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Treatment of dairy manure effluent using freshwater algae: Algal productivity and recovery of manure nutrients using pilot-scale algal turf scrubbers

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ABSTRACT

Cultivating algae on nitrogen (N) and phosphorus (P) in animal manure effluents presents an alternative to the current practice of land application. The objective of this study was to determine values for productivity, nutrient content, and nutrient recovery using filamentous green algae grown in outdoor raceways at different loading rates of raw and anaerobically digested dairy manure effluent. Algal turf scrubber raceways (30 m^2 each) were operated in central Maryland for approximately 270 days each year (roughly April 1–December 31) from 2003 to 2006. Algal biomass was harvested every 4–12 days from the raceways after daily additions of manure effluent corresponding to loading rates of 0.3 to 2.5 g total N (TN) and 0.08 to 0.42 g total P (TP) m^{-2} d^{-1}. Mean algal productivity values increased from approximately 2.5 g DW m^{-2} d^{-1} at the lowest loading rate (0.3 g TN m^{-2} d^{-1}) to 25 g DW m^{-2} d^{-1} at the highest loading rate (2.5 g TN m^{-2} d^{-1}). Mean N and P contents in the dried biomass increased 1.5–2.0-fold with increasing loading rate up to maximums of 7% N and 1% P (dry weight basis). Although variable, algal N and P accounted for roughly 70–90% of input N and P at loading rates below 1 g TN, 0.15 g TP m^{-2} d^{-1}. N and P recovery rates decreased to 50–80% at higher loading rates. There were no significant differences in algal productivity, algal N and P content, or N and P recovery values from raceways with carbon dioxide supplementation compared to values from raceways without added carbon dioxide. Projected annual operational costs are very high on a per animal basis ($780 per cow). However, within the context of reducing nutrient inputs in sensitive watersheds such as the Chesapeake Bay, projected operational costs of $11 per kg N are well below the costs cited for upgrading existing water treatment plants.

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1. Introduction

Water quality in the Chesapeake Bay has declined dramatically in the past 50 years, primarily because of eutrophication (Horton and Eichbaum, 1991; Chesapeake Bay Foundation, 2004). Restoration of the bay poses significant challenges because of increasing population pressure, conversion of farmland to urban/suburban development, and the expense of infrastructure needed to achieve significant and sustained nutrient reductions from agricultural and urban sources (Chesapeake Bay Foundation, 2004). Approximately $19 billion is needed to achieve 2010 bay restoration goals that include nitrogen (N) and phosphorus (P) reductions of 45 million kg $year^{-1}$ and 3 million kg $year^{-1}$, respectively (Chesapeake Bay Commission, 2004). Although agricultural sources are estimated to contribute roughly 40% of the N and P inputs in the 166,000 km^2 watershed, keeping land in agricultural use is important for health of the watershed because agricultural lands generally export less N (17 kg ha^{-1} $year^{-1}$) than land in urban/suburban development (30 kg ha^{-1} $year^{-1}$) (Chesapeake Bay Foundation, 2005). The challenge and opportunity for the agricultural community is to develop and implement technologies that can reduce export of farm nutrients into the watershed while increasing farm profits (Chesapeake Bay Foundation, 2006).

Among agricultural sources of N and P, animal manures (poultry, dairy, beef, and swine) are estimated to contribute 18% of the N and 25% of the P that enter the Chesapeake Bay (Chesapeake Bay Foundation, 2004). An alternative to the current practice of spraying dairy manure effluents on agricultural fields is to grow crops of algae using the effluents and thus convert manure N and P into potentially valuable algal biomass. There is considerable literature on the treatment of raw and anaerobically digested swine manure effluent by immobilized algae (Jimenez-Perez et al., 2004), algal cultures, (Ayala and Bravo, 1984) and suspended algae in high rate pond systems (Costa et al., 2000; Goh, 1986; Olguin et al., 1997, 2001; Olguin, 2003). Algal productivity, nutrient content and nutrient recovery using attached algae with dairy and swine effluents have been studied in laboratory-scale algal turf scrubber

Abbreviations: ATS, algal turf scrubber; TP, total phosphorus; TN, total nitrogen; DW, dry weight.

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(ATS) units (Wilkie and Mulbry, 2002; Kebede-Westhead et al., 2003, 2004, 2006). The objective of this study was to determine comparable values using outdoor pilot-scale ATS raceways and dairy manure effluent.

