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Assessing Suitability of Technosols of Varying Granulometry for Ecological Restoration using Native *Atriplex lampa* and *Parkinsonia praecox* in the Monte Desert, Argentina

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Abstract: Desertification is the process of land degradation in arid, semi-arid, and dry sub-humid areas, which threatens the sustainability worldwide. Sustainable and innovative management strategies for restoring these degraded lands are essential to combat desertification. Use of industrial products, which creates technosols—an artificial substrates that mimic a conducive environment for plant growth, is one of the promising approaches for controlling desertification. In the present investigation, the sand residues of varying granulometry discarded during shale gas and oil processing as potential components of technosols were evaluated for seedling emergence of *Atriplex lampa* and *Parkinsonia praecox*, two native shrubs of Monte Desert of Argentina. The experiment was conducted with coarse and fine sand granulometry substrate and under controlled photoperiod and temperature conditions. Seedling emergence of both species was significantly influenced by granulometry of technosols. *A. lampa* had shown the highest emergence (~60%, SE = 7.54), while *P. praecox* averaged ~21% (SE = 2.86). The highest emergence rates for the two species were found in coarse sand granulometry (T0), 50% CG / 50% FG (T2), and 25% CG / 75% FG (T3) (~49%, SE = 10.20). These results signify the importance granulometry of technosols for seedling establishment for restoration of degraded arid lands.

Key words: Desertification, seed-based restoration, seedling, substrate granulometry, framework species.

The Monte Desert is one of Argentina's most arid ecosystems (Busso and Fernández, 2018). In much of its large extension from 22° to 55° south latitude, with an area of 3 million km², it is affected by desertification due to overgrazing and hydrocarbon activity (Mazzonia and Vázquez, 2009). Its southern extent, known as Southern Patagonic (Roig *et al*., 2009), overlaps with the Vaca Muerta formation, South America's largest shale oil reserve and a site of immense economic significance. Geologically, Vaca Muerta is often compared with some of the world's most productive hydrocarbon basins, including the North Sea, western Siberia, Alaska, and the Middle East (Stinco and Barredo, 2014).

A central component of shale oil and gas extraction is hydraulic fracturing, which requires massive inputs of silica-based sand to keep rock fractures open and facilitate the release of hydrocarbons (Wenbo and Tannant, 2006). Although specific estimates for Argentina are lacking, the U.S. Geological Survey reported that between 1990 and 2012, approximately 654 mt of industrial silica was used for this purpose. In 2011 alone this value was 26.3 mt slightly up from previous years (USDI and USGS, 2012). But in process of separating this industrial grade silica a large portion of sand with unsuitable granulometry—either too coarse or too fine—is rejected and disposed of in large dumping sites. These accumulations exacerbate environmental degradation but if repurposed, they hold potential value for ecological restoration.

The present study examines the reuse of such rejected sand residues, initially intended for hydraulic fracturing, as technosols or soil amendments to support the restoration of native shrub communities. Previous research suggests that the incorporation of sand can improve soil structure, such as by stabilizing swelling clays (Louafi and Bahar, 2012; Tahir and Marschner, 2016), while technosols with tailored textures have been shown to support the germination and establishment of shrub species in arid environments (Macci *et al*., 2022; Azevedo-Lopes *et al*., 2024; Ruiz *et al*., 2024). Building on these results, the current investigation evaluates the effects of different granulometric fractions of sand residues, each with distinct physicochemical properties, on the seedling emergence of two native Monte Desert shrubs, *Atriplex lampa* and *Parkinsonia praecox*. Both species are recognized as framework species in ecological restoration (Pérez *et al*., 2020), making them suitable candidates for re-establishing vegetation cover and ecological function in degraded arid lands of Argentinean Patagonia.

Materials and Methods

Sand residue used: Sand residues were collected from a sand treatment plant for hydraulic fracturing located near the town of Añelo (Argentine Patagonia). The Añelo town is the epicenter of hydrocarbon exploitation through hydraulic fracturing, situated in the hydrocarbon-rich shale oil and gas basin known as "Vaca Muerta" (Stinco and Barredo, 2014). The sand residues used for the experiments consisted of two residual sand fractions called: coarse sand granulometry (CG), generated in the first separation of sands through a 30-micron sieve, and fine sand granulometry (FG), generated in the flocculation of the fine particles through the addition of anionic polyacrylamide.

