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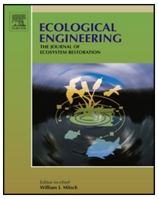

Hydrodynamic regime considerations for the cultivation of periphytic biofilms in two tertiary wastewater treatment systems

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ABSTRACT

As the demand for biofuel products continues to rise along with the need for tertiary wastewater treatment processes to facilitate the removal of phosphorus, increasing importance is placed on the design of cultivation systems for the production of algal biomass. In addition to traditional open ponds and photobioreactors, attached algal growth systems can provide high rates of biomass production while simultaneously removing nutrients from wastewater effluent. The potential economic viability of these attached growth systems is dependent on the optimization of bed flow characteristics, inflow water quality parameters, and hydrodynamic regimes in order to maximize biomass productivity. This study monitored the productivity and nutrient removal rates of a pilot-scale attached growth system (AGS1) used to remove phosphorus from wastewater effluent at a municipal wastewater treatment plant in Fayetteville, Arkansas. These results were compared with the results from a similar system in the same watershed that was monitored in a previous study (AGS2). The performance of AGS2 was documented in a companion article in *Ecological Engineering*. In spite of the similarities between the systems' locations and influent characteristics, the productivities of the two systems were very different. The rates of biomass production in AGS1 and AGS2 were 4.4 ± 4.8 and 26.7 ± 16.0 g dry weight m^{-2} d^{-1}, respectively. Potential reasons for the dramatic differences in performance between the two systems are explored in this article.

1. Introduction

The ecological services provided by algal growth systems are combined with the potential economic value of algal biomass for a number of industrial applications. For example, the potential for high lipid contents in algal cells, in addition to productivities that are superior to other bioenergy crops, makes algae a promising feedstock for biofuel production (Chisti, 2007; Dismukes et al., 2008; Bajpai and Tyagi, 2006; Hu et al., 2008). In their 2008 study, Dismukes et al. noted that biomass cultivation from aquatic phototrophs would require only a fraction of the amount of land that would be required for the cultivation of corn in order to displace gasoline consumption in the United States. In addition, algal growth systems have also been shown to effectively treat wastewater while generating large amounts of biomass (Adey et al., 1993, 2011, 2013; Craggs, 2001). The United States Department of Energy's Aquatic Species Program's study of the potential biofuel feedstock applications of algae concluded that systems which coupled wastewater treatment with algal biomass production were the most compelling in terms of economic value (Mulbry et al., 2008).

There are several types of artificial growth systems that have been investigated for the industrial-scale production of algae. These include photobioreactors, open ponds, and attached growth systems (Eriksen, 2008; Ugwu et al., 2007; Lee, 2001). While enclosed bioreactors and open pond or raceway systems constitute a more traditional approach to algae cultivation, they are generally used

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Abbreviations: ATS, algal turf scrubber; TP, total phosphorus; TSS, total suspended solids.

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for the monoculture of microalgae. Attached growth systems allow for the cultivation of macroalgae in a mixed assemblage (Adey et al., 2013; Sandefur et al., 2011). Macroalgae, with its relatively high sugar content, is potentially desirable for the production of bioethanol and butanol (Jones and Mayfield, 2012; Cai et al., 2013). In addition, attached growth systems, which involve the cultivation of a polyculture, do not require the expensive environmental controls found in enclosed systems (Sandefur et al., 2011).

Attached growth systems are designed to simulate a stream environment for the production of periphytic biofilms (Johnson and Wen, 2010; Hoffman, 1998). These oxygenic phototrophic films are composed of microbial communities that are attached to a growth surface. Microorganisms present in the periphytic assemblages include cyanobacteria, benthic diatoms, and green algae (Roeselers et al., 2008). These organisms use carbon dioxide to assimilate nutrients in biomass production. The photosynthetic activity in biofilm growth systems shifts the equilibrium of carbon dioxide in the water, resulting in higher pH levels that drive phosphate precipitation from the water column (Craggs et al., 1996a, 1996b). The removal of phosphorus by precipitation, in addition to removal via biomass assimilation, can lead to large reductions in the phosphorus concentrations of the irrigation water (Roeselers et al., 2008; Craggs et al., 1996a, 1996b).

Flow rate and nutrient concentrations are generally considered to be the major factors driving biomass production (Blersch et al., 2013; Adey and Loveland, 2007). Growth has been shown to increase with increased velocity in artificial stream systems, and investigations of periphyton growth has suggested that there is a critical flow velocity at which the growth and chlorophyll-a content is maximized (Labiod et al., 2007; Barr et al., 2008; Carpenter et al., 1991; Cronk and Mitsch, 1994). Potential explanations for this phenomenon include altered light regimes and the breakdown of diffusion boundary layers resulting from higher levels of turbulence (Grobbelaar, 2009; Dodds and Biggs, 2002; Blersch et al., 2013). The altered light regimes resulting from turbulence in the water column have been shown to occur at Reynolds numbers in excess of 3000. This intermittent lighting has been shown to increase photosynthetic efficiency in algal cells, and can be driven by turbulence (Grobbelaar, 2009). This is coupled with increased nutrient and metabolite exchange between algal cells and the surrounding environment under more turbulent flow regimes, which can also stimulate productivity (Grobbelaar, 2009; Dodds and Biggs, 2002).