2. Methods

2.1. Algal turf scrubbers and dairy manure

Algal biomass was produced from four 30 m^2 outdoor pilot-scale ATS raceways (Fig. 1). Two raceways were constructed at a 1% slope and two were constructed at a 2% slope. Each raceway consisted of a 1 × 30 m section of 0.75 mm landfill liner (Gundle Linings Technology, Houston, TX, USA) covered with 6 mm mesh nylon netting (Apex Mills, Inwood, NY, USA), a 3700 L underground concrete sump at the base of the raceway, a tipping trough at the top of the raceway, and a submerged water pump (Zoeller Pump Co., Louisville, KY, USA) in the sump to deliver a flow rate of 93 L min^{-1}. The recirculating effluent consisted of fresh water (untreated well water or chlorinated drinking water) and daily additions of raw or anaerobically digested dairy manure effluent from the USDA's Dairy Research Unit in Beltsville, Maryland, USA. Although rainwater was usually sufficient to replenish water lost to evaporation, additional fresh water was added as needed to maintain an effluent volume of 3500 L. The characteristics of Beltsville dairy manure effluent have been described (Wilkie and Mulbry, 2002). The mean raw manure effluent nutrient values were 1600 mg L^{-1} total N (TN) and 230 mg L^{-1} total P (TP). However, nutrient concentrations in the dairy manure effluent varied more than 4-fold throughout this study, primarily because of seasonal changes in water use in the dairy barns. The carbon content of the manure effluents was not measured routinely, but varied with type of manure. The C/N ratios of raw solid-separated and anaerobically digested dairy manure effluents ranged from 9 to 12 and 4 to 6.5, respectively. Typically, 20–60 L of manure effluent (containing 500–2300 mg L^{-1} TN and 85–300 mg L^{-1} TP) were added every morning to each raceway to achieve loading rates corresponding to 0.3–2.5 g TN and 0.08–0.42 g TP m^{-2} d^{-1}. In the spring of 2004, experiments were conducted to determine the effect of carbon dioxide supplementation on algal productivity and nutrient recovery using raw dairy manure. In these experiments, raceway effluent pH was maintained between 7.0 and 7.5 on one of two raceways using a pH controller to regulate the flow of carbon dioxide into the effluent sump (addition of carbon dioxide lowered effluent pH). The other raceway did not receive carbon dioxide. In the summer of 2006, experiments were conducted to qualitatively test the effect of minimizing rapid water temperature increases during the summer months on algal growth. During this period, raceway effluent temperature was maintained below 32 °C using temperature controllers to regulate inflow of untreated well water (15–20 °C) into the effluent sumps. Since this treatment also diluted the raceway effluents, the loading rates reported during this period (June–July 2006) are overestimates. Grazer populations of chironomid larvae were controlled by adding Bacillus

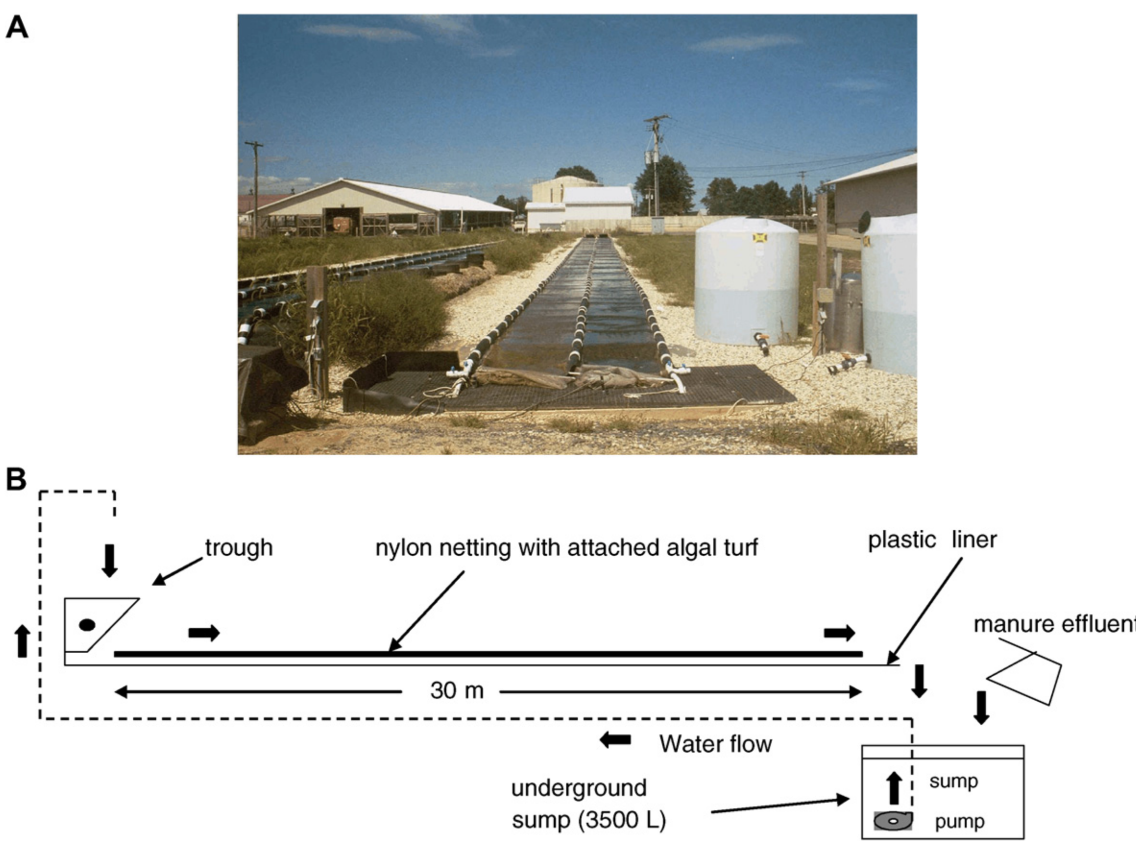

Fig. 1. Photograph (panel A) and schematic drawing (panel B) of pilot-scale raceways at the Dairy Research Unit in Beltsville, Maryland. Each raceway is 1 m in width, 30 m in length, and has a water depth of 1–3 cm. Two raceways (left of center in panel A) were constructed at a 1% slope and two raceways (center in panel A) were constructed at a 2% slope. Raceway effluents (approximately 3500 L for each raceway) are contained in four separate underground concrete tanks covered by plastic grating (foreground in panel A) and are continuously recycled from the sumps to the top of the raceways using four separate sump pumps at a flow rate of 93 L min^{-1}. A trough at the top of each raceway fills and tips over, releasing pulses of effluent that wash over the attached algal turf every 8–15 s before draining into the concrete sump at the base of the raceway. Raw or anaerobically digested dairy manure effluent (20–60 L d^{-1}) is added daily to the recirculating scrubber effluent of each raceway. Water from adjacent storage tanks is added only when rainwater is inadequate to replenish water lost to evaporation.