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Enhanced efficiency for better wastewater sludge hydrolysis conversion through ultrasonic hydrolytic pretreatment

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ABSTRACT

The major requirements for accelerating the process of anaerobic digestion and energy production are breaking the structure of waste activated sludge (WAS), and transforming it into a soluble form suitable for biodegradation. This work investigated and analysed a novel bench-scale ultrasonic system for WAS disruption and hydrolysis using ultrasonic homogenization. Different commercial sonoreactors were used at low frequencies under a variety of operating conditions (intensity, density, power, sonication time, and total suspended solids) to evaluate the effects of the equipment on sludge hydrolysis and to generate new insights into the empirical models and mechanisms applicable to the real-world processing of wastewater sludge. A relationship was established between the operating parameters and the experimental data. Results indicated an increase in sonication time or ultrasonic intensity correlated with improved sludge hydrolysis rates, sludge temperature, and reduction rate of volatile solids (33.51%). It also emerged that ultrasonication could effectively accelerate WAS hydrolysis to achieve disintegration within 5–10 min, depending on the ultrasonic intensity. This study also determined multiple alternative parameters to increase the efficiency of sludge treatment and organic matter reduction, and establish the practicality of applying ultrasonics to wastewater sludge pretreatment.

1. Introduction

Wastewater treatment processes using biological methods such as single or combination aerobic, anaerobic, and anoxic treatments have been core technologies for many several decades. Besides their advantages in terms of simplicity, ease of operation, economy, and effectiveness, these biological treatment processes also generate a large amount of biological sludge [1,2]. Processing and disposal of the sludge have become a heavy burden on environment and society and poses hazards if not handled appropriately. However, properly treated biosolids, especially WAS, represent very significant and valuable resources that can be recycled for many beneficial applications [3].

Many solutions and treatment technologies of WAS have been investigated and developed so far. For example, alkaline stabilisation, aerobic digestion, composting, thermal stabilisation, landfilling and ocean dumping are established methods of disposal, which have been implemented to varying degrees, and with mixed results. However, in recent years, given that more globally sustainable environmental management methods are required, anaerobic sludge treatment technologies are becoming more popular because they offer many advantages compared to other methods. This is especially the case through the use of sustainable applied bioenergy sources. However, if this technology is going to have widespread application, the acceleration, and control of anaerobic decomposition processes that effectively exploit bioenergy resources in this process represents a big challenge. Obtaining better efficiency from sludge hydrolysis or liquefaction is a key factor in creating a more homogenous and efficient WAS solution for the effective application of bioenergy technology. This technology, if properly understood and implemented, can significantly reduce sludge

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production, which must otherwise be treated as expansion or new construction of other expensive sludge treatment systems [4–9].

The rigid structure of aging sludge combined with the relative impermeability of microbial cell walls causes the amalgamation of biosolids in WAS, which creates a major problem. Such amalgamation prevents cell wall disruption and the release of inner cell products, which otherwise help to break down the overall mass. These problems hinder effective sludge digestion [10], and hence pretreatment is required to disrupt cell membranes, in order to completely lyse microbial cells in the solution. A well-performing ultrasonic system for WAS disruption and hydrolysis process will significantly improve the capacity of the system, and more important, may then reduce the capital cost. In addition, the system can easily be retrofitted to an existing sludge treatment system.

The sludge flocculates, with bacteria cells disintegrated by pressure, combined with free radicals (such as ˙OH, ˙H, ˙N, and ˙O) and hydro-mechanical shear forces produced by ultrasonic cavitation at low frequencies, can break down quickly and effectively [4,11–15]. This results in the release of extracellular polymeric substances (EPS) and intracellular organic substances. This method can convert recalcitrant organic matter that is usually not readily biodegradable, into an abundant, readily biodegradable substrate that is available to increase the anaerobic community structure and enhance the activity of the bacterial consortium in the anaerobic digestion reactor. Furthermore, it increases in volatile solids degradation and biogas production.

In a nutshell, the sludge biological hydrolysis stage enhances important factors that may intervene to shorten the duration of anaerobic digestion (AD) and accelerate the process of biogas generation [4,13,16]. This results in overall enhancement of the AD performance, thus representing an important milestone in the new design or upgrade of the capacity of existing anaerobic sludge treatment systems. At the present time, ultrasonic pretreatment of sludge is considered to be a highly effective, environmentally friendly [17], and cost-effective method compared with other techniques [18].

