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Optimizing an Anaerobic Hybrid Reactor Series for Effective High-Strength Fresh Leachate Treatment and Biogas Generation

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Abstract: Treating high-strength fresh leachate is challenging and of great interest due to the inherent variability in its physical and chemical characteristics. This research aims to enhance the efficiency of the anaerobic hybrid reactor (AHR) series in treating high-strength fresh leachate and achieving biogas generation from fresh leachate at ambient temperatures. The AHR series used consists of two serially connected reactors termed the first anaerobic hybrid reactor (AHR-1) and the secondary anaerobic hybrid reactor (AHR-2). AHR-1 treated high-concentration fresh leachate with an organic loading rate (OLR) between 5 and 20 kgCOD/m^3·d. AHR-2 treated the effluent from the first tank and removed organic matter from the system. The experiment was conducted for 210 days, showing that an OLR of 10 kgCOD/m^3·d resulted in the most suitable COD removal efficiency, ranging from 82 to 91%. The most suitable OLR for biogas production was 15 kgCOD/m^3·d. The AHR series proved to be an efficient system for treating high-strength fresh leachate and generating biogas, making it applicable to leachate treatment facilities at waste transfer stations and landfill sites. Treating leachate and utilizing it as a renewable energy source using the AHR series presents a practical and efficient waste management approach. High-strength leachate can be effectively treated with the AHR series; such methods may be integrated into industries treating leachates with high COD values.

Keywords: anaerobic digestion efficiency; wastewater-to-energy; sustainable waste management; methane recovery; leachate valorization

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1. Introduction

The amount of waste being produced worldwide is on the rise as cities grow and populations increase. Waste-to-energy (WTE) technologies like incineration, anaerobic digestion and mechanical biological treatment (MBT) are becoming more popular. These approaches not only help decrease the amount of waste going into landfills but also harness energy from waste, providing a twofold advantage [1–3]. Effective handling of solid waste (MSW) is crucial for promoting sustainable urban development [1]. Challenges in managing waste in developing countries include insufficient waste collection and the practice of open dumping in non-engineered landfills, resulting in pollution and harm to the environment [4]. To tackle these problems, it is essential to adopt waste management strategies that prioritize converting waste into energy and promoting circularity in handling MSW [5].

Fresh leachate is a highly concentrated liquid waste that often contains hazardous components [6]. It is generated during waste collection and landfilling processes and, if not managed properly, can significantly impact the environment. Leachate treatment is critical to minimize its environmental impact. Organic pollutants and high concentrations of suspended solids and toxins in fresh leachate can inhibit the function of beneficial bacteria in wastewater treatment systems [7]. Untreated leachate discharge can contaminate groundwater, surface water, and the surrounding ecosystems, posing severe environmental and health risks [8,9]. Fresh leachate is characterized by both a high chemical oxygen demand (COD) and a high biochemical oxygen demand (BOD_5), making its treatment challenging. Traditional wastewater treatment methods are ineffective in reducing this contamination level [10,11]. Furthermore, leachates with high concentrations of ammonia, sulfate, and calcium present significant obstacles to biological treatment methods, reducing the efficiency of leachate treatment and adversely affecting methane (CH_4) gas production processes [12,13]. Leachate treatment is crucial for sustainable waste management approaches [14,15].

Fresh leachate treatment remains a challenge due to limited studies on the subject. Achieving efficient fresh leachate treatment would address pollution problems and reduce greenhouse gas emissions during leachate management. Effective and swift leachate management can reduce water and air pollution and minimize the prevalence of disease by controlling the spread of pathogens into the environment, thereby reducing health risks to the public. Anaerobic treatment systems are popular solutions for managing high-concentration wastewater [15] and are suitable for treating wastewater with complex compositions. Biogas production is a key advantage of anaerobic leachate treatment [16]. Biogas primarily consists of CH_4 and carbon dioxide (CO_2), both of which significantly impact the environment [17]. CH_4 production from leachate helps to reduce atmospheric CH_4 emissions, thereby contributing to climate change mitigation. Furthermore, CH_4 produced from fresh leachate can be reused as energy, providing a renewable energy source [18,19]. Biogas is thus a valuable resource for energy production, offsetting energy costs associated with leachate treatment systems.

Developing technologies for renewable energy production from leachate represents a sustainable economic and environmental approach [20] and aligns with circular economy principles and efficient resource use (a closed loop). Transforming waste into valuable resources is a fundamental aspect of sustainable waste management. Leachate is, therefore, increasingly viewed as a resource for energy production and environmental protection [21]. By converting high-strength leachate into biogas, not only does our proposed anaerobic hybrid reactor series contribute to sustainable waste management, but it also unveils significant opportunities for renewable energy production and economic gains, paving the way for a circular economy. This study aims to determine the optimal operating conditions to enhance the efficiency of anaerobic hybrid reactors in treating high-concentration fresh leachate and facilitating biogas production. It then evaluates the rate and quality of biogas and CH_4 production, assessing COD removal efficiency and providing valuable information for effective and sustainable waste management practices.

2. Materials and Methods

This research was conducted to enhance the efficiency of the anaerobic hybrid reactor (AHR) series system. The treatment of high-concentration fresh leachate is aimed primarily at biogas production. The experimental procedures and analytical methods used are detailed in the following.

