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Advances in Energy-Producing Anaerobic Biotechnologies for Municipal Wastewater Treatment

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ABSTRACT

Municipal wastewater treatment has long been known as a high-cost and energy-intensive process that destroys most of the energy-containing molecules by spending energy and that leaves little energy and few nutrients available for reuse. Over the past few years, some wastewater treatment plants have tried to revamp themselves as "resource factories," enabled by new technologies and the upgrading of old technologies. In particular, there is an renewed interest in anaerobic biotechnologies, which can convert organic matter into usable energy and preserve nutrients for potential reuse. However, considerable technological and economic limitations still exist. Here, we provide an overview of recent advances in several cutting-edge anaerobic biotechnologies for wastewater treatment, including enhanced side-stream anaerobic sludge digestion, anaerobic membrane bioreactors, and microbial electrochemical systems, and discuss future challenges and opportunities for their applications. This review is intended to provide useful information to guide the future design and optimization of municipal wastewater treatment processes.

1. Introduction

Municipal wastewater treatment plants (WWTPs) play a key role in wastewater sanitation and the protection of public health [1]. However, the high economic and energy costs and the pollution transfer issues (from water to solids and/or air) of activated sludge processes make them unsustainable and increasingly unaffordable, especially with today's ever-tightening water and air emission regulations. Despite substantial modifications in reactors and processes over the years such as the development of membrane bioreactors [2] and aerobic granular sludge systems [3] and the optimization of process operations [1], the core strategy of activated sludge processes (i.e., destroying energy-containing molecules by spending energy) remains unchanged. To make a fundamental change toward resource recovery [4,5], revolutionary technologies and processes will have to be implemented. Anaerobic technologies are considered to be one of the most promising solutions.

Shifting from aerobic to anaerobic treatment of municipal wastewater offers an exciting opportunity to turn municipal wastewater treatment facilities into self-sustained operators or even net energy producers [6,7]. In contrast to the activated sludge process, which is energy intensive and resource wasteful, anaerobic processes avoid the energy consumption of aeration and produce an energy output instead [8]. Moreover, the nutrients in wastewater can be preserved to allow subsequent reuse or recovery [4], thereby further increasing energy and economic benefits. In conventional treatment processes, the need for carbon consumption prohibits the utilization of all the organic matter for anaerobic energy production. It is notable that such usage is now becoming possible due to the emergence of carbon-independent nutrient-removal biotechnologies [9].

Anaerobic wastewater treatment is not new. It has long been practiced in treating high-strength industrial wastewaters and sewage sludge [10]. In such processes, complex biosolids can be efficiently broken down by anaerobic microorganisms in the

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absence of oxygen, generating a methane-rich biogas for energy recovery and yielding a stabilized sludge that is suitable for land use [1]. These sludge-derived products can partially offset the high cost of the activated sludge process for municipal wastewater treatment; however, energy recovery is usually very limited because most of the organic matter is still wasted in the water phase. Therefore, improving energy production requires either partitioning more organic matter to the sludge phase for anaerobic digestion (side-stream treatment) or directly treating the low-strength water anaerobically (mainline treatment)—a process that faces different technological challenges.

Side-stream sludge treatment through anaerobic digestion has been practiced for years; however, enhancing this process requires new technologies to enrich the organic matter content in sludge and improve the conversion efficiency of the sludge biomass. For the mainline anaerobic process, the slow growth and poor activity of anaerobic microorganisms have become a critical issue. Municipal wastewater is characterized by low organic strength, a significant percentage of particulate organic content, and frequently psychrophilic conditions, which are unfavorable for the growth of methanogens [11]. Therefore, these characteristics hamper the hold-up of dense biomass in conventional anaerobic bioreactors such as up-flow anaerobic sludge blanket (UASB) and expanded granular sludge bed (EGSB) reactors due to easy biomass washout, and deteriorate the overall treatment performance. Better anaerobic technologies and more efficient reactors are needed to address these challenges.

Here, we outline several representative energy-producing anaerobic technologies for future municipal wastewater treatment: bio-concentration and enhanced anaerobic sludge digestion for side-stream treatment; and anaerobic membrane bioreactors (AnMBRs) and microbial electrochemical systems (MESs) for mainline treatment [9]. We summarize recent advances in these biotechnologies and highlight remaining challenges and required future developments for practical application. This paper focuses exclusively on energy production and relevant anaerobic biotechnologies. Progress in anaerobic platforms for integrated energy and resource recovery from wastewater can be found in other review papers [9,12,13]. This review may provide useful information to guide the future design and optimization of municipal wastewater treatment processes and is intended to encourage more thinking and research on anaerobic wastewater treatment biotechnologies.

