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Enhanced phosphorus removal from wastewater by growing deep-sea bacterium combined with basic oxygen furnace slag

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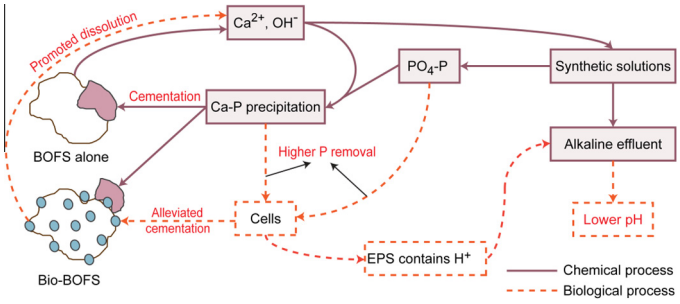
HIGHLIGHTS

- Bio-BOFS showed a better performance of P removal than unitary bacterium and BOFS.
- Solution pH of 7.8–8.0 was maintained by bacterium in Bio-BOFS system.
- Bio-BOFS alleviated cementing of BOFS and enlarged the particle size of BOFS.
- More than 90% phosphorus removal rate for salinity water was achieved by Bio-BOFS.

GRAPHICAL ABSTRACT



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ABSTRACT

As one solid waste with potential for phosphorus removal, application of slags in water treatment merits attention. But it was inhibited greatly by alkaline solution (pH > 9.5) and cemented clogging generated. To give one solution, phosphorus removal was investigated by combining deep-sea bacterium *Alteromonas* 522-1 and basic oxygen furnace slag (BOFS). Results showed that by the combination, not only higher phosphorous removal efficiency (>90%) but also neutral solution pH of 7.8–8.0 were achieved at wide ranges of initial solution pH value of 5.0–9.0, phosphorus concentration of 5–30 mg/L, salinity of 0.5–3.5%, and temperature of 15–35 °C. Moreover, sedimentary property was also improved with lower amount of sludge production and alleviated BOFS cementation with increased porosity and enlarged particle size. These results provided a promising strategy for the phosphorus recovery with slags in large-scale wastewater treatment.

1. Introduction

Effective phosphorus removal from aquatic systems, especially from shallow coastal environments is important for both phosphorus recovery and eutrophication controlling (Elser and Bennett, 2011; Föllmi, 1996). As one kind of mass industrial solid waste, open dumping of steel slag not only occupies land but causes potential pollution by dust as well as the alkalinity to air, soil and groundwater (Asuman Korkusuz et al., 2007). Attentions has been attracted to the use of steel slags as potential adsorbents in regulating the phosphorus cycle through uptake from and slowly release to the water as well as alternatives to the basal medium for construction of artificial wetland, tidal flats and seagrass beds recently (Claveau-Mallet et al., 2014; Hayashi et al., 2011; Hussain et al., 2015; Tsukasaki et al., 2015; Yamamoto and Liu, 2013). Among variety slags generated from different steelmaking processes, slag from the basic oxygen furnace (BOFS) presents the highest phosphorus adsorption capacity (Barca et al., 2012; Oguz, 2004). However, several challenges are faced to utilize slag filters in large-scale water treatment. First, the high pH value

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caused by dissolution and hydrolysis of metal (Ca, Fe, Al, Mg) oxide in BOFS brings to consequently environmental issues (Hussain et al., 2015; Mayes et al., 2006). Unlike application of slag in small scale filters, neutralization is not performable to implement slag to large scale water treatment as in wetland and artificial marine concrete substrates irrespective of the additional costs and salinity led by acid (e.g. HCl) addition. Furthermore, the clogging of slag filters related to the declined pore size and the more compact precipitate structure blocks off the phosphorus removal sustainably (Claveau-Mallet et al., 2014). Therefore, it will benefit more to both ecosystem and waste disposal to develop more eco-friendly phosphorus removal system of BOFS for large-scale water treatment.

Biological assistance and treatment are always favored for large-scale water systems. Yet for improvement of BOFS treatment system, the high pH value led by slag dissolution and the salinity of seawater constrict the biological integration greatly. Deep-sea microbes can not only adapt to some extreme strict environments including low/high temperature, high pressure, hyper salinity, and alkalinity, but also play significant roles in pollutant removal (Takai et al., 2001). Some deep-sea bacteria can even balance the solution pH to the right ranges through secreted extracellular polymers (Zhou et al., 2013). In this regard, to combine BOFS with deep-sea bacteria, with efficient phosphorus removal and alkalinity resistance/regulation, could offer a potential solution for phosphorus removal and slag disposal as well as provide artificial basal constructions for sea-bed beings and marine wetland treatment.

In this study, deep-sea bacterium of efficient phosphorus removal and pH buffering was screened. Phosphorus removal from wastewater by the combined bacterium and BOFS system was systematically investigated. Particle size and surface porosity were analyzed to reveal the mechanism involved in the alleviation of BOFS cementation.