There have been many studies of sludge homogenised by ultrasound, with relatively interesting results [4,13,18–21]. However, they have only been proven on a small laboratory scale, and lack clear and consistently defined parameters in a form useful to engineers, consultants, designers, and scientists for larger scale, practical industrial applications [22,23]. Therefore, we seek to clarify some of the key factors and update this application, in order to optimise the efficiency of the treatment process, and generate higher-quality effluent outputs. Instead, it will enable them to employ a sophisticated, predictable real-time, real-world, practical process to degrade various types of sludge.

In this study, we first investigated the influence of variables on system performance using different sonicators at low frequency for WAS disintegration under various operational conditions, and also discussed the specific energy of ultrasonic treatment. Secondly, we aimed to identify and establish the relationships and influences among the operating parameters (intensity, density, frequencies and sonication time) of ultrasonic and experimental data (sludge temperature, pH, total suspended solids, total biodegradable material, *etc.*). Thirdly, new insights into the empirical models and mechanisms of sludge disintegration using different sonoreactors were explored. Finally, it attempted to comprehensively understand and clarify the influence of sonication on ultrasonic sludge disintegration.

2. Methods

2.1. Characterizations of raw sludge

Municipal wastewater consists of liquid and some biosolid wastes produced in homes, factories, commercial establishments, and from any point or non-point sources, such as agricultural runoff, urban pavements and surfaces, construction, *etc*. subsurface, surface, or storm water that enters the municipal wastewater collection systems. Depending on the type and extent of wastewater treatment, any of the materials that enter the municipal wastewater collection system may ultimately find their way into the sludge. Since influent is not constant in character from place to place or from time to time, the sludge resulting from its treatment varies highly in content (Table 1). The sewage sludge was collected from five municipal wastewater treatment plants (WWTPs) in South Korea. Table 1 summarizes the sludge characteristics from each of the tested plants.

2.2. Ultrasonic system configuration and experimental set-up

Fig. 1 shows a diagram that illustrates the ultrasound sonoreactor used in this study. The device was equipped, among other factors, with a power supply, a probe, and transducers. Two types of low-frequency ultrasound sonoreactors were used. The first sonoreactor was a horn-type ultrasound system (Fig. 1a) with three ultrasonic devices that, in turn, had the following specifications: UP-800 (800 W, 20 kHz, E-Chrom Tech Co., Ltd, Taiwan), VCX-850 (850 W, 20 kHz, Germany), and VCX-700 (700 W, 20 kHz, Sonics & Materials, Inc., USA). The second sonoreactor was a bath-type ultrasound system (Fig. 1b), MU-1500 (1500 W, 28 kHz, Mirae Ultrasonic Tech. Co., Korea) with a frequency of 28 kHz. The volume of the reactor was 20 L, and it was equipped with 20 transducers arranged at the bottom and two sides of the reactor. All of the experiments were conducted in the 75%–85% amplitude range of the ultrasonic processors.

2.3. Sampling and analysis

Sonicated sludge samples from the inline sonoreactor were collected during continuous operating mode over a desired period of time. All of the sample collections followed proper laboratory protocols for the sampling, preservation, and storage of specimens. The reagents used for testing the samples were analytical grade and were used without further purification

The quality of the sonicated sludge was determined by measuring the following: total dry solids (TS), total suspended solids (TSS), volatile solid (VS), total chemical oxygen demand ($TCOD_{Cr}$), soluble COD_{Cr}, total nitrogen (TN), ammonia nitrogen (NH_4^+–N), total phosphorus (TP), and phosphate (PO_4^{3-}–P) concentrations. These variables were all analysed according to standard methods [24]. Alkalinity concentration was determined by the titration method using $0.02N{\bullet}H_2SO_4$ solution [25]. The pH values and temperature were measured with a CyberScan pH 510 m (Thermo Fisher Scientific Inc., USA). Mean particle size (MPS) and particle shapes in the sludge were measured using a Dynamic Imaging Particle Analysis System (Fluid Imaging Technologies Inc., US).

2.5. Data analysis

The data obtained from experiment and modelling were analysed statistically using Origin 8.1 (OriginLab Corporation, USA) and Excel 2010 (Microsoft, USA), with a Solver add-in program. Statistical analysis of variance (ANOVA) was also conducted to assess the statistical significance of the model (P-value < 0.05).

3. Results and discussions

3.1. Effects of ultrasonic irradiation on WAS floc structure and size

Breaking the physical structure of activated sludge so that it can be transformed into a soluble form suitable for biodegradation,