2.1. Anaerobic Hybrid Reactor (AHR) Series System

This study involved an experimental trial at the laboratory level. The AHR system used was made from cylindrical acrylic tubes, which are durable and transparent, allowing observation of the operation of the system during experiments. The AHR series had a cylindrical shape, with a diameter of 20 cm and a height of 100 cm, and consisted of a serial connection of AHR-1 and AHR-2 with a total operational volume of 40 L. AHR-1 and AHR-2 were packed with nylon fiber media, which played a crucial role in bacterial adhesion and increased the surface area available for microbial growth [22]. The integration of suspended and attached growth systems, as exemplified by the Up-flow Anaerobic Sludge Blanket with the Down-flow Hanging Sponge (UASB-DHS) technology discussed in Mazhar et al. [23], represents a significant advancement in the field of wastewater treatment. This study underscores the potential of combining the UASB with the DHS system to achieve high efficiency in pollutant removal, notably BOD, COD, TSS, and VSS, with removal efficiencies reaching up to 93%. Such efficiencies are attributed to the dual-action mechanism where the anaerobic UASB reactor effectively breaks down organic matter, producing biogas, and the DHS system, functioning aerobically, provides additional polishing of the effluent. The characteristics of the media attachment in the reactor before the start of the experiment are shown in Figure 1.

Figure 1. Nylon fiber carriers in the AHR series system.

2.2. Experimental Procedure

The AHR series system used in this research consisted of two reactors connected in series. AHR-1 received fresh leachate and was set with a specific organic loading rate (OLR). AHR-2 received the effluent from AHR-1. A schematic of the AHR series is shown in Figure 2. This experiment was conducted at room temperature. Before the experiment, sludge, which was collected from an anaerobic leachate treatment system in the Racha Thewa area, Bang Phli, Thailand, was cultured inside the reactors. The experiment started with an OLR of 1 kgCOD/m^3·d for 60 days, after which the OLR was continuously increased to 20 kgCOD/m^3·d. The hydraulic retention time (HRT) ranged from 5 to 30 days, whereas the sludge retention time (SRT) was 15 days. The OLR was controlled between 5 and 20 kgCOD/m^3·d, consistent with Sakulrat et al. [24], who studied a single-tank AHR system. The performance assessment of the AHR series involved the analysis of the quantity of biogas produced. The COD values of both the influent and effluent were determined. The leachate effluent released from AHR-1 provided the influent for AHR-2. The percentage of COD removal within the AHR series was calculated using Equation (1).

$$\%\text{COD Removal of AHR series} = ((Ci_{AHR1} - Cf_{AHR2})/Ci_{AHR1}) \times 100 \quad (1)$$

where Ci_{AHR1} is the initial concentration of COD (mg/L) in AHR-1, and Cf_{AHR2} is the final concentration of COD (mg/L) in AHR-2.

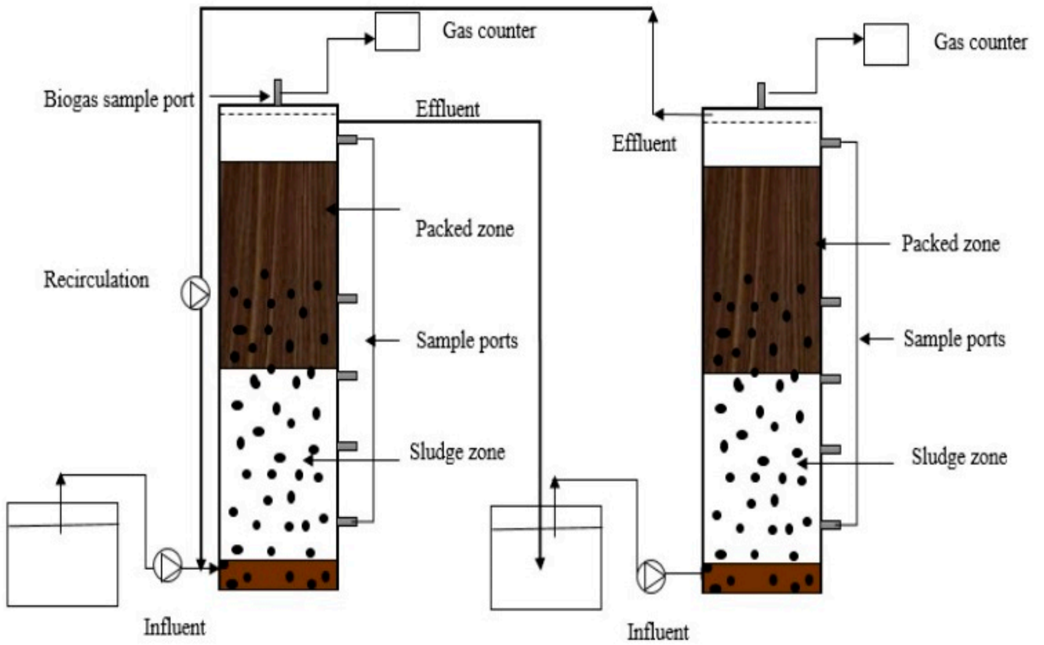


Figure 2. AHR series schematic diagram.

