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Short communication

Effect of the sequence ultrasonic operation on anaerobic degradation of sewage sludge

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ABSTRACT

In this study, ultrasonic disintegration (UD) was used on excess sludge during the anaerobic degradation (AD) process to improve treatment efficiency. After applying AD for 7 days followed by UD for 15 min, soluble chemical oxygen demand (SCOD) concentration reached 4320.5 mgL^{-1}; this was 1.6 times when UD was applied alone for the same treatment time. Intermittent UD during the AD process was more efficient than pretreating sludge using UD under the same ultrasonic energy consumption. According to the central composite design, the optimized application of intermittent UD was 3 min every 2 days. At the optimized operation levels, SCOD concentration and VS concentration reached 3482.5 and 2690 mgL^{-1} (VS removal: 41.6%). The morphological characteristics and bacterial community structure of sludge changed significantly, enhancing the efficiency of sludge degradation during the AD process with intermittent UD. The intermittent ultrasonic technology had a significant impact, increasing the sludge anaerobic degradation efficiency and reducing energy consumption in engineering applications.

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1. Introduction

Activated sludge processes are widely used to treat both municipal wastewater and industrial effluents (Mohammadi et al., 2011). When microbes degrade organic pollutants in the activated sludge process, large amounts of excess sludge are produced. Because this excess sludge typically contains a large number of organics and heavy metals, it creates significant environmental risks and high disposal costs. Sludge pretreatment and anaerobic degradation (AD) is a promising technology of minimizing excess sludge for both environmental and economic reasons (Tiehm et al., 2001; Zhang et al., 2012a).

Ultrasonic treatment is a promising technology for sludge disintegration because its multiple effects, including high shear force, thermal hydrolysis, free radical species, and ultrasound, can disintegrate bio-macromolecules and bacteria in sludge (Tiehm et al., 2001). Studies have shown that long-term high-density ultrasonic treatment disintegrates sludge solids, breaks cell walls, and releases organic compounds (Kim et al., 2010; Mohammadi et al., 2011). In contrast, Zheng et al. (2012) concluded that low power ultrasonic pretreatment also improves activated sludge biodegradability, proposing an optimal ultrasonic density of 0.15 W/mL and duration of 10 min Zhou et al. (2014) found that low-strength ultrasound stimulation enhanced cell production and pollution removal to treat photosynthetic bacteria wastewater (0.3 W/cm^2 with 40 kHz frequency). Low ultrasonic density can enhance the enzyme activity and facilitate nutrient uptake, improving cellular metabolic function (Delgado-Povedano and Luque de Castro, 2015). Meanwhile, Dähnke et al. (1999) studied ultrasonic reactors with a heterogeneous density distribution of cavitation bubbles, indicated that high and low density ultrasound can be applied in the same ultrasonic system. Thus, it is reasonable to assume that applying intermittent ultrasound in the AD process will efficiently reduce sludge.

In order to efficiently disintegrate and degrade sludge during AD process, AD-UD method was carried out and optimized by the indexes of soluble chemical oxygen demand (SCOD) concentration and volatile solids (VS) concentration, morphological characteristics and bacterial community structure of the degraded sludge were also investigated.

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2. Materials and methods

2.1. Materials

Excess sludge was collected from the secondary sedimentation tank of the Shenshuiwan wastewater treatment plant, in Shenyang, China. The characteristics of the sewage sludge used for the subsequent experiments were as follows: SCOD concentration of 227.5 ± 27.5 mgL^{-1}, total chemical oxygen demand (TCOD) concentration of 6527.0 ± 275.5 mgL^{-1}, total solid (TS) concentration of 5280 ± 50 mgL^{-1}, VS concentration of 4610 ± 50 mgL^{-1}.

2.2. Experimental methods

Sludge disintegration was performed using an ultrasonic cell disruption system with a frequency of 20 kHz and a probe of Φ 20 mm (GM1200D, Shunmatech LTD, China). Because of the direction of complex cavitation processes near powerful ultrasound sources, the reactor was made by polymethyl methacrylate with a 500 mL volume (Φ60 × 180 mm). A 100 W ultrasonic probe was immersed 10 mm into a sludge volume of 400 mL. A mixed anaerobic supernatant (SCOD concentration of 3765.5 ± 275.5 mgL^{-1}) from an anaerobic baffle reactor and raw sludge (v:v = 1:3) were added into the ultrasonic disintegration (UD) reactor. AD experiments were implemented for 7 days (Zhang et al., 2012a), at a temperature of 35 °C. After each sampling or operating period, reactors were sparged with N_2 gas to remove dissolved oxygen. All experiments were duplicated, and average values calculated.

Raw sludge was treated with AD for 0 or 3 days and UD treatment was applied at different working times ranging from 0 to 30 min (0, 5, 10, 15, 20, 25, 30 min) after AD. Another batch of raw sludge was treated with AD for 0–7 days (8 reactors), followed by UD of 15-min. SCOD concentration was measured to determine the influence of UD on AD.

