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Effect of coagulant on acidogenic fermentation of sludge from enhanced primary sedimentation for resource recovery: Comparison between $FeCl_3$ and PACl

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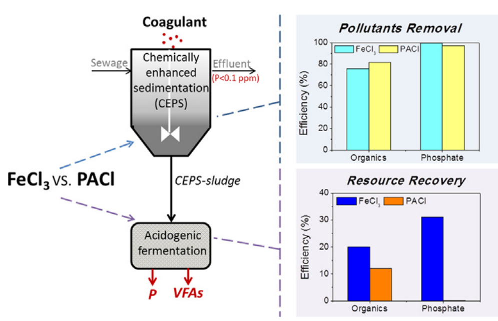
HIGHLIGHTS

- PACl and $FeCl_3$ perform similarly for chemically enhanced primary sedimentation (CEPS).
- Fe coagulant shows no inhibitory effect on organic hydrolysis of CEPS Fe-sludge.
- PACl coagulant has an inhibitory effect on the organic hydrolysis of CEPS Al-sludge.
- $FeCl_3$ is more favored than PACl in CEPS use for organic and P recovery from the sludge.

GRAPHICAL ABSTRACT



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ABSTRACT

$FeCl_3$ and PACl as coagulants in chemically enhanced primary sedimentation (CEPS) were compared in terms of their efficiencies in removing pollutants from wastewater and their effects on the acidogenic fermentation of CEPS sludge for resource recovery. PACl was found to be more effective than $FeCl_3$ for removing suspended solids by CEPS, with around 20% higher removal efficiency. However, the coagulated Al-sludge experienced more difficulty and had lower efficiency than Fe-sludge in organic hydrolysis and acidogenesis. The batch fermentation results showed that $FeCl_3$ dosed at 10–30 mg Fe/L_{sewage} had little influence on sludge hydrolysis and volatile fatty acid (VFA) production, whereas an obvious inhibitory effect was observed for PACl in organic hydrolysis of the sludge. The specific hydrolysis rate constant ($K_{h,P}$) for sludge fermentation decreased from 0.0321 for the sludge without PACl to 0.017 for the Al-sludge obtained at a dosage of 24 mg Al/L_{sewage}. Compared to the Al-sludge, the Fe-sludge had a much higher VFA yield and significant PO_4–P release during the sludge fermentation, which is attributed to the reduction of Fe(III) to Fe(II) under anaerobic conditions and the resulting disintegration of sludge flocs. By simple pH adjustment of the fermented Fe-sludge supernatant, up to 31% of the phosphorus in wastewater can be recovered in the form of vivianite as P fertilizers. VFAs produced in the supernatant are valuable organic carbon resources that can be recovered for beneficial uses.

1. Introduction

Chemically enhanced primary sedimentation (CEPS) refers to the wastewater treatment step that doses chemicals (Fe^{3+} or Al^{3+}) for coagulation, flocculation, and sedimentation to remove particulate and suspended pollutants [1]. Compared with conventional primary sedimentation, CEPS demonstrates superiority in removing suspended solids, organics, and phosphorus, thereby greatly reducing the pollutant loading for secondary biological treatment. CEPS is an energy-saving and cost-effective strategy for municipal wastewater treatment that is particularly suitable

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for constantly growing megacities [2,3]. For example, Hong Kong has the largest CEPS treatment plant in the world, i.e., Stonecutters Island Sewage Treatment Works, which doses $FeCl_3$ (10–12 mg Fe/L_{sewage}) to treat 1.7 million m^3 of sewage every day [4]. In Shanghai, polyaluminum chloride (PACl)–based enhanced primary treatment followed by an A^2/O process was adopted in Bailonggang Wastewater Treatment Plant, with a capacity of 1.2 million m^3/d, accounting for more than 25% of the total wastewater treatment capacity of Shanghai [5].

With the improved removal by CEPS as compared to simple primary sedimentation, a large portion of pollutants is concentrated into CEPS sludge instead of flowing to the downstream biological treatment process, which is energy-intensive with significant CO_2 emission. However, disposal of sewage sludge is known as one of the most challenging environmental problems for megacities. Up to 800 tons and 1000 tons of dewatered sludge are produced every day from Stonecutters Island Sewage Treatment Works and Bailonggang Wastewater Treatment Plant [4,5], respectively. In contrast, concentrated pollutants in CEPS sludge such as organics and phosphorus can be valuable resources that should be recovered rather than wasted. Thus, more sustainable alternatives are greatly needed for CEPS sludge processing to achieve both sludge reduction and resource recovery.

Anaerobic digestion has been applied to treat CEPS sludge for biogas production [6]. However, it was reported that compared with simple primary sludge, the methane yield of CEPS sludge with a coagulant addition of 17–85 mg/L_{sewage} of Fe or Al decreased by 20% to 50%, which was probably due to the low alkalinity (<1200 mg/L) for sludge digestion [7–9]. Instead of methane production, volatile fatty acids (VFAs) produced from sludge by acidogenic fermentation have more valuable applications, such as for biosynthesis of polyhydroxyalkanoates (PHA) [10] and for denitrification used in biological nitrogen removal (BNR) [11]. However, the effect of coagulants in the sludge on organic hydrolysis and acidogenesis has not been well investigated. Cabirol et al. [9] found VFA accumulation during the digestion of alum-based CEPS sludge. In contrast, Kim and Chung [12] reported reduced VFA production during the fermentation of synthetic CEPS sludge when the coagulant dosage was increased. The issue of nutrient release from CEPS sludge during fermentation must also be addressed because it may affect the use of VFAs in the supernatant.

