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Role of algal biofilm in improving the performance of free surface, up-flow constructed wetland

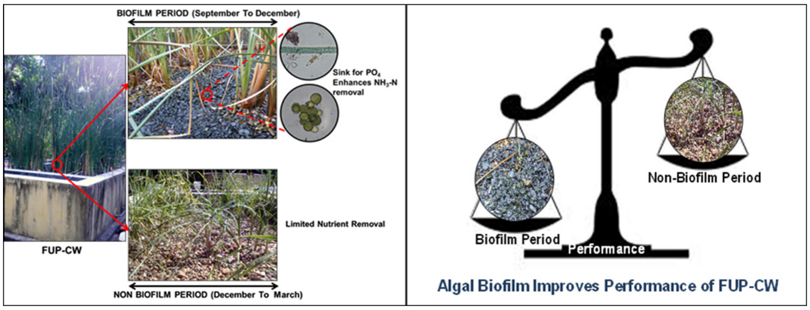
Neha Badhe, Shaswati Saha, Rima Biswas *, Tapas Nandy

CSIR-National Environmental Engineering Research Institute, Nagpur, Maharashtra 440020, India

HIGHLIGHTS

- First-ever-study reporting role of algal biofilm in enhancing performance of CW.
- The biofilm enhanced pollutant removal was in the order of phosphates > ammonia > COD.
- Biofilm significantly improved phosphate removal.
- Ammonia removal improved in presence of biofilm, higher temperature and longer HRT.
- COD removal during winter season was compensated by biofilm.

GRAPHICAL ABSTRACT



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ABSTRACT

The role of algal biofilm in a pilot-scale, free-surface, up-flow constructed wetland (CW), was studied for its effect on chemical oxygen demand (COD), ammonia and phosphate removal during three seasons-autumn, winter and early spring. Effect of hydraulic retention time (HRT) was also investigated in presence and absence of algal biofilm. Principal Component Analysis was used to identify the independent factors governing the performance of CW. The study showed algal biofilm significantly improved nutrient removal, especially phosphate. Ammonia removal varied with HRT, biofilm and ambient temperature. Increase in biofilm thickness affected ammonia removal efficiency adversely. Algal biofilm-assisted COD removal compensated for reduced macrophyte density during winter. Two-way ANOVA test and the coefficients of dependent factors derived through multiple linear regression model confirmed role of algal biofilm in improving nutrient removal in CW. The study suggests that algal biofilm can be a green solution for bio-augmenting COD and nutrient removal in CW.

1. Introduction

Constructed wetlands are low-maintenance, ecologically-engineered and self-adaptive treatment process and have high application potential for treating various kinds of domestic, agricultural, industrial wastewaters, acid mine drainage and even landfill leachates (Ghosh and Gopal 2010; Konnerup et al., 2009; Saeed and Sun 2012; Zhao et al., 2010). This treatment process has been implemented with success in Europe, America, Australia, and New Zealand (Meng et al., 2014; Prochaska et al., 2007). CW can be classified by the type of plants (free floating, rooted, emergent and submerged systems) or by the type of flow (horizontal or vertical) (Stefanakis and Tsihrintzis, 2012). The vertical flow constructed wetland systems (VFCW) became very popular in Europe due to their enhanced ability to oxidize ammonia nitrogen (Vymazal, 2011; Zhao et al. 2010).

Despite of various advantages, constructed wetlands have struggled to obtain good removal of nutrients, such as nitrogen and phosphates (Brix et al., 2001; Vymazal et al., 1998). Nitrogen

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* Corresponding author. Tel.: +91 712 2249886 (341); fax: +91 712 2249900.
E-mail address: ra_biswas@neeri.res.in (R. Biswas).

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removal mechanisms in wetland are primarily due to microbial transformations in the root zone, uptake by plant and other living organisms, volatilization of ammonia and cation exchange of ammonia (Brix, 1994). Typical nitrogen removal rates observed in long term operations of CW in Europe is only up to 35%, or up to 50% following modifications to stimulate transformation of nitrogen (Hu et al., 2012; Tang et al., 2009; Verhoeven and Meuleman, 1999). Higher nitrogen removal efficiency has been demonstrated in CW with continuous and intermittent artificial aeration (Fan et al., 2013; Tao et al., 2010). Phosphate removals have been typically reported between 20% and 30% in wetlands (Zhao et al., 2010). In most constructed wetlands, phosphate removals do not exceed more than 50% (Verhoeven and Meuleman, 1999). Phosphate removal in wetlands is associated with filter properties of the filter media rather than biological mechanisms. Filtration, adsorption and chemical precipitation of phosphates in the filter media are the major routes of phosphate removal (Vymazal 2010; Vymazal et al., 2000). Hence the most sustainable removal process for phosphorus is permanent retention of phosphate through binding to the filter bed (Lantzke et al., 1998). Medium with high phosphorus binding capacity such as shale, calcite, zeolite, bauxite, carbonate materials etc., have been widely studied in CW so that adsorbed phosphorus could be retained for few years without the need of replacing the media (Stefanakis and Tsihrintzis, 2012; Tang et al., 2009; Arias et al., 2003; Brix et al., 2001). Arias et al. (2003) has demonstrated the use of exchangeable filter units in CW to enhance phosphorus removals. Biofilm carriers like polypropylene pellets to enhance biological transformation of nitrogen and phosphorus have also been studied in CW (Tang et al., 2009).

