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Challenges in biogas production from anaerobic membrane bioreactors

Cheng Chen [a], Wenshan Guo [a], Huu Hao Ngo [a, *], Duu-Jong Lee [b], Kuo-Lun Tung [b], Pengkang Jin [c], Jie Wang [d], Yun Wu [d]

[a] Centre for Technology in Water and Wastewater, School of Civil and Environmental Engineering, University of Technology Sydney, Sydney, NSW, 2007, Australia
[b] Department of Chemical Engineering, National Taiwan University, Da'an District, Taipei City, 10617, Taiwan
[c] School of Environmental and Municipal Engineering, Xi'an University of Architecture and Technology, Xi'an, 710055, China
[d] School of Environmental and Chemical Engineering, Tianjin Polytechnic University, Tianjin, 300387, China

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ABSTRACT

Spectacular applications of anaerobic membrane bioreactors (AnMBRs) are emerging due to the membrane enhanced biogas production in the form of renewable bioresources. They produce similar energy derived from the world's depleting natural fossil energy sources while minimizing greenhouse gas (GHG) emissions. During the last decade, many types of AnMBRs have been developed and applied so as to make biogas technology practical and economically viable. Referring to both conventional and advanced configurations, this review presents a comprehensive summary of AnMBRs for biogas production in recent years. The potential of biogas production from AnMBRs cannot be fully exploited, since certain constraints still remain and these cause low methane yield. This paper addresses a detailed assessment on the potential challenges that AnMBRs are encountering, with a major focus on many inhibitory substances and operational dilemmas. The aim is to provide a solid platform for advances in novel AnMBRs applications for optimized biogas production.

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1. Background

1.1. Biogas and its sustainability

Biogas represents one of the most highly appreciated opportunities to utilize certain categories of biomass to fulfill partially the world's energy needs. Biogas commonly refers to a mixture of gases produced by the biological breakdown of organic matter in the absence of oxygen, of which methane, hydrogen and carbon monoxide can be combusted or oxidized with oxygen. The energy output/input can reach up to 28.8 MJ/MJ under favorable conditions, contributing to a very efficient use of the valuable biomass [1]. The resultant energy release allows biogas to be used as a biofuel to replace conventional fossil energy sources (coal, oil, natural gas) in power and heat production, and also as a versatile renewable energy source to fuel vehicles with lower sale price compared to diesel and petrol [2,3].

In general, widespread installation and proper functioning of biogas production systems can provide many benefits to users and the wider community. Advantages include energy sustainability, resource preservation and environmental conservation. On the one hand, the long-term utilization of declining fossil fuels is considered unsustainable because of their limited reservoirs and non-renewable nature. Biogas derived from various biological sources can reduce the heavy dependence on these depleting natural resources, and address the energy insecurity concerns due to its renewable, widely applicable, and abundant characteristics [2,4]. On the other hand, the valorization of the generated biogas is that it is energy efficient (a typical value for electrical efficiency is 33% while for thermal efficiency it is 45%) and environmentally friendly due to the low emission of hazardous pollutants, for example volatile organic compounds (VOCs) [5]. In terms of the current CO_2-mitigation policy, biogas, as a nearly GHGs-neutral replacement for fossil fuels, can be produced from widely available renewable feedstocks, and their production barely contributes to the net carbon emission [6]. Optimistically, the rapid development of biogas production not only can reduce the world's heavy reliance on fossil

* Corresponding author.
E-mail address: h.ngo@uts.edu.au (H.H. Ngo).

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fuel and thereby global energy needs, but also reduce the carbon footprint from fossil fuel utilization. This means decelerating the drift to global warming and climate change.

1.2. Mechanisms of biogas production

Biogas can be produced from anaerobic digestion using the locally available residual biomass from various sources (animal waste, domestic sewage, industrial wastewater, agricultural waste, etc.). The anaerobic digestion of complex organic matter to biogas (mainly methane and carbon dioxide) involves four key steps, these being hydrolysis, acidogenesis, acetogenesis and methanogenesis (see Fig. 1). A balanced methane fermentation process requires individual degradation phases to be carried out by distinct consortia of bacteria, namely fermentative bacteria, syntrophic acetogens, homoacetogens, hydrogenetrophic methanogens and aceticlastic methanogens. The symbiotic relationship among these microorganisms contributes to efficient anaerobic digestion and biogas production [3,7,8]. The final phase, conducted by methane-forming bacteria, is the most crucial stage in biogas production where the methanogens convert their primary substrates including acetate, hydrogen and carbon dioxide into methane. There are two pathways for methane formation, in which approximately 75% of methane production derives from decarboxylation of acetate and the remaining 25% originates from CO_2 and H_2 [9]. The methane-forming stage is also the most sensitive and rate limiting step in the whole process since methane-forming bacteria have a much slower growth rate compared to acid-forming bacteria, and are sensitive to inhibitors such as ammonia, temperature, pH and other operational conditions. It is therefore imperative to retain sufficient slow-growing methanogenic bacteria and prevent active biomass from being washed out from the fermenter, and to reduce inhibitory levels.

