Jurnal Serambi Engineering JSE
Volume XI, No.3, Juli 2026 Hal 19683 - 19697
p-ISSN : 2528-3561
e-ISSN : 2541-1934

A Review on The Enhancement of Biogas Production Through Pre-Treatment of Domestic Wastewater Sludge for Methane Gas Utilization

Almalita Mardiah, Nopa Dwi Maulidiany*

Environmental Engineering Study Program, Faculty of Engineering, Universitas Indonesia
***Corresponding author**: nd.maulidiany@ui.ac.id

Received: May 11, 2026 Approved: May 25, 2026

Abstract

Anaerobic Digestion (AD) is a prevalent and cost-effective method for managing domestic wastewater sludge, often accounting for 20–60% of plant operational costs. This process supports the circular economy by converting organic matter in Waste Activated Sludge (WAS) into renewable biogas. However, WAS is notoriously resistant to degradation due to complex compounds, such as lignocellulose and Extracellular Polymeric Substances (EPS), which severely impede hydrolysis. Therefore, pre-treatment is essential to modify the sludge structure, solubilise organics, accelerate hydrolysis, and enhance methane production. This systematic literature review, conducted according to the PRISMA Checklist 2020, analyses the effectiveness of various pre-treatment methods (mechanical, chemical, physico-chemical, biological, and combined) on domestic sludge. The review found that methane production enhancement varied widely, from 0% to an exceptional 524%, depending on the method and operational parameters. Significantly, combined techniques, such as High-Pressure Homogenisation (HPH) paired with Free Nitrous Acid (FNA), achieved the highest reported increase in methane yield, reaching 524%.

Keywords: *sewage sludge, anaerobic digestion, methane yield optimization, sludge conditioning, biosolids management*

Abstrak

Pengelolaan limbah cair domestik melalui *Anaerobic Digestion* (AD) umum digunakan karena biayanya yang rendah, sektor ini dapat menyumbang 20-60% dari total biaya operasional IPAL. Konsep ekonomi sirkular diterapkan dengan mengubah materi organik dalam *waste activated sludge* (WAS) menjadi biogas dan menghasilkan energi terbarukan. Namun, lumpur sekunder sulit terdegradasi akibat kandungan kompleks seperti lignoselulosa dan *extracellular polymeric substances* (EPS) sehingga memperlambat hidrolisis. Oleh karena itu, *pre-treatment* direkomendasikan untuk memodifikasi struktur lumpur, melarutkan bahan organik, mempercepat hidrolisis, dan meningkatkan produksi metana. Tinjauan literatur ini bertujuan menganalisis efektivitas berbagai metode pre-treatment (mekanis, kimia, fisikokimia, biologis, dan kombinasi) pada limbah cair domestik. Menggunakan metode *systematic literature review* berdasarkan PRISMA Checklist 2020, tinjauan ini mengidentifikasi peningkatan produksi metana yang bervariasi dari 0% hingga 524%, bergantung pada jenis pre-treatment, karakteristik sampel, dan parameter operasional. Metode kombinasi, seperti HPH dengan FNA, menunjukkan peningkatan produksi metana tertinggi hingga mencapai 524%.

Kata Kunci: *lumpur limbah, pencernaan anaerobik, optimasi metana, pengkondisian lumpur, manajemen biosolid*

1. Introduction

The treatment of domestic wastewater using the Anaerobic Digestion (AD) process has become a ubiquitous method due to its comparatively low operating costs [1], [2]. Sludge, the solid residue generated from AD operations, is a growing waste stream, particularly in urban areas, with its volume increasing commensurate with population growth. The management of domestic sewage sludge, encompassing both primary and waste activated sludge (WAS), constitutes a significant burden on the operational expenditure of wastewater treatment plants (WWTPs), typically accounting for 20% to 60% of the total budget [3]. This escalating cost necessitates concerted efforts to minimise sludge production, enhance process efficiency, and maximise sludge reuse and valorisation [4]. Furthermore, numerous nations have adopted the concept of a circular economy [5] by converting a substantial portion of the organic matter in WAS into biogas. This approach not only generates renewable energy but also simultaneously reduces the volume of solid sludge.

Depending on the wastewater treatment process, sludge is classified as primary, secondary, or mixed, each possessing distinct physical and biochemical properties. Primary sludge is generally easier to degrade than secondary sludge, as the former contains more readily biodegradable polysaccharides and lipids. In contrast, secondary sludge is predominantly composed of microorganisms, exopolymeric substances (proteins and polysaccharides), and complex, undigested organic and mineral matter. Consequently, the hydrolysis stage is often slow, presenting a rate-limiting step for the degradation of recalcitrant sludge [6]. This limitation is primarily attributed to the high content of complex components, such as lignocellulose and Extracellular Polymeric Substances (EPS), embedded within biologically active sludge flocs [7], [8].

