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Overview of pretreatment strategies for enhancing sewage sludge disintegration and subsequent anaerobic digestion: Current advances, full-scale application and future perspectives

Guangyin Zhen[a,b], Xueqin Lu[a], Hiroyuki Kato[c], Youcai Zhao[d], Yu-You Li[a,*]

[a] Department of Civil and Environmental Engineering, Graduate School of Engineering, Tohoku University, 6-6-06 Aza-Aoba, Aramaki, Aoba-ku, Sendai, Miyagi 980-8579, Japan

[b] School of Ecological and Environmental Sciences, East China Normal University, Shanghai 200241, PR China

[c] Sewerage Works Division, Sewerage and Wastewater Management Department Water and Disaster Management Bureau, 2-1-3 Kasumigaseki, Chiyoda-ku, Tokyo, Japan

[d] The State Key Laboratory of Pollution Control and Resource Reuse, School of Environmental Science and Engineering, Tongji University, Shanghai 200092, PR China

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ABSTRACT

Sewage sludge management is now becoming a serious issue all over the world. Anaerobic digestion is a simple and well-studied process capable of biologically converting the chemical energy of sewage sludge into methane-rich biogas, as a carbon-neutral alternative to fossil fuels whilst destroying pathogens and removing odors. Hydrolysis is the rate-limiting step because of the sewage sludge complex floc structure (such as extracellular polymeric substances) and hard cell wall. To accelerate the rate-limiting hydrolysis and improve the efficiency of anaerobic digestion, various pretreatment technologies have been developed. This paper presents an up-to-date review of recent research achievements in the pretreatment technologies used for improving biogas production including mechanical (ultrasonic, microwave, electrokinetic and high-pressure homogenization), thermal, chemical (acidic, alkali, ozonation, Fenton and Fe(II)-activated persulfate oxidation), and biological options (temperature-phased anaerobic digestion and microbial electrolysis cell). The effectiveness and relative worth of each of the studied technologies are summarized and compared in terms of the resulting sludge properties, the digester performance, the environmental benefits and the current state of real-world application. The challenge and technical issues encountered during sludge cotreatment are discussed, and the future research needs in promoting full-scale implementations of those approaches are proposed.

1. Introduction

Sewage sludge is increasingly produced during wastewater biological treatment process. It contains a myriad of toxic substances such as pathogens, heavy metals and some organic contaminants, which creates odors and hygiene concerns. Improper use and disposal of sewage sludge causes severe environmental impacts and health hazard to the public. The water industry is facing unprecedented economic and environmental constraints because of not only increasingly stringent regulations [1] but large amounts of sewage sludge produced. The disposal of sewage sludge is one of the expensive items in a wastewater treatment plant (WWTP), usually accounting for up to 50% of the total operating costs of the plant [2]. Thus, the promotion of economically feasible treatment methods represents one of the most critical missions for waste management authorities.

Nowadays, there have been several representative techniques for sewage sludge disposal applied in practice, e.g. landfill, compost, drying-incineration, anaerobic digestion, land application and recycling as building materials. Amongst them, anaerobic digestion is of great promise for sewage sludge treatment as it removes odors and pathogens, stabilizes sludge and more importantly, produces renewable energy in the form of methane. This can either cover part of the energy requirements for sewage sludge treatment or, to a certain degree, alleviate human's dependence on fossil fuels. For these reasons, anaerobic sludge digestion reduces the capital costs of a wastewater treatment plant (WWTP) and is deemed as an essential part of a modern WWTP. Anaerobic digestion involves a series of steps, i.e. hydrolysis, acidogenesis (fermentation), acetogenesis and methanogenesis. Many researchers in the literature agree that hydrolysis is the rate-limiting step in sewage sludge anaerobic digestion because of the

* Corresponding author.
E-mail addresses: zhenguangyin@163.com (G. Zhen), gyokuyu.ri.a5@tohoku.ac.jp (Y.-Y. Li).

