Ecological Engineering 83 (2015) 466–475

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

Phosphorus application with recycled products from municipal waste water to different crop species

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ARTICLE INFO

Article history:
Received 20 February 2015
Received in revised form 10 June 2015
Accepted 28 June 2015
Available online 3 August 2015

Keywords:
Struvite
Sewage sludge ash
Amaranth
Sorghum
Maize
Sunflower
Sequential P extraction

ABSTRACT

The recycling of phosphorus (P) from residues of waste water treatment is an important approach to conserving world P resources, and different processes have been developed to gain a clean and efficient P fertilizer from these residues. In this study, two greenhouse experiments were carried out to determine the P fertilizing effect of eight different P recycling products, namely a solar-dried sewage sludge (SSS), an untreated sewage sludge ash (Al(ut)-SSA), a H_2SO_4-digested SSA (Al-SSA), four thermo-chemically treated SSAs (two Mg-SSAs and two Ca-SSAs), and struvite. These products were compared with triple superphosphate (TSP) and a control (CON) without P application. Five different crops were included in the experiments. Plant P uptakes and soil P fractions were studied as affected by the P recycling products and cultivated crops as well as by the interactive effects of both. The relative plant P uptakes after application of the P products compared to TSP ranged in this order: SSS, Al(ut)-SSA (84.3%, 84.6%) < Al-SSA (90.6%) < both Ca-SSAs, 1Mg-SSA (93.1–98.7%) < 2Mg-SSA (104%) < struvite (119%). The readily plant available P pools in the soil increased mainly after the application of struvite, TSP, and Mg-SSAs and were also affected by cultivated crops. The P application with struvite and treated SSAs can be considered as a suitable measure to provide P for crop cultivation.

1. Introduction

Currently, mainly mined phosphate rock (PR) is used as phosphorus (P) fertilizer in agriculture, but global PR resources are limited and moreover primarily found in politically unstable regions (Jasinski, 2014). Secondary phosphate resources like animal slurries and manure as well as residues from bioenergy production, ashes, bone and meat meal are commonly used to provide P to agricultural fields (Bachmann et al., 2011; Eichler-Löbermann et al., 2007; Reijnders, 2014; Vassilev et al., 2013). Municipal waste water however is also a promising P resource, incurring about 3 MT of P globally each year (Elser, 2012). Sewage sludge products or sediment from waste water treatment plants can be used directly after hygienization as P fertilizer (Tuszynska et al., 2013), but the direct application of sewage sludge as fertilizer is declining in Europe since untreated sludge may contain high concentrations of harmful substances (Renner, 2000; Nanzer et al., 2014a). The organic contaminants in sewage sludge can be destroyed by incineration, but after incineration heavy metals are enriched in the resulting sewage sludge ash (SSA) and the P solubility of SSA is usually low (Franz, 2008). Therefore, several new recycling processes have been developed during the last years to separate heavy metals and to improve the P solubility of SSAs (Adam et al., 2009; Sartorius et al., 2012; Donatello and Cheeseman, 2013). Among others, acid or alkaline leaching can be applied to improve the P solubility (Petzet et al., 2012). The thermo-chemical treatment of SSAs, whereby chloride (Mg-Cl_2, Ca-Cl_2) is added to the ash at about 1000 °C to produce a metal-depleted solid residue, was described as a promising approach by Mattenberger et al. (2008) and Adam et al. (2009). After these treatments, heavy metal concentrations in SSAs usually undercut the European (EU) limit values for concentrations of heavy metals in sewage sludge products (Council Directive 86/276/EEC).

Another promising example of P recovery from sewage is struvite ($MgNH_4PO_4$ $6H_2O$, magnesium ammonium phosphate). Struvite contains only small amounts of harmful substances and is characterized by relatively high P solubility (Johnston and Richards, 2003; Kern et al., 2008; Rahman et al., 2014).

The P solubility of the waste water products differ according to their chemical P composition, which in turn is influenced by the salt used for P precipitation and the kind of chemical treatment (Phan et al., 2009). However, the P fertilizer effect of these products also depends on soil characteristics. Nutrient uptake efficiency and mobilization mechanisms of crops are also important for high

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http://dx.doi.org/10.1016/j.ecoleng.2015.06.044
0925-8574/

utilization of applied P (Richardson et al., 2011) and tests regarding the P availability for different crops are required to improve the production process and consequently the quality of these products. The effects of struvite and other precipitated phosphates have been tested in pot experiments with perennial ryegrass (Johnston and Richards, 2003) and rye (Römer, 2006) on different soils. On loamy sands struvite was evaluated by Gonzalez-Ponce et al. (2009) when applied to lettuce and by Massey et al. (2009) to spring wheat. Results showed especially for struvite a good efficacy which was comparable to highly soluble commercial P fertilizers. For thermo-chemically treated and H_2SO_4-digested SSAs, positive effects on ryegrass were observed by Nanzer et al. (2014b) and Severin et al. (2013).

Although these studies showed a general potential of P recycling products to increase crop growth and nutrient uptake, investigations concerning interactions of different P recycling products and various crops are rarely available. Beside the effect of the P recycling products on plant growth, investigations regarding their effects on soil P pools are of interest as well and contribute to an understanding of the transformation processes of applied P in the soil. The sequential extraction is a common wet chemical method (Hedley et al., 1982; Tiessen and Moir, 1993), whereby different P fractions of decreasing bioavailability become extracted step by step by using stronger extracting agents. This allows the investigation of the effect of P products and crop species on soil P cycles, and also provides information about the pathway of remaining P in the soil and helps to predict its prospective availability.