Therefore, a pre-treatment process is highly recommended to modify the sludge structure, solubilise the organic matter, and also increase the accessible surface area, thereby accelerating hydrolysis the rate limiting stage for secondary or mixed sludge and ultimately boosting methane production. The maximisation of methane yield is currently crucial, as methane possesses a high energy value and can be further processed into alternative energy sources, such as electricity, heating systems, or vehicle fuel. Utilising methane from wastewater also contributes to reducing reliance on fossil fuels and mitigating greenhouse gas emissions [9], particularly when compared to the direct release of methane into the atmosphere. Accordingly, various pre-treatment methodologies including mechanical, chemical, physico-chemical, and biological techniques, both individually and in combination have been developed to enhance the conversion of sludge into readily accessible, soluble organic material for maximal biofuel production [10].

This review aims to conduct a comprehensive analysis of the efficacy of these diverse pre-treatment alternatives, considering their underlying principles, influential variables, and the resulting percentage increase in methane gas production. Specifically, the review focuses on pre-treatment methods applied to domestic or urban wastewater sludge. Furthermore, various technical challenges identified across multiple studies are summarised to provide a critical overview of the multifaceted aspects of pre-treatment technology.

2. Methodology

This review article employed a systematic literature review methodology, guided by the PRISMA Checklist 2020 principles. This systematic approach aimed to comprehensively identify and rigorously evaluate previous research based on the methodologies they utilised. The process encompassed several distinct stages: keyword identification (specifically, 'Domestic Wastewater', 'Pre-Treatment', and 'Biogas Production'), document screening, and final document selection. Article selection was performed based on defined inclusion criteria: studies published between 2015 and 2025, from both national and international sources, which were fully accessible as complete PDF files (primarily via ScienceDirect), and which specifically addressed the pre-treatment of wastewater sludge for enhancing biogas production. Conversely, exclusion criteria comprised articles concerning general wastewater treatment processes and any articles published prior to 2015. This review presents detailed research data concerning the type of sample, the pre-treatment methods applied to the sample, and the resulting percentage increase in methane gas production. A schematic representation of the article review process is presented as follows:

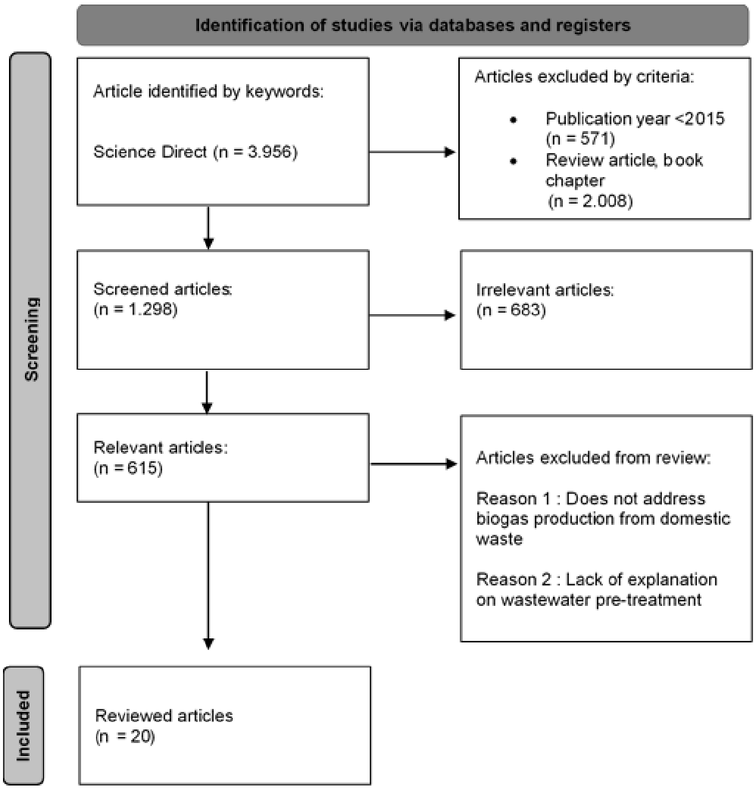

Figure 1. Literature Review Flowchart
Source: PRISMA (2020)

3. Results and Discussion

Based on the article review data presented in the preceding table, a diverse range of pre-treatment methods has been explored to enhance methane production from various types of waste and sludge. These methods encompass Hydrothermal, Free Nitrous Acid (FNA), Forward Osmosis, Dilute Acid–Thermal, the combined approach of High-Pressure Homogenisation (HPH) and FNA, N_2-Nanobubble Water, Hyperthermophilic Biological Hydrolysis, Thermal, Sonication, Ozonation, Alkali, Electro-Oxidation, Fenton, Peracetic Acid (PAA), Thermo-Alkaline, and Electrochemical Pre-treatment, as well as the implementation of additives such as Biochar and Sodium Iron Chlorophyllin-H_2O_2. The observed increase in methane production varies significantly, clearly demonstrating the complex interactions between the specific pre-treatment technique, the characteristics of the sample matrix, and the optimised operational parameters.