1.3. Biogas production by anaerobic membrane bioreactors (AnMBRs)

The slow growing nature of methanogenic organisms and microbial complexity in the systems have made the operation of biogas fermenters difficult. The success of efficient biogas production depends on the effective retention of methanogenic bacteria in the reactor through decoupling of solids retention time (SRT) and hydraulic retention time (HRT) [10]. Research has mostly focused on retaining a high density of functioning anaerobic microorganisms, in order to achieve efficient biogas production. The most recent development in biogas production is the incorporation of anaerobic bioprocesses with membrane separation techniques in a membrane bioreactor (MBR), the purpose being to increase biomass concentration extensively in the bioreactor. In an anaerobic membrane bioreactor (AnMBR), high cell concentrations can be sustained under reasonably high hydraulic load and sufficient mixing due to completely decoupling HRT from SRT [11].

Moreover, due to the sufficient retention of active microorganisms, AnMBRs generally have high product concentration and productivity and relatively good toxic resistance, and simplify the separation of product and/or biomass by using micro-filtration or ultra-filtration, thus leading to an improved biogas production economy [6]. The reported biogas production was well documented with the methane yield up to 0.36 L CH_4/g $COD_{removed}$ (0.30 L CH_4 (STP)/g $COD_{removed}$, the volume of methane produced at 0 °C Standard Temperature and 1 atm Standard Pressure) and the high methane content up to 90% [12]. However, the optimization of biogas production from AnMBRs has not gained much attention due to the as yet under-developed nature of AnMBRs [7]. For extreme conditions, such as high salinity, thermophilic temperature, high organic loading rate (OLR) and presence of toxicity, membrane assisted anaerobic processes can be hampered and biogas productivity can be compromised.

Several review papers on biogas production (most are recent) are available in the literature. Ylitervo et al. [6] provided a general review of the MBR technology in ethanol and biogas processes and summarized the development of MBRs and the membrane technologies for these biofuels. Wang et al. [11] reviewed the progress in biogas technology in China and briefly introduced AnMBRs as one of the emerging technologies. Mao et al. [2] discussed advances in biogas production from anaerobic digestion in recent years and provided brief information on AnMBRs for biogas production. He et al. [4] summarized the recent performance of AnMBRs for methane and hydrogen production. Minardi et al. [13] reviewed membrane applications for biogas production and purification

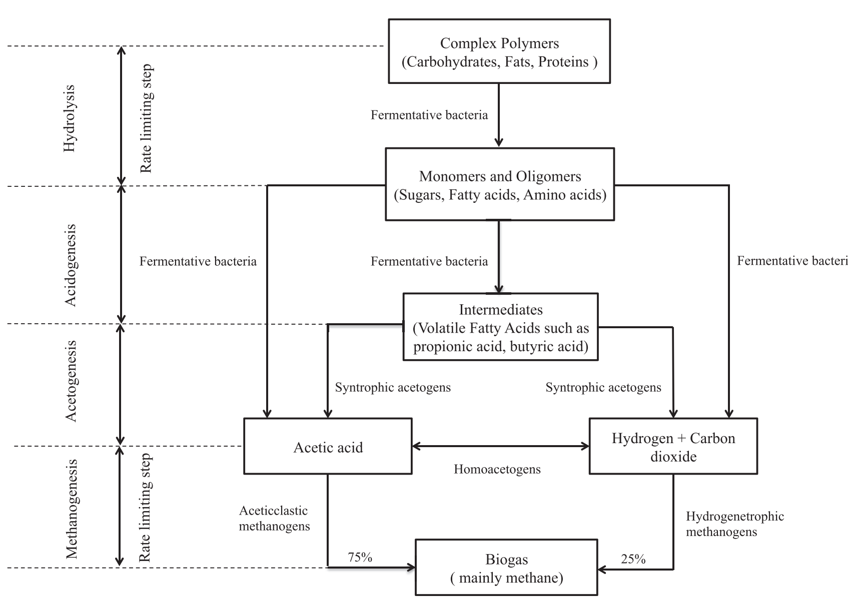

Fig. 1. A schematic diagram showing the comprehensive processes of biogas production from anaerobic processes [2,7].

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