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Characterization of biomass residues and their amendment effects on water sorption and nutrient leaching in sandy soil

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HIGHLIGHTS

- Two distinctive biorefinery residues were effective as soil amendments.
- Biorefinery residues could improve water holding capacity of sandy soil.
- Biorefinery residues could improve ammonium and phosphate leaching of sandy soil.
- There is correlation between residue SSA and amendment efficiency.

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ABSTRACT

In this study, we evaluated the efficiency of two types of biomass residues (fermentation residues from a bioethanol process, FB; brown mill residues from a papermaking process, BM) as amendments for a sandy soil. The characteristics of these residues including specific surface areas, morphologies and nutrient sorption capacity were measured. The effects of biorefinery residues on water and nutrient retention were investigated in terms of different particle sizes and loadings. The results indicated that bio-based wastes FB and BM were able to significantly improve water and nutrient retention of sandy soil. The residues with larger surface areas had better water and nutrient retention capability. Specifically, in the addition of 10% loading, FB and BM was able to improve water retention by approximately 150% and 300%, while reduce 99% of ammonium and phosphate concentration in the leachate compare to the soil control, respectively.

1. Introduction

The use of low-cost crop residues (e.g. sugarcane bagasse residue after sugar extraction) to produce second-generation biofuel (e.g. ethanol) is a promising sustainable approach to partially offset current petroleum-dominant energy market (Farrell et al., 2006; Balat et al., 2008; Geddes et al., 2011). As a result, a large number of biorefinery residues will be produced in newly-built biorefinery processes. Meanwhile, large quantity of bio-based wastes from current biomass related processes (e.g. pulp and paper processes) also need better utilization instead of burning. One of the promising approaches to use bio-based waste is as a low-cost soil amendment. As reported in previous literature, the addition of organic matters improved water holding capacity of a soil (Johnson et al., 2007). In addition, the removal of bio-based waste from agricultural fields or forests to biomass processing locations instead of leaving in the crop field had adverse impact on soil quality and productivity, and led to accelerating evaporation, water and nutrient losses (Lindstrom, 1986; Blanco-Canqui and Lal, 2009). It is essential to return part of biomass residues back to soil as approximately 41% of biomass should be kept in all major land use areas in order to prevent soil erosion according to previous studies (Holt, 1983; Lindstrom, 1986).

Productivity of sandy soils, characterized by low water and nutrient holding capacity, is limited by the lack of available water as well as nutrients that are required by plant growth (Andry et al., 2009). Meanwhile, in arid area, it is imperative to use water efficiently because of water shortage. Synthetic hydrophilic polymers have been investigated as soil amendment materials to retain water and nutrient in arid area. It has been reported that hydrophilic polymers such as polyacrylic acid and polyacrylamide gels

Abbreviations: FB, fermentation residues from a bioethanol process; BM, brown mill from a papermaking process; WRV, water retention value.

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were able to retain water up to 500 times of their weight (Holliman et al., 2005). These synthetic polymers could improve water retention in sandy soils (Aldarby et al., 1992), therefore facilitated the growth of plants (Flannery and Busscher, 1982; Johnson, 1984). However, despite the superior water retention capacity, their wide applications as soil amendments have been limited by a variety of factors such as non-renewable, non-biodegradable, low salt tolerance, possibility of releasing toxic residues and high cost (Holliman et al., 2005; Andry et al., 2009). Bio-based materials such as manures, starch, pristine plant fiber, cellulose (including carboxymethylcellulose, CMC), and chitosan have been studied as soil amendments as well. The drawbacks for their use include low retention, high price, low salt tolerance and their competitiveness with food (Mamilov et al., 2001; He et al., 2002; Andry et al., 2009; Radwan et al., 2012).

The use of biomass residues (biorefinery and pulping residues) as soil amendments not only adds an avenue to biomass processing industries but also offsets the negative impacts of biomass residues' removal on soil properties. Johnson et al. reported that corn stove fermentation residues were capable to improve properties of severely-eroded soil such as water stable aggregates and decreased bulk density without adverse impacts on crop growth (Johnson et al., 2007). Galvez et al. claimed that bioethanol by-products led to N_2O emissions and larger increases in soil respiration, N availability, and enzymatic activity in comparison with other amendments such as sewage sludge and composts (Galvez et al., 2012). (Gell et al., 2011) reported that no crop phytotoxicity was significant after seven-day application of bioethanol residues.

The impact of biorefinery residues and their characteristic difference on water and nutrient retention capacity of sandy soil remains unclear. Therefore, in this study, we aim to evaluate the efficiency of biomass residues as sandy soil amendments according to their characteristics, particle size ranges, and loading levels. These two distinctive biomass residues (fermentation residues (FB) from a cellulosic bioethanol process using sugarcane bagasse as raw materials; brown mill residues (BM) from waste stream of a papermaking process) are different in compositions (lignin-dominated or cellulose-dominated), particle sizes, and specific surface areas. The understanding for the correlation between their characteristics and water and nutrient retention capacity of sandy soil is very beneficial for the large-scale use of bio-wastes as soil amendments in the field in the future.