Table 1. Effect of Pre-Treatment Method on Maximum Methane Yield

No.	Title	Sample Type	Pre-Treatment Method	Variables	Methane Production Without Pre-Treatment	Maximum Methane Production With Pre-reatment	Maximum Methane Enhancement(%)	Reference
1.	Hydrothermal pretreatment of sewage sludge for enhanced anaerobic digestion: Resource transformation and energy balance	Mixed faecal and activated sludge	Hydrothermal Pre-Treatment	Independent: • Heating temp (90°C, 125°C, and 155°C) • Sludge Retention Time (10 days & 20 days) • Organic Loading Rate (3.5 g COD/L-day, 7.0 g COD/L-day)	• SRT 10 days = 303 mL/g VS • SRT 20 days = 302 mL/g VS	• SRT 10 days = 328 mL/g VS (HTP 125°C) • SRT 20 days = 391 mL/g VS (HTP 155°C)	• SRT 10 days = 8,3% • SRT 20 days = 29,5%	[11]
2.	Enhancing anaerobic digestion using free nitrous acid: Identifying the optimal pre-treatment condition in continuous operation	Thickened Activated Sludge IPAL Luggage Point, Brisbane, Australia	Free Nitrous Acid (FNA) Pre-treatment	Independent: • Free Nitrous Acid Concentration - Phase 1 (Day 0-50) = 0 mgN/L - Phase 2 (Day 51-173) = 2,2; 4,4; 7,2 mgN/L - Phase 3 (Day 174-282) = 7,2 mgN/L - Phase 4 (Day 282-317) = 7,2 mgN/L • Pre-treatment duration - Phase 1 = - - Phase2 = 24 jam - Phase 3 = 8 jam - Phase 4 = 48 jam	534 mL/g VS (Reactor 1)	715,2 mL/g VS (Reactor 4)	33,9% (Reactor 4)	[12]
3.	Enhancing biogas production from the anaerobic treatment of municipal wastewater by forward osmosis pretreatment	Domestic Wastewater (Girona WWTP, Spain)	Forward Osmosis Pre-Treatment	Independent: • % Water recovery (50% and 70%) • AD reactor temp (25 °C and 35 °C)	• 20 mL/g TCOD (25°C) • 35 mL/g TCOD (35 °C)	• 69 mL/g TCOD (25 °C and 70% water recovery) • 136 mL/g TCOD (35 °C and 70% water recovery)	• 245% (25 °C and 70% water recovery) • 288% (35 °C and 70% water recovery)	[13]

No.	Title	Sample Type	Pre-Treatment Method	Variables	Methane Production Without Pre-Treatment	Maximum Methane Production With Pre-reatment	Maximum Methane Enhancement(%)	Reference
4.	Enhanced biogas production in dilute acid-thermal pretreatment and cattle dung biochar mediated biomethanation of water hyacinth	Water Hyacinth Plant and activated sludge	Dilute Acid-Thermal Pre-treatment with cattle dung biochar	Independent: • Biochar addition percentage (0,5%; 1%; 1,5%)	1122,37 mL	2781,34 mL (1% biochar addition)	147,8%	[14]
5.	Combining high pressure homogenization with free nitrous acid pretreatment to improve anaerobic digestion of sewage sludge	Activated Sludge (from a WWTP in Beijing, China)	Combined High Pressure Homogenization (HPH) and Free Nitrous Acid (FNA)	Independent: • Pre-treatment type (FNA only, HPH only, HPH-FNA combination)	95,4 mL	595,75 mL (HPH-FNA combination pre-treatment)	524%	[8]
6.	Enhanced hydrolysis of waste activated sludge for methane production via anaerobic digestion under N_2-nanobubble water addition	Activated Sludge (from a WWTP in Ibaraki, Japan)	N_2-Nanobubble Water (N_2-NBW) Addition	Control: • Nanobubble pressure (0,24 MPa) • Pre-treatment duration (30 minutes) • AD duration (14 days) • Batch reactor (250 mL) • Incubation temp (37°C)	311,4 mL/g VS	402,1 mL/g VS	29%	[1]
7.	Enhanced methanization of sewage sludge using an anaerobic membrane bioreactor integrated with hyperthermophilic biological hydrolysis	Faecal Sludge (Qinghe WWTP, Beijing, China)	Hyperthermophilic Biological Hydrolysis	Independent: • HRT in anaerobic membrane bioreactor (5,10,15, dan 20 hari)	145 L/kg VS	246 L/kg VS (HRT AnMBR 20 days)	69,7%	[2]
8.	Enhancement of biogas production from sewage sludge in a wastewater treatment plant: Evaluation of	Urban Sewage Sludge	Thermal Pre-Treatment (Autoclave), Thermal Pre-Treatment (water bath), and Sonication	Independent: • Pre-treatment method (termal and sonication)	190,04 NLbiomethane /kgVSLoaded NL: Normal Liter	Thermal (autoclave): 287,48 NLbiomethane /kgVSLoaded (30	Termal (autoclave): 51,27% Sonication: 33,61%	[15]

