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Research article

High-rate algal pond coupled with a matrix of *Spirogyra* sp. for treatment of rural streams with nutrient pollution

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ABSTRACT

This study evaluated the unique features of a filamentous algae matrix (FAM) that can be applied to high rate algal ponds (HRAPs) as a promising way to remove nutrient from polluted rural streams. The results show that the HRAPs, coupled with the FAM, effectively removed nitrogen and phosphorus (79.8% and 81.2%, respectively), and achieved high production of DO, with a maximum of 11.0 g O_2 g FAM^{-1} d^{-1}. The FAM functioned wells as a screen to prevent excessive algae loss from the system and obtained relatively high biomass growth rate (0.032 mg L^{-1} d^{-1} for nitrogen and 0.344 mg L^{-1} d^{-1} for phosphorus). The harvested FAM was a useful fertilizer and the rate of addition of FAM were 1.52 kg d^{-1} ha^{-1} of nitrogen and 0.44 kg d^{-1} ha^{-1} of phosphorus. Thus, combining the HRAP with the FAM was an effective nutrient removal and resource utilization system for rural streams.

1. Introduction

Since the 1950s, high rate algal ponds (HRAPs) have been widely used to treat wastewater and recover resources (Sutherland et al., 2014b). It is highly likely that nutrient from non-point source (NPS) pollutants would flow into small rural streams. Thus, the increased pressure to reduce such nutrient loading from NPS discharge streams has resulted in a renewed interest in improving the performance of HRAPs for domestic and agricultural wastewater treatment. Direct cleaning of contaminated rural streams using natural treatment processes is being actively researched (García et al., 2000; Sutherland et al., 2014a). These natural treatment processes were developed recently using autotrophic organisms that utilize carbon dioxide instead of organic carbon as a carbon source (Park and Craggs, 2010).

One of the main objectives of HRAPs is to prevent algal washout under natural conditions of water bodies in the short term, using algae that can be cultured easily. The final effluent concentration of suspended solids (SS) can increase due to algae loss, which influences the taste and odor of the water. Algae cultivation has been identified as a useful technique for wastewater treatment as it is sufficiently efficient at preventing secondary contamination. The hydraulic retention time (HRT) is considered an operating condition that determines both the amount of nutrient loading and the effluent water quality (García et al., 2000). In general, longer HRTs are favored to ensure sufficient nutrient removal and to conform to discharge consent conditions during the winter, or minimum growth, periods. However, when wastewater treatment is considered along with resource recovery, shorter HRTs are regarded as more desirable to achieve higher microalgal productivity during the summer, or maximum growth, periods (Park and Craggs, 2010). Pond depth and biomass concentration affect the degree of light absorption and photosynthesis, which determines the uptake of nutrient and the biomass productivity (Grobbelaar, 2010). Light absorption and photosynthesis are also influenced by many factors, including physical, chemical, and biological factors such as light intensity, turbulence, pH, salinity, species diversity and viral infections (Grobbelaar, 2000; Larsdotter, 2006).

Species of the chlorophyte alga *Spirogyra* are characteristically haplobiontic haploid and form new filaments by fragmentation and by germination of zygospores. The growth of *Spirogyra* sp. is

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considerably affected by environmental conditions, particularly temperature (Kuo, 1991; Gupta and Rastogi, 2008; Khalaf, 2008; Khataee et al., 2013). There are over 275 known species of *Spirogyra*; their silky masses rest at the bottom and float on the surface of water bodies. The optimum growth temperature of this genus ranges between 15 and 30 °C. Species of *Spirogyra* have been found in polluted water bodies and in closed filter or screen facilities in water supply and wastewater systems, and can cause problems such as slime production in water supplies. As *Spirogyra* sp. is frequently washed out and causes deterioration of effluent quality, it has not been used to remove nutrient by most previous studies.

The purpose of the current study was to evaluate the applicability of HRAPs using a filamentous algae matrix (FAM) comprising *Spirogyra* sp. to purify contaminated rural streams. Therefore, comprehensive studies on the characteristics, including photosynthesis, DO production, and specific growth rate, of the FAM were conducted.

2. Materials and methods

2.1. Wastewater characteristics and weather conditions

Influent wastewater was supplied from small polluted rural streams to the test ponds located at the Rural Research Institute, Ansan-si, Gyeonggi-do, Korea. The operational conditions and used wastewater characteristics are presented in Table 1; it is notable that the nutrient concentrations were low for rural streams. Therefore, the influent concentrations of nutrient were controlled artificially by adding NH_4Cl for total nitrogen (TN) and K_2HPO_4 for total phosphorus (TP), in order to adjust the concentration of nitrogen and phosphorus according to our testing parameters.

