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Phototrophic periphyton techniques combine phosphorous removal and recovery for sustainable salt-soil zone

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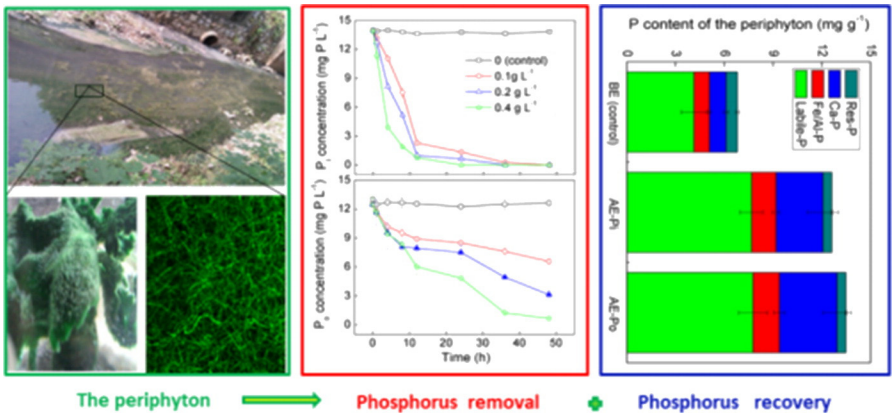
HIGHLIGHTS

- Phototrophic periphyton is effective in removing P (P_o and P_i) from wastewaters.
- Adsorption with physiochemical characteristic dominated P removal mechanism by periphyton.
- The P within periphyton is mainly in forms of Labile-P and Ca-P.
- The periphyton has vast potential application in recovering P for salt-soil zone

GRAPHICAL ABSTRACT



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ABSTRACT

The P (P_i as KH_2PO_4 and P_o as ATP) removal processes by phototrophic periphyton were investigated by determining the removal kinetics, metal content (Ca, Mg, Al, Fe, Cu, and Zn) of the solution and P fractions (Labile-P, Fe/Al-P, Ca-P, and Res-P) within the periphyton. Results showed that the periphyton was able to remove completely both P_i and P_o after 48 h when periphyton content was greater than 0.2 g L^{-1} (dry weight). The difference between P_i and P_o removal was the conversion of P_o into P_i by the periphyton, after that the removal mechanism was similar. The P removal mechanism was mainly due to the adsorption on the surfaces of the periphyton, including two aspects: i) the adsorption of PO_4^{3-} onto metal salts such as calcium carbonate (~50%) and ii) complexation between PO_4^{3-} and metal cations such as Ca^{2+} (~40%). However, this bio-adsorptional process was significantly influenced by the extracellular polymeric substance (EPS) of periphyton, water hardness, initial

Abbreviations: α, the initial adsorption rate (mg g^{-1} h^{-1}); β, the desorption constant (g mg^{-1}); m, mass of adsorbent (g); t, time (h); C, the constant of boundary layer effect; H, Shannon index; R, ideal gas constant (8.314 J mol^{-1} K^{-1}); T, temperature (K); V, the volume of solutions (L); k_1, pseudo-first-order kinetic model rate constant (h^{-1}); k_2, pseudo-second-order kinetic model rate constant (mg g^{-1} h^{-1}); q_e, the amount of P adsorbed onto the periphyton at equilibrium (mg g^{-1}); $q_{e,cal}$, the amount of P adsorbed onto the periphyton calculated by model at equilibrium (mg g^{-1}); q_m, the maximum adsorption capacity for the periphyton (mg g^{-1}); q_t, the amount of P adsorbed onto the periphyton at time t (mg g^{-1}); C_0, initial P concentration (mg L^{-1}); K_{id}, intraparticle rate constant (mg g^{-1} $h^{-0.5}$); P_i, inorganic phosphorus (mg L^{-1}); P_o, organic phosphorus (mg L^{-1}); TP, the total phosphorus content (mg L^{-1}); R^2, linear regression coefficient; ANSW, artificial non-point source wastewater; ATP, disodium adenosine triphosphate ($C_{10}H_{14}O_{13}N_5P_3Na_2 \cdot 3H_2O$); DW, dry weight of the periphyton (g); EPS, extracellular polymeric substance of the periphyton; PDW, pure distilled water.