No.	Title	Sample Type	Pre-Treatment Method	Variables	Methane Production Without Pre-Treatment	Maximum Methane Production With Pre-reatment	Maximum Methane Enhancement(%)	Reference
	pretreatment techniques and co-digestion under mesophilic and thermophilic conditions			• Thermal pre-treatment temp (70˚C, 90˚C, dan 120˚C) • Thermal pre-treatment duration (0.5, 1, 2, 3, 4 hours) • AD temp (37˚C and 55˚C)		menit; pressure 2 bar; 120˚C) Sonication: 253,92 NLbiomethane /kgVSLoaded (15 minutes; 20kHz; 50 Watt) Thermal (waterbath): 218,4 NLbiomethane /kgVSLoaded (90˚C;0,5 hour)	Termal (waterbath): 14,92%	
9.	Effect of the ozonation pretreatment on biogas production from waste activated sludge of tehran wastewater treatment plant	Waste Thickened Activated Sludge (WTAS) from South Tehran WWTP	Ozonation	Independent: • Ozone dosage (0,05 and 0,1 g O_3/g TS • Sludge retention time (10 days and 30 days)	10 days: 14,75 L biogas/kgVSin 30 days: 103 Lbiogas/kgVSin	10 days: • 39 L biogas/kgVsin (0,05 gO_3/ g TS) • 35 L biogas/kgVSin (0,1 gO_3/gTS) 30 days: • 103 L biogas/kgVsin (0,05 gO_3/ g TS) • 103 L biogas/kgVsin (0,05 gO_3/ g TS)	10 days: • 164% (0,05 gO_3/ g TS) • 137% (0,1 gO_3/gTS) 30 days: • 0% (0,05 gO_3/ g TS) • 0% (0,05 gO_3/ g TS)	[16]
10.	Optimizing alkali-pretreatment dosage for waste-activated sludge disintegration and enhanced biogas production yield	Waste-Activated Sludge (WAS) from a Sewage Treatment Plant (STP) in Bhandewadi, Nagpur, India	Alkali-pretreatment	Independent: • Alkali reagen type (NaOH; $Ca(OH)_2$; $Mg(OH)_2$; KOH) • Alkali dosage (0,04; 0,08; 0,12 g alkali/gTS)	140-150 mL/gVS	NaOH: 244 mL/gVS $Ca(OH)_2$: 226 mL/gVS $Mg(OH)_2$: 216 mL/gVS	NaOH: 72,77% $Ca(OH)_2$: 60,9% $Mg(OH)_2$: 52,9% KOH: 79,8%	[17]

No.	Title	Sample Type	Pre-Treatment Method	Variables	Methane Production Without Pre-Treatment	Maximum Methane Production With Pre-reatment	Maximum Methane Enhancement(%)	Reference
						KOH: 253,52 mL/gVS		
11.	Sustainable enhancement of biogas production from a cold-region municipal wastewater anaerobic digestion process using optimized sludge-derived and commercial biochar additives	Thickened waste-activated sludge (TWAS) from Saskatoon Wastewater Treatment Plant – SWTP (Cold Region)	Biochar Addition (Sludge-Derived Biochar using conventional furnace pyrolysis and microwave pyrolysis)	Independent: • Biochar additive type (Sludge-Based Biochar (SBC) (furnace pyrolysis), Activated Sludge-Based Biochar (ASBC)(microwave pyrolysis)	221 mLCH_4/gVS	TSBC: 252 mLCH_4/gVS TASBC: 332 mLCH_4/gVS	TSBC: 14,02% TASBC: 50,22%	[18]
12.	Evaluation of electro-oxidation and Fenton pretreatments on industrial fruit waste and municipal sewage sludge to enhance biogas production by anaerobic co-digestion	Mixed industrial fruit juice waste and municipal sewage sludge	Elektro-Oxidation and Fenton	Independent: • Pre-treatment method (elektro-oxidation and fenton) • H_2O_2 ratio : Fe^{2+} pada metode fenton (500:1 dan 1000:1)	407 mL	Elektro-oxidation: 523 mL Fenton: 567 mL	Elektro-oxidation: 28% Fenton:39%	[19]
13.	Peracetic acid pretreatment improves biogas production from anaerobic digestion of sewage sludge by promoting organic matter release, conversion and affecting microbial community	Activated sludge and dewatered sludge (Changsha Municipal WWTP, China)	Preacetic-acid (PAA) Addition	Independent: • PAA dosage (1,2,3,4 millimole (mM)/gVS)	212,29 mL biogas/g VS	297,94 mL biogas/g VS (pada 2 mM/g VS PAA)	40,35%	[20]
14.	Optimization of alkaline hydrothermal pretreatment of biological sludge for enhanced methane generation under anaerobic conditions	Waste Activated Sludge (WAS) from Hurma Municipal WWTP (Antalya, Turkey)	Hydrotermal-alkaline	Independent: • Reaction temp (130˚C, 160˚C, 190˚C) • Reaction time (10,20,30 minutes) • VS content (1%, 3%, 5%)	216 mLCH_4/gVS	464 mLCH_4/gVS (190˚C, 10 minutes, 0,2 mgNaOH/mgVS, 5% VS content)	114%	[21]