In this study, two greenhouse experiments were carried out to determine the P fertilizing effect of different P recycling products including a solar-dried sewage sludge (SSS), an untreated SSA, a H_2SO_4-digested SSA, four thermo-chemically treated SSAs, and struvite. The waste water products were compared with a common rock-phosphate-based P fertilizer, triple superphosphate (TSP), and a control (CON) without P application. Five different crops including monocot and dicot species (maize, forage rye, sorghum, amaranth, and sunflowers) were included in this study. Maize was cultivated in both experiments. The aim of this study was to compare the effect of the P recycling products on (1) P availability for crops, (2) crop yield, and (3) on soil P pools as well as to determine the interactions between the fertilizer treatments and the cultivated crops.

2. Material and methods

2.1. Fertilizer treatments and experimental design

Two pot experiments were carried out, a main experiment including four different crops and a control experiment including two different crops. Maize was cultivated in both. The control experiment (2012) was conducted to verify the results of the main experiment (2011). In both experiments the same fertilizer treatments were applied (see below). The soils used were moderately acidic loamy sands and according to the World Reference Base for Soil Resources, the soil is classified as Stagnic Cambisol. The soils were collected from the A horizon of a field experiment from the experimental station of the University of Rostock. The double lactate (dl) soluble P (Pdl) concentrations were below 56 mg kg^{-1} soil, indicating a suboptimal P supply for plants according to the German soil-P classification. The soil characteristics of the soil in both years were similar, since it was collected from the same field (soil 2011 vs. 2012: Pdl40.1 vs. 48.0, Mgdl 120 vs 147, Kdl 61.2 vs. 63.5, Pt 515 vs 517 (all values in mg per kg soil), pH 5.19 vs. 5.29, soil organic matter 2.31 vs. 2.38%). In both experiments, 6 kg of air-dried and sieved (2 mm) soil was filled into Mitscherlich pots. The soils were amended with the recycled P products, or highly soluble mineral P in the form of triple superphosphate (TSP) at a rate equivalent to 200 mg P per pot. In addition a control treatment without P application was carried out (CON). Since with the treatments also other nutrients beside P were applied (see Table 1), the addition of N, K, and Mg was adapted to ensure a uniform supply of these nutrients to all treatments according to the following amounts per pot: N: 0.5 g, K: 1.0 g, and Mg: 0.3 g with nutrient salts.

Beside the TSP and the control treatment eight recycled P products remaining from waste water treatment were applied. A solar-dried sewage sludge (SSS) was produced by solar radiation in a greenhouse, assisted by a turning and conveying machine, yielding granulate of about 10 mm with a dry matter concentration of up to 90%. The precipitating agent used in the sludge was iron (Fe) salt. Furthermore, untreated and treated sewage sludge ashes (SSA) were applied (the nomenclature was done according to the main P binding form in the ashes). For the untreated ash, sewage sludge was mono-incinerated, whereat P was precipitated in the waste water with aluminum salt (Al(ut)-SSA). The five treated SSAs also based on mono-incinerated sludge but these ashes were further treated to improve the bioavailability of P and to reduce the concentration of heavy metals. For Al-SSA, P was also precipitated in the waste water with Al before the sludge was mono-incinerated. The ash was then treated by a H_2SO_4-washing procedure and 300 g H_2SO_4 (96%) per kg SSA was added to increase the P availability. The other four SSAs were thermo-chemically treated, whereby heavy metals were evaporated in a rotary furnace at a temperature of 1000 °C after the addition of $MgCl_2$(Mg-SSA) or $CaCl_2$(Ca-SSA) as a chlorine donor at a rate of 100 mg kg^{-1} ash. Afterwards, 30% H_2SO_4 was added to increase the P availability. A more detailed description of the process can be found in Mattenberger et al. (2008) and Adam et al. (2009). The raw sewage sludges used to produce the two Mg-SSAs and Ca-SSAs were derived from different batches from the same waste water

Table 1
Application rate (g per pot), element concentration (g kg^{-1}) and pH values of the recycling products and TSP.

	Rate g	Pt g kg^{-1}	Pca	K	Mg	Ca	N	Al	Fe	Alox	Feox	pH
SSS	6.5	30.6	22.4	1.9	3.8	19.3	19.0	15.5	35.4	n.a.	n.a	6.5
Al-(ut)SSA	2.0	98.6	29.9	9.5	15.1	76.1	–	95.6	20.6	56.4	11.6	11.2
Al-SSA	3.4	58.5	45.9	5.1	7.7	42.6	–	55.8	10.4	54.1	10.3	1.9
1Ca-SSA	4.5	44.4	29.1	4.4	15.0	96.1	–	26.2	54.5	12.7	3.7	3.9
2Ca-SSA	3.2	62.4	46.0	4.1	9.3	96.9	–	23.9	29.2	11.5	3.0	3.6
1Mg-SSA	5.1	39.4	34.5	7.9	52.2	61.2	–	17.9	43.5	8.7	11.2	5.1
2Mg-SSA	3.0	65.9	44.0	4.8	49.1	54.3	–	17.1	38.1	8.6	4.8	4.0
Struvite	1.8	121.7	102.7	0.6	93.4	4.9	41.7	39.6	18.5	0.1	1.9	7.5
TSP	1.2	167.0	168.9	-	8.9	106.7	–	29.4	22.5	0.0	0.1	2.3

Pt = total P, Pca = P soluble in citric acid, Alox, Feox = oxalate soluble Al and Fe, SSS = solar dried sewage sludge, SSA = sewage sludge ashes, ut = untreated, TSP = triple superphosphate, n.a. = not analyzed.