Nitrate and phosphate removal from agricultural subsurface drainage using laboratory woodchip bioreactors and recycled steel byproduct filters

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ARTICLE INFO

ABSTRACT

Woodchip bioreactors have been increasingly used as an edge-of-field treatment technology to reduce the nitrate loadings to surface waters from agricultural subsurface drainage. Recent studies have shown that subsurface drainage can also contribute substantially to the loss of phosphate from agricultural soils. The objective of this study was to investigate nitrate and phosphate removal in subsurface drainage using laboratory woodchip bioreactors and recycled steel byproduct filters. The woodchip bioreactor demonstrated average nitrate removal efficiencies of 53.5—100% and removal rates of 10.1—21.6 g N/m^3/d for an influent concentration of 20 mg N/L and hydraulic retention times (HRTs) of 6—24 h. When the influent nitrate concentration increased to 50 mg N/L, the bioreactor nitrate removal efficiency and rate averaged 75% and 18.9 g N/m^3/d at an HRT of 24 h. Nitrate removal by the woodchips followed zero-order kinetics with rate constants of 1.42—1.80 mg N/L/h when nitrate was non-limiting. The steel byproduct filter effectively removed phosphate in the bioreactor effluent and the total phosphate adsorption capacity was 3.70 mg P/g under continuous flow conditions. Nitrite accumulation occurred in the woodchip bioreactor and the effluent nitrite concentrations increased with decreasing HRTs and increasing influent nitrate concentrations. The steel byproduct filter efficiently reduced the level of nitrite in the bioreactor effluent. Overall, the results of this study suggest that woodchip denitrification followed by steel byproduct filtration is an effective treatment technology for nitrate and phosphate removal in subsurface drainage.

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1. Introduction

Agricultural subsurface drainage is a widely adopted water management practice to increase crop production in the Midwestern United States and many other areas (Fausey et al., 1995). Subsurface drainage removes excess water from the soil profile through a network of underground perforated pipes or surface ditches, which allows cultivation of agricultural fields with poor natural drainage. However, subsurface drainage systems also provide direct conduits that can transport nutrients from agricultural fields to surrounding natural water bodies (Sims et al., 1998; Jaynes et al., 2001). Elevated nutrient levels in surface waters can lead to a number of negative water quality impacts including harmful algal blooms, hypoxic zones in the ocean, and contamination of drinking water supplies (Anderson et al., 2002; Rabalais et al., 2002; Schilling, 2005).

Nitrate has been a major water quality concern for many subsurface drainage systems due to its high solubility and mobility in soils. Nitrate-nitrogen concentrations in subsurface drainage water often exceed the United States Environmental Protection Agency (USEPA) drinking water standard of 10 mg/L. Increased nitrate loading into the Mississippi River Basin from agricultural drainage in the Midwest has been identified as a major contributor to growing hypoxia in the Gulf of Mexico (Rabalais et al., 2002). Many nutrient management practices have been implemented in fields to reduce nitrate loads from subsurface drainage systems, including improved fertilizer application, controlled drainage, and denitrification bioreactors (Gilliam and Skaggs, 1986; Delgado et al., 2005; Schipper et al., 2010).

Phosphorus transport from agricultural fields to surface waters

occurs through two primary pathways: surface runoff and subsurface drainage. Early work on agricultural phosphorus transport focused on soil erosion and surface pathways, and many studies have demonstrated that phosphorus loss occurs predominantly in surface runoff (Sharpley et al., 1993; Heathwaite and Dils, 2000). Recent studies suggest that subsurface drainage is also an important phosphorus transport pathway, and the leaching of phosphorus to subsurface drainage can be enhanced by low soil phosphorus adsorption capacity and development of preferential flows (Sims et al., 1998; Algoazany et al., 2007; Kleinman et al., 2015). Smith et al. (2015) showed that 49% of soluble phosphorus and 48% of total phosphorus losses occurred through subsurface drainage in the St. Joseph River Watershed in northeastern Indiana. King et al. (2015) demonstrated that more than 90% of all measured phosphorus concentrations in subsurface drainage of a watershed in central Ohio exceeded recommended levels (0.03 mg/L) for minimizing harmful algal blooms. It is necessary to develop practices that can control the concentrations of both nitrogen and phosphorus in subsurface drainage to protect aquatic ecosystems and public health.

