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Reduction of excess sludge production in sequencing batch reactor through incorporation of chlorine dioxide oxidation

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ABSTRACT

In this study, chlorine dioxide (ClO_2) instead of chlorine (Cl_2) was proposed to minimize the formation of chlorine-based by-products and was incorporated into a sequencing batch reactor (SBR) for excess sludge reduction. The results showed that the sludge disintegrability of ClO_2 was excellent. The waste activated sludge at an initial concentration of 15 g MLSS/L was rapidly reduced by 36% using ClO_2 doses of 10 mg ClO_2/g dry sludge which was much lower than that obtained using Cl_2 based on similar sludge reduction efficiency. Maximum sludge disintegration was achieved at 10 mg ClO_2/g dry sludge for 40 min. ClO_2 oxidation can be successfully incorporated into a SBR for excess sludge reduction without significantly harming the bioreactor performance. The incorporation of ClO_2 oxidation resulted in a 58% reduction in excess sludge production, and the quality of the effluent was not significantly affected.

1. Introduction

The wide use of an activated sludge process for wastewater treatment results in the production of a considerable amount of excess sludge, which must be safely disposed of due to its potential environmental risk. However, the disposal of these solid wastes is extremely costly, which may account for up to 60% of the total operating costs of a wastewater treatment plant [1]. The high cost is impractical, especially for municipal wastewater treatment plants that operate on a large scale. Therefore, excess sludge disposal represents an increasing challenge for wastewater treatment plants.

Several technologies, which involve mechanical, chemical, thermal and biological methods, have been explored for excess sludge reduction [2]. Among these technologies, chemical oxidation processes have shown great potential but high costs limit their application [3]. Biological methods present a relatively inexpensive alternative, however, sludge reduction through the manipulation of the ecosystem appears to be difficult in full-scale aerobic wastewater treatment processes.

An ideal method of solving excess sludge-associated problems is to reduce sludge production during wastewater treatment rather than during post-treatment of the sludge produced. Recently, some researchers have focused on combined process by incorporating chemical oxidation into activated sludge processes. Ozonation [4,5], chlorination [6], hydrogen peroxide oxidation [7] and fenton oxidation [8] have been successfully incorporated into the activated sludge process for excess sludge reduction. Chemical oxidation-assisted sludge reduction processes are more efficient for excess sludge reduction and have the advantages of easy control, stable performance and high operation flexibility.

Because it is a strong oxidant, ozone (O_3) has been widely applied in excess sludge reduction. A combined activated sludge process and ozone oxidation system has been successfully developed. In this combined system, the excess sludge production can be greatly reduced with the partial ozonation of the returned sludge from the activated sludge process [5,6]. A disadvantage of the ozonation-assisted sludge reduction process is its high operational cost because the generation and application of ozone is expensive.

Improving the cost effectiveness of such a sludge minimization requires the use of chemical oxidizers. Chlorine (Cl_2) was proposed to replace O_3 and was used in reducing excess sludge. Combining chlorination with an activated sludge process resulted in a 65% reduction in excess sludge production [6]. Although the

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Table 1
Wastewater treatment performance in the operation cycle of the SBR.

Parameters	Influent		Effluent		Removal rate
	Range	Average	Range	Average	
Total suspended solid (TSS, mg/L)	60–450	255	7.5–13.5	9.71	96%
Chemical oxygen demand (COD, mg/L)	100–500	300	20–30	26.5	91.2%
Biochemical oxygen demand (BOD_5, mg/L)	80–190	300	5.2–17.5	11.6	92%
Total nitrogen (TN, mg/L)	20–40	30	9–17.5	12.5	58%
Total phosphorus (TP, mg/L)	2–8	5	0.42–0.64	0.56	89%
Ammonium nitrogen (NH_4^+-N, mg/L)	5–30	17.5	1.0–2.5	2.1	88%
pH	6.8–7.8	7.3	6.8–7.8	7.3	–

chlorination-activated sludge process is more cost-effective than the ozonation-activated sludge system, the chlorination-generated potential harmful byproducts, including trihalomethanes (THMs), pose a serious challenge to the full-scale application of this technology.

As a novel neutral oxy-chlorine species, chlorine dioxide (ClO_2) has often been used as an alternative chemical oxidant for Cl_2 to minimize the formation of chlorine-based by-products [9,10]. ClO_2 is a more powerful oxidant than Cl_2, and ClO_2 accepts five electrons when reduced to a chloride ion. Based on its molecular weight and the number of transferred electrons, ClO_2 has approximately 263% more available chlorine, which is greater than 2.5 times the oxidizing capacity of the chlorine in Cl_2 [11]. Recent studies have focused on the use of ClO_2 to oxidatively eliminate undesired organic pollutants from surface water and wastewater [12–14]. Combining ClO_2 oxidation with an activated sludge process may is a promising technology for the minimization of excess sludge production.