Based on the above results, intermittent UD was applied for 2.1 min per day during a 7-days AD process. In another comparison reactor, sludge was pretreated by UD in the first day for 15 min, and the disintegrated sludge was treated by AD for 7 days. SCOD concentration and VS concentration of sludge in the reactor was examined before and after applying UD.

The central composite design – response surface methodology (CCD-RSM) was used to optimize sludge degradation parameters. The optimal experiment was further expanded using Design Expert (Version 8.0.6, Stat-Ease Inc. USA). Table 1 shows the two independent variables. Finally, the morphological characteristics and bacterial community structure of the degraded sludge were further analyzed.

2.3. Analytical methods

Sample collection and ultrasonic treatment occurred every day, making it difficult to collect and measure the gas. As such, sludge disintegration and degradation characteristics were evaluated using SCOD concentration and VS removal. The sludge sample was centrifuged at 9000 rpm for 10 min with a centrifuge (3H16RI, Hersey LTD, China); the supernatant was then filtered through a 0.45 μm membrane filter. SCOD in the filtrate and VS of sludge were measured using APHA Standard Methods (Clesceri et al., 1998). The sludge was treated in an alkali solution with 0.5 mol/L NaOH for 22 h, and the filtrate was sampled to determine TCOD (Tiehm et al., 2001).

The bacterial community structure was analyzed using pyrosequencing technology. Bacteria abundance was quantified using real-time PCR. The primer sets 338F (5′- ACTCCTACGGGAGGCAGCA-3′) and 806R (5′- GGACTACHVGGGTWTCTAAT-3′) of 16S rRNA were used to target all bacteria (sourced from Shanghai (China) Majorbio Bio-pharm Technology Co., Ltd.). The morphological structure of the bacterial community was measured using a transmission electron microscope (JEM-1200EX, Japan Electron Optics Laboratory).

Table 1
Experimental range and levels of the independent variables.

Variables	Factor	Units	Low	High	−α	+α
Interval time	X_1	day	0	2	−0.41	2.41
UD time	X_2	min	1	5	0.17	5.82

Notes: when interval time lower than 0 day, interval time was seen as 0 day.

3. Results and discussion

3.1. Ultrasonic sludge disintegration

As Fig. 1(a) shows, after applying UD for 30 min, the SCOD concentration increased to 4537.5 mgL^{-1}. This indicated that strong physical effects (such as hydromechanical shear forces) and sonochemical reactions (such as free radicals) generated by collapsing cavitation bubbles disintegrated the sludge, releasing soluble organics from the solids into the liquid phase (Liu et al., 2015). The SCOD concentration was 1246.0 mgL^{-1} in the sludge after applying AD for 3 days; this level was 2.6 times the concentration in raw sludge. This change indicated that organic matter in the sludge solid phase dissolved in the liquid phase, and AD selectively disrupted weak and sensitive cells (Zhang et al., 2015). After applying AD-UD for 30 min, the SCOD concentration was 5787.5 mg L^{-1}, a level 1.3 times than when UD was used alone for the same treatment time.

As Fig. 1(b) shows, after applying continuous AD for 7 days, the SCOD concentration significantly increased with prolonged AD; the SCOD concentration ultimately reached 1985.5 mg L^{-1}. After 7 days of AD, followed by applying UD for 15 min, the SCOD concentration reached 4320.5 mg L^{-1}. This was 1.6 times that of applying UD alone for the same treatment time. The incremental changes in SCOD concentration when applying UD each day were very obvious. The results indicated that AD may produce organic acids, enhancing the effect of ultrasonic cavitation (Yuan and Zhu, 2016). UD then damages bacterial cell walls and releases cytoplasmic materials into the aquatic phase (Li et al., 2016).

Alkaline pretreatment can induce the swelling of particulate organics at a high pH, making the cellular substances more susceptible to enzymatic reactions (Baccay and Hashimoto, 1984). When applying UD with Es (specific energy) of 15,000 kJ/kg·TS, a previous study found that the disintegration degree of chemical oxygen demand ($DD_{COD} = (SCOD - SCOD_0)/(TCOD - SCOD_0)$) of sludge with UD, alkaline-UD (at pH 9), and alkaline-UD (at pH 11) were 30.1%, 51.2%, and 63.8%, respectively (Kim et al., 2010). In this study, the DD_{COD} of sludge with UD, UD-AD (AD for 3 days), and AD-UD (AD for 3 days) were 36.8%, 60.3%, and 63.5%, respectively. The ultrasonic efficiencies identified in this study were similar to findings by Kim et al. (2010), because the DD_{COD} decreased as sludge TS increased (Zhang et al., 2012b). However, the alkaline-UD method, addition of a lot of alkaline substances, can cause secondary pollution, increase input costs and corrode ultrasonic equipment.

3.2. Applying intermittent UD in the AD process

As Fig. 2(a) shows, the SCOD concentration reached

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