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Research article

Effectiveness of pig sludge as organic amendment of different textural class mine tailings with different periods of amendment-contact time

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ABSTRACT

The present study assesses the effect of tailing texture (loamy sand (LT) and sandy loam (ST)), dose of pig sludge (0, 50, 100 and 200 t ha^{-1}) and amendment-contact time (14, 28 and 42 days) on physicochemical quality of amended substrate using *Lolium perenne* var Nui as a bioindicator. The main properties of LT differed of ST in levels of total organic carbon (0.19 and 0.58%), in pH (4.6 and 8.5), total Cu (202 and 1647 mg kg^{-1}) and Zn content (31 and 137 mg kg^{-1}). Soil pore water of experimental substrates was characterized for pH, electrical conductivity (EC) and Cu^{2+} ion activity (pCu^{2+}) while ammonium nitrogen (NH_4^+-N), infiltration rate and general physicochemical characteristics were measured in substrates. Shoot biomass (SB), root biomass (RB) and the RB:SB ratio was calculated for *L. perenne*. The results showed there to be a significant interaction ($p < 0.05$) between tailing texture, sludge dose and amendment-contact time for pCu^{2+}, infiltration rate, SB, RB, and RB:SB ratio, but not for pH, EC, or NH_4^+-N. However, sludge dose and amendment-contact time significantly affected all variables. By increasing dosages of pig sludge, pore water pH increased, and this was associated with decreases in pCu^{2+} and the infiltration rate. High doses of pig sludge (100 and 200 t ha^{-1}) impaired growth of *L. perenne* irrespective of tailing texture and amendment-contact time, likely because of the rise of EC (up to 14 mS cm^{-1}). For both tailing textures, the highest biomass was obtained after incorporation of 50 t ha^{-1} of pig sludge, with increasing values as amendment-contact time rose. In conclusion, effective management of pig sludge for tailing reclamation should guarantee doses < 50 t ha^{-1} and amendment-contact time > 28 days, irrespective of tailing texture.

1. Introduction

Assisted phytostabilization consists of the *in-situ* reclamation of chemically degraded soils and mine wastes enriched with potentially toxic compounds using suitable plant species and substrate amendments to promote plant establishment and growth (Mench et al., 2006). Through several mechanisms, substrate amendments and plant roots allow immobilization of metals into harmless forms for other organisms (Rodríguez et al., 2018). Mine tailings differ from soils as they are a mineral substrate that resembles volcanic ash due to containing abundant primary minerals than soils (Li and Huang, 2015). Tailing characteristics are very limiting for sustaining biological activity owing to acidity, salinity, lack of organic matter, lack of nutrients, compaction (Zornoza et al., 2016), and lack of heterotrophic bacteria (Solís-Dominguez et al., 2012). Therefore, assisted phytostabilization is an adequate and safe method for reclamation of post-operative mine tailing facilities (Touceda-González et al., 2017).

The use of sedimentable organic solids obtained from the solid-liquid separation of pig slurries (pig sludge) as organic amendment for assisted phytostabilization has been scarcely reported in the literature (España et al., 2016). Pig sludges are a potential amendment for assisted phytostabilization of mine tailing facilities based on their nutritional content, organic matter, and the ability of pig sludges to neutralize acid tailings (Ginocchio, personal communication). This residue

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is readily available at large volumes in central Chile where approximately 92% of pork production is located (2 200 000 pigs) (ODEPA, 2017). However, application of pig sludges to mine tailings may also result in severe inhibition of plant growth because of the formation of volatile inhibitors, such as ammonia, that takes place after application of fresh biosolids (Wong et al., 1983).

There is still little information on how inherent physical characteristics of tailings, like texture, porosity, pore volume, and specific surface area, can affect the efficacy of organic amendment applications. Furthermore, there is unclear information about amendment-contact time required once they are incorporated into tailings to obtain suitable substrates that can adequately promote plant establishment and growth. Several studies have used different amendment-contact times, from days to a year (Gardner et al., 2010; Mingorance et al., 2017), but their motivation is unknown.

With the scarce information available on pig sludge as an organic amendment for mine tailings, our research group carried out exploratory studies on the application of different doses of pig sludge into sandy loam tailings (España et al., 2016), and a mixture of pig sludge with pig manure in loamy sand tailings (Ginocchio, personal communication). These studies demonstrated the adverse effects of pig residues on plant growth in fine particle-size tailings and highlighted that the use of pig sludge as an organic amendment for reclamation of tailings represents a challenge based on its high humidity, low particle size, low porosity, high plasticity, and high electrical conductivity. Therefore, a thorough evaluation of this by-product as an organic amendment for mine tailings is needed to achieve effective reclamation at mine closures. A better understanding of its proper use with regards to tailings texture, application dosage, and amendment-contact time is necessary to avoid limitations for plant establishment and development. We conducted a randomized factorial pot experiment under greenhouse conditions with the objective of assessing the effect of tailing texture, application dose of pig sludges, and amendment-contact time of amended substrate on plant establishment and growth using *Lolium perenne* var Nui as the indicator plant. We hypothesized that pig sludges can be employed as organic amendments in assisted phytostabilization of mine tailing facilities when adequate preparation is utilized.