2. Enhanced side-stream anaerobic sludge digestion

2.1. Technological advances

Enhancing side-stream energy recovery through bio-concentration and sludge digestion is a relatively mature and low-cost technology. The process flow is similar to that of conventional activated sludge treatment, but relies more on anaerobic than aerobic degradation of organic matter. There are two key steps in this process: ① up-concentration of organic matter into sludge biomass at a minimal energy consumption; ② high-rate anaerobic digestion of the carbon-laden sludge to produce energy-rich biogas, as shown in Fig. 1(a). The bio-concentration of organic matter can be readily achieved through the adsorption, assimilation, and accumulation of sludge biomass at a very short sludge age and moderate aeration [14], while anaerobic digestion of the resulting sludge biomass is favored by the raised carbon content. Such a process has been successfully practiced in several WWTPs, including the Strass WWTP in Austria. In this plant, the contact stabilization process is adopted to partition most of the influent organic matter into sludge for anaerobic digestion [15].

The energy efficiency of such a process is usually limited by a slow solubilization of the organics from the sludge biomass. Thus, pretreatment is commonly applied to make organic matter more amenable to utilization by acidogens and methanogens [16]. Many pretreatment methods such as hydrothermal, microwave irradiation, ultrasound, mechanical shearing, chemical, and biological (enzymatic) pretreatment are effective in breaking down the sludge biomass, but are energy or cost intensive [17]. Methods that can utilize locally available low-value energy and resources are preferable. In this respect, thermal hydrolysis offers a useful option, since it can directly utilize the lower-value heat generated from the co-generator or heat pumps [17]. This *in situ* waste heat utilization, together with the significantly decreased volume of sludge slurry relative to the bulk sewage, makes it possible to reach a high temperature with minimal or even zero extra energy input. Nevertheless, the performance of such a pretreatment depends strongly on the bio-concentration level, sludge properties, and availability of heat energy, which may vary significantly with operating conditions. The most successful application case so far is the Blue Plains WWTP in the US. This plant adopts a similar side-stream anaerobic process to that used in the Strass WWTP, but adds a Cambi thermal hydrolysis process (with raised temperatures and pressures) to enhance biomass solubilization [15]. This setup doubles the methane yield as compared with a conventional sludge-digestion process.

Other frequently encountered problems are the low organic content and unbalanced composition of the obtained sludge, both of which lower methane production. Co-digestion of the sludge with other organic-rich wastes (e.g., food wastes) provides a feasible solution [18]. This solution not only raises the available carbon concentration but also balances the carbon/nutrient ratio, leading to an improved biogas yield and energy balance [19]. In addition, the utilization efficiency of anaerobic digesters can be improved, partially offsetting reactor investment and maintenance costs. This strategy has been proved useful for improving biogas production and has been successfully applied for over eight years at the Strass WWTP.

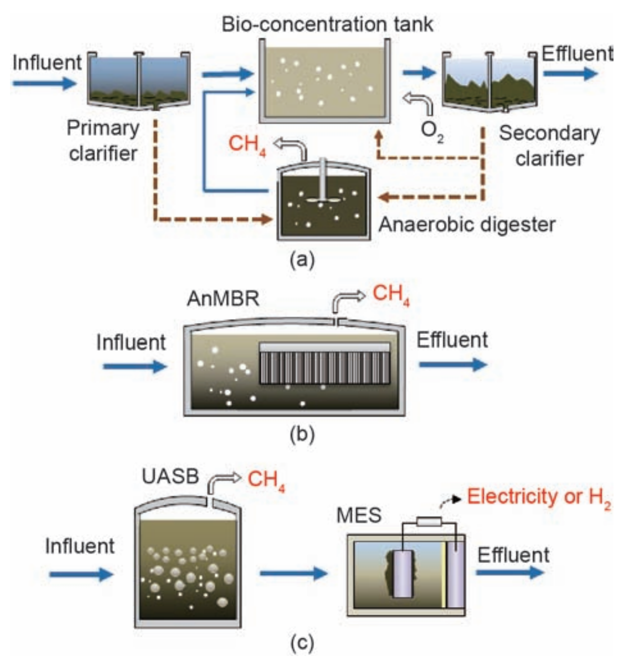

Fig. 1. Schematic diagram of several representative anaerobic energy-producing processes. (a) Enhanced side-stream anaerobic sludge digestion; (b) AnMBR; (c) the anaerobic digestion-MES integrated system.