Nutrient removal in CW can also be mediated by biological route. Algae are known to take-up ammonia and phosphate for their growth. Recently, studies have focussed on the potential activity of algal biofilm for nutrient and heavy metal bioremediation from wastewater. Improving treatment efficiency in waste stabilization ponds with algal biofilm has attracted research attention. Babu (2011) improved nitrification rate in waste stabilization ponds by introducing baffles with algal biofilm. Baffles improved the population of autotrophic nitrifiers in the attached algal biofilm. The slime formed from algal growth also loosely bound phosphorus and acted as a good biological sink for phosphorus (Babu, 2011). Another mechanism is luxury uptake of phosphorus by bacteria. Luxury uptake is the storage of phosphorus within the biomass in the form of polyphosphate. Polyphosphate can be present as acid-soluble or acid-insoluble form. Acid-soluble polyphosphate is actively involved in metabolism, while acid-insoluble polyphosphate is stored within the bacteria cells for use when the external phosphate concentration becomes limiting (Powell et al., 2008).

So far, role of algal cells in nutrient uptake has been studied mostly in the context of eutrophication of water bodies, wastewater treatment in polishing lagoons and in waste stabilization ponds. Role of algal slime as potential nutrient sink in constructed wetland has been never explored. One reason for such lack of studies could be due to the fact that algal slime bio-layer cannot be developed on the dry surface of a subsurface flow constructed wetland (SSCW). SSCWs are generally preferred over the free-surface flow constructed wetlands (FSCW) due to aesthetic reasons. In this study, the constructed wetland was operated in such a way that, the water level was maintained just over the surface of filter bed allowing formation of algal slime on the filter bed. In this manuscript, a proof of the concept study on impact of algal biofilm on treatment efficiency of urban sewage in a pilot-scale CW with respect to COD, ammonia–nitrogen and phosphate–phosphorus removal is reported.

2. Methods

2.1. Pilot scale unit

A pilot scale, free-surface, up-flow, constructed wetland (FUP-CW) with an effective volume of 4.6 m^3 was packed with gravels as filter medium and planted with emergent macrophyte, *Typha latifolia* (Fig. 1). Urban sewage was collected from a sewage carrying canal. The settleable solids in the sewage, was initially allowed to settle in a sedimentation tank and the supernatant was then pumped into the inlet tank of the FUP-CW at a controlled flow rate. The flow rate of the sewage pumped into FUP-CW was controlled through a peristaltic pump (Masterflex console drive, model number 77200-62). From a slit present at the bottom of the inlet tank, the effluent entered into the mesocosm and reached the surface of filter media in an up-flow mode. The treated effluent flowed out through an outlet pipe on the other end of mesocosm and was collected into the outlet collection tank. The height of the outlet pipe was 1 cm above the surface of the filter media. This small height difference between the outlet pipe and filter media allowed the filter media to be just immersed under a liquid layer of approximately <1 cm thickness. The pre-settled urban sewage had the characteristics in the range: pH 6.7–7.4, COD 140–450 mg/L, total nitrogen (TN) 25–36 mg/L, ammonia–nitrogen (NH_4–N) 4.5–16 mg/L, total phosphate (TP) 5–30 mg/L, soluble phosphate–phosphorus (PO_4–P) 3–15.5 mg/L, total suspended solids (SS)130–370 mg/L and fecal coliform 35×10^4–90×10^4 CFU/100 mL.

2.2. Experimental method

The up-flow constructed wetland was operated for a period of two years. The observations were recorded from two sets of experimental studies conducted between September 2012 to March 2013 and September 2013 to March 2014, covering three seasons, namely, autumn (September–November), winter (December–February) and early spring (March). The selection of experimental period during the same time of the year was done to eliminate the variability arising due to seasonal change. The values interpreted included the standard deviation from two sets of observations. During the study period, the average temperature was 24 °C and average weekly rainfall received during September to October was 37 mm.

Algal biofilm formation was allowed to develop on the surface of wetland during the month of August. The effect of biofilm on the performance of FUP-CW was studied between September to mid-December and this period was designated as the biofilm period. The biofilm was washed off manually after mid-December. Thereafter the top-layer gravels of the filter media that were exposed to sunlight were regularly washed to prevent algal growth till the end of the study period, i.e. 31st March. The period between mid-December to end of March was designated as the non-biofilm period.

The performance of FUP-CW was tested at two HRTs, 1.5 d and 2.5 d; both during the biofilm (September to mid-December) and the non-biofilm period (mid-December to March). The influent loading rate used in the study ranged from 20 to 60 g COD m^{-2} d^{-1} and hydraulic loading rate was in the range 0.2–0.4 m d^{-1}.

2.3. Analytical methods

Wastewater samples were analysed for pH, chemical oxygen demand (COD), dissolved oxygen (DO), water temperature, ammonia–nitrogen (NH_4–N), nitrate–nitrogen (NO_3–N), total nitrogen (TN), total phosphorus (TP), and soluble phosphorus (SP).