A total of 300 kg of sand residue was collected from each stockpile of FG and CG at the sand treatment plant. For this purpose, 50 sub-samples of 6 kg each were collected from different areas at the center of each pile, a location chosen to avoid the presence of seeds from plants growing near the sand plant. The samples were transported in clean, covered plastic drums to prevent contamination and were stored for 7 days at the Laboratory of Rehabilitation and Restoration of Arid and Semi-arid Ecosystems (LARREA) before use. Using this material, five substrate treatments were formulated by combining coarse and fine granulometries. T0 (100% CG); T1 (75% CG-25% FG); T2 (50% CG-50% FG); T3 (25% CG-75% FG); and T4 (100% FG). Three composite samples (each comprising 20 subsamples) were taken from T0, T1, T2, T3, and T4. pH, electrical conductivity, texture, sand granulometry, organic and inorganic carbon, total nitrogen, available phosphorus, available potassium, and magnesium were determined in the analytical services laboratory at CERZOS-CONICET – UNS (Buenos Aires, Argentina) following standard methodology (Bray and Kurtz, 1945; Schollenber and Simon, 1945; Gee and Bauder, 1986; Grewal *et al.*, 1991 Bremner, 1996). Additionally, in the LARREA nursery garden at National University of Comahue (Neuquén, Argentina), the samples were arranged in culture trays to measure surface hardness using a soil durometer (DUSU XX) and the volumetric water content through TDR 300. Five measurements were taken from each tray and averaged to obtain a single value.

The extraction of fine grains involves flocculation with polyacrylamide; the presence of this compound or its monomer may pose health risks (Semla *et al*., 2017), therefore, the content of the same was determined in the Laboratory of YPF Technology (Buenos Aires, Argentina) using nuclear magnetic resonance spectroscopy (Bruker Avance III of 11.2 Tesla). Since the technique has a quantification limit of 2-3%, it was combined with thermogravimetric tests (end-ramp and isothermal steps) using a TA 5500 equipment to characterize the organic content.

Species selected: The species selected for this study were *Atriplex lampa* (Moq.) D. Dietr. and *Parkinsonia praecox* (Ruiz & Pav. ex Hook.) Hawkins, both of them are characteristic components of plant communities in the Southern Patagonic Monte Desert (Neuquén, Argentina). These species are considered promising contenders for ecological restoration due to their functional traits: *A. lampa* contributes to soil stabilization and erosion control, while *P. praecox*, a leguminous shrub, contributes to atmospheric nitrogen fixation in to soil (Villagra *et al*., 2011; Zúñiga and Pérez, 2014). Both species exhibit physiological dormancy and have also been documented for dormancy alleviation (Paredes *et al*., 2018; Rodriguez Araujo *et al*., 2023). The seeds were procured from the Arid Germplasm Bank (LARREA), which reported high germination potential, with average values of 85.00% (SE = 4.60) for *A. lampa* and 93.33% (SE = 1.92) for *P. praecox*.

Seedling emergence: Seedling emergence evaluation was performed at the LARREA nursery garden using a completely randomized factorial design. The factors were species (*A. lampa and P. praecox)* and substrate treatments (T0, T1, T2, T3, and T4). Twenty-five seeds were sown in 900 cm^3 trays. Each species–substrate treatment combination consisted of five replicates, and emergence was evaluated in a germination chamber with temperature regulation (20°C-10°C, +/-1°C) and photoperiod (12 h light/12 h dark). Over 40 days, the trays were watered with 20 mL of water every 48 hours, and seedling emergence was evaluated at each interval. An emerged seedling was considered one with the cotyledons completely expanded on the surface of the substrate.