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complex floc structure (such as extracellular polymeric substances) and hard cell wall, leading to high retention times, low organic solids degradation and unsatisfactory methane output [3,4]. To accelerate the hydrolysis and enhance subsequent methane productivity, a variety of sludge pretreatment options, such as mechanical, thermal, chemical, biological processes or integrations of these, have been developed at laboratory or pilot level so far with various levels of success [4–7]. If properly designed, pretreatments can facilitate the release of intracellular substances by rupturing the cell wall and make them more accessible to subsequent microbial actions. The favorable characteristics of pretreatment in improving microbial cell lysis, bioavailability, organic solids degradation, methane production, mass reduction and avoidable costs of digestate dewatering have been repeatedly documented.

In the view of the beneficial role in sludge disintegration, pretreatment has gained much more concerns within scientific communities in the past decade, inducing great progresses in both journal publications and the field. The ScienceDirect shows that the number of publications per year with sludge “pretreatment (pre.)” and “anaerobic digestion (AD)” as topics increased sharply: only 36 papers published in 2000, over 100 papers per year since 2006 and up to 609 papers in 2015, with the corresponding percentage of “sludge pre.-AD”-based papers in all papers related to “sludge AD” rising from 24.5% in 2000 into 43.6% in 2015 (Fig. 1). This shows the ever-growing importance of pretreatment played in sewage sludge anaerobic digestion. Pretreatment seems have become an indispensable step nowadays prior to anaerobic digestion of sewage sludge. In the recent past, Carrere et al. [8,9], Pilli et al. [10,11], Cano et al. [12], Le et al. [13], Meyer and Edwards [14], and Joo et al. [15] have made the state of the art overview of most reported pretreatment techniques with unique favor or emphasis so as to evaluate the potentials and effectiveness of pretreatment in accelerating sludge anaerobic digestion.

This review is an attempt to comprehensively review and analyze the relative worth of each pretreatment alternative in terms of principle mechanisms, recent developments, potentials, current state of commercial operations and possible benefits. Recently emerging pretreatments as well as novel approaches are firstly reviewed. Furthermore, the possible technical issues stated in several studies are summarized to critically outline different aspects of pretreatment technologies. In addition, a significant consideration for selecting a pretreatment technology is economic-environmental benefit. Pretreatment has the ability to enhance sludge reduction and methane recovery, but meanwhile leads to additional energy input and greenhouse gas (GHG) emissions. A systematic assessment of different pretreatment technologies for biogas production is quite necessary and imperative for deciding which one would be the most suitable from an industrial point of view. Therefore, this review will also propose a “cost-benefit analytic method” to assess the technical availability of each pretreatment method from the energetic, economic and environmental perspectives of view, with the aims of providing valuable guidelines for their feasibility for further applications on a pilot- and full-scale, and helping the industry to determine the most cost-efficient cotreatment route to ensure the optimal sludge conversion and energy recovery.

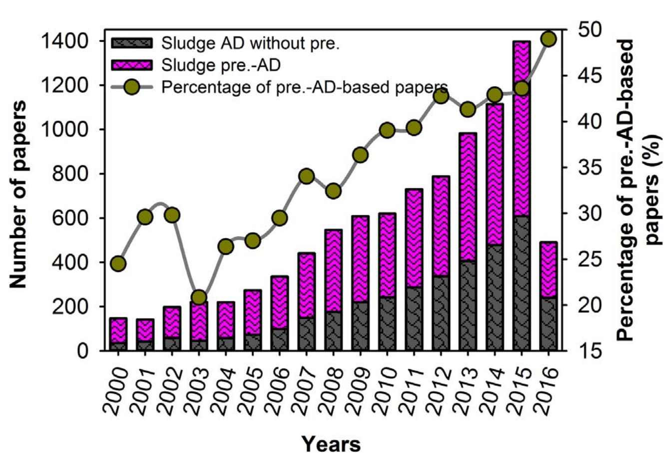

Fig. 1. ScienceDirect bibliometric study with the topics “sludge AD”, or “sludge pre.-AD” (February 2016); sludge AD: sludge “anaerobic digestion” alone; “sludge pre.-AD”: the combination of sludge “pretreatment” with “anaerobic digestion”.