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Co-precipitation
P recovery

P concentration, temperature and light intensity. This study not only deepens the understanding of P biogeochemical process in aquatic ecosystem, but provides a potential biomaterial for combining phosphorous removal and recovery from non-point source wastewaters, especially around salt-soil zone.

1. Introduction

Input of excessive phosphorus (P) from non-point source wastewater is an important cause for eutrophication of surface water bodies, such as lakes, rivers, reservoirs etc., and thus pose many environmental, economic and social problems (Chen et al., 2015; Schindler et al., 2008; Smith & Schindler, 2009). As a result, many technologies are currently in place to remove excess P from wastewaters, among them biological methods using phototrophic periphyton is a subject of great concern (Boelee et al., 2011; Guzzon et al., 2008; Roeselers et al., 2008; Shi et al., 2007; Sukačová et al., 2015).

Commonly, phototrophic periphyton is coated in the surfaces of the substrates (such as sediments, cobbles, macrophytes and woody debris) of an aquatic system (Davey & O'toole, 2000), it can be described as the surface attached microbial communities which is driven by light energy with a photosynthetic component (Roeselers et al., 2008). It is composed of multilayered consortia of photoautotrophs (e.g., unicellular and filamentous cyanobacteria, benthic diatoms and green microalgae) and heterotrophs (bacteria, fungi and protozoa) and is also dominated by more photoautotrophic microorganisms (Guzzon et al., 2008). The layers are embedded in a common extracellular polymeric substance (EPS), secreted by the community, that mediates the adhesion of photo and heterotrophs (Donlan, 2002; Sutherland, 2001). These communities are ubiquitous in most aquatic environments and plays a significant role in nutrient cycling (Battin et al., 2003) and purification of water ecosystems (Sabater et al., 2002).

Previous studies have identified key roles of periphyton in removing P in natural systems and thus periphytons acted as an important sink for P (Drake et al., 2012; McCormick et al., 2006). Comparing with traditional suspended algae (mixed or monocultures) wastewater purification systems, the major advantage of periphyton–based measure is that the system can avoid separation of suspended algal biomass and water, in addition to that nutritious compounds can be retained in algal biomass which further can be harvested and used as fertilizers in agriculture (Schumacher & Sekoulov, 2002). As a result, periphyton-based methods were applied to remove P from wastewaters and subsequently acquired a favorable effect in removing P from wastewaters (Boelee et al., 2011; Cao et al., 2016; Guzzon et al., 2008; Jöbgen et al., 2004; Posadas et al., 2013; Sukačová et al., 2015; Zamalloa et al., 2012).

Wu reviewed that the mechanisms might be responsible for contaminant removal included uptake, adsorption and biodegradation (Wu et al., 2014). However, the detailed removal mechanism of P, especially of P_o, in the presence of phototrophic periphyton is still in dispute. It was reported that periphyton had a high affinity for P hence act as an important storehouse of P (McCormick et al., 2001; Noe et al., 2002). Studies indicated that P concentration ranging between 1.1 to 2.8 mg g^{-1} (dry weight) is optimal for algal growth (Müller, 1983). Zamalloa et al. (2012) used microalgae biofilm to remove P from domestic wastewater and found that about 95% of total P was recovered in the algae biomass. Guzzon et al. (2008) observed that P removal by periphyton was accumulated inside the cells of phototrophs, mainly in the cytoplasm of the green algae. These researchers argued that assimilation was the main removal mechanism of P by periphytons. On the other hand, some studies suggested that the adsorption or co-precipitation of P with metal salts (especially with $CaCO_3$) was the main P removal mechanism (Dodds, 2003; Lu et al., 2014a; Lu et al., 2014b; Scinto & Reddy, 2003). To our knowledge, the quantification of P (especially of organic phosphorous, P_o) removal mechanism in the presence of phototrophic periphyton was not well studied.