Statistical analyses: An analysis of the physicochemical variables (texture, sand granulometry, organic and inorganic carbon, total nitrogen, pH, electrical conductivity, available phosphorus, available potassium, and magnesium) of the substrate treatments was performed using principal component analysis (PCA). All physicochemical variables, except for organic carbon, were compared using Analysis of Variance (ANOVA). In the case of organic carbon, the assumptions of normality were not met, so a Generalized Linear Model (GLM) with a fixed effect of substrate treatment (T0, T1, T2, T3, and T4) was used. The gamma distribution and log link function were applied. Correlations (Pearson coefficient) were also performed between hardness and water content in each substrate treatment. Emergence was analyzed using generalized linear mixed models (GLMMs) with a negative binomial distribution and a log link function. The lme4 package in the R statistical language and InfoStat software were used for analysis and modeling (Di Rienzo *et al*., 2011).

Results and Discussion

Physicochemical characterization of the substrates: Nuclear magnetic resonance spectroscopy did not quantify polyacrylamide in T4, but its presence was inferred at a very low percentage (1.13%) through thermogravimetric tests (Table 1). The PCA conducted on the physicochemical variables of the substrate treatments differentiated them along component 1, which accounts for 76.5% of the variability (Fig. 1). In the negative portion, T0 and T1 were grouped, characterized by a greater proportion of coarse sand and higher pH values, although the latter was not statistically significant. In the positive portion, T4 was positioned, distinguished by higher nutrient content (OC, K, Mg, N) and a greater proportion of fine and very fine particles. The differences observed in T4 for these variables were statistically significant (Table 1). Substrates T2 and T3 were located in the central region of the plot, exhibiting intermediate values for the studied variables.

The pH values indicate that the substrate treatments used were slightly to moderately alkaline in reaction. The electrical conductivity of the substrate treatments varies from 2.93-4.30 $dS\ m^{-1}$ and was classified as slightly saline under T0, T1, T2, and T3, whereas it was classified as moderately saline under T4. The PCA revealed a gradient of nutrient content in the substrate, and coarse granulometry (T0) was positioned at

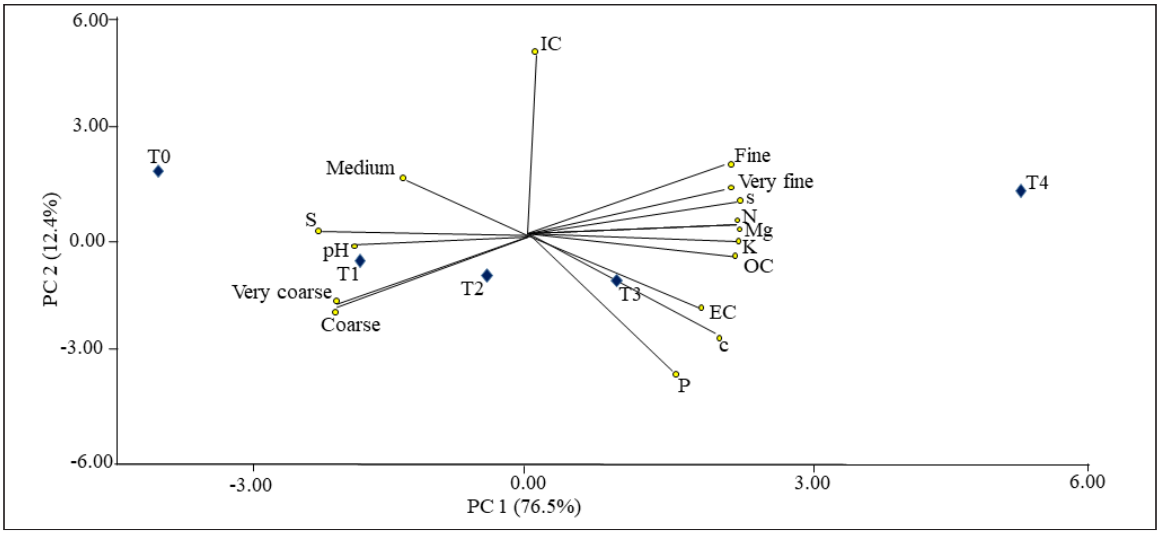

Fig. 1. Principal component analysis (PCA) conducted on the physical and chemical variables of the substrate treatments (T0: 100% coarse granulometry; T1: 75% coarse granulometry - 25% fine granulometry; T2: 50% coarse granulometry - 50% fine granulometry; T3: 25% coarse granulometry - 75% fine granulometry; and T4: 100% fine granulometry). EC: electrical conductivity, IC: inorganic carbon; OC: organic carbon, N: total nitrogen; K: available potassium; Mg: available magnesium; P: extractable phosphorus; c: clay; s: silt; S: sand; Sand granulometry: very fine, fine, medium, coarse, very coarse.