2.3. Sample Collection and Analysis Methods

The methods for collecting and analyzing the samples used in this study are as follows. Fresh leachate samples from the On-Nut waste transfer station in Bangkok, Thailand, were analyzed for their physical and chemical properties before designing the reactor tanks. The parameters analyzed included pH, COD, BOD, total solids in leachate, total volatile fatty acids, total Kjeldahl nitrogen (TKN), ammonia nitrogen, and heavy metals. The leachate samples were stored at a temperature not exceeding 4 °C prior to analysis. The biochemical methane potential (BMP) of fresh leachate and effluent from the anaerobic reactors was determined to assess the potential for CH_4 production following the method presented by Holliger [25]. Gas samples were collected to analyze the main components of biogas, namely CH_4, CO_2, and O_2, using a Clarus 580 Gas Chromatograph (Shimadzu, Kyoto, Japan). Wastewater was collected daily from the reactors, and the pH of this water was measured using a pH meter. Total solids in leachate were determined by filtering through a glass microfiber filter (GF/C) according to standard methods [26]. The concentration and percentage of CH_4, CO_2, and hydrogen sulfide (H_2S) were measured daily using a Biogas 5000 system (Geotech, Chelmsford, UK). Samples from AHR-1 and AHR-2 were collected for COD analysis once per week. The volatile solids on the nylon fiber media were analyzed at the end of the experiment. Finally, the relationship was analyzed using descriptive statistics to evaluate the enhancement of AHR series efficiency.

3. Results and Discussion

3.1. COD Removal Efficiency

This study found that the AHR series had an average COD removal efficiency of 91% at an OLR of 10 kgCOD/m^3·d and maintained a COD removal efficiency of 88% when the OLR increased to 15 kgCOD/m^3·d, consistent with a previous study by Maleki et al. [27]. Increasing the OLR from 1.36 to 3.18 kgCOD/m^3·d caused the COD removal efficiency to decrease from 94.1% to 90.2% and the biogas production to decrease from 0.34 to 0.31 L/g.

This shows that the anaerobic system suits wastewater with high organic content and offers a viable alternative mechanism for COD removal. The AHR series system is environmentally friendly and provides energy for reuse, as described in research's Genethlio [28]. Figure 3 shows the COD removal efficiency at different OLR levels. Increasing the OLR from 10 to 15 kgCOD/m^3·d allowed a good COD removal efficiency to be maintained, demonstrating the stability and efficiency of the system when treating wastewater. This flexibility demonstrated the adaptability of the AHR series system, showing that efficient COD removal can be maintained throughout a controlled OLR increase. Rinquest showed that higher OLR values could result in a decrease in COD removal efficiency [29]. Harsha and Maurya found that an increased organic load could affect the ability of microorganisms to grow and efficiently remove COD [30]. As shown in Figure 4a,b, the relationships between the percentage of COD removal CH_4 production and between biogas production and CH_4 production in the AHR series exhibited linear regression with R^2 values of 0.96 and 0.97, respectively.

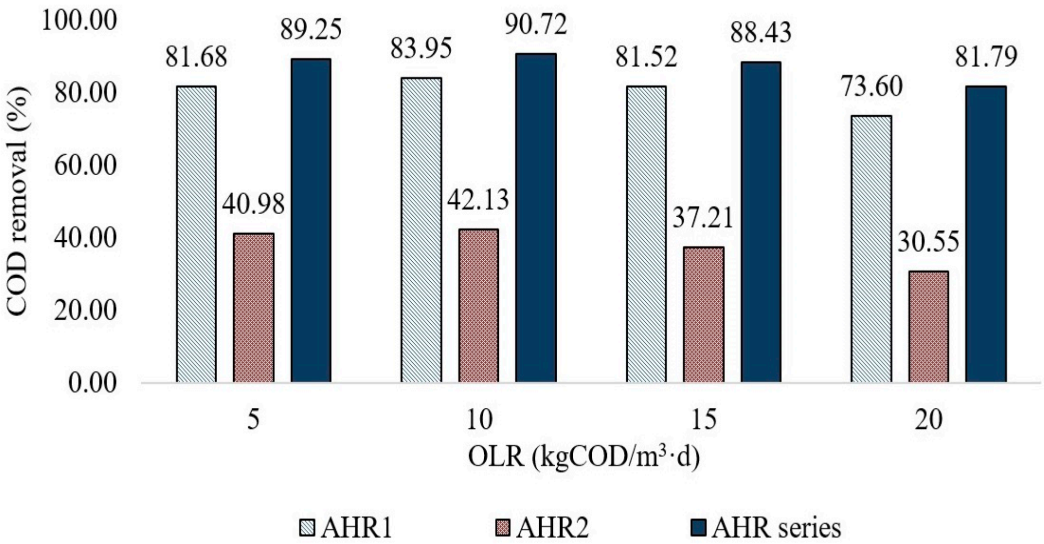
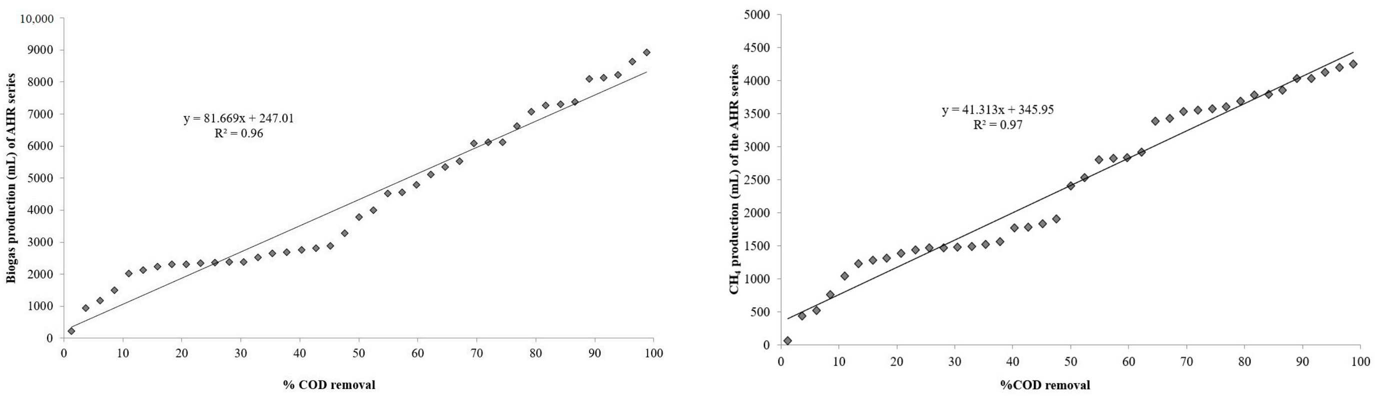