The experiment was carried out outdoors. The temperature ranged between 6 and 33 °C for the entire experimental period and did not vary significantly between day and night owing to the tropical night phenomenon that occurs during summer from June to August. The HRAPs were located near the shore, where wind and atmospheric conditions are favorable for FAM cultivation, with an average humidity of 55%, average wind speed of 1.8 m s^{-1}, and average wind direction of 196.5 SSW.

2.2. Schematic diagram of HRAPs and details of system operation

The experiment was carried out in a pilot-scale plant (Fig. 1). The storage tank (ST) had a volume of 8 m^3, length (L) of 4 m, width (W) of 2 m and height (H) of 1 m. The HRAPs consisted of two basins with a total volume of 12 m^3, L of 10 m, W of 2 m, and H of 0.6 m. A baffle was set to regulate the plug flow, and each basin was separated into five compartments, each with L = 1 m, W = 2 m, and H = 0.6 m, for a total number of compartments of 10(Ci = C1, C2,.., C10). The depth of the HRAPs structure was 0.6 m in total, but the actual depth of the pond was 0.3 m. The algae in the pond were selectively dominated by *Spirogyra* sp. that had adhered to and grown on the surface of the sand from an artificial pond located nearby and that had been seeded in the HRAPs, forming the FAM. The duration of the experiment was 210 days, the first 60 days of which were for algal cultivation.

Table 1
Operational conditions in the HRAPs and wastewater characteristics during the 150 days of wastewater treatment.

Parameters	Values[a]
Flow rate (L d^{-1})	910-1110 (1010)
Depth (mm)	300
HRT (days)	4
DO (mg L^{-1})	3.4–6.5 (4.7)
SCOD (mg L^{-1})	3.2–15.1 (8.5)
SS (mg L^{-1})	16.3–30.7 (22.7)
Chl-*a* (mg m^{-3})	1212–2500 (1625)
Conductivity (μs cm^{-1})	1320–2021 (1670)
VLR (g m^{-3} d^{-1})	
TCOD	1.25–5.16 (2.70)
TN	2.41–3.33 (2.85)
TP	0.22–0.42 (0.31)

Acronyms: HRT (hydraulic retention time); DO (dissolved oxygen); SCOD (soluble chemical oxygen demand); SS (suspended solids); Chl-*a* (Chlorophyll *a*); VLR (volumetric loading rate); TCOD (total chemical oxygen demand); TN (total nitrogen); TP (total phosphorus).

[a] Data in parentheses are averages.

One of the remarkable characteristics of HRAPs is their ability to maintain high algal photosynthetic activity (Borowitzka and Moheimani, 2013). To achieve this, the pond depth was kept at 300 mm (including a 50 mm sand bed) to facilitate sunlight transmission to the algae (Borowitzka, 2005). The 50 mm sand bed was laid at the bottom of the pond for microbial culture. The ST was covered with a lid to maintain constant wastewater composition by preventing growth of algae and dilution with rainfall.

2.3. Algae performance

2.3.1. Specific growth rate of algae

The specific growth rate of the algae was calculated according to the following equation (Eq. (1)):

$$\left(\frac{dX}{dt}\right) = \mathrm{K}\cdot\mathrm{S}\cdot S_m \tag{1}$$

where X_t is the chlorophyll *a* (Chl-*a*) residual concentration at time *t* in μg L^{-1}, K is the specific growth rate of algae in mg L^{-1} d^{-1}, *S* is the concentration of nitrogen or phosphorus influent in mg L^{-1}, S_m is the average nitrogen or phosphorus concentration for the reaction at time *t* in mg L^{-1}, and X_0 is the initial Chl-*a* concentration at time t_o in μg L^{-1} (Reynolds, 1995).

2.3.2. Specific rate of nutrient removal

The specific rate of nutrient removal (O'Brien, 1981) was estimated from Eqs. (1) and (2):

$$-\left(\frac{1}{X_m}\right)\cdot\left(\frac{dS}{dt}\right) = K_2\cdot S_o \tag{2}$$

where X_m is the average Chl-*a* concentration in μg L^{-1}, K_2 is the specific rate of nitrogen removal in mg L^{-1} d^{-1}, S_0 is the sum of NH_4^+-N and NO_3^--N concentration at time t_o in mg L^{-1}, and *t* is the reaction time in one day.

$$K_3 = -\ln\left(\frac{P_t}{P_o}\right)\Big/(X_m\cdot t) \tag{3}$$

where K_3 is the specific rate of phosphorus removal in mg L^{-1} d^{-1}, P_t is the PO_4^--P concentration at time *t* in mg L^{-1}, P_0 is the influent PO_4^--P concentration in mg L^{-1}, X_m is the average Chl-*a* concentration in mg L^{-1}, and *t* is the reaction time in one day.

2.4. Microscopic images

Microalgae species were identified and cell wall integrity was assessed using an optical microscope (Aixoplan Zeiss, Germany) equipped with an MRc5 camera, using Axioplan LE software. The microalgae were identified based on the traditional literature (Bourrelly, 1966; Komarek and Fott, 1983).