In addition to increasing photosynthetic efficiencies and community metabolism, turbulent flow also has a role in the colonization of biofilms (Labiod et al., 2007). In their investigation of the relationship between flow regime and periphyton dynamics, Labiod et al. (2007) noted that during the initial stage of periphyton accumulation, diatom species tend to dominate. However, after approximately three weeks of growth, the authors observed a selection of benthic algae, followed by chlorophytes and cyanophytes in the film. Finally, after a one-month development period, a periphytic mat composed largely of long filamentous algae species was observed (Labiod et al., 2007). This climax community is the goal of attached growth systems, with the filamentous species acting as a support structure for other organisms and forming the base of a larger community. However, it should be noted that the climax community will vary by season in outdoor systems (Adey, 1982).

While turbulence is important for production and community development in attached growth systems, site constraints can limit the slope and resulting velocity in retrofitted algal flow-ways. This study presents performance data for an attached growth system that used municipal wastewater treatment plant effluent as an irrigation source, and compares the system's performance to that of another attached growth system that was operated in the same watershed. Factors that could have contributed to differences in performance between the two systems, principally hydrodynamic regime and influent nutrient concentrations, are explored.

2. Materials and methods

The first algal growth system (AGS1) consisted of a 30 m long by 3 m wide flow-way, and was located at a municipal wastewater treatment plant in Fayetteville, Arkansas. The plant's treatment processes included screening, clarification, biological water treatment, filtration, and disinfection with UV light. The algal turf received effluent after the UV disinfection step and before the effluent was discharged into the Illinois River (see Fig. 1). The effluent was redirected to the initial sedimentation step after passage over the growth system. The flow-way was lined with outdoor carpet on which the algal community was cultivated. Effluent was discharged onto the flow-way at a rate of 12.5 $\mathrm{L\,s^{-1}}$ from a broad-crested weir located at the top of the system.

Operation began in June of 2010 and continued through July of 2011. During a one-month startup phase, the flow-way was seeded with filamentous green algae from the genus *Cladophora*. The algae used to seed the system were taken from streams within the local watershed. The filaments were attached to stones and placed in the flow-way at 3 m intervals. By July 1, 2010 the algal community was established and data collection began.

The sampling regime involved the monitoring of productivity as well as total phosphorus (TP) removal across the system. The biomass was harvested by scraping the flow-way every 4 to 7 days, depending on the season. The interval between harvests depended on the rate of reestablishment of the biofilm, with the goal being to collect the biomass immediately after the growth peak. It was important to harvest before the end of the accrual phase and the beginning of autogenic sloughing in the loss phase which would decrease the amount of recoverable biomass (Labiod et al., 2007). During each harvest, samples were taken from three 1 $\mathrm{m^2}$ sections roughly at 7.5 m, 15 m, and 22.5 m down the flow-way from the system inflow. The biomass from each sampling section was scraped off of the carpet and onto 1 mm screen for draining. The remainder of the flow-way was also harvested in this manner, and the total weight of the wet biomass was measured. The algae samples from the 1 $\mathrm{m^2}$ sections were dried at 105 °C for 24 h to determine the dry weight of the algae (Greenberg, 1992). Dry weights from the three samples were used to determine an average productivity value on a dry weight basis for each growth period.

The phosphorus concentrations at the system inflow and outlet were monitored from July 2010 through January 2011. The effluent used to irrigate the growth system was sampled daily at 1400 h, and analyzed for TP, total suspended solids (TSS), and ammonia. The laboratory methods for the characterization of the effluent included the colorimetric method for TP, the Nesslerization method for ammonia, and a filtration method for TSS (USEPA, 1971; APHA, 2005a; APHA, 2005b). Grab samples of the effluent entering and exiting the system were collected twice a week and were analyzed for TP (Greenberg, 1992). In addition, multi-parameter water quality monitoring devices (YSI, Inc.) were deployed at the system inflow and outflow to monitor pH, dissolved oxygen, specific conductivity, and water temperature. These instruments recorded values for each parameter at 10 min intervals during three one-week long deployments in the summer and fall. These methods were similar to those used to monitor AGS2, and are described by Sandefur et al. (2011).

The second attached algal growth system (AGS2) was operated in Springdale, Arkansas from March through November of 2009.