one end of the gradient with the lowest nutrient content, and the fine granulometry (T4) at the opposite end with the highest nutrient content (Fig. 1). The texture of the substrate treatments was varied from sandy in T0, sandy loam in T1, T2, loam in T3 to silty clay loam in T4. Regarding the size of the particles under sand granulometry, an increasing trend in particle

Table 1. Average values and standard error of the physicochemical parameters of the substrate treatments (n=3)

Physico-chemical parameters		T0	T1	T2	T3	T4
pH		8.00 (0.20)[a]	8.00 (0.06)[a]	7.90 (0.06)[a]	7.97 (0.03)[a]	7.87 (0.03)[a]
EC (dS m^{-1})		2.93 (0.60)[a]	3.90 (0.15)[ab]	3.90 (0.43)[ab]	3.67 (0.14)[ab]	4.30 (0.14)[b]
IC (%)		0.11 (0.70)[a]	0.03 (0.01)[a]	0.05 (0.02)[a]	0.06 (0.03)[a]	0.09 (0.01)[a]
OC (%)		0.08 (0.05)[a]	0.17 (0.05)[ab]	0.19 (0.11)[ab]	0.28 (0.1)[ab]	0.39 (0.11)[b]
Nt (%)		0.01 (3.8 E-3)[a]	0.01 (3.8 E-3)[a]	0.02 (0.01)[ab]	0.03 (4.9 E-3)[b]	0.05 (4 E-3)[c]
K (µg g^1)		43.07 (12.71)[a]	96.43 (12.47)[b]	143.87 (0.75)[bc]	195.40 (10.87)[c]	316.70 (31.00)[d]
Mg (µg g^1)		56.10 (6.98)[a]	139.17 (0.83)[b]	198.73 (12.69)[c]	294.6 (14.72)[d]	483.03 (10.37)[e]
Pe (µg g^1)		5.50 (2.01)[a]	8.23 (0.91)[ab]	9.83 (1.09)[ab]	12.63 (0.81)[b]	10.33 (3.42)[ab]
Texture	Clay (%)	7.23 (2.64)[a]	13.4 (2.05)[ab]	14.63 (0.98)[ab]	16.57 (2.83)[ab]	18 (5.71)[b]
	Silt (%)	2.17 (0.89)[a]	3.93 (1.68)[ab]	7.23 (0.73)[b]	13.07 (1.94)[c]	26.47 (1.42)[d]
	Sand (%)	90.60 (3.36)[a]	82.67 (2.22)[b]	78.33 (0.32)[bc]	70.33 (0.93)[c]	55.53 (4.37)[d]
Sand granulometry	Very fine sand (%)	1.50 (0.40)[a]	3.50 (0.61)[ab]	4.63 (1.14)[b]	7.80 (0.64)[c]	18.83 (1.36)[d]
	Fine sand (%)	14.5 (1.51)[a]	18.17 (3.38)[ab]	17.27 (0.43)[ab]	22.2 (1.10)[b]	49.2 (2.14)[c]
	Medium sand (%)	24.9 (4.75)[a]	27.17 (6.73)[a]	21.57 (2.45)[a]	20.23 (2.47)[a]	21.97 (1.87)[a]
	Coarse sand (%)	49.97 (3.60)[a]	44.03 (6.83)[a]	48.37 (1.25)[a]	41.43 (1.66)[a]	8.30 (1.47)[b]
	Very coarse sand (%)	9.10 (2.20)[a]	7.10 (2.48)[a]	8.13 (0.52)[a]	8.30 (1.10)[a]	1.63 (0.12)[b]
Polyacrylamide content (%) by nuclear magnetic resonance spectroscopy						Negative
Polyacrylamide content (%) by Thermogravimetry - Organic fraction (%)						1.13 (0.005)