2. Materials and methods

2.1. Tailings and pig sludge used

Two sulfidic copper mine facilities abandoned for more than 20 years were a feature of the present study; they were selected by their differences in textural class (Table 1). The first is the Cauquenes tailings facility (Libertador Bernardo O'Higgins Region, central Chile, 34°16′55.2″S, 70°42′21.6″W; subalpine maritime climate of dry summer; average annual temperature: 14.6 °C; annual rainfall: 506 mm), with loamy sand texture (LT). The second is the Huana tailings facility (Coquimbo Region, north-central Chile; 30°42′32.0″S, 70°57′14.0″W; cold semi-arid climate; average annual temperature: 15.2 °C; annual rainfall: 159 mm), with sandy loam texture (ST). Tailings were collected from the top 20 cm layer (upper oxidation zone), air-dried, and sieved < 2 mm before use.

Pig sludge was obtained from a treatment plant (solid-liquid separation of pig slurry) located in central Chile in the Libertador Bernardo O'Higgins Region. It was collected after centrifugation of primary and secondary sludges and stored in a cold room (7–10 °C) until the assay was commenced. The fact of being sedimentary solids confers a clay texture with high electrical conductivity, and according to its pH, this sludge continues in an active state of biological digestion (O'Kelly, 2005).

2.2. Experimental design

A completely randomized experimental design was used. Three different factors were considered: texture of mine tailings (T), dose of pig sludge (D), and amendment-contact time of experimental substrates (CT). We incorporated four experimental doses of pig sludge (0, 50, 100, and 200 t ha^{-1}; dry weight basis) in each selected tailing; all experimental substrates were amendment-contacted for three periods of time (14, 28, and 42 d). A total of 24 treatments with four replicates (96 experimental units) were considered. Experimental design was based on the study of Cárcamo et al. (2012).

Experimental substrates were prepared by mixing three batches of 24 kg of each tailing with 0.46, 0.92 and 1.85 kg of pig sludge (dry weight basis) corresponding to each selected dose of 0, 50, 100, and 200 t ha^{-1}, respectively. Substrates were manually mixed until homogenization; their field capacity was determined by the ISO 11269-1: 2012 (E) method (ISO, 2012). A sample of each batch of experimental substrate was collected for characterization (Table S1, supporting information) and then distributed in 4 L plastic pots (1.8 kg of substrate per pot), with four replicated pots, and irrigated with tap water up to 70% field capacity. Experimental pots were randomly distributed throughout the benches of a greenhouse (16–25 °C temperature, natural spring photoperiod). All pots were randomly relocated once a week to avoid bias. At the end of each CT (14, 28, 42 d), the infiltration rate was measured with a mini-disk infiltrometer (Decagon Devices, Inc., 2365 NE Hopkins Ct, Pullman, WA 99163, United State of America (USA)) by modifying the methodology proposed by Zhang (1997). A total of 17 measurements were obtained per pot. The lower chamber of the infiltrometer was filled with 85 mL of tap water, and the suction tube (upper chamber) was adjusted according to type and texture of the substrate. The mini-disk infiltrometer was placed in each pot, making certain there was a flat surface, and the infiltrating time, elapsed every 5 mL of water, was recorded up to 17 values.

The assays with CT of 14, 28 and 42 days lasted 8, 10 and 12 weeks

Table 1
Characterization of pig sludge, sandy loam and loamy sand tailings.

Parameter	Pig sludge	Loamy Sand Tailings (LT) (Cauquenes dump)	Sandy Loam Tailings (ST) (Huana dump)
pH	6.61	4.60	8.50
EC (mS cm^{-1})	17.36	0.35	0.24
N_{total} (%)	7.04	0.02	0.02
C_{total} (%)	45.60	0.19	0.58
CEC (cmol(+) kg^{-1})	n.d	3.71	15.50
Available elements			
N (mg kg^{-1})	15 566	77	38
P_{Olsen} (mg kg^{-1})	2058	4	1
K (mg kg^{-1})	9620	36	57
Cu (mg kg^{-1})	1.6	1.4	0.2
Total metal content			
Zn (mg kg^{-1})	2743	31	137
Cu (mg kg^{-1})	553	202	1647
Texture			
Clay [1] (%)	n.d	6.1	8.1
Silt [1] (%)	n.d	11.3	25.3
Sand [1] (%)	n.d	82.6	66.6
S_{total} [2] (%)		0.41	0.06
Fe_2O_3 [2] (%)		6.42	10.4
Al_2O_3 [2] (%)		19.48	15.68
SiO_2 [2] (%)		56.82	49.98
CaO [2] (%)		1.13	5.93
Porosity (%)	1	n.d	n.d
Pore volume (cm^3 g^{-1})	n.d	0.006	0.004
Specific surface area (m^2 g^{-1})	n.d	6	3

n.d: not determined.
CEC: Cation exchange capacity.
[1] Sand, silt and clay fractions represent respectively: 2–0.063, 0.063–0.002 and < 0.002 mm.
[2] SERNAGEOMIN (2018)