Figure 3. COD removal efficiencies of the AHR series at various OLRs.



(**a**) (**b**)

Figure 4. Relationships between (**a**) %COD removal and biogas production of the AHR series and (**b**) %COD removal and CH_4 production of the AHR series.

A vital objective of the AHR series system is to enhance COD removal efficiency and biogas production, which were analyzed using a one-way analysis of variance (ANOVA) at a 95% confidence level to assess the relationships between variables. The R^2 value, which explains the relationship between the independent variables affecting COD removal efficiency and biogas production, suggested that values greater than 0.5 indicate a moderate relationship between parameters [31]. Therefore, the starting OLR directly influences both COD removal efficiency and biogas production. The related factor, a primary variable in this experiment, is OLR, which is correlated with CH_4 production in the AHR series and has a statistical significance at p-value < 0.05.

High-strength fresh leachate can be effectively treated using various methods, as demonstrated in the literature. One study investigated the treatment of fresh leachate from municipal solid waste incineration plants using an expanded granular sludge bed (EGSB) reactor, achieving an average COD removal efficiency of 87% [32]. Another study examined the coagulation–flocculation process followed by biological treatment for landfill leachate, where coagulation treatment achieved a COD removal efficiency of 35%, and the anaerobic filter achieved 20%, with the combined technologies achieving 51.52% [33]. Additionally, the use of organic modified bentonites was effective in the pretreatment of high-strength landfill leachate, with a COD removal efficiency of 67% under optimum conditions [34]. However, our study's AHR series demonstrated a higher COD removal efficiency, achieving an average of 91% at an OLR of 10 kgCOD/m^3·d, and even maintained an 88% efficiency when the OLR increased to 15 kgCOD/m^3·d. This not only aligns with but also surpasses the efficiencies reported in previous studies, marking a significant advancement in the treatment of high-strength leachate and showcasing the AHR series as a robust and efficient solution.

3.2. *Removal of Organics in Solid*

The volatile suspended solids (VSS) in the influent and effluent of the system can be used to assess the efficiency of organic matter reduction. A decrease in the VSS of the treatment system indicates the leachate treatment efficiency of the system. As shown in Figure 5, increasing the OLR causes the VSS of the system to increase. At an OLR of 5 kgCOD/m^3·d, the VSS concentration ranged between 1520 and 4245 mg/L. Increasing the OLR to 10, 15, and 20 kgCOD/m^3·d resulted in a continuous increase in both the VSS and total biomass of the AHR series.

