5%, attributed to cavitation-induced disintegration of organic particles (Estevam et al., 2024).

Effect of Pretreatment on sCOD/COD Removal

Pretreatments also enhanced COD solubilization and removal efficiencies. In algal biomass, alkaline thermochemical pretreatment increased soluble COD by 32%, reflecting enhanced release of biodegradable organics (Estevam et al., 2024). Shockwave pretreatment of algae demonstrated similar improvements, although COD remained nearly unchanged, sCOD increased by approximately 70% compared to the untreated control. The result is confirming that shockwave effectively solubilized additional organic matter (Lee et al., 2022).

For sewage sludge, thermal pretreatment at 70 °C achieved 12-14% COD solubilization, showing conversion of particulate COD into soluble fractions that are more accessible for microorganisms (Guo et al., 2022). TAP further enhanced solubilization, with a reported 30.3% increase in sCOD_{ref}, indicating a substantial rise in the fraction of COD present in soluble form. This higher solubilization correlates with the improved biogas yield observed under TAP (Toutian et al., 2020). In the case of POME, enzymatic pretreatment achieved 49.7% COD removal, while ultrasonic pretreatment delivered the highest performance with 96% COD removal compared to 91% in the control, due to particle disruption and improved homogenization of the substrate (Shafwah et al., 2021; Isa et al., 2020).

CONCLUSIONS

pH and pretreatment are important factors for noticed in optimizing biogas production and reduction Chemical Oxygen Demand (COD) levels in anaerobic digestion. In the neutral to slightly alkaline pH range 6.8–8.3 is the best for bacteria, because it provides a balanced environment for acidogenic and methanogenic bacteria. which leads to optimal biogas production and efficient COD removal . In particular, studies show that at neutral pH (6.8 until 7.5) COD removal can reach up to 80%, while at slightly alkaline pH (7.8 until 8.3), can be even higher, namely 86.34%. On the other hand, low pH conditions (5.0 until 6.7) inhibit methanogenesis because it occurs accumulation of volatile fatty acids resulting in much lower biogas production and COD removal efficiency of only 40 until 50% only.

In addition, various pretreatment methods effectively increase substrate availability and accelerate hydrolysis, thus providing efficient impact to the whole process. As For example, thermal alkali pretreatment of algal biomass increased methane yield by 229%. Meanwhile, enzymatic

pretreatment of palm oil mill effluent (POME) resulted in a 52.17% increase in biogas yield.

LIMITATION & FURTHER RESEARCH

This review demonstrates that selecting an appropriate pretreatment method can overcome technical challenges and significantly improve the efficiency of anaerobic digestion systems. Limitations of this review are due to the summarized nature of the data. Not yet encompassing overall review of each original study. It is hoped that future research can increasing its focus on optimizing the integration of specific pretreatment techniques with pH control systems in one continuous process to maximize efficiency and economic feasibility in the process.

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