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Research paper

Integrating a tidal flow wetland with sweet sorghum for the treatment of swine wastewater and biomass production

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ABSTRACT

Swine wastewater treatment and reuse has become a large challenge due to the growth of confined farms in China. Current treatment approaches either fail to control and quantify pollution in soil and water, such as in land applications, or lack productivity, such as in constructed wetlands. To explore the possibility of simultaneous treatment and reuse of wastewater to yield biomass and energy, we integrated sweet sorghum [*Sorghum bicolor* (L.) Moench] in pilot scale tidal flow wetlands to examine the effects of retention/interval frequency, batch loading rate, and influent concentration on nutrients removal, biomass production and energy yield. The results showed that a total of 80 L/m^2 per load and 2 days of retention with 1 day of draining was the maxim load to achieve an optimal biomass production of 10.50 kg/m^2 and a NH_4^+-N removal of 95.43 ± 4.54%. Various retention/interval patterns and batch loads at the same hydraulic loading rate showed a spectrum of removal effects and biomass yields. Sweet sorghum grew well around an influent NH_4^+-N concentration of 110 mg/L. A heavy batch load of 120 L/m^2, even with a low hydraulic loading rate, decreased biomass production and the removal rate. Higher heating value was not affected by different wastewater application scenarios. Adding wetland cells to the series was not suggested because they enhanced total nitrogen and NH_4^+-N removal, but not phosphorus and COD removal, and produced a lower total biomass with twice land requirement. A rapid growth period of approximately 35 days with top removal at the boot stage was proposed to achieve increased removal rate and higher biomass yield. The uptake of nitrogen by sweet sorghum greatly increased under a luxurious nitrogen supply. Change of nitrogen content and phosphorus content in soil was not predicted by loading rate.

1. Introduction

The proliferation of confined animal farms has resulted in a large quantity of wastewater. The wastewater usually contains not only nutrients, such as nitrogen and phosphorus, but also harmful components, such as antibiotics and heavy metals (Do Amaral et al., 2014; Tao et al., 2014). The industrial treatment of animal wastewater is usually not economically feasible. The direct discharge of wastewater has led to serious pollution of the land and water and even crop products (Zicari et al., 2013; Larson, 2015). Confined animal farms are challenged or even closed due to insufficient treatment of wastewater. On the other hand, industrial agriculture are mining aquifers far more quickly than they can be replenished (Gordon et al., 2008). The high use of fossil fuels (Lynch et al., 2011) and chemical fertilizers led to serious environmental risk (Zhu and Chen, 2002). An integrative and cost-effective approach to treat and reuse the wastewater must be explored to build a sustainable system linking animal raising, crop farming and/or bioenergy production.

Liquid slurry/wastewater is directly spread over the field in most countries as the main treatment approach. Land application of wastewater can increase the production of biomass and may change the soil properties (Campi et al., 2014; Molari et al., 2014). It has also been proven to be an alternative water source (Medeiros et al., 2011; Xiao et al., 2013). However, land application of animal farm wastewater introduces pathogens, antibiotics, and heavy metals into fields, which increases the risk of product, soil, and ground water contamination (Ma et al., 2013; Brooks et al., 2014; Kessler et al., 2014; Tao et al., 2014; Adhikari et al., 2015). In addition, it is unclear how the different land application scenarios influence the biomass production and removal of nutrients. Therefore, a quanti-

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tative management and environmental proof approach should be established to guarantee the safe treatment of wastewater and the economic benefit of the treatment.

Constructed wetlands have become a popular low cost approach to treat animal wastewater (Cronk, 1996). However, most reported wetlands focus on the treatment function without examining the productivity of plants (Kadlec and Wallace, 2008). In China, many animal facilities are surrounded by high-quality fields that are leased by different households. It is difficult and not economically feasible for animal facility owners to control these fields to construct large wetlands without an economic benefit. Therefore, a novel approach targeting both an economic benefit and treatment function is strongly encouraged for the sustainable management of animal farm wastewater in China.

Some herbaceous plants were proved to yield higher biomass and bioenergy using wastewater irrigation (Molari et al., 2014). Sweet sorghum (Sorghum bicolor (L.) Moench) is a C4 plant capable of both high biomass and sugar yields (Amaducci et al., 2004; Zhao et al., 2009). It stores readily fermentable sugars in the stalk that can be converted to liquid fuels and bio-based products. It is an annual crop that is readily established from seed. It can regrow following harvest where the climate is favorable (Erickson et al., 2012). Sweet sorghum has the ability to maintain high yields under a wide range of environmental conditions, from limited fertilization and water supply to sufficient nutrients or superfluous water supply, which makes it an ideal plant to treat wastewater and produce fodder and bioenergy (Wight et al., 2012; Ceotto et al., 2014). Irrigation with wastewater not only significantly conserves fresh water, but also increases the biomass yield of sweet sorghum (Rocateli et al., 2012; Sakellariou-Makrantonaki et al., 2012; Zema et al., 2012; Enciso et al., 2015). However, the relationship between the nutrient uptake, yield and water use of sweet sorghum is not well understood (Adams et al., 2015). Moreover, whether sweet sorghum can survive under wetland conditions has not been previously reported. Therefore, a quantitative assessment of the responses of sweet sorghum to the main nutrients and wastewater supply is crucial to achieve the goals of both the production of biomass and treatment of wastewater.