Therefore, the objective of this study was to obtain a mechanistic understanding of P removal in the presence of phototrophic periphytons by: i) determining P_i and P_o removal kinetics under different levels of periphyton content; ii) assessing the influence of various environmental conditions to P_i and P_o removal rates and iii) evaluating the relative magnitude of different mechanisms occurred during the P_i and P_o removal process.

2. Materials and methods

2.1. Phototrophic periphyton culture

Biofilm substrate (diameter 12 cm and length 55 cm, Industrial Soft Carriers, China) was used for in situ collection and growth of phototrophic periphyton in Xuanwu Lake (TN: 1.90 mg L^{-1}, TP: 0.1 mg L^{-1}, pH: 7.8, ammonia: 0.53 mg L^{-1} and nitrate: 0.73 mg L^{-1}), East China. To avoid human interference on periphyton growth, once the biofilms was covered on the substrate surface, the periphyton with their substrates was taken to the indoor culture. The indoor culture of the periphyton was conducted in glass tanks (each tanks are of 100 cm in length, 60 cm in width and 40 cm in height). Firstly, the tanks were sterilized using 95% alcohol solution and rinsed with distilled water. Then, the collected periphyton biofilms along with their substrates were submerged into the glass tanks filled with nutrients medium solution [composed of macro nutrient (such as 20 mg L^{-1} $NaCO_3$, 150 mg L^{-1} $NaNO_3$, 40 mg L^{-1} K_2HPO_4, 75 mg L^{-1} $MgSO_4 \cdot 7H_2O$, 36 mg L^{-1} $CaCl_2 \cdot 2H_2O$) and micro nutrient (such as 2.86 mg L^{-1} H_3BO_4, 1.81 mg L^{-1} $MnCl_2 \cdot 4H_2O$, 0.22 mg L^{-1} $ZnSO_4$, 0.39 mg L^{-1} Na_2MoO_4, 0.079 mg L^{-1} $CuSO_4 \cdot 5H_2O$, 4.94 mg L^{-1} $Co(NO_3)_2 \cdot 6H_2O$) as well as organic matters (6 mg L^{-1} citric acid and ammonium ferric citrate). To reduce the influence of extreme climatic condition on the growth of periphyton, the glass tanks were kept in a greenhouse with air temperature kept at 25–30 °C. When dense periphyton biofilm was formed (i.e., when the thickness of periphyton biofilms exceeded 5 mm) it was regarded as matured and collected for the following experiments.

2.2. P removal by the periphyton

Two species of P (P_i and P_o) were studied in this work. P_i stock solutions (100 mg L^{-1}) were prepared by dissolving 0.4387 g K_2HPO_4 into 1 L distilled water. Previous studies found that ATP was an effective substrate for tracing P_o dynamics in phytoplankton and periphyton (Bentzen et al., 1992; Scinto & Reddy, 2003). Thus, P_o stock solution (100 mg L^{-1}) was prepared by dissolving 0.6505 g ATP (disodium adenosine triphosphate, $C_{10}H_{14}O_{13}N_5P_3Na_2 \cdot 3H_2O$, sigma) into 1 L distilled water. All P concentrations used in the experiments were diluted from stock solutions.

The periphyton was gently peeled off by hand and placed into 0.25-L flasks under initial P (inorganic and organic) content of about 13 mg L^{-1}, which was prepared with pure distilled water (PDW) and artificial non-point source wastewater (ANSW) that mainly composed of nutrient pollutants (1.5 g L^{-1} $NaNO_3$, 0.02 g L^{-1} $NaCO_3$, 0.06 g L^{-1} K_2HPO_4, 0.036 g L^{-1} $MgSO_4 \cdot 7H_2O$, 0.075 g L^{-1} $CaCl_2 \cdot 2H_2O$, 0.001 g L^{-1} $ZnSO_4$, 0.001 g L^{-1} $CuSO_4 \cdot 5H_2O$ and 0.006 g L^{-1} $C_6H_{10}FeNO_8$).

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