This experimental study was conducted on the CEPS process in connection to the performance of acidogenic sludge fermentation for resource recovery. Its aim was to compare the efficiency of chemical coagulants, namely, $FeCl_3$ and PACl, for pollutant removal from wastewater by CEPS and to investigate the inhibitory effects of Fe and Al coagulants on the hydrolysis and VFA yield of the CEPS sludge. In addition to batch tests, semicontinuous reactors were also operated for the fermentation of Fe-based and Al-based CEPS sludge to evaluate the overall recovery of organic carbon and phosphorus resources from wastewater.

2. Materials and methods

2.1. Experimental

2.1.1. Jar tests for CEPS treatment

Raw domestic sewage was taken regularly from the Stanley Sewage Treatment Works in Hong Kong. The average wastewater quality parameters during the experimental period were as follows: pH 7.02 ± 0.05, total chemical oxygen demand (TCOD) 395 ± 54 mg/L, soluble chemical oxygen demand (SCOD) 147 ± 30 mg/L, total phosphorus (TP) 5.8 ± 0.2 mg/L, orthophosphate–phosphorus (PO_4-P) 4.2 ± 0.2 mg/L, total nitrogen (TN) 51.2 ± 2.0 mg/L, ammonia-nitrogen (NH_4^+–N) 24.7 ± 0.5 mg/L, and total alkalinity (TA) 193.5 ± 2.5 mg $CaCO_3$/L. Fe- and Al-based CEPS tests were first conducted on the fresh sewage samples using a laboratory jar tester. Different doses of $FeCl_3$ (4–25 mg Fe/L_{sewage}) and PACl (3–16 mg Al/L_{sewage}) were added to a series of 1-L beakers, each filled with 500 mL wastewater, without pH adjustment, followed by rapid mixing at 200 rpm for 1 min, slow stirring at 30 rpm for 15 min, and then sedimentation for 1 h. The supernatant was then siphoned off for analysis.

2.1.2. Batch fermentation of CEPS sludge

Based on the jar-test results, three dosages of $FeCl_3$ (10, 20, and 30 mg Fe/L_{sewage}) and PACl (8, 16, and 24 mg Al/L_{sewage}) were chosen for the subsequent CEPS tests. The coagulants were dosed at a predetermined dosage into 20 L of sewage in a flocculation tank to perform the same flocculation and sedimentation process as described above. After sedimentation, 19.33 L supernatant was withdrawn, and the rest 0.67 L sediment was obtained as the CEPS sludge (denoted as Fe-sludge or Al-sludge), being 30 times reduced in volume. A simple primary sludge was obtained as the control sludge (0 mg/L) from the wastewater without a coagulant addition after the same sedimentation and supernatant discharge procedure. Glass bottles were used as anaerobic reactors, or fermenters, for the sludge fermentation test. Each 550-mL bottle was filled with 470 mL of a sludge sample and 30 mL of a seed sludge from a laboratory acidogenic fermenter. The bottle fermenters filled with the different sludge samples, i.e., Fe-sludge, Al-sludge, and the control sludge, were placed in a temperature-controlled air chamber (37 °C ± 1 °C) with magnetic stirring for sludge mixing. At the beginning of the batch experiments, the fermenters were sparged with nitrogen gas to ensure anaerobic conditions, and the pH was not regulated during the fermentation process. The batch fermentation test on each sludge sample was conducted in duplicate reactors for 9 d and was sampled daily to monitor the process.

2.1.3. Semicontinuous fermentation of CEPS sludge

In addition to the batch tests, sludge fermentation was also carried out in a semicontinuous mode for both Fe-sludge (20 mg Fe/L_{sewage}) and Al-sludge (16 mg Al/L_{sewage}). During the experimental process, the CEPS sludge was fed into the respective fermenter once a day to replace one-fourth of the sludge mixture, resulting in a solids retention time (SRT) and hydraulic retention time (HRT) of 4 d. The fermented sludge from the batch tests was used as the seed sludge to ensure a quick start-up. The fermenters were kept in a temperature-controlled air chamber (37 °C ± 1 °C) with magnetic stirring. The volatile solid (VS) concentrations of the feed sludge (Fe-sludge and Al-sludge) were adjusted to a constant 5.0 g/L with DI water to provide a consistent feed concentration for the entire semicontinuous experiments. The sludge discharged daily from the fermenters was sampled and analyzed to evaluate the fermentation performance. To recover phosphorus from the fermented sludge, especially Fe-sludge, the fermented sludge mixture was centrifuged at 4000 rpm for 10 min, and 2-M NaOH was added into the supernatant to adjust its pH to 7.5 to form P-containing precipitates.

2.2. Analytical methods

The pH of the sludge mixture was measured using a pH meter (Starter 3100, Ohaus, USA). To analyze the fermented sludge samples, the sludge mixtures from the fermentation reactors were immediately centrifuged at 8000 rpm for 10 min to obtain the supernatants for determination of the soluble parameters. Measurement of the suspended solids (SS), total solids (TS) and volatile solids (VS), SCOD, NH_4-N, TN, PO_4-P, TP, and TA (titrated to pH 4.3) were conducted in accordance with standard methods [13]. VFAs