T0 (100% CG); T1 (75% CG-25% FG); T2 (50% CG-50% FG); T3 (25% CG-75% FG) y T4 (100% FG). EC: electrical conductivity, IC: inorganic carbon; OC: organic carbon, N_t: total nitrogen; K: available potassium; Mg: available magnesium; Pe: extractable phosphorus. Sand granulometry: very fine sand (0.12-0.062 mm); fine sand (0.25-0.12 mm); medium sand (0.5-0.25 mm); coarse sand (1-0.5 mm); very coarse sand (1-2 mm). Different letters indicate significant differences between substrate treatments (α=5%)

Table 2. Average values and standard error of hardness (kg cm-²) and water content (%) of the substrate treatments (n=5); and correlation analysis between these two variables. Pearson correlation coefficient (r²) and p-value are shown

Substrates	Hardness (kg cm^{-2})	Water content (%)	r^2	p-valor
T0	0.08 (0.01)	15.22 (1.77)	-0.76	1.7 e-9
T1	0.07 (0.02)	7.98 (0.64)	-0.61	9.8 e-6
T2	0.20 (0.04)	5.29 (0.33)	-0.44	2.8 e-3
T3	0.98 (0.42)	33.06 (4.26)	-0.35	0.02
T4	0.39 (0.11)	32.78 (3.57)	-0.63	3.1 e-6

size (from very fine sand to Coarse sand) was observed in T0, T1, T2 and T3, while in T4 the content of very coarse sand and coarse sand was recorded lower than the of fine and medium sand. The analysis of the hardness and water content of the substrate treatments showed an inverse correlation in three treatments: T0 (r^2 = -0.76; p = 1.7e^{-9}), T1 (r^2 = -0.61; p = 9.8e^{-6}), and T4 (r^2 = -0.63; p = 3.1e^{-6}) (Table 2). In these substrate treatments, as the water content increased, the hardness decreased. The average hardness values (n = 45) were higher in T3 and T4. In T3, the hardness was 0.98 kg cm^{-2} (SE = 0.42) with a water content of 33.06% (SE = 4.26), and in T4, the hardness was 0.39 kg cm^{-2} (SE = 0.11) with 32.78% water content (SE = 3.57). In T2, the average hardness value was 0.20 kg cm^{-2} (SE = 0.04), with a water content of 5.29% (SE = 0.33). T0 and T1 were the substrate treatments with the lowest average hardness values, measuring 0.08 kg cm^{-2} (SE = 0.01) with a water content of 15.22% (SE = 1.77) in T0, and 0.07 kg cm^{-2} (SE = 0.02) with a water content of 7.98% (SE = 0.64) in T1.

Emergence of seedlings

The Monte Desert ecosystem is characterized by high soil heterogeneity at both patch and landscape scales (Bisigato and Bertiller, 2004), which naturally creates conditions for the establishment of different species with different soil preferences (Ruiz *et al*., 2024). This heterogeneity is exacerbated by desertification (del Valle, 1998; Mazzonia and Vazquez, 2009), which generates desert pavements with total loss of properties for seeding emergence. In this case, technosols can be the best option for creating conditions that allow seeds from the reference ecosystem to germinate, received naturally through wind or by planned sowing.

No significant interaction was found between species and substrate treatments (p = 0.1026). However, the effect of both the species (p <0.0001) and substrate treatments (p = 0.0008) was statistically significant. The species, *A. lampa* showed the highest seedling emergence (59.57%, SE = 7.54%), while *P. praecox* observed with 20.74% seedling emergence (SE = 2.86%). Amongst the different substrate treatments, T0 (56.56%, SE = 11.30%) followed by T2 (48.07%, SE = 10.2%), and T3 (42.20%, SE=9.08%) resulted in the highest emergence rates, while T4 (16.28%, SE = 3.42%) showed the lowest (Fig. 2).

