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Microwave enhanced advanced oxidation treatment of municipal wastewater sludge

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ABSTRACT

Three sludge types (primary sludge, secondary sludge, and anaerobic digested sludge) and centrate produced from a local municipal wastewater treatment plant were treated by the microwave enhanced advanced oxidation process. All sludge types exhibited a certain degree of solids solubilization and phosphorus release, as well as altered physical properties after the treatment. The extent of treatment was influenced by the inherent characteristics of sludge itself, besides the treatment process conditions, such as temperature and hydrogen peroxide dosage. The microwave enhanced advanced oxidation process was very effective for the treatment of all types of sludge for purpose of solids solubilisation, and nutrients release for resource recovery. Very high soluble chemical oxygen demand concentrations (62%) and total suspended solids reduction (75%) were obtained in the treated secondary sludge conducted in the pilot-scale continuous-flow system. The microwave enhanced advanced oxidation treatment system shall be used for treating both primary and secondary sludge, and therefore, the system shall be installed in the treatment train after an aerobic biological treatment system, and before an anaerobic digestion system to gain the maximum process efficiency.

1. Introduction

Various solids disintegration and nutrient release from sewage sludge, such as mechanical, ultrasound, chemical, and thermal methods have extensively been investigated [1]. Among them, thermal hydrolysis process has been proved to be very effective for treating sludge [2,3] and two industrial processes, namely, Cambi process and BioTHELYS are widely used in the wastewater treatment plants (WWTPs) [4,5]. A combination of thermal heating and chemicals, such as ozone, hydrogen peroxide, acids or alkali resulted in higher rates of degradation, compared to individual thermal or chemical treatment [6]. Microwave enhanced advanced oxidation process (MW/H_2O_2-AOP) is a thermal chemical process, which uses MW irradiation in combination with H_2O_2 to generate highly reactive hydroxyl radicals for reacting with organic slurry. The MW/H_2O_2-AOP consists of two distinct processes: thermal decomposition and oxidation. The first process involves the breakdown of large molecules into smaller and soluble organic components, and the second process involves oxidation or gasification of the resulting organic by-products. Both thermal decomposition products and intermediate oxidation products can be further oxidized to form final products, such as volatile fatty acids (VFA), CO_2 and water [7]. The MW/H_2O_2-AOP has been shown to be very effective for sludge treatment; it breaks down the floc structure to release cytoplasm from microorganism cell and oxidizes many biomolecules, such as proteins and nucleic acids. As a result, some of the resulting organic compounds become soluble in the solution. Metals and inorganic materials are also released in the process [8,9,10,11,12].

For the MW/H_2O_2-AOP, microwave temperature, hydrogen peroxide dosage, heating time, and power intensity are the factors affecting the process efficiency. Each factor can be selected independently in a batch operation. However, each factor is intertwined with each other in a continuous-flow system: the heating rate of the substrate is controlled by its flow rate through the microwave applicator; a higher flow rate results in a lower heating rate of the substrate, and a shorter process retention time; and a higher flow rate also reduces the amount of microwave radiation transmitted to the substrate [13,14,15,16]. The advantages of operating at a continuous-flow system over a batch-operation system are: (1) ability to simultaneously introduce H_2O_2 and sludge at any pre-set temperatures; and (2) enhanced treatment efficiency due to addition of H_2O_2 at higher temperatures. Elevated MW temperatures increase the decomposition of H_2O_2 into highly reactive hydroxyl radicals, and curtail catalase activity resulting in lower amounts of H_2O_2 required in the process [9,16,17,18,19,20].

Earlier studies on sludge were conducted on the treatment of

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aerobic secondary sludge from the membrane-enhanced biological phosphorus removal (MEBPR) system located at the University of British Columbia (UBC), Canada. It has yet to be studied on sludge produced from different treatment systems, or sludge types besides secondary sludge. The objectives of this study were to examine the effects of the MW/H_2O_2-AOP treatment on three sludge types (primary sludge, secondary sludge from biological trickling filters, anaerobic digested sludge) and centrate from a local WWTP. This was: (1) to determine the treatability of these sludge types using the MW/H_2O_2-AOP; (2) to assess which type of sludge was the best fit into a new wastewater train including the MW/H_2O_2-AOP; and (3) to determine where this system could be installed to gain the maximum process efficiency for the WWTP.

2. Materials and methods

2.1. Microwave system

A closed-vessel microwave digestion system (Ethos TC Digestion Lab station 5000, Milestone Inc., USA) with operating frequency of 2450 MHz and maximum power supply of 1000 W was used for batch-mode microwave treatment. It consists of dual magnetrons with a rotating microwave diffuser, which allows for homogeneous microwave distribution. The system can accommodate up to 12 vessels, each with approximately 100 mL volume, in a single run. Maximum operating temperature and pressure are 220 degrees Centigrade (°C) and 30 bar (435 psig), respectively. This system allows for real-time temperature control using an independent system controller and temperature probe and a magnetic mixing device with a maximum speed of 200 rpm for mixing of the samples during the process.