2. Sewage sludge production and anaerobic digestion

2.1. Sewage sludge production

In biological wastewater treatment process, the part of chemical oxygen demands (COD) removed is converted into biosolids, which makes up sewage sludge. Sewage sludge usually represents 1–2% of the treated wastewater volume. As per UN-Habitat's statistics [16], the existing WWTPs in USA, for instance, generate over 6.5 million tons dry solids (Mt DS) annually; it is estimated to be around 3.0 and 2.0 Mt per year produced in China and Japan, respectively (Fig. 2). The figures are naturally anticipated to increase in the near future when considering the growing applications of wastewater treatment plants in developing countries. The main disposal routes and rates are different in different countries, heavily depending upon the economic development level. As illustrated in Fig. 2, in developed countries such as USA the reuse and disposal rate reaches up to 94% and it is roughly 97% in Japan, where more than half (52%) of sewage sludge is being recycled to produce building materials and 12% anaerobically digested for bioenergy recovery. Comparatively, the situation of sewage sludge use and disposal in developing countries is far beyond optimism. For example, in China over 80% of sewage sludge is dumped improperly. Even for landfill, the most commonly used method in China, a majority of sludge is being disposed of directly after mechanical dewatering with higher than 80% moisture content and very low compressive strength. Note that for a sanitary landfill, the threshold of sludge water content is 60% from the view of safety regulations [17]. The simple disposal not only causes the wasting of resources but also brings about a series of secondary disasters (e.g. landslide, environmental pollution, etc.). Sewage sludge management is highly complex and costly, representing a stern global challenge. It is apparent that more efforts devoted to sludge management are still urgently required in developing countries.

2.2. Basic principles of anaerobic digestion

Anaerobic digestion, as stated before, comprises several successive biochemical processes (i.e. hydrolysis, acidogenesis, acetogenesis and methanogenesis) involving different groups of microbes (Fig. 3) [2,19,20]. In the first step, complex organic matters such as proteins, polysaccharides and lipids are solubilized and hydrolyzed into simple soluble components (e.g. amino acids, long-chain fatty acids (LCFAs), sugars and alcohols) under the assistance of extracellular enzymes. Key bacteria involved in hydrolytic phase include *Clostridium*, *Cellulomonas*, *Bacteroides*, *Succinivibrio*, *Prevotella*, *Ruminococcus*, *Fibrobacter*, *Firmicutes*, *Erwinia*, *Acetovibrio*, *Microbispora*, etc. [19,21]. The hydrolyzed molecules in the second step are converted by acidogenic (or fermentative) bacteria such as *Peptoccus*, *Clostridium*, *Lactobacillus*, *Geobacter*, *Bacteroides*, *Eubacterium*, *Phodopseudomonas*, *Desulfovibrio*, *Desulfobacter*, *Sarcina*, etc. [20,22], to short-chain volatile fatty acids (VFAs) and other minor by-products such as ammonia (NH_3), H_2 and CO_2. During acetogenesis process, acetogens further decompose the higher organic acids (e.g. propionic and butyric acids) to form primarily acetic acid, and H_2 via β-oxidation; however, the conversions are only favorable thermodynamically under particularly low concentrations of the reaction products (acetate and H_2) (i.e. acetate concentration: 10^{-4}–10^{-1} mol/L; H_2 partial pressure required for propionate: 10^{-6}–10^{-4} atm; and for butyrate: $(1.0–7.0)\times10^{-3}$ atm) [23,24]. Typical acetogenic bacteria