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TECHNOSOLS FOR THE REMEDIATION AND REHABILITATION OF LANDSCAPES AFFECTED BY TAILINGS

G.F. Soto-Mundaca
Dept. of Environmental Sciences and Renewable Natural Resources, Faculty of Agronomical Sciences, Universidad de Chile

A.F. Gallaud-Parquet
Natural Resources Information Center, Chile

C.L. Soto-Mundaca
Tecnosuelos SPA, Chile

L.M. Morales-Salinas
Dept. of Environmental Sciences and Renewable Natural Resources, Faculty of Agronomical Sciences, Universidad de Chile

INTRODUCTION

The rehabilitation and remediation of mining tailings deposits, as well as their externalities (erosion and acid drainage) have always been approached from a classic paradigm of Research, Development and Innovation (R&D&I), i.e.: (a) the consequences on the surrounding ecosystems were investigated; (b) the respective knowledge was sought to be developed; (c) then the technology that was capable of controlling such negative externalities through prototypes, (d) and finally scaling up the solution. However, this has not yielded results: to date there is no solution offered by science and technology that is affordable from an economic point of view, and that addresses a problem that, in terms of surface area and volume, is difficult to dimension.

In this regard, raising the problem of rehabilitation and remediation of mine tailings deposits and its consequences on the surrounding ecosystems as a problem of scale as the main dimension (and not only of contamination), is the first step to properly address a possible solution.

The second step in the process of correctly posing the problem is to direct the reasoning towards the soil, since it is the ecosystem that houses the primary production on earth, and therefore, it is the medium that can make possible the rehabilitation and remediation of mining tailings deposits, as well as its externalities (erosion and acid drainage). In this regard, soil has a set of physical (texture, structure, density, porosity, water storage capacity, permeability (hydraulic conductivity)), chemical (pH Cation Exchange Capacity (CEC), electrical conductivity, fertility), and physicochemical (adsorption capacity) properties that make it the ideal material to cover the set of dimensions that must be addressed in the rehabilitation or remediation of a tailings deposit, as well as its externalities on its environment (Brady & Weil, 2008; Hillel, 2008; Hillel, 2008). Weil, 2008; Hillel, 2004).

The third step is to look at how to make use of an edaphic ecosystem to rehabilitate, remediate a tailings deposit, and take care of the pollution they generate on the surrounding ecosystems. However, one arrives again at the problem of how to dispose of very large quantities of soil, and thus returns to the beginning of the main dimension of the problem: scale.

Since the aim is to minimize environmental impacts and, therefore, not to extract soil for this purpose, TECNOSOLES made from waste (environmental liabilities), which are already very abundant, are probably the most reasonable solution, adapted to all the dimensions of the problem: scale on the one hand, and land use on the other.

Technosols are soils whose properties are of technical origin (IUSS Working Group WRB. 2007), i.e. they are manufactured, and are a promising alternative for landscape rehabilitation and remediation of large contaminated sites, especially when abundant waste materials from other industries are used in their manufacture.

The objective of this work was to evaluate the physicochemical properties of Technosols on the material of a tailings deposit with respect to their capacity to support biomass, in particular *Vachellia caven* (hawthorn), through the analysis of their overvictimization.

MATERIALS AND METHODS

The trial was conducted at the ANTUMAPU campus of the University of Chile (33º34'04.54 "S 70º37'52.49"; 616 masl) during the summer season (2018-2019), in the greenhouse of the Center for Forest Seeds and Trees (CESAF), Faculty of Forestry Sciences and Nature Conservation.

Mixtures were made using agricultural irrigation reservoir sediments (S) and stabilized household sludge (L) in different proportions: A=75%S-25%L, B=50%S-50%L and C=25%S-75%L, in 5900 cm pots[3] (Figure 1). Pre-treated *Vachellia caven* was sown, at

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the time of pot assembly, and a replicate of the trial without sowing (Table 1).

Mixture	Treatment
A=75%S+25%L	Hawthorn
B=50%S+50%L	Hawthorn
C=25%S+75%L	Hawthorn
A=75%S+25%L	Hawthorn-free
B=50%S+50%L	Without hawthorn
C=25%S+75%L	Without hawthorn

Table 1: Trial treatments.