No.	Title	Sample Type	Pre-Treatment Method	Variables	Methane Production Without Pre-Treatment	Maximum Methane Production With Pre-reatment	Maximum Methane Enhancement(%)	Reference
				• NaOH concentration (0, 0,1, 0,2 mgNaOH/mgVS)				
15.	Optimization of thermo-alkaline pretreatment on municipal sludge and enhanced subsequent anaerobic digestion	Municipal Sludge (MS) from Nanning Municipal WWTP, Guangxi, China	Termo-alkaline	Independent: • Waterbath temp (70˚C, 80˚C, 90˚C) • Cooling time (80,100,120 minutes) • Sampel pH (10,11, and 12)	1927 mLCH$_4$ (T80)	3434 mLCH$_4$ (T80)	78,2%	[22]
16.	Enhancing biogas production of anaerobic co-digestion of industrial waste and municipal sewage sludge with mechanical, chemical, thermal, and hybrid pre-treatment	Mixed industrial fruit juice waste, fruit processing waste, and municipal sewage sludge	• Mechanical: ultrasonik (US), microwave • Chemical: acid, alkaline • Termal • Hybrid: Ultrasonic-Acid (US-AC), Ultrasonic-Alkaline (US-AL)	Independent: • Pre-treatment type • US operation time (15-30 minutes) • Microwave power output (200 W, 400 W) • Acid pH (2 and 4) • Alkaline pH (9 and 11) • Autoclave operation time (15 and 30 minutes)	407 mLCH$_4$	• US (15 min): 594 mLCH$_4$ • MW (400 W): 536 mLCH$_4$ • AC (pH 4): 449 mLCH$_4$ • AL (pH 9): 571 mL CH$_4$ • T (15 min): 358 mLCH$_4$ • US-AC (15 min, pH 4): 548 mLCH$_4$ • US-AL (15 min, pH 9): 792 mLCH$_4$	• US: 45,9% • MW: 31,6% • AC: 10,3% • AL: 40,3% • T: -12% • US-AC:34,6% • US-AL: 94,5%	[23]
17.	Sewage sludge digestion beyond biogas: Electrochemical pretreatment for biochemicals	Waste Activated Sludge (WAS) from a municipal WWTP (Shatin, Hong Kong)	Electrochemical Pre-treatment (EPT)	Independent: • Input voltage (0−15V). • EPT operating mode (continuous, 2s on/2s off, and 2s on/8s off). • WAS pH before EPT (7, 9, dan 11). • WAS VS concentration (low 4 g/L, medium 8 g/L, and high 15 g/L).	145 N mLCH$_4$/gVSadded	• Ti-EPT: 178 ± 8 N mL CH$_4$/g VSadded. • Carbon-EPT: 117 ± 3 N mL CH$_4$/g Vsadded • Graphite-EPT: CH$_4$ production inhibited	• Ti-EPT: 22,7% • Carbon-EPT: -19,3%	[24]