To the best of our knowledge, there have been no reports related to ClO_2-assisted activated sludge reduction in the literature. In this study, we are the first to demonstrate that ClO_2 oxidation can be successfully incorporated into an activated sludge process to achieve excess sludge reduction. Excess sludge from a sequencing batch reactor (SBR) was subjected to various ClO_2 doses and the ClO_2 treated sludge liquor was then returned to the SBR system upon the completion of the ClO_2 treatment. To evaluate the feasibility of the proposed method, this study investigated the sludge disintegration ability of ClO_2, its sludge reduction efficiency and the effluent quality of the SBR system.

2. Materials and methods

2.1. Waste activated sludge cultivation

A SBR from the Nanhai municipal wastewater plant, which is located in Foshan, China was used to cultivate the waste activated sludge. The SBR, which had a working volume of 1260 L, was operated for two cycles per day, and the distribution of each 8 h cycle was as follows: an influent period (0.5 h), an aeration period (4 h), a precipitation period (1.5 h), a drainage period (0.5 h) and an idle period (1.5 h). The airflow rate was fixed at 700 L/h which maintains the DO at approximately 2–3 mg/L in the aeration phase. During steady operation, a portion of the mixed liquor was regularly discharged to maintain a mixed liquor suspended solids (MLSS) concentration of approximately 3500 mg/L and a sludge retention time (SRT) of 11.6 days so that the excess sludge was cultivated under sludge loading rate of 0.112 kg BOD_5/kg MLSS/day. The SBR was operated for more than 12 months and was controlled by a programmable logic controller (PLC). The composition of the domestic wastewater and wastewater treatment performance during the operation cycle of the SBR are shown in Table 1.

2.2. ClO_2 disintegration of waste activated sludge

The sludge disintegrability of ClO_2 was studied using beaker experiments. We subjected 100 mL of waste activated sludge at a concentration of 15 g/LMLSS to varying doses of ClO_2 from 1 to 20 mg ClO_2/g dry sludge to investigate the effect of the ClO_2 dose on sludge disintegration and to determine the optimal ClO_2 dose. Subsequently, sludge disintegration by ClO_2 was evaluated at the previously determined optimal ClO_2 dose, and the MLSS, soluble chemical oxygen demand (SCOD), nitrogen and phosphorus were monitored. Highly pure ClO_2 (95%) was supplied by a ClO_2 generator (HYCB-50, China). ClO_2 was generated using the hypochlorite reaction with hydrochloric acid according to Eq. (1).

$$5NaClO_2 + 4HCl \rightarrow 4ClO_2 + 5NaCl + 2H_2O \quad (1)$$

All of the experiments were conducted at least in duplicate at room temperature ($25 \pm 2\,^{\circ}C$) and the average value was reported for all data.

2.3. ClO_2-activated sludge process combined system

Fig. 1 presents a schematic representation of the ClO_2-activated sludge process combined system. The previously described SBR was combined with a separated ClO_2 oxidation reactor in which highly pure ClO_2 (95%) was supplied by a ClO_2 generator. The ClO_2 oxidation reactor was a plexiglass cylinder with a working volume of 5 L (150 mm in diameter and 355 mm in height). A coarse bubble diffuser was placed at the bottom of the reactor to disperse pure ClO_2 gas, and a magnetic stirrer was used to facilitate the reaction between the sludge and ClO_2. ClO_2 doses were controlled using a manual valve. During operation, 50% of the excess sludge in the SBR was pumped into the ClO_2 oxidation reactor, in which the sludge was disintegrated. The disintegrated sludge was then returned to the SBR for further biological treatment and the effluent quality was monitored daily. An identical SBR that did not incorporate ClO_2 oxidation was used as control. Both SBRs were fed with the same domestic wastewater (Table 1) and operated at room temperature ($25 \pm 2\,^{\circ}C$) for 12 months.

2.4. Analytical methods

SCOD, MLSS, TN, NH_4^+-N, and TP and were measured according to standard methods [15]. For the SCOD measurement, all samples were filtered through a 0.22 um-pore-size syringe filter unit.

Protein content was determined using Lowry's method and polysaccharide content was analyzed using the anthrone method [16].

Sludge morphologies before and after ClO_2 treatment were determined using a scanning electron microscope (SEM) (XL-30, Philips, Holland). Before observation, a sample was collected and fixed overnight using paraformaldehyde and glutaraldehyde in a buffer solution (0.1 M cacodylate, pH 7.5, at $4\,^{\circ}C$), followed by