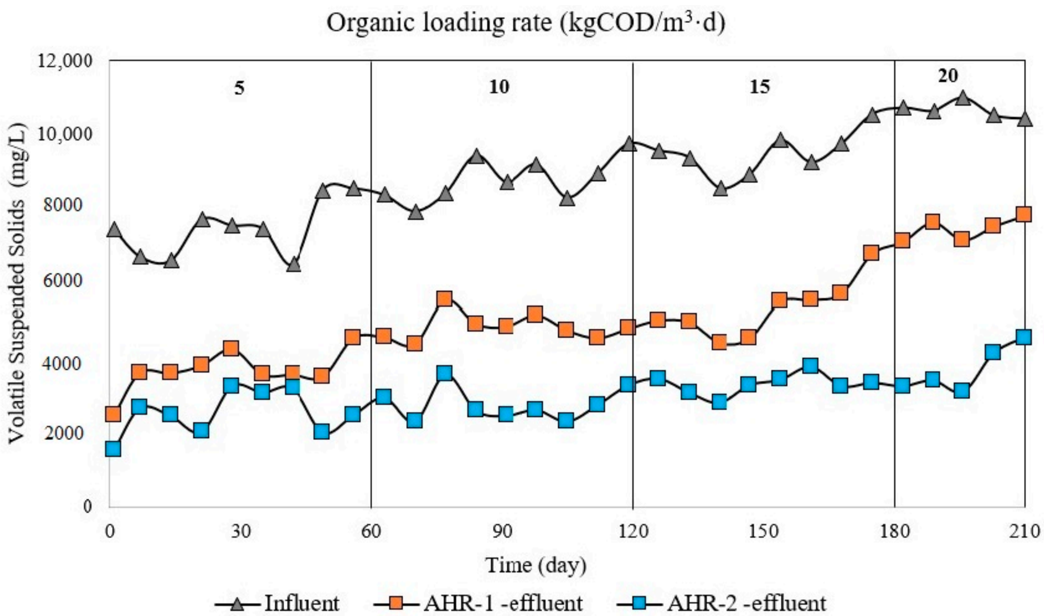


Figure 5. Volatile suspended solids in the influent and effluent of AHR reactors.

3.3. *Quantitative Assessment of Biogas and Methane Production*

Quantitative assessments of the volume of biogas and CH_4 produced in AHR-1, AHR-2, and the AHR series were performed. Biogas and CH_4 production (both in mL/day) are shown in Table 1.

As shown in Table 1, the AHR series produced the highest biogas and CH_4 at an OLR of 15 kgCOD/m^3·d, with biogas production at 6476 mL/day and CH_4 production at 3857 mL/day. When the OLR was increased to 20 kgCOD/m^3·d, the production of biogas and CH_4 decreased. Increasing the OLR provides results consistent with the findings of Maleki et al., who found that biogas production decreased when the OLR was increased from 1.36 to 3.18 kgCOD/m^3·d. AHR-1 and AHR-2 both showed efficient biogas and CH_4 production and have excellent potential for biogas production [35]. The AHR series is also environmentally friendly, aligning with the concepts of Moujanni et al. [36]. The cumulative biogas and CH_4 volumes are shown in Table 2.

Table 1. Quantitative evaluation of biogas and CH_4 production.

OLR (kgCOD/m^3·d)	Biogas Production (mL/Day)			CH_4 Production (mL/Day)		
	AHR-1	**AHR-2**	**AHR Series**	**AHR-1**	**AHR-2**	**AHR Series**
5	1404	713	2117	840	377	1217
10	3102	1435	4537	1961	810	2771
15	4409	2067	6476	2676	1181	3857
20	5357	2599	7956	2628	1160	3788

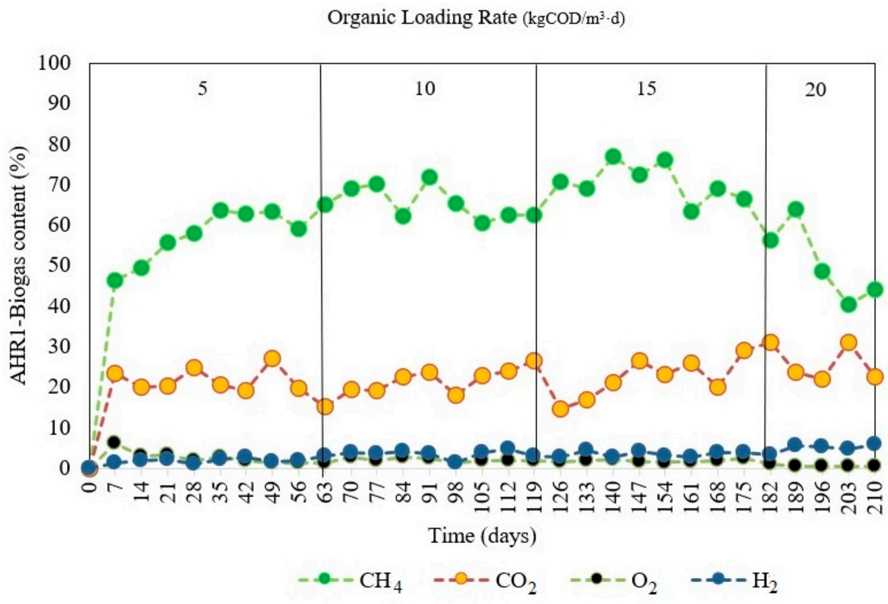
Table 2. Cumulative biogas and CH_4 (210 days) using AHR-1, AHR-2 and the AHR series.

OLR (kgCOD/m^3·d)	Cumulative Biogas (mL)			Cumulative CH_4 (mL)		
	AHR-1	**AHR-2**	**AHR Series**	**AHR-1**	**AHR-2**	**AHR Series**
5	84,217	42,805	127,022	50,376	22,618	72,994
10	186,116	86,107	272,223	117,651	48,591	166,242
15	264,537	124,012	388,549	160,577	70,840	231,417
20	160,699	77,973	238,672	78,841	34,803	113,644