In this study, we introduced sweet sorghum to wetlands with different designs to simultaneously examine biomass production, energy yield and wastewater treatment. Pilot scale vertical tidal flow wetlands were established to examine the parameters for the quantitative management of a sweet sorghum wetland. The results are practical references for adopting the new approach to treat animal farm wastewater and biomass production.

2. Experimental design

2.1. Experimental design and site

Two types of wetlands were designed in the experiment (Fig. 1). The letters A, B, and C denote vertical tidal flow (flood-drain) systems, which included 3 tanks in a row respectively, with flow according to gravity in each treatment. F represents a field-like one tank tidal flow system. The key parameters of each treatment are shown in Table 1. Treatment A included 2 cycles. Cycle 1 was started by the influent being pumped into A1, where it remained for one day and then flowed out through connected pipes to A2, where it remained for one day and then flowed out through connected pipes to A3 and finished. The effluent from A3 was manually poured into A1 again for a second cycle that had the same flow pattern as cycle 1. Cycle 1 and cycle 2 completed one batch in treatment A. Each batch followed the same pattern until the experiment was finished. For treatment B, the influent entered B1 and flowed through B3. Each mesocosm experienced 2 days of flooding and 1 day of draining. Treatment C followed the same pattern as treatment B, but with only half of the volume of wastewater loading. To ensure that enough water was available for use, C was supplied with 7.5 L of tap water in each batch. Therefore, the difference between B and C was the concentration of the influent. At the end of July, extreme high temperatures and dry weather resulted in a very dry substrate. Thus, starting from August 6, and for the safe growth of plants, the volume of wastewater loading for treatment B and C were doubled. Cycle 2 of treatment A was canceled. The F group included 4 treatments, F1, F2, F3 and F4, and each treatment had one mesocosm with a flood-drain loading pattern.

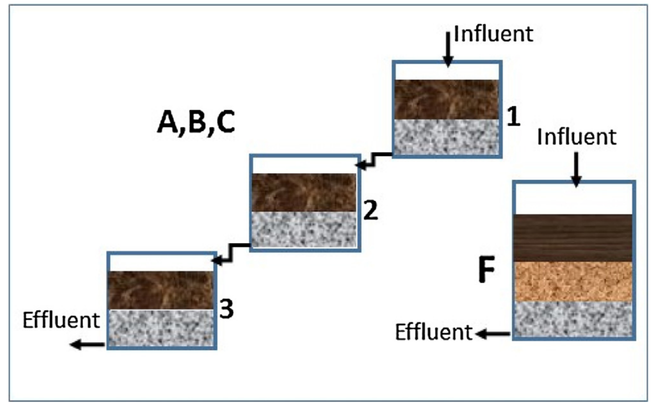

Fig. 1. Mesocosms constructed in a pig farm yard in Huayuan Village Chongming County, Shanghai, China, 2015.

The experiment was performed in a pig farm with approximately 1000 heads in Chongming Island, Shanghai, China. The annual average temperature and precipitation are 16 °C and 1200 mm, respectively. In this study, liquid waste from the pig feedlots were firstly processed through solid-liquid separation using a mechanical sieve (0.45 mm). The solid part was added to the digester for biogas production, and the liquid part went through facultative ditches with 60 days of hydraulic retention time (HRT). There were four parallel ditches each at 3.5 m wide × 50 m long × 1.5 m deep. Between every two ditches a soil-bank at 4 m width is naturally dominated by *Alternanthera philoxeroides* (Mart.) Griseb in summer and fall, *Ranunculus muricatus* L. in winter and spring. Water hyacinth (*Eichhornia crassipes*) and water lettuce (*Pistia stratiotes* L.) were also adopted for better removal. The effluent from the facultative ditches was used in this experiment.

Sorghum bicolor L. Moench was sown on April 25th, 2015, in each mesocosm in A, B, and C. Sixty-five seedlings were retained for the treatment of wastewater starting on May 26th. On June 19th, 2015, thirty seedlings remained after thinning. For treatment F, on June 19th, the same seeds were sown in the mesocosms. On July 13th, 30 seedlings were reserved and treatments were started for the F treatments. Treatments with wastewater according to Table 1 were conducted through the last experimental day on August 20th, 2015, when the plants in most of the mesocosms wilted due to aphid infection. The above ground biomass was collected and the fresh weights were recorded. The samples of each treatment (approximately 1/10) were collected randomly and delivered to the lab for analysis of the N and P contents in the plants.

The mesocosm for the A, B and C treatments had dimensions of 50 cm × 50 cm × 50 cm. The inlet was 5 cm under the top, and the outlet was on the opposite side close to the bottom. The sampling outlet was 10 cm from the bottom on the side wall. For each batch, the influent and effluent samples from the 1st, 2nd and 3rd mesocosm were collected on the day that the water was intended to be released. The F mesocosm was taller, with dimensions of 50 cm × 50 cm × 80 cm. The mesocosms in the A, B and C treatments