Irrigation of the plants was controlled with moisture sensors by performing a water balance. The physical characterization of the Tecnosol was carried out (texture; bulk density ($D_{b,}$ Mg - m^{-3}); usable moisture (HA, % vol.); penetration resistance (RP, MPa) and saturated hydraulic conductivity (K_{sat} cm d^{-1})); and chemical characterization (organic matter (OM, %), pH, and electrical conductivity (EC dS - m^{-1})). In addition, buckthorn germination and survival were determined.

The statistical model chosen for the analysis was the Tuckey Mean Comparison Model, since it allowed control of type I error (false positives), and the data complied with the assumptions of normality and equality of variances (Montgomery, 2004; Canavos, 1988).

RESULTS

Technosols have a sandy-loam texture, with a higher % of sand in the mixture with a higher proportion of sediment, being in the limit from sandy-loam to sandy-loam. The triangle used for this evaluation was the triangle proposed by the USDA (1999).

The same trend was observed in D_b , increasing its value in the mixtures with higher % of sand. The three mixtures independent of the presence of hawthorn, present values of D_b lower than those reported for this textural class (<1.4 Mg m^{-3}) (Table 2).

Distinct lowercase letters indicate statistically significant differences between mixtures; capital letters indicate statistically significant differences between treatments according to the Tuckey mean comparison test (p-value < 0.05).

HA independent of the proportion of the mixture and the presence of hawthorn, reports values lower than expected for a sandy loam texture (Sandoval et al., 2012). For both treatments Ksat increases as the proportion of sediment is higher. This implies that sediment incorporation improves soil drainage, which could be beneficial for plant growth under excess water conditions. These results are congruent with those found by Asencio et al. (2013).

In relation to the sediments of the reservoir, constituted by the erosion of the Limarí river basin in Chile, their analysis is presented in Table 3:

In relation to mechanical resistance, there is a tendency to increase with a higher proportion of mineral particles. This finding is significant for soil stability and its capacity to support structures and plants, although excessive compaction could negatively affect root development.

Distinct lowercase letters indicate statistically significant differences between mixtures; capital letters indicate statistically significant differences between treatments according to Tuckey's test (p-value < 0.05).

The Tecnosols evaluated present a high EC, observing a tendency to decrease with the presence of hawthorn. As the proportion of sludge increases, the MO content increases considerably (Seguel and Horn, 2006). The Tecnosols have a moderately acid to acid pH (Table 4).

Technosols with a higher proportion of sludge show a positive trend towards hawthorn germination and survival, suggesting that the inclusion of sludge can provide nutrients and

Mix	Treatment	Ksat (cm d)$^{-1}$	Average	RP (Mpa)	Average	HA (%vol)	Average
A		82.4(±21.9) b		1.6(±0,30) a		7.4(±1.99) a	
B	Hawthorn	43.1(±22.1) ab	47.3 A	1.8(±0,12) a	1.59 A	4.2(±0.94) a	0.056 A
C		16.3(±6.76) a		1.4(±0,23) a		5.9(±0.84) a	
A		67.9(±6.14) b		1.6(±0,13) a		3.4(±0.82) a	
B	Without hawthorn	55.6(±4.26) ab	50.9 A	1.3(±0,34) a	1.42 A	6.8(±3.47) a	0.043 A
C		29.1(±3.01) a		1.3(±0,31) a		3.0(±1.23) a	

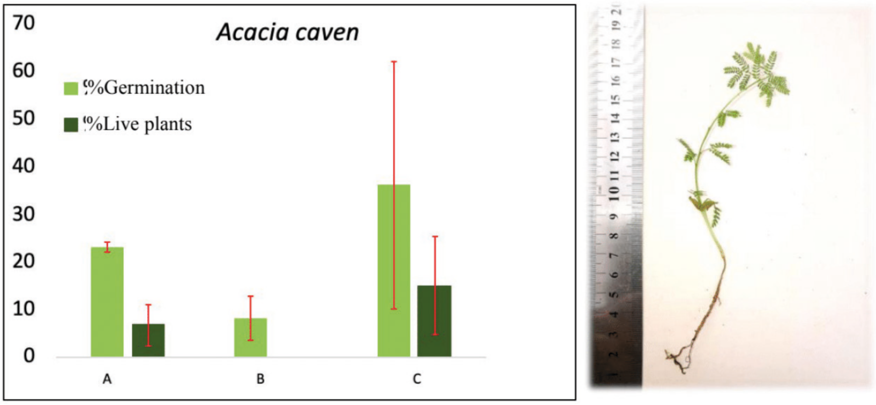
Table 2. Saturated hydraulic conductivity (K_{sat} , cm - d^{-1}) and Penetration resistance (RP, MPa) Usable moisture (HA, %), for A=75%S-25%L, B=50%S-50%L and C=25%S-75%L with and without hawthorn seeding in average values (±SE) n=3.