The evaluated species showed different emergence capacities in the formulated technosols, consistent with the soil preferences observed in natural conditions (Hernández and Pérez, 2023; Rodríguez Araujo and Pérez, 2023). *Atriplex lampa* showed higher emergence in substrates with fine–coarse granulometric combinations and moderate salinity, likely due to its ability to colonize a wide range of soil types, including saline soils (Fernández, 2020). *Parkinsonia praecox* did not exhibit high emergence in any of the treatments applied. This contrasts with previous studies, which reported emergence rates exceeding 50% in coarse-textured substrates (equivalent to T0 in this study) from seed with a potential germination of 89% (SD 3%) (Saldía, 2025). The colonization of sandy or stony, desertified, and disturbed sites (Pece *et al*., 2013; Guevara *et al*., 2024) suggests a tendency for these species to colonize particular types of soils. However, in experimental conditions, *P. praecox* exhibited excessive fungal proliferation, which may have been influenced by the laboratory environment in which the experiment was conducted. This species possesses abundant reserves in its cotyledons, and prolonged exposure to moist substrates could lead to seed loss due to fungal attack, a phenomenon that may not occur in nature. For this reason, new studies are required on this species in natural or semi-natural conditions.

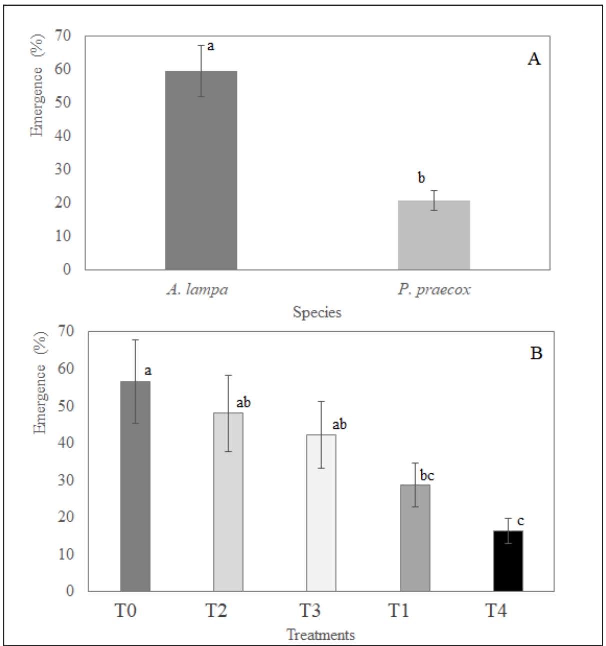

Fig. 2. A. Mean emergence and standard error of A. lampa and P. praecox in the study treatments. B. Mean emergence and standard error for each substrate treatment: T0: 100% coarse granulometry; T1: 75% coarse granulometry - 25% fine granulometry; T2: 50% coarse granulometry - 50% fine granulometry; T3: 25% coarse granulometry - 75% fine granulometry; and T4: 100% fine granulometry. Different letters indicate significant differences (a=5%).