No.	Title	Sample Type	Pre-Treatment Method	Variables	Methane Production Without Pre-Treatment	Maximum Methane Production With Pre-reatment	Maximum Methane Enhancement(%)	Reference
				• WAS conductivity level (1, 2, 3, and 4 mS/cm). • Electrode material (graphite, carbon, and titanium)				
18.	Pretreatment of sludge with sodium iron chlorophyllin-H_2O_2 for enhanced biogas production during anaerobic digestion	Waste Activated Sludge (WAS) from Shahu Municipal WWTP (Wuhan, China)	Sodium Iron Chlorophyllin-H_2O_2 (SIC-H_2O_2) blending	Independent: Pre-treatment type (SIC-H_2O_2, SIC, H_2O_2, Fe2+ -H_2O_2).	150 mLCH_4/L	• SIC-H_2O_2: 348 mLCH_4/L • SIC: 225 mLCH_4/L • H_2O_2: 272 mLCH_4/L • Fe2+ -H_2O_2: 285 mLCH_4/L	• SIC-H_2O_2: 132% • SIC: 50% • H_2O_2: 81,3% • Fe2+ -H_2O_2: 90%	[25]
19.	Impact of process parameters of thermal alkaline pretreatment on biogas yield and dewaterability of waste activated sludge	Waste Activated Sludge (WAS)	Termal-Alkaline	Independent: • Treatment temp (various ranges, including below 100˚C and above 100˚C). • Alkali dosage (optimum range 40-60 mg NaOH/g TS). • Treatment duration (1.5-5 hours for low temp TAP)	Various ranges 0-50 to 250-300 mL CH_4 per g VSadded	Not specifically stated as a single figure	In the range of 22-97%, dependent on the initial WAS biodegradability	[26]
20.	Combined hydrothermal and free nitrous acid, alkali and acid pretreatment for biomethane recovery from municipal sludge	Thickened waste activated sludge (TWAS)	• Hydrothermal pretreatment (HTP) • Free Nitrous Acid (FNA) pretreatment • Acid pretreatment (menggunakan HCl) • Alkaline pretreatment (using NaOH) • HTP + FNA • HTP + Acid • HTP + Alkaline	Independent: • Pre-treatment type (HTP, FNA, Acid, Alkaline, HTP+FNA, HTP+Acid, HTP+Alkaline).	388 L CH_4/g VSS added	• FNA: 417 L CH_4/g VSS added • Alkaline (ALK): 471 L CH_4/g VSS added • Acid: 444 L CH_4/g VSS added • HTP: 502 L CH_4/g VSS added • HTP + FNA: 594 L CH_4/g VSS added • HTP + Alkaline (ALK):	• FNA: 8% • Alkaline (ALK): 21% • Acid: 15% • HTP: 30% • HTP + FNA: 53% • HTP + Alkaline (ALK): 36% • HTP + Acid: 40%	[27]

No.	Title	Sample Type	Pre-Treatment Method	Variables	Methane Production Without Pre-Treatment	Maximum Methane Production With Pre-reatment	Maximum Methane Enhancement(%)	Reference
						527 L CH_4/g VSS added • HTP + Acid: 544 L CH_4/g VSS added		

Physical Pre-Treatment

Physical pre-treatment methods operate on the principle of mechanical or thermal disintegration to rupture the complex structure of organic matter within sludge or waste, thereby enhancing solubilisation and substrate availability for anaerobic microorganisms [28]. Hydrothermal Pre-Treatment (HTP**)**, for instance, involves heating the sludge to high temperatures to lyse microbial cells and break down the organic matrix. In [11], HTP applied to a mixture of faecal and activated sludge resulted in an 8.3% increase in methane yield at a Sludge Retention Time (SRT) of 10 days (temperature 125˚C) and a 29.5% increase at an SRT of 20 days (temperature 155˚C). Temperature and SRT are established as key variables influencing HTP effectiveness, with higher temperatures generally leading to greater enhancement.

The addition of N_2-Nanobubble Water (N_2-NBW) also promotes methane production by accelerating the hydrolysis of waste activated sludge. [1] demonstrated a 29% increase in methane yield from waste activated sludge with the introduction of N_2-NBW at a pressure of 0.24 MPa for 30 minutes. The addition of NBW increases the negative charge of sludge particles due to the presence of •OH radicals. This facilitates microbial access to organic matter and triggers sludge solubilization as well as the degradation of cellular materials. Consequently, the hydrolysis stage is accelerated, leading to enhanced methane production during the anaerobic digestion process. However, the observed increase was not particularly significant, as it is speculated that the addition of N_2-NBW may also promote acidification during digestion, thereby leading to enhanced VFA production [1].

Sonication (ultrasound) utilises high-frequency sound waves to induce cavitation, making it highly effective for cell disruption. Cavitation is the phenomenon where ultrasound waves (typically in the 20–40 kHz frequency range) propagate through a medium, causing pressure fluctuations that lead to the formation of microbubbles. Once these bubbles reach a critical size, they violently collapse (implode), releasing significant energy and locally creating extreme temperature and pressure conditions [29]. In [15] study showed that sonication could increase biogas production by 33.61% in urban sewage sludge, with its efficacy being dependent on the duration and frequency of the sound waves employed. Conversely, Thermal Pre-treatment involves heating the sludge across various temperatures and durations to solubilise solid organic matter. [15] investigated thermal pre-treatment using both an autoclave and a water bath, reporting methane production increases ranging from 14.92% (water bath, 90˚C, 0.5 hours) to 51.27% (autoclave, 90˚C, 30 minutes, 2 bar) for urban sewage sludge.

