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Research article

Enhanced sludge properties and distribution study of sludge components in electrically-enhanced membrane bioreactor

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A B S T R A C T

This study investigated the impact of electric field on the physicochemical and biological characteristics of sludge wasted from an electrically-enhanced membrane bioreactor treating medium-strength raw wastewater. This method offers a chemical-free electrokinetic technique to enhance sludge properties and remove heavy metals. For example, sludge volume index (SVI), time-to-filter (TTF), mean sludge particle diameter (PSD), viscosity, and oxidation-reduction potential (ORP) of 21.7 mL/g, 7 min, 40.2 μm, 3.22 mPa s, and −4.9 mV were reported, respectively. Also, X-ray fluorescence (XRF) and X-ray diffraction (XRD) analyses provided mechanisms for heavy metal removal so as to establish relevant pathways for nutrient recovery. Furthermore, variations in dissolved oxygen (DO), conductivity, viscosity, ORP, total suspended solids (MLSS), and volatile suspended solids (MLVSS) were interrelated to evaluate the quality of wasted sludge. A pathway study on the transport and chemical distribution of nutrients and metals in sludge showed great potential for metal removal and nutrient recovery.

1. Introduction

Waste sludge disposal problems are compounded by large amounts of excess sludge due to high growth of microbes and low sludge quality. From 25 to 65% of the total operation cost of a wastewater treatment plants (WWTP) may result from the handling and management of excess sludge (Zhao and Kugel, 1996). Waste sludge can be managed either by preventing excess sludge production inside the aerobic reactor or using end-of-pipe techniques to improve the sludge quality for reuse or safe disposal.

Techniques for reducing excess activated sludge in-situ and improving sludge characteristics can be broadly classified into physicochemical and biological methods. Physicochemical approaches involve physical changes in sludge growth via chemical addition to alter the characteristics of sludge. Some of these approaches include ozonation process, alkaline or acid treatment, thermal treatment, calcium carbonate addition, and ultrasonic treatment. Ozonation treatment has been employed via 20 mg ozone/g mixed liquor suspended solids (MLSS) per day in an aeration tank to reduce the production of excess sludge by 50% (Kamiya and Hirotsuji, 1998). Improvements in sludge volume index (SVI) as compared to sludge treatment without ozonation was observed but the economic cost of this technique was high due to the fact that high amount of energy was required for ozonation. In addition, ozonation may lead to the formation of refractory organic carbon with high toxicity. In-situ treatment of the sludge by alkaline, acid, thermal, and their combination have also been employed (Rocher et al., 2001) by gentle alkaline waste treatment conditions (20 min at 60 °C and pH 10 by NaOH addition) to solubilize waste activated sludge. A reduction of 37% of the excess sludge was obtained without altering the purification yield of the process (Rocher et al., 2001). Piirtola et al. (1999) have also indicated that the blend of talc and chlorite improves sludge settleability and filterability, whereas calcium carbonate can improve only settleability to about 50%. A one-time dose of 1.2 g of the blend of talc and chlorite per gram of volatile suspended solids (MLVSS) has reduced the SVI from 800 to lower than 200 mL/g while a daily dose of 0.1 g/g of MLVSS has maintained low SVI (Piirtola et al., 1999). Further, the disruption of sludge flocs and lyses of bacterial cells from an aeration tank have been investigated using low-frequency and high-intensity ultrasonic treatment (Gonze et al., 2003). A significant decrease in sludge volume was noticed with significant improvements in the sludge settleability and filterability.

In an effort to improve waste sludge properties by integrated techniques, a pioneer work related to the interaction between

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Nomenclature

μ	micro
c	centi
F/M	food-to-microorganism ratio
g	gram
h	hour
k	kilo
L	liter
LMH	liter per meter squared per hour
m	meter
min	minute
Pa	Pascal
s	second
S	siemen
V	volt
W	watt

biological process and electrokinetics in one operational unit was carried out for the processing of waste sludge generated from municipal wastewater treatment (Elektorowicz and Oleszkiewicz, 2010). Considerable metal removal, such as 71–90% of zinc, 70–97% of nickel, 50–69% of copper, 61% of cadmium, and 83–99% of iron was achieved. The interdependence of flocs and efficiency of a pilot scale submerged membrane electro-bioreactor (SMEBR) has also been observed to cause changes in the structure and morphology of suspended solids under the electric field (Ibeid et al., 2013). Although the results from Ibeid et al. (2013) described the changes in sludge particle size diameter (PSD); the study offered no interpretation or mechanism about the mobility and distribution of sludge components (i.e. fate of ions or metals).