Sediment	EC (dS m)-1	Average	MO % MO % MO % MO % MO % MO % MO % MO % MO % MO % MO % MO	Average	pH	Average
1	3,0		1,9		7,1	
2	3,4	2,96	3,8	2,8	7,3	7,3
3	2,5		2,7		7,6	

Table 3. Electrical conductivity (EC, dS m^{-1}), organic matter (OM, %), and pH, for

Mix	Treatment	CE(dS m)-1	Average	MO % MO % MO % MO % MO % MO % MO % MO % MO % MO % MO % MO	Average	pH	Average
A		2.67(±0.72) a		1.50(±0,15) a		6.80(±0,03) b	
B	Hawthorn	4.10(±0.74) a	3,76 A	2.60(±0,12) a	3.88 A	6.00(±0,07) a	6.03 A
C		4.52(±1.10) a		7.53(±1.01) b		5.30(±0,03) a	
A		3.61(±1.40) a		3.40(±0,29) a		6.00(±0,15) b	
B	Without hawthorn	4.50(±1.77) a	4.5 A	4.61(±0,29) a	4.87 A	5.50(±0,06) a	5.77 A
C		5.40(±2.08) a		6.60(±2.09) b		5.80(±0.38) ab	

Table 4. Electrical conductivity (EC, dS - m^{-1}), organic matter (OM, %) and pH, for A=75%S+25%L, B=50%S+50%L and C=25%S+75%L with and without hawthorn seeding in. Mean values (±SE) n=3.



Germination (%) live plants (%) for A=75%S+25%L, B=50%S+50%L and C=25%S+75%L. Mean values (±DS) n=3.

improve soil physical properties, thus favoring initial plant growth. However, it is of concern that germination does not exceed 50%, indicating that, despite the potential advantages of sludge, there are limiting factors affecting the success of hawthorn establishment.

The low plant survival, especially in mixture B, highlights the importance of soil health and soil microbiology. The presence of the fungus causing plant death suggests an imbalance in the soil microbiota, which may be related to the quality of the sludge used or to environmental conditions that favor the development of pathogens. This underscores the need for careful management of organic inputs and monitoring of soil health to prevent pest and disease problems.

In general, Technosols have adequate mechanical stability, not exceeding 2 MPa, a critical value for root development and root anchorage (Threadgill, 1982). The low HA in the mixtures is mainly due to the fact that the retention of Permanent Wilt Point (PMP) is high in organic materials, which generates a low hydraulic conductivity.

The acid pH of the Tecnosols generates moderate limitations in the availability of certain nutrients, particularly phosphorus, calcium and magnesium. Soil acidity can affect not only buckthorn germination and growth, but also microbial activity, which is crucial for organic matter decomposition and nutrient release. These results are comparable to those obtained by Fernández-Covelo et al. (2010), who compared three types of Tecnosols with sludge, associated with *Eucalyptus globulus* as a species.

CONCLUSIONS

The rehabilitation and remediation of mine tailings deposits represents a significant challenge that has historically been addressed through traditional research and development approaches. However, these methods have failed to provide effective and economically viable solutions. In this context, the study of Technosols emerges as a promising alternative by integrating residual materials in their composition, which allows addressing the problem from a perspective of scale and sustainability.

The results of this work show that Technosols, by combining sediments and sludge, can improve the physicochemical properties of the soil, favoring the germination and survival of species such as *Vachellia caven*. Despite the advances, the low germination rate and soil health problems, related to microbiota and the presence of pathogens, highlight the need for careful management and continuous monitoring.

In conclusion, although Technosols offer a viable avenue for the remediation of contaminated soils, further research is required that delves into the relationship between soil quality and plant health, as well as strategies that mitigate the negative impacts associated with acidity and pathogens. This integrated approach could be key to achieving effective and sustainable rehabilitation of mining-affected ecosystems.

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