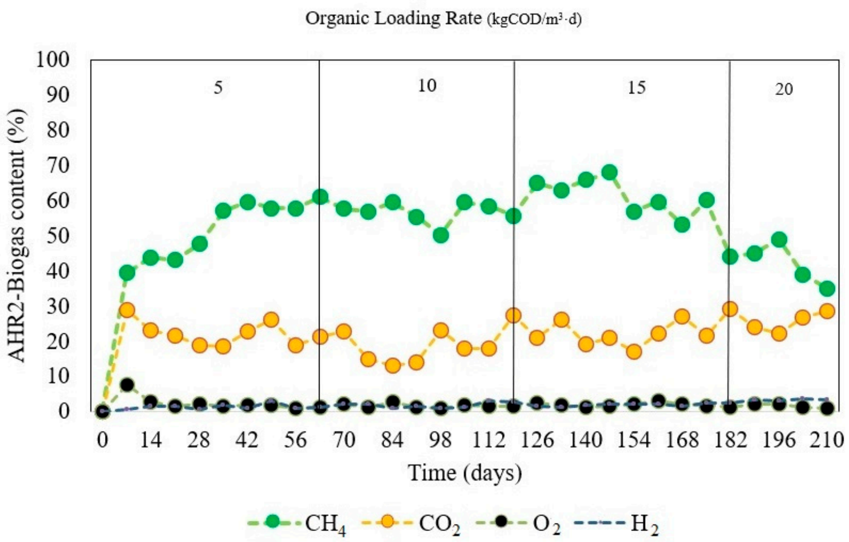
As shown in Table 2, the AHR series produced the highest cumulative biogas and CH_4 at an OLR of 15 kgCOD/m^3·d, with a cumulative biogas production of 388,549 mL and a cumulative CH_4 production of 231,417 mL. The next highest production occurred at an OLR of 10 kgCOD/m^3·d. Conversely, increasing the OLR from 15 to 20 kgCOD/m^3·d caused the production of biogas and CH_4 to decrease.

3.4. Assessment of the Quality of Biogas and CH_4 Production

To enhance the efficiency of biogas production, it is necessary to produce large quantities of high-quality biogas. The quality of CH_4, expressed as a percentage, is an essential parameter in assessing the use of biogas for energy applications [37,38]. Figure 6 shows the quality of CH_4 at OLR conditions of 5, 10, 15, and 20 kgCOD/m^3·d. This study found that the operation of AHR-1 and AHR-2 complemented the efficiency of the other. AHR-1 resulted in a CH_4 quality of up to 60.8%, while AHR-2 had a slightly lower CH_4 quality of 57.1%. These results indicate that AHR-1 had more suitable conditions for CH_4 production and was able to consistently maintain higher quantities and quality of CH_4. Increasing the OLR to 20 kgCOD/m^3·d caused CH_4 production to decrease, indicating that the efficiency of the system decreases when the OLR is increased above 15 kgCOD/m^3·d. Higher OLR values influence the function of the CH_4-producing microbial community due to overloading. The primary objective of the AHR is anaerobic digestion, which involves microbes that produce acids to generate biogas. The results of this study are consistent with the findings of Collivignarelli et al. and Umiejewska et al. [39,40].



(**a**)



(**b**)

Figure 6. CH_4 contents (%) in (**a**) AHR-1 and (**b**) AHR-2.

3.5. Methane Production Rate

Analysis of the relationship between OLR and CH_4 yield (L/g COD removed) for AHR-1, AHR-2, and the AHR series systems showed that the maximum CH_4 production per COD removal was achieved by setting the OLR of the system to 15 kgCOD/m^3·d. AHR-1 resulted in an average CH_4 production per COD removal of 0.57–0.76 L/g COD removed, whereas AHR-2 achieved an average of 0.27–0.47 L/g COD removed. The AHR series removed an average of 0.33–0.67 L/g COD. Yodthongdee found that the efficiency of anaerobic wastewater treatment depends on the ability to remove COD and CH_4 formation per COD removal [41]. Analyses of the relationships between OLR and CH_4 yield (L/g COD removed) for AHR-1, AHR-2, and the AHR series systems showed logarithmic curves with coefficient of determination (R^2) values of 0.72, 0.35, and 0.41, respectively, as shown in Figure 7a–c.