2. Materials and methods

2.1. Synthetic wastewater

Synthetic wastewater was comprised of 4 g/L glucose, 2 g/L CH_3COONa, 20 g/L NaCl, 1.185 g/L $MgSO_4{\cdot}7H_2O$, and 2.4 g/L NH_4Cl. Initial phosphate concentrations were obtained by diluting stock solution of 3000 mg/L KH_2PO_4 in deionized water. pH values of synthetic wastewater were adjusted using 1 M HCl or 1 M NaOH solutions.

2.2. BOFS media

BOFS was collected from Group Co. Ltd of Jinan Iron and Steel, Shandong Province, China. BOFS size was of 0.180–0.425 mm (specified as $BOFS_{40}$ according to the mesh number, and the same as below), 0.097–0.180 mm ($BOFS_{80}$), and <0.097 mm ($BOFS_{160}$). Dried BOFS were kept in a desiccator prior to experiments. The elemental composition of BOFS was determined using a wavelength dispersive X-ray fluorescence (WDXRF) spectrometer (ZSX Primus II, RigakuI) as shown in Table 1.

2.3. Studied bacterium

Studied bacterium was screened from pure isolations from surface sediments of South China Sea, based on the phosphorus removal efficiency (RE) and capability of pH adjustment in synthetic wastewater. 10% (v/v) of activated axenic deep-sea bacterial solution was inoculated in shake flasks containing 100 mL sterile synthetic wastewater with different initial phosphorus concentrations and pH values. The flasks were then shaken at 200 rpm at 25 °C for 24 h. 5 mL sample was taken out to measure the optical density at 600 nm (OD_{600}) and pH value. Meanwhile, sample in the paralleled flask was centrifuged at 10,000 rpm for 10 min, and the supernatants were tested for total phosphorus (TP).

Studied bacterium was identified by 16S rDNA analysis following the methods described in literature (Jiang et al., 2008).

Table 1
Chemical composition of BOFS (wt%) measured by WDXRF.

Element	Ca	Fe	Si	Mg	Al	Mn	S	Cl
Wt (%)	60.7	19.9	6.37	3.43	2.35	2.53	0.411	0.313

2.4. Batch tests

BOFS size was optimized at dosage of 3 g/L BOFS with 10% (v/v) activated bacterium inoculated in 100 mL sterile synthetic wastewater in a 250 mL Erlenmeyer glass flasks (Bio-BOFS), while the respective bacterium (Bio) and BOFS were set as controls. The effects of general variables including BOFS dosage, initial pH, initial phosphorus concentration, salinity and temperature, which might be encountered in situ treatment, were investigated by batch experiments. Erlenmeyer glass flasks were shaken in a thermostatic shaker at 200 rpm at 25 °C (except for temperature tests) for 24 h to reach equilibrium. Turbid liquid was stratified and BOFS was separated at the bottom of flask after 20 min standing. The supernatant was then centrifuged at 10,000 rpm for 10 min to separate cells. TP was measured by the method of molybdenum antimony with a UV–visible spectrophotometer at 700 nm wavelength (Rice et al., 2012).

2.5. Particle size and pore size distribution of BOFS

BOFS at the flask bottom was sampled and washed thrice with deionized water. Part of the BOFS was then resuspended in 500 mL deionized water for particle size analysis and the rest was dried at 105 °C for 24 h for pore size analysis. Particle size was determined by a laser particle size analyzer (BT-9300H, Baxter instrument co., LTD, China). Pore size was given by a surface areas and porosity analyzer (ASAP2020HD88, Micromeritics, USA).

All tests were carried out in triplicate and the average values were reported.

3. Results and discussion

3.1. Screening and identifying of the studied bacterium

Strain 522-1 was screened out for it grew well under a wide range of phosphorus concentrations with phosphorus removal efficiency reached up to 99.2% (1.3 mg p g^{-1} cell dry weight h^{-1}) in 24 h at 20 mg/L phosphorus as shown in Fig. 1a. With phosphorus concentration increased ($\leqslant$20 mg/L), maximum biomass as indicated by OD_{600} at the earlier stationary phase (24 h) increased and paralleled to phosphorus removal. This meant that bioremoval of phosphorus is growth-dependent. However bacterial growth was remained almost unchanging as solution phosphorus still increased (>20 mg/L) which led to a sharply dropped phosphorus removal efficiency on concentration. It was indicated that integration with adsorption would be more favored strategy to enhance phosphorus removal efficiency than biomass increment at improper nutrient ratio scenarios for large-scale treatment. Strain 522-1 was also found adaptive to wide solution pH (5.0–9.0) and could regulate solution pH to neutral about 7.2 at initial pH ranges from 4.5 to 9.0 (Fig. 1b). It was indicated that solution pH buffering was more than biomass-dependent from the steady OD_{600} and equilibrium pH at initial pH from 6.0 to 9.0, and from