2. Material and methods

2.1. Materials

Fermentation sugarcane bagasse residues (FB) were collected from waste stream of a bioethanol pilot plant. The collected residues were placed in a sieve (US standard test sieve #270) and washed with warm tap water until effluent became clear and then dried in an oven at 70 °C for 24 h. Brown mill residues (BM) were collected from waste stream after screening in a papermaking process using slash pine as the raw material (Buckeye Technologies, Perry, FL, USA). BM residues were dried at 70 °C for 24 h and then milled in a laboratory mill (Model 4, Thomas Willey, Swedesboro, NJ, USA) equipped with a screen with a mesh opening size of 2 mm. Both FB and BM were separated into three size ranges (A: 0.297–0.5 mm, B: 0.178–0.297 mm, C: 0.089–0.178 mm) by using a set of ASTM standard test sieves (#35, 50, 80 and 170) and a Octagon 200 test sieve shaker at an amplitude of 8 for 15 min. The soil was collected from Hastings, Florida. It is classified as Ellzey fine sand series (sandy, siliceous, hyperthermic, Arenic Endoaqualf) (Baillie, 2001). Boric acid, sodium hydroxide, sodium tetraborate, sulfuric acid, phenol, ethylenediamine tetraacetic acid disodium salt dehydrate, sodium nitroprusside, ammonium chloride, antimony potassium tartrate, ammonium molybdate, ascorbic acid, ammonium persulfate, potassium phosphate monobasic were purchased from fisher scientific (USA) and used as received. Sodium hypochlorite solution (Clorox House bleach) was purchased in local grocery store (The Clorox Company, Oakland, California, USA). The nutrient solution at a concentration of 3000 ppm was prepared by dissolving anhydrous ammonium chloride and potassium phosphate monobasic in autoclaved deionized water and stored at 4 °C to prevent microbial growth.

2.2. Soil and leachate samples preparation

Soil (150 g as dry weight equivalent) and FB or BM (1%, 3%, 5%, and 10% dry weight of soil) were manually mixed in a beaker before loading to soil columns. Basically, nutrient solution was transferred to columns loaded with soil and FB/BM mixtures and the leachates were collected (for detailed description of soil column and the leachate collection procedure, please refer to Supplementary information). All leachate samples were then stored at 4 °C in the refrigerator and the pH is kept less than 2 by adding sulfuric acid (H_2SO_4) before analysis. The soil–FB or BM residue mixtures were temporarily stored in zip-bags and used for water retention value (WRV) analysis.

2.3. Biomass residues characterization

2.3.1. Composition analysis

Compositions of biomass residues (FB and BM) were analyzed according to the National Renewable Energy Laboratory (NREL) method (Sluiter et al., 2008). Monomer sugar contents after cellulose hydrolyzation were measured by High Pressure Liquid Chromatography (Agilent Technologies HPLC 1200 series, Santa Clara, CA, USA) equipped with BioRad Aminex HPX-87H column (Hercules, CA, USA). The acid soluble lignin was determined by UV–Vis spectroscopy (Beckman DU800 UV/Vis Spectrophotometer, Brea, CA, USA). Both acid insoluble lignin and ash content were obtained by gravimetric analysis.

2.3.2. Specific surface area measurement

Specific surface areas (SSAs) of FB and BM at different particle sizes were determined by N_2 sorption isotherms on a NOVA 1200 series volumetric gas adsorption instrument (Quantachrome, FL, USA). The sample was loaded in a specific glass cell and the cell was submerged in liquid nitrogen. The densities of all the samples were pre-measured by a multipycnometer (Quantachrome, FL, USA) and used as a parameter for further SSA analysis. The specific surface area was calculated by multipoint nitrogen adsorption in a relative pressure range of 0.05–0.2 P/P_0 in accordance to BET method developed by Brunauer et al. (1938).

2.3.3. Scanning electron microscopy (SEM) for morphology analysis

Scanning electron microscopy (SEM) with a field emission gun (FEI XL-40 FEG-SEM, operating voltage of 30 kV, FEI, Hillsboro, Oregon, USA) was used to examine the morphologies of both biomass residues FB and BM. All samples were coated with platinum before scanning.

2.3.4. Fourier transform infrared spectroscopy (FTIR)

Fourier transform infrared spectroscopy (FTIR) was used to investigate the sorption of nutrient ions on biomass residues (FB and BM). FTIR spectra were recorded on Spectrum BX spectrometer from PerkinElmer (Massachusetts, USA) (for detailed sample preparation and testing parameters, please see Supplementary information).

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