Denitrification bioreactors have emerged as an important edge-of-field treatment technology to reduce nitrate loads from subsurface drainage (Blowes et al., 1994; Greenan et al., 2006; van Driel et al., 2006; Schipper et al., 2010; Christianson et al., 2011). These bioreactors typically utilize an organic carbon medium to support the growth of denitrifying bacteria which use organic electron donors to reduce nitrate to nitrogen gas (Greenan et al., 2006). Woodchips are by far the most widely used materials in field-scale denitrification bioreactors and have shown the ability to deliver long-term (>10 years) nitrate removal while requiring minimum maintenance (Blowes et al., 1994; Robertson, 2010; Christianson et al., 2011; Cooke and Bell, 2014). Under field operating conditions, woodchip bioreactors have demonstrated nitrate removal efficiencies ranging from 33 to 100%, and removal rates of 2–22 g N/m³/d (Schipper et al., 2010). Phosphorus is an essential element for the metabolism and growth of denitrifying bacteria. Hunter (2003) studied the effects of phosphate on denitrification of groundwater in sand columns and found that an N/P mass ratio of 100 or less was required to effectively reduce nitrate and prevent nitrite accumulation. The high N/P ratio suggests that a relatively small amount of phosphate is needed for the denitrifying bacteria, which agrees with the observation that wood-based bioreactors do not substantially remove phosphate (Jaynes et al., 2008). Phosphate sorption materials such as drinking water treatment residuals and biochar have been used to amend laboratory bioreactors to enhance phosphate removal (Zoski et al., 2013; Bock et al., 2015).

Emerging phosphate removal technologies are being developed to reduce phosphorus pollution using low-cost adsorption materials, such as natural minerals, synthetic filtration products, and industrial byproducts (steel slag, steel wool and turnings, fly ash, drinking water treatment residuals and others) (Penn et al., 2007; McDowell et al., 2008; Chardon et al., 2012; Erickson et al., 2012). The phosphorus adsorbents typically provide metal cations (iron, aluminum, or calcium) to bind with dissolved phosphorus to form insoluble compounds (Weng et al., 2012; Lyngsie et al., 2014). Steel chips, wools and turnings are common byproducts produced during metal processing, and they are typically recycled for steel production. These readily available steel byproducts are expected to possess high phosphate adsorption capacity due to their high iron content (Erickson et al., 2012; Weng et al., 2012). Therefore, recycled steel byproducts can be potentially used as cost-effective filtration materials to remove phosphate from subsurface drainage. Hence, we propose a two-stage treatment system using woodchip bioreactors followed by recycled steel byproduct filters to simultaneously remove nitrate and phosphate in subsurface drainage.

The objective of this study was to determine the nitrate and phosphate removal efficiency of a woodchip bioreactor followed by a steel byproduct filter in the laboratory. In this study, batch adsorption experiments were conducted to determine the phosphate adsorption capacity of selected steel chips and turnings. Column experiments were performed to evaluate the nitrate and phosphate removal by woodchips and selected steel byproducts under continuous flow conditions. The impacts of influent nutrient concentrations and hydraulic retention times on the performance of the bioreactor and the steel byproduct filter were investigated. The results of this study may lead to the development of new edge-of-field treatment systems that combine woodchip denitrification and steel byproduct filtration for nitrate and phosphate removal in subsurface drainage.

2. Materials and methods

2.1. Woodchips and steel byproducts

Table 1 summarizes the characteristics of the steel byproducts and woodchips used for this study. Four different steel byproducts were collected from a metal machining factory located in Sioux Falls, SD. Small chips, medium chips, medium turnings and large turnings were produced by processing carbon steel using different machines. After collection, steel byproducts were washed using non-phosphate soap and air dried before use. The surfaces of the steel byproduct particles were oxidized and covered with rust (iron oxides) after cleaning. All mixtures of steel byproducts and water were slightly acidic. Woodchips made from cottonwood trees were obtained from a supplier in Sioux Falls, SD. These woodchips were washed with distilled water to remove dirt and floating fine particles, and air dried before use.

2.2. Batch phosphate adsorption experiments

Batch adsorption experiments were conducted to determine the phosphate adsorption isotherm and kinetics of the steel byproducts. A temperature controlled orbital shaker (Model MaxQ 4000, Thermo Scientific, Waltham, MA) was used for the adsorption experiments. For the isotherm test, each steel byproduct (0.5–1 g) was placed in a 100 mL phosphate solution that had varying concentrations (10–40 mg P/L). The phosphate solution was prepared by dissolving $NaH_2PO_4 \cdot H_2O$ in water and the pH was adjusted to 7 using 1.0 M NaOH solution. After 24 h of adsorption at 20 °C and 100 rpm shaking, the phosphate concentration of each sample was measured. The adsorption kinetics test was also conducted at a temperature of 20 °C and 100 rpm shaking. Each steel byproduct (0.5–1 g) was placed in a 100 mL phosphate solution with an initial concentration of 30 mg P/L and a pH of 7. Samples were collected at different time intervals (0.5, 1, 2, 3, 6, and 24 h) for phosphate measurement. A Langmuir isotherm was used to model the phosphate adsorption capacity at different equilibrium concentrations. The phosphate adsorption rates were modeled using first-order reaction kinetics. These two models have been used to describe phosphate adsorption onto iron-based materials (Fu et al., 2013; Lalley et al., 2016).

2.3. Column reactor experiments

Fig. 1 shows the schematic of the two-stage upflow column reactors with the woodchips and steel byproducts. These two reactors were used for the column experiments. Both reactors were made of clear acrylic pipes and had an inside diameter of 8.7 cm. The woodchip reactor had 1.2 m of woodchips and 6 sampling