These physical pre-treatment methods enhance methane production by accelerating hydrolysis through floc disintegration (EPS), particle size reduction, and cell wall rupture, which releases soluble organic matter for better microbial accessibility. While thermal pre-treatment (HTP) typically yields superior methane production due to extreme solubilization via high temperature and pressure. This effectively converts the solid matrix into highly bioavailable dissolved organics, providing a more accessible substrate for anaerobic digestion than methods relying solely on mechanical shear or limited oxidation.

Chemical Pre-Treatment

Chemical pre-treatment methods utilise various chemical agents to fracture the complex structure of organic matter, thereby boosting solubilisation and significantly shortening the hydrolysis time. The resulting more open material structure facilitates the interaction between microbial cells and the chemicals, promoting the solubilisation of cell walls and membranes, and ultimately supporting enzymatic attacks on the intracellular contents [30]. Free Nitrous Acid (FNA) operates as a powerful oxidative agent capable of disintegrating sludge flocs and solubilising organic matter. [12] reported a 33.9% increase in methane yield from thickened activated sludge following FNA pre-treatment. In this process, the concentration of FNA and the pre-treatment duration are critical parameters that influence efficiency.

The application of alkaline solutions (e.g. NaOH, $Ca(OH)_2$, $Mg(OH)_2$, KOH) offers another pre-treatment option, functioning by enhancing the solubilisation of organic matter through the cleavage of hydrogen and ester bonds. In [17] found that alkali pre-treatment increased methane production from waste-activated sludge (WAS) by 52.9% to 79.8%, depending on the specific alkaline reagent used, for example, KOH provided the highest enhancement at 79.8%. Furthermore, Ozone (O_3), as a strong oxidant, effectively disrupts organic macromolecules. [16] demonstrated that ozonation of waste thickened activated sludge (WTAS) could increase biogas production by up to 164% (at an ozone dose of 0.05 g O_3/g TS) for a 10-day SRT, although no significant enhancement was observed for a 30-day SRT. Additionally, Peracetic Acid (PAA) is also a potent oxidising agent shown to boost the release of organic matter and methane conversion. [20] reported that PAA pre-treatment of activated sludge and dewatered sludge increased biogas production by 40.35% at a PAA dose of 2 mM/g VS. Finally, Electro-Oxidation and the Fenton process exploit oxidative mechanisms to generate highly reactive hydroxyl radicals. [19] observed a 28% increase in methane yield with Electro-Oxidation and a 39% increase with Fenton pre-treatment in a blend of industrial fruit juice waste and urban sewage sludge.

Among various chemical methods, ozonation (O_3) has proven to be the most effective due to its strength as a potent oxidant. It generates non-selective hydroxyl radicals capable of degrading nearly all organic compounds [31]. Unlike alkaline pre-treatment, which primarily cleaves hydrogen and ester bonds, ozonation achieves the total destruction of the cellular matrix, converting refractory compounds into highly bioavailable organic fragments. Furthermore, because ozone decomposes into oxygen, it leaves no chemical residues that could inhibit the subsequent anaerobic digestion process.

Biological Pre-Treatment

Biological methods, or the addition of biological/enzymatic agents, aim to accelerate the degradation of complex organic matter into simpler forms via microbial or enzymatic activity. Hyperthermophilic Biological Hydrolysis, for example, involves hydrolysis at extremely high temperatures (e.g.,70˚C) driven by thermophilic microorganisms. In [2] experiment proved that this method increased methane production from faecal sludge by 69.7%, where the hydrolysis retention time (HRT) in the anaerobic membrane bioreactor (AnMBR) was a critical variable, with a 20-day HRT yielding the optimal results.

The principal advantage of biological methods is that they are environmentally friendly and entail relatively low energy consumption compared to intensive physical or chemical counterparts. However, their disadvantages include a frequently longer required incubation time and a high sensitivity to operational conditions (such as temperature and pH), which must be maintained optimally for microbial growth.

Combination Method Pre-Treatment

Combined pre-treatment methods are implemented by integrating two or more techniques to exploit the resulting synergistic effects, simultaneously overcoming the inherent limitations of each single technique. This integrated approach consistently leads to a more substantial enhancement of methane production during the Anaerobic Digestion (AD) process. For instance, [8] demonstrated that the combination of High-Pressure Homogenisation (HPH) and Free Nitrous Acid (FNA) on waste activated sludge (WAS) achieved a remarkable methane production increase, reaching 524%. Optimal synergy was achieved through HPH's cellular physical disintegration followed by FNA’s organic matter oxidation. Similar effectiveness is observed with the Thermo-Alkali combination, where the synergy between heat and alkali has proven highly efficient in sludge structure disintegration. [21] and [22] reported methane yield increases of 114% from WAS and 78.2% from urban sludge, respectively, driven by enhanced solubilisation of complex organic matter (such as polysaccharides, proteins, and lipids) and accelerated cellular disintegration.