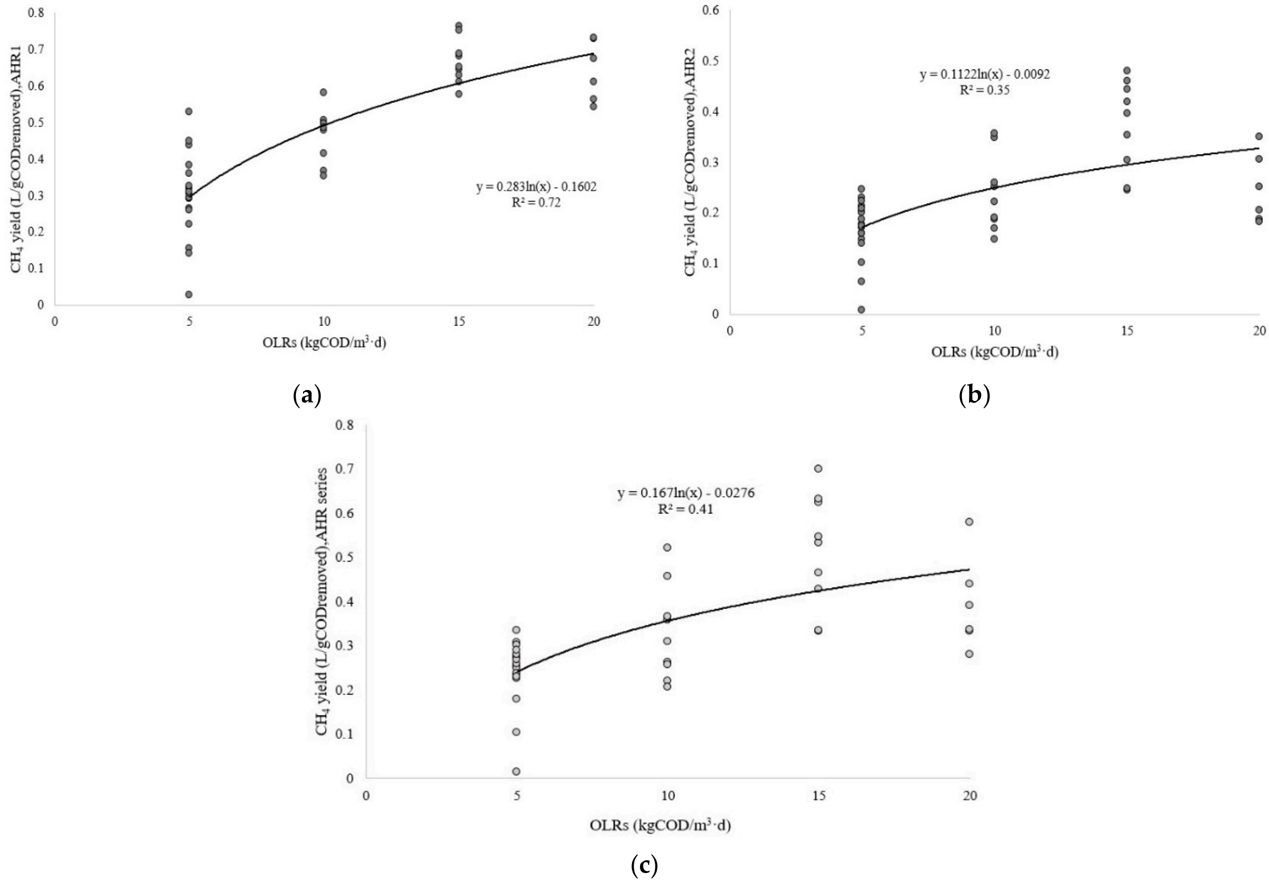


Figure 7. Relationships between (**a**) OLR and CH_4 yield of AHR-1, (**b**) OLR and CH_4 yield of AHR-2, and (**c**) OLR and CH_4 yield of the AHR series.

Furthermore, at an OLR of 5–15 kgCOD/m^3·d, the production of biogas and CH_4 was found to increase. However, when increasing the OLR to 20 kgCOD/m^3·d, CH_4 tended to decrease due to reduced components within the biogas. Analysis of the relationship between OLR and the production of biogas and CH_4 in the AHR series showed logarithmic curves with R^2 values of 0.86 and 0.81, respectively, as shown in Figure 8a,b.

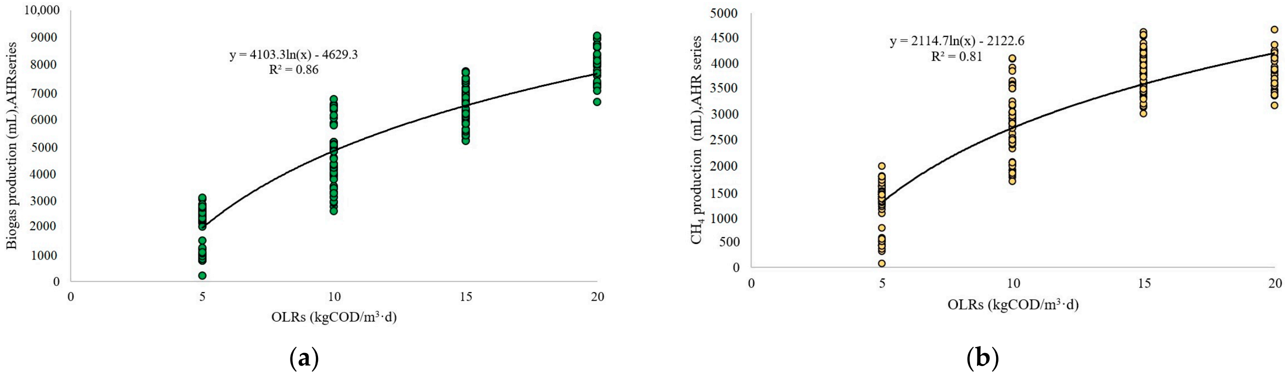


Figure 8. Relationships between (**a**) OLR and biogas production in the AHR series and (**b**) OLR and CH_4 production in the AHR series.