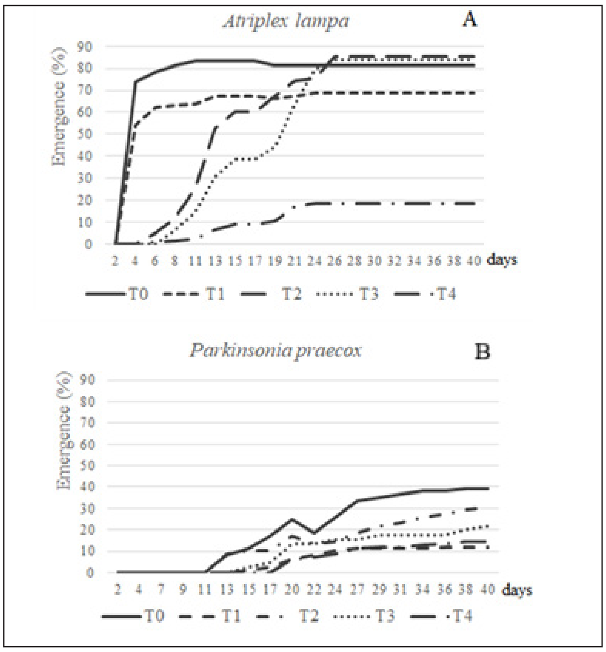

Fig. 3. A, B. Percentages of emergence over time for the species A. lampa and P. praecox, in different substrate treatments (T0: 100% coarse granulometry; T1: 75% coarse granulometry - 25% fine granulometry; T2: 50% coarse granulometry - 50% fine granulometry; T3: 25% coarse granulometry - 75% fine granulometry; and T4: 100% fine granulometry).

A. lampa reached its maximum emergence peaks more rapidly, particularly in the treatments T0 and T1, on days 8 and 13, respectively. In contrast, *P. praecox* reached its peak after 31 days of the trial in T0 (Fig. 3). Low and delayed emergence of seedlings in T3 and T4 may be due to intense fungal infection, observed on the surface of these substrate treatments in case of *P. praecox*.

The T4 treatment (with the highest proportion of fine granulometry) showed elevated levels of clay, hardness (negatively correlated with moisture content), total nitrogen (N), available phosphorus (P), magnesium (Mg), and potassium (K). These values exceeded those typically recorded in native soils of the Monte Desert (González and Pérez, 2024). Although high levels of nitrogen (N) and phosphorus (P) can promote seedling emergence in dryland species worldwide (Ceccon *et al*., 2003), the high content of fine particles and soil hardness in T4 can severely restrict emergence. Research by Mayence *et al*. (2017) on the emergence of three tree species in different substrates confirms the difficulty of emergence in fine-textured soils. Similarly, Uselman *et al*. (2015) reported contrasting responses depending on plant functional type: a mix of native grasses exhibited higher emergence in sandy loam soils compared to clay loam soils, whereas a shrub seed mix performed better in clay loam soils. Therefore, although T4 is not considered suitable as a technosol for the shrub species *Atriplex lampa* and *Parkinsonia praecox*. Its potential use should be further explored with other plant functional groups.

Polyacrylamide did not degrade into its toxic monomer (acrylamide) during the flocculation of the fine fraction of fracking sand, confirming the irreversibility of the polymerization process (Zohuriaan-Mehr and Kabiri, 2008). This supports the safe use of polyacrylamide—commonly referred to as "hydrogel"—as a soil amendment to improve seedling survival in restoration projects (Akhter *et al*., 2004; Al-Humaid and Moftah, 2007). Hydrogel application has been associated with improved soil physical properties, including reduced compaction, enhanced aggregation, and increased porosity (Agaba *et al*., 2010; Yu *et al*., 2015). Although its effectiveness may vary depending on soil texture (Abedi-

Koupai *et al*., 2008; Agaba *et al*., 2010; Abdallah, 2019), this technique has been widely adopted in restoration initiatives in the Monte Desert (González and Pérez, 2017; Pérez *et al*., 2020), as well as in other arid regions worldwide (Bainbridge, 2007; Chirino *et al*., 2011).

Conclusions

Desertification processes often lead to soil loss or the formation of substrates through a eolian deposits, resulting in contrasting characteristics (UNCCD, 2017). These changes in the soil severely affect the germination of native plants (Ruiz *et al*., 2024). The present study demonstrated that specific combinations of granulometries and physicochemical properties of residue materials (technosols) can promote the emergence of framework species for the ecological restoration of arid lands. *A. lampa* emerged as a suitable species that achieves high emergence values (close to the potential germination potential. The substrate treatments T0, T2, and T3, with seedling emergence rates ranging from 56.6% to 42.2% may be considered viable "technosol formulas". *A. lampa* produces seeds in large quantities, a key trait supporting its designation as a framework species. This characteristic enables high seeding densities in the technosol, making this combination suitable for use in seed-based restoration.

Author contributions: *FG*, DP, MEO, conceived and designed the research; FG, FF performed the experiments; FG, CM, MEO analyzed the data; FG, DP wrote and edited the manuscript.

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