Furthermore, [14] showed that combining Dilute Acid–Thermal Pre-treatment with the addition of biochar (which acts as a microorganism carrier and inhibitor adsorbent) boosted methane production from water hyacinth and activated sludge by 147.8%, confirming the role of the acid-heat combination in breaking down the lignocellulosic matrix. Other studies, [27] confirmed that combining Hydrothermal Pre-treatment (HTP) with reagents like FNA, HCl, or NaOH yielded superior results compared to single methods, with HTP + FNA showing the highest increase at 53%. Additionally, [23] found that the Ultrasonic–Alkali (US–AL) combination resulted in the maximum methane production increase of 94.5% in mixed industrial and urban wastewater sludge.

The key advantage of combined methods lies in their capacity to offset the drawbacks of single techniques for example, by coupling physical disintegration with chemical solubilisation thereby doubly increasing substrate release and availability. Nonetheless, it must be considered that increased operational complexity and potentially higher costs pose significant challenges for full-scale implementation.

Opportunities and Challenges of Implementing Wastewater Sludge Pre-Treatment

The application of sludge pre-treatment offers significant opportunities for substantially boosting biogas production from wastewater. This process effectively disrupts the complex organic material within the sludge, accelerating the crucial hydrolysis stage [32] and increasing substrate availability for methane-producing bacteria, which consequently enhances the overall biogas yield [33]. Furthermore, improved biodegradability reduces the required retention time for sludge stabilisation [34] and drastically minimises the volume of sludge requiring final disposal, leading to considerable savings in handling and disposal costs. The generated biogas becomes a valuable source of renewable energy, reducing reliance on fossil fuels and mitigating greenhouse gas emissions. Additionally, the resulting digestate (residue after digestion) exhibits better quality for use as organic fertiliser, and the sludge's dewatering capability is often enhanced, simplifying subsequent handling processes.

However, the implementation of these technologies is not without its challenges. The initial capital investment required for high-intensity equipment, such as High-Pressure Homogenisation (HPH), can be prohibitively high, particularly for wastewater treatment plants (WWTPs) with constrained budgets [35]. Moreover, the substantial operational energy consumption required to run methods like HPH must be carefully evaluated to ensure that the incremental biogas production adequately compensates for the energy input. Operational and maintenance complexity also increases, necessitating skilled labour and strict maintenance schedules. The highly variable characteristics of wastewater sludge can further compromise pre-treatment effectiveness, demanding meticulous parameter adjustment. There is also the potential for the formation of inhibitory compounds during pre-treatment that could disrupt microbial activity within the digester, alongside prevailing challenges in the scalability and full-scale application of technologies which are still frequently tested only at laboratory scale [36].

4. Conclusion

Wastewater sludge pre-treatment offers substantial potential for enhancing biogas production and improving overall waste management efficiency. A diverse range of methods including physical, chemical, biological, and combined techniques have proven effective in disrupting complex organic matter, accelerating hydrolysis, and significantly increasing substrate availability for methane generation, consequently boosting biogas yield. This enhancement in biodegradability not only leads to higher biogas production but also substantially reduces the volume of sludge requiring disposal and shortens the necessary retention time for stabilisation, ultimately resulting in savings on handling and disposal costs. The recovered biogas constitutes a valuable source of renewable energy, contributing to a reduced dependence on fossil fuels and a decrease in greenhouse gas emissions. Furthermore, the resulting digestate exhibits improved quality for organic fertiliser use, and sludge dewatering capability is enhanced, simplifying subsequent handling procedures.

Notwithstanding these benefits, the implementation of pre-treatment technologies faces several challenges. High initial capital investment costs for advanced pre-treatment equipment, such as High-Pressure Homogenisation (HPH), often present a significant barrier. Substantial operational energy consumption, particularly for energy-intensive methods, remains a primary concern, necessitating careful cost-benefit analysis to ensure that the increased biogas yield adequately compensates for this energy input. The increased operational complexity and stringent maintenance requirements demand skilled personnel and efficient management. Additionally, the inherent variability in wastewater sludge characteristics can impact pre-treatment effectiveness, requiring careful parameter adjustment to optimise performance. Finally, the potential formation of inhibitory compounds during pre-treatment may disrupt microbial activity within the digester, underscoring the need for effective monitoring and mitigation strategies.

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