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Pilot-scale study of sludge pretreatment by microwave and sludge reduction based on lysis–cryptic growth

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HIGHLIGHTS

- Studied microwave (MW) pretreatment in a large pilot-scale sludge reduction system.
- The sludge quantity to be finally disposed off was reduced by 38.60% on average.
- Achieved 13.64% cost savings compared to operation without MW pretreatment.

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ABSTRACT

To evaluate the performance of microwave (MW)-chemical hybrid sludge treatment system, a pilot scale MW disintegration unit (treatment capacity of 500 L/d) was constructed. The results showed that organic matter, nitrogen, and phosphorus were effectively released from the MW-pretreated sludge. The values of COD released were 15.91%, 15.07%, 13.83%, 19.35%, and 15.07% for the MW, MW-acid, MW-alkali, MW-H_2O_2, and MW-H_2O_2-alkali treatment processes, respectively. Additionally, for a wastewater treatment system with a capacity of 200 m^3/d, when coupled with a MW sludge pretreatment unit, the sludge production and sludge yield were greatly reduced by 38.60% and to 0.35 kg VSS/kg $COD_{consumed}$, respectively. The total operating cost of the lysis–cryptic growth system was 13.64% lower than that of the CAS system without a MW unit.

1. Introduction

Biological sewage treatment plants around the world produce large and ever-increasing amounts of excess sludge. Owing to regulatory restrictions and the inadequate availability of landfill sites, sludge treatment and disposal have become serious concerns in the normal operation of sewage treatment systems (Ma et al., 2012; Odegaard, 2004). Improper treatment of the sludge poses major risks to public health. Currently, the treatment and disposal of excess sludge constitute 50–60% of the operating costs of wastewater treatment plants (WWTPs) (Campos et al., 2009). Therefore, cost-effective disposal of the excess sludge into the environment is a serious challenge faced by researchers.

Reduce, reuse, and recycle (the 3Rs) are the three basic options available for sludge treatment (Romero et al., 2013). Among the 3R treatment options, reducing the amount of sludge produced is regarded as the ideal method for solving the problems associated with sludge treatment. Much effort has been expended in developing sludge disintegration and solubilization techniques that feed back to the biological processing step for further biodegradation (Odegaard, 2004). This type of process is known as lysis–cryptic growth (Guo et al., 2013; Romero et al., 2013; Wang et al., 2009).

In most of the 3R treatment technologies, breaking the cell walls of the sludge particles is a key problem, owing to the protection offered by the extracellular polymeric substances (EPS). Therefore, pretreatment technologies can be used to disrupt the cell walls, which also help improve biogas production, recover materials such as proteins, volatile fatty acids (VFAs), nitrogen, and phosphorus, and improve sludge dewatering. There are many sludge pretreatment technologies available involving physical, chemical, mechanical, or biological hydrolysis, or a combination of these methods (Carrere et al., 2010; Tyagi and Lo, 2011). All the existing pretreatment techniques have their drawbacks, and consequently, an effective and economical pretreatment method is still required (Jang and Ahn, 2013).

The microwave (MW) technology has gained widespread popularity as an effective thermal method for sludge treatment (Tyagi and Lo, 2013). Another promising application of MW technology is in pyrolysis, which involves heating dried sludge at temperatures above 300 °C in the absence of water and oxygen, to produce valuable gases and oils (Manara and Zabaniotou, 2012). The major

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driving force behind the rise in the use of MW technologies is the fact that heating with MW energy is superior to conventional heating, mainly in terms of its ability to heat rapidly and selectively, thereby accelerating reaction rates. MW heating provides instant on/off control and increases energy efficiency, with the capacity to enhance the yield and quality of the product. In addition, it minimizes hazardous product formation and emissions, thereby rendering the technique environmentally friendly.

Previous studies have reported that significantly higher solubilization of the volatile suspended solids (VSS) can be achieved by combining MW and chemical pretreatment techniques (Tyagi and Lo, 2013). Toward this end, MW-alkali/acid (e.g., MW-acid (MW-H) and MW-alkali (MW-OH)) and MW-enhanced advanced oxidation processes (MW/H_2O_2-AOP; e.g., MW-H_2O_2 and MW-H_2O_2-OH) have been developed to improve the MW sludge pretreatment performance (Wang et al., 2015). It has been suggested that scaling up is the most important obstacle in the path to full-scale applications of MW-based pretreatment technologies (Tyagi and Lo, 2013). Presently, while there are over 120 papers focused on the MW sludge pretreatment technology (based on the web of science search), most studies so far have been conducted on small laboratory scale, and the results obtained cannot be directly implemented in full-scale applications. Srinivasan et al. (2014) proved the feasibility of MW technology in practical applications by successfully operating a pilot MW oven treating cattle manure. To the best of the authors' knowledge, so far, there have been no large-scale pilot studies assessing the suitability of the MW sludge pretreatment technology or describing the influence of MW pretreatment on subsequent sludge reduction system. Furthermore, because laboratory experiments cannot be used to evaluate the performance of the techniques in practical applications, there have been no thorough evaluations of the economic impact of the MW treatment technology in the WWTPs.