Nonetheless, Hasan et al. (2014) has investigated the impact of electric field on the sludge properties using the SMEBR treating municipal wastewater. The time necessary to filter 100 mL of the sludge sample has decreased by 78% after treatment whilst the SVI has averaged 119 mL/g (Hasan, 2012; Hasan et al., 2014). The results obtained from the SMEBR defined standard operating procedures and offered conclusions for pollutants' removal in a pilot scale study under real operating conditions. However, no scientific basis was provided for probable distribution mechanism of the sludge components. For instance, the impact of dissolved oxygen (DO) due to enhanced aeration, which can better explain the dispersion of flocs, particle size changes, and removal of soluble chemical oxygen demand (sCOD) during the hybrid processes, was not fully captured. Therefore, the elaboration of the above factors in terms of selected operating conditions for real wastewater sludge characterization is required. In this research, a new configuration of the SMEBR has been introduced to complement the research findings of previous studies and provide mechanisms for the fate of metals, organics and inorganics.

2. Materials and methods

2.1. Experimental set-up

The waste sludge samples were collected from the bioreactor and analyzed immediately to avoid any changes on the characteristics. The rectangular bioreactor was made up of polycarbonate walls with a submerged microfiltration (MF) flat sheet membrane from KUBOTA Corporation and two pairs of aluminum and stainless steel porous electrodes (aluminum as anode and stainless steel as cathode), designed in a vertical and parallel configuration. Previously, electrokinetic reactor configuration has been developed using circular hollow fiber membrane and electrodes placed concentric to each other in a cylindrical reactor (Elektorowicz et al., 2011). However, the present reactor has been designed using rectangular flat sheet polymer membrane (Giwa, 2014).

The current assembly of electrically-enhanced rectangular MBR set-up consisted of three zones: filtration zone, inter-electrode zone, and anoxic zone as shown in Fig. 1 (Giwa, 2014). The reactor design consisted of rectangular flat sheet polymer membranes aligned in an anode-cathode-membrane-cathode-anode configuration, which may be represented by (*X-A-C-M-C-A-X*) where *X* and *M* refer to the anoxic (low oxygen) zones between reactor wall and anode, and membrane module, respectively. The assembly contained an object-oriented design built-in to (a) enhance migration and distribution of contaminants, (b) protect membrane from anodized precipitants, (c) cease ammonium oxidation, (d) retain phosphate by anoxial zone, and (e) promote mobility and charge neutralization for flocculation as shown in the block diagram Fig. 1.

The mixed liquor contained predominantly negatively charged colloidal aggregates, and smaller flocs particles consisting of higher carbonates, phosphates, silicates, and organic matter (Xiao et al., 2009). The two cathodes were placed close to the membrane on opposite sides in the filtration zone to ensure repulsion of charges by the cathodes and prevent direct aluminum release from the anode on the membrane. The placement of the cathodes also ensured that coagulated solids move close to the electrodes on both sides of the membrane, rather than depositing on the membrane surface. The anoxic zone between reactor wall and anodes kept anodic surface oxidation in control by controlled oxygen zone around it. This would hinder anodic activation through surface polarization. Thus, the anode surface was likely to consume more and more OH^-, thereby minimizing electrode polarization. Also, the anoxic zone restricted the oxidation of ammonia into nitrate and further into NO_x in mixed liquor stream.

Prior to the test, fresh activated sludge was collected from the nearby MBR wastewater treatment plant at Masdar City, Abu Dhabi (UAE) with initial F/M ratio of 0.59 1/d. The reactor was fed with degritted raw municipal medium-strength wastewater at a continuous flux of 15.2 LMH for 120 days. The volume and effective volume ratio of the reactor were 31.5 L and 0.71, respectively. Influent flow rate was maintained at 40 L/d. The pore diameter and surface area of the membrane were 0.4 μm and 0.11 m^2, respectively. The materials of the membrane included polyethylene terephthalate, acrylonitrile butadiene styrene (ABS), polypropylene, and chlorinated polyethylene in different proportions. A 1.5 L of sludge was wasted daily, hence maintaining a hydraulic retention time (HRT) and a sludge retention time (SRT) of 13.5 h and 10 days, respectively. The volume of the electrical zone between the electrodes was 8.04 L (26% of the total effective volume).

2.2. Characterization of waste sludge

The performance of the reactor was monitored based on the quality of treated effluent and wasted sludge. Fresh samples were collected and analyzed in duplicates to ensure results' reproducibility. Treated effluents were analyzed for chemical oxygen demand (COD), ammonia (NH_4^+-N), total nitrogen (TN), total phosphorus (TP), and ortho-phosphate (PO_4^{3-}-P) using HACHDR 3900 Bench top Spectrophotometer with radio frequency identification (RFID) technology. The sludge mean particle size diameter (PSD) was determined by the Horiba Laser Scattering Particle Size Distribution Analyzer (LA-950), while sludge viscosity was measured by HAAKE Rheo Stress 6000 Rheometer. Also, the SVI was measured using a 1 L graduated cylinder, where the sludge sample