A 915 MHz pilot-scale MW/H_2O_2-AOP system was operated in a continuous-flow mode, which consisted of a Sairem microwave generator (5 kW), an applicator (1 m long, hollow aluminum conduit) and a substrate feeding system; a reaction chamber with a total volume of 0.6 L was placed inside the applicator. The feeding system included feeding and hydrogen peroxide pumps, a holding tank (46 L), a H_2O_2 tank and a reservoir tank. It can be operated at temperatures ranging from 90 to 120 °C and pressures less than 200 kPa.

2.2. Substrate

Sewage sludge (primary, secondary and anaerobic digested sludge) was collected from a local WWTP. The primary sludge was the solids obtained from the primary sedimentation tanks in the primary treatment system. The overflow from primary treatment tanks was further treated in a biological trickling filter system. The settled solids from the secondary clarifiers were obtained as the secondary sludge. A mixture of both the primary sludge and secondary sludge (2–1 ratio) was then treated by anaerobic digestion. The high strength dewatered sludge liquor (centrate) was collected from anaerobic digested effluent (digested sludge) after the centrifugal treatment.

2.3. Experiments

Primary sludge, secondary sludge, anaerobic digestion sludge, and centrate were used for the batch mode operation in a 2,450 MHz laboratory scale microwave digestion unit. Five sets of microwave treatments were conducted at two different temperatures, 90 and 110 °C. The microwave heating ramp rate was 20 °C/min and samples were held for 5 min at the targeted temperature. Two H_2O_2 dosages were used in the process (0.6 and 1% H_2O_2 per %TS) as shown in Table 1. The operating conditions, including temperature and hydrogen peroxide dosage selected in this study, were near optimal, based on earlier studies [13,15,21].

Two sets of secondary sludge were treated in a continuous-flow MW/H_2O_2-AOP system at 90 and 110 °C and a dosage of 1% H_2O_2 per %TS was used. H_2O_2 was added to the MW/H_2O_2-AOP system when the temperature of sludge reached 60 °C.

2.4. Chemical analysis

Both the raw and treated samples were centrifuged at 3500 rpm for 15 min. The samples were then vacuum filtered using 0.45 µm fibreglass filter paper. Soluble chemical oxygen demand (SCOD), orthophosphate (ortho-P), ammonia, volatile fatty acids (VFA) and metals in the soluble portion of the samples were measured. All of the chemical analyses were carried out following the procedures outlined in Standard Methods [22]; all samples were run in triplicate. Both initial and treated samples were also analyzed for total solids (TS), total suspended solids (TSS), total chemical oxygen demand (TCOD), and total Kjeldahl nitrogen (TKN). Orthophosphate, ammonia, TKN were determined by a flow injection system (Lachat Quik-Chem 8000 Automatic Ion Analyzer, Lachat Instruments, USA). A Hewlett Packard 6890 Series II gas chromatograph, equipped with a flame ionization detector (FID), was used to measure VFA. Volatile separation was accomplished with a HP free fatty acid phase column. Calcium (Ca), and magnesium (Mg), as well as soluble TP and TP were determined using a Perkin Elmer Optima 7300 DV Optical Emission Spectrometer.

Dewaterability, with three replicates, was determined in terms of capillary suction time (CST) by using the Komline-Sanderson capillary suction timer with a paper support block, stainless steel reservoir with 18 mm inner diameter and 25 mm height, and a digital timer. Particle size measurement, each with three replicates, was conducted through a Malvern Instrument Mastersizer 2000 analyzer, with a Hydro S automated sample dispenser unit. Particle sizes measured in the Mastersizer 2000 ranged from 0.2 µm to 2000 µm.

3. Results and discussion

3.1. Characteristics of sludge

Each sludge type exhibited recognizably different chemical and physical properties. High TS, TSS, TCOD and VFA concentrations, but low pH, were present in primary sludge and secondary sludge types. The anaerobic digested sludge and centrate had very low solids content and VFA concentrations (Table 1). The secondary sludge also contained high TP and TKN contents, as well as a higher volume of larger particle sizes (Table 2).

3.2. Secondary sludge

The MW/H_2O_2-AOP treatment of secondary sludge has been studied extensively, and the significant factors affecting this process have also been examined in earlier studies [8,10,11,12,15,21,23]. However, it was the first time that the secondary sludge from the trickling filter reactor was studied by our research team. As expected, the SCOD and VFA concentration increased at a higher temperature and a higher H_2O_2 dosage (Table 1 and Fig. 1). At a low H_2O_2 dosage (0.6% H_2O_2 per %TS), the SCOD increased from 4.3% to 22% and 25% of TCOD at 90 and 110°C, respectively. The SCOD increased to 42 and 48% of TCOD at 1% H_2O_2 per %TS. At least 10% higher SCOD concentration was obtained in the continuous-flow system than that of the batch system with the same H_2O_2 dosage (1% H_2O_2 per %TS). This was due to deactivation of catalase enzyme prior to addition of H_2O_2 at 60°C. As a result, more H_2O_2 was available for the process, essentially equivalent to a higher dosage. A similar trend was observed in VFA. The TSS reduction corresponded to increased SCOD and VFA concentrations. The solids disintegration, in terms of TSS reduction, increased SCOD and VFA, were comparable to the earlier studies using the secondary sewage from the MEBPR system [11,12,21].

Higher SCOD in the treated MW/H_2O_2-AOP effluent would have enhanced the rate of hydrolysis, resulting in facilitating