Therefore, we built a pilot-scale lysis–cryptic sludge reduction system consisting of a MW disintegration unit (capacity: 500 L/d) and a conventional activated sludge (CAS) system (capacity: 200 m^3/d), with the goal of developing a cost-efficient sludge reduction technology. The objectives of this study were: (1) to evaluate the MW-chemical hybrid treatment in a pilot system; (2) to examine the performance of the pilot system over a long period of time; (3) to evaluate the performance of the integrated system for sludge reduction; and (4) to conduct a cost and energy consumption analysis of the MW treatment system.

2. Methods

2.1. The experiment site

This study (including the batch and sludge reduction experiments) was carried out in the Jizhuangzi wastewater treatment plant in Tianjin, China. The pilot system consisted of two parts, a MW treatment system (capacity: 500 L/d of concentrated sludge) and a CAS system (aeration tank volume: 146.7 m^3; sewage treatment capacity: 200 m^3/d). A schematic diagram of the integrated wastewater and sewage treatment processes is shown in Fig. S-1. The CAS system has been described in a previous paper (Ma et al., 2012). Details of the main configuration and features of the lysis–cryptic growth system are listed in Table 1.

2.2. Pilot-scale MW apparatus

An automatic industrial MW oven (JWX-10-W,) operating at 2450 MHz was designed in-house and assembled by the Julong Corp (Baoding, China). The treatment capacity of the oven was 500 L/d (10 batches per day at 50 L per batch). The power of the MW oven was adjustable and the maximum power was 10 kW. All the components in the MW system including the pumps (sludge influent and acid, alkali, and H_2O_2 dosage pumps), sensors (for temperature, pH, and liquid level), and the rotating system (a rotating blade homogenizer) were automatically controlled with a programmable logic controller (PLC, Omron CP1H-40XA with a touch screen console center). A schematic diagram of the experimental MW setup is provided in Fig. S-2.

Table 1
Main configuration and facilities of the lysis–cryptic growth system.

No.	Unit	Specification and parameters (size: length × width × height)
1	Sewage tank	Concrete; 37.8 m^3; 5.00 × 2.10 × 4.20 m
2	Thin screen	304 stainless steel; 80 mesh
3	Aeration basin	Concrete; 146.7 m^3; 8.15 × 5.00 × 4.20 m
4	Tube settler	Concrete; 1.33 m^3/(m^2 h); Tube Φ 80 × 1000; 5.00 × 3.00 × 4.20 m
5	Recirculation sludge tank	Concrete; 23.4 m^3; 5.00 × 1.30 × 4.20 m
6	Gravity thickener	Steel; 3.85 m^3; 1.50 × 1.50 × 2.50 m
7	Thickened sludge storage tank	Steel; 2.50 m^3; 1.50 × 1.50 × 1.50 m
8	Microwave oven	Steel; JWX-10-W; working volume, 50 L; output power-rating, 10 kW; 1.5 × 1.3 × 1.9 m
9	Post-reactor	304 stainless steel; 2.0 m^3; Φ 1.50 m I.D. × 2.50 m height
10	NaOH solution tank	Polyethylene; 75 L

2.3. Sludge MW treatment

The practical performances of five MW-based sludge treatments (i.e., MW, MW-acid (MW-H), MW-alkali (MW-OH), MW-H_2O_2, and MW-H_2O_2-OH) were compared with batch experiments, using the pilot-scale MW oven described above. The details of the treatment conditions are listed in Table 2 (approaches 1–5). The thickened sludge (21,500 mg/L) from the gravity thickening tank of the pilot wastewater treatment system was fed to the MW oven for the experiments. The chemical oxygen demand (COD), NH_4^+-N, total nitrogen(TN), PO_4^{3-}-P, and total phosphorus (TP) contents of the thickened sludge fed to the MW oven were 132 mg/L, 11.3 mg/L, 22.3 mg/L, 3.2 mg/L, and 28.8 mg/L, respectively. The same values were observed for these parameters after MW pretreatment in the pilot-scale system.

2.4. Sludge reduction experiments

The sludge reduction system was set up by attaching the MW pretreatment unit to the CAS, as illustrated in Fig. S-1. Activated sludge was discharged from the recirculation sludge tank of the CAS system and sent to the gravity thickening tank. Ten batches of concentrated sludge (500 L/batch) from the gravity thickening tank, with a total suspended solids (TSS) content of approximately 21.5 g/L, were pumped into the MW treatment apparatus and treated. Then the pretreated sludge was continuously recirculated to the aeration tank using a pump.

During the control period (days 1–29) the sludge treated by MW was not recirculated to the CAS system. During this time, the influent flow rate for the CAS system was 200 m^3/d with a hydraulic retention time (HRT) of 11.74 h. During days 30–60, the sludge treated by the MW unit was recirculated to the CAS system. During this period, the MW-alkali treatment approach (approach 3; Table 2) was used to treat the sludge. This treatment technique was chosen from the results of initial experiments comparing the performance of the various MW-based treatment techniques.