3.6. Identifying the Optimum OLR

The most suitable OLR to maintain an efficient anaerobic treatment system was identified in this study as 15 kgCOD/m^3·d; at this value, the CH_4 production and effective COD removal were maximized. Increasing the OLR above 15 kgCOD/m^3·d causes the efficiency of the system to decrease. This is consistent with Musa et al. [42], who found that an OLR of 0.52 gCOD/L·d achieved approximately 90% COD removal efficiency, but that the efficiency dropped to below 50% when the loading rate was increased to 15 gCOD/L·d. Similarly, Tritt and Kang reported that a similar reactor achieved a maximum COD removal efficiency of 95% at an OLR of 1 kgCOD/m^3·d with an HRT of 7.5 days [43]. At an OLR higher than 4.0 kgCOD/m^3·d, the COD removal efficiency was 75% with an HRT of 2 days. Increasing the OLR causes the volatile solids (VS) in the system to increase, which in turn increases the biomass in the system, as shown by Pereira and Yilmaz [44,45].

3.7. Biomass and Microbial Activities

As shown in Table 3, at the beginning of the experiment, the influent leachate to AHR-1 and AHR-2 had equal VSS values of 149 gVSS/reactor. Setting the system to an OLR of 5 kgCOD/m^3·d for 60 days caused the VSS to decrease. AHR-1 contained a suspended VSS of 73 g and an attached VSS of 5 g. Since AHR-2 received effluent from AHR-1, its VSS was lower, both suspended in the system and attached to the media. The specific methanogenic activity (SMA) is essential for describing microbial activity. This study found that setting the OLR at 5 kgCOD/m^3·d resulted in an SMA system of 0.39 LCH_4/gCOD removed in the AHR series. When increasing the OLR to 10, 15, and 20 kgCOD/m^3·d, the SMA increased to average values of 0.35, 0.52, and 0.44 LCH_4/gCOD removed, respectively. Increasing the OLR to 20 kgCOD/m^3·d resulted in the AHR series reaching a high VSS of 303 gVSS, but the SMA decreased by 0.08 LCH_4/gCOD removed. This indicates that the system is efficient over an OLR range between 10 and 15 kgCOD/m^3·d, whereas the SMA increased from 0.35 to 0.52 LCH_4/gCOD removed.

Table 3. The specific methanogenic activity (SMA) of biomass inside the AHR series.

Day of Operation	AHR-1, Biomass (gVSS)		AHR-2, Biomass (gVSS)		AHR Series, Biomass (gVSS)		Total Biomass (gVSS)	SMA of AHR Series (LCH_4/gCOD Removed)
	Suspended	Attached	Suspended	Attached	Suspended	Attached		
0	149	0	149	0	298	0	298	-
60	73	5	50	3	129	8	137	0.27
120	97	11	58	9	165	20	185	0.35
180	106	13	68	11	204	24	228	0.52
210	130	16	74	13	274	29	303	0.44

4. Future Prospects

The promising outcomes of our investigation into optimizing anaerobic hybrid reactors for the treatment of high-strength fresh leachate and biogas generation set the stage for several future research directions. Foremost, exploring the integration of additional treatment stages or technologies could further enhance effluent quality and biogas yield, potentially incorporating nutrient recovery processes for a more holistic approach to waste management. A detailed environmental impact assessment is an issue that will be studied in the future. This includes analyzing the system's carbon footprint, the impact on greenhouse gas emissions, and the potential impact on the local ecosystems. Moreover, the development and application of system dynamic models could offer deeper insights into the long-term operational efficiencies, economic viability, and environmental impacts of scaled-up systems. This approach would not only refine our understanding of the anaerobic digestion process in varying climatic and waste composition scenarios but also bolster the feasibility of deploying such systems in diverse geographical contexts, particularly in developing countries where waste management challenges are most acute. Ultimately, advancing these research areas could significantly contribute to the global pursuit of sustainable, energy-positive waste management solutions. To promote the widespread adoption of sustainable leachate treatment technologies, policymakers and the waste management industry must collaborate closely, including addressing challenges in high-strength fresh leachate treatment. This entails updating policy frameworks to incentivize sustainability and foster public–private partnerships, thereby overcoming existing adoption barriers and advancing global waste management practices.

5. Conclusions

The main goal of this research was to optimize the operational settings of the AHR series to handle concentrated fresh leachate and boost biogas production effectively. After conducting experiments, the study determined that an OLR of 15 kgCOD/m^3·d and an HRT of 7 days were optimal for maximizing biogas and CH_4 yields. AHR-1 had an average CH4 production per COD removal of 0.57–0.76 L/gCOD removed; the corresponding value for AHR-2 was 0.27–0.47 L/gCOD removed. The AHR series had an average of 0.33–0.67 L/gCOD removed. The significance of this study lies in its guidance for leachate management, especially in treating leachate with a high organic load. For example, leachate treatments may be integrated into alternative energy developments using emerging environmental technology. Future research and development should aim to maximize the potential of the AHR series for sustainable waste management practices. As the global waste management challenge persists, the findings of this study can encourage the development of an environmentally friendly, efficient, and more effective waste treatment system suitable for use in scenarios with high organic loads. This technology may help to support a transition to more sustainable wastewater management in the future.

Author Contributions: S.S.: methodology, formal analysis, writing-original draft; K.W.: supervision, resources, project administration, review and editing; S.T.: supervision, resources, project administration; C.C.: review and editing, project administration, validation; P.C.: review and editing, project administration, validation. All authors have read and agreed to the published version of the manuscript.

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