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Analysis of the incorporation of sludge from a water treatment plant (WTP) into soil for use in impermeable layers of a sanitary landfill

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Article

Keywords
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Abstract

The collection and treatment of water are crucial to ensure the provision of safe drinking water for the population. Raw water is treated using physical and chemical processes to produce treated water for distribution to cities, but the processes also generate waste. The waste from Water Treatment Plants (WTP) is known as WTP sludge. Disposing of WTP sludge in an environmentally friendly manner is crucial. In order to minimize the environmental impact, waterproof barriers are designed in landfills to prevent the contamination of underground water resources provoked by the percolation of generated liquids. This study assessed the geotechnical feasibility of using WTP sludge as a waterproofing material in landfills. The benefits of this process include a decrease in soil extraction from quarries and the environmentally sound disposal of waste. The approach is based on the growing demand for sustainable practices in the treatment and disposal of waste, while also seeking a technical alternative to partially replace soil in geotechnical structures, aiming for resource conservation. The study characterized the sludge from the WTP and conducted tests on compaction, hydraulic conductivity, and oedometric consolidation. Two different fractions of the soil-sludge mixture (2.5% and 5%) were used, with moisture contents ranging from 17.62 to 46.71%. The results showed that the addition of sludge either maintained (2.5%) or improved (5%) the permeability characteristics of the residual soil under study. In optimal conditions, the permeability was approximately 10^{-9} m/s, which renders it suitable for use in waterproofing layers for landfills.

1. Introduction

Since the 21st century, urbanization has grown all over the world. Unfortunately, population growth in urban areas has been largely unplanned, leading to the construction of homes in irregular areas. As a result, the lack of basic infrastructure for the population, the importance of implementing improvements to the basic sanitation system, and the availability of drinking water became evident (Rangel, 2005).

According to research carried out for the World Bank by Kaza et al. (2018), around 1.4 billion tons of municipal solid waste (MSW) are generated worldwide every year, which represents 1.27 kg per capita per day.

In addition to MSW, sludge from water or sewage treatment processes is also disposed of in landfills or dumps. In these treatment processes, substances are added to promote the agglutination of particles, which then settle as sediment, resulting in water treatment plant (WTP) sludge (Rodrigues & Holanda, 2013). The characteristics of WTP waste depend on the quality of the raw water, the chemicals used, and the treatment technology applied. Studying the composition of sludge is important to improve understanding of the resulting waste and establish reuse methodologies. Its disposal is a major environmental problem, as around 1 to 5% of the volume of raw water treated results in solid content, i.e. WTP sludge (AWWA, 1978; Katayama, 2012).

On the other hand, the efficiency of landfills is closely related to the performance of the layers used to waterproof them. To minimize the infiltration of leachate into groundwater, it is necessary to use layers with low hydraulic conductivity and high shear strength (Dixon et al., 1999).

The lining layers in landfills, whether they are bottom layers, daily covers, or final covers, have multiple purposes such as isolating the waste from the external environment, draining percolate and gases, and separating the landfill into cells. The layers can be made of synthetic materials (such as

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geosynthetic barriers), of natural materials, such as compacted soils, of mixtures of soil with other low permeability materials, or even a combination of geosynthetics and compacted soils. Therefore, using WTP sludge for geotechnical purposes, such as mixing it with soil for bottom waterproofing layers, daily cover, and final cover for landfills, can be a technically promising solution for its disposal, provided that the relevant geotechnical parameters are respected, and the behavior of the soil-sludge mixture proves to be suitable for use in landfill layers.

Daniel & Koerner (1993) and Sharma & Reddy (2004) studied the use of different types of soil as cover layers and concluded that for a compacted soil cover system, the material used must meet certain criteria to achieve good performance, such as: having low saturated permeability ($k_s \leq 10{-}7$ m/s) to minimize water infiltration into the residual material layers below the cover; proper soil compaction to ensure that the compaction energy is evenly distributed across all soil layers; and the compacted cover layer must not crack.

The study by Rahardjo et al. (2017) used compacted soil to minimize rainwater infiltration into a landfill in Singapore. The results demonstrated good performance of this cover system, minimizing leachate movement to the surrounding area.

In another study, Rahardjo et al. (2018) identified that the presence of concrete particles reduced the water retention and storage capacity of surface soil by 45% compared to soil without concrete particles. In addition to the low water retention capacity, the mixture also exhibited a lower permeability coefficient, which was due to the finer concrete particles in the mixture. In research on the use of another type of waste, Ou et al. (2022) presented experimental results showing that the reuse of residual slag from tunnel excavations, in the appropriate proportion, can be recycled as one of the components of injection material for tunnel engineering, demonstrating performance similar to the original grouting injection material mix.

Gonçalves et al. (2017) point out that using WTP sludge in landfill layers to be justified requires the geotechnical criteria for landfill waterproofing such as adequate granulometric distribution and low permeability. If the parameters of the mixture are found to be adequate, its use has the advantage of not reducing the useful life of the landfill and allowing for the decrease of soil borrow areas for waste containment operationalization.

Although still considered scarce, there has been an observed increase in the number of studies focusing on the geotechnical properties of WTP sludge in recent years (Boscov et al., 2021).

To investigate potential applications of sludge and avoid improper disposal, studies have explored the possibility of using WTP sludge, as well as wastewater treatment plant (WWTP) sludge and leachate treatment plant (LTP) sludge, as a construction element, either associated with soil or not.

Regarding the application of WTP and WWTP sludge, Castilhos Junior et al. (2012) conducted physicochemical characterizations of both types of sludge collected from the treatment plants in Jurerê Internacional, located in Florianópolis, Santa Catarina. The authors also characterized mixtures of sludge with quicklime, for chemical stabilization, and clayey soil. They concluded that, although WTP and WWTP sludge are not suitable for direct use as cover material, their mixtures with soil and lime met geotechnical requirements for application in landfill cover layers.

The study by Mazzutti et al. (2023) indicated that for the WTP sludge from the water treatment plant in Frederico Westphalen - RS, the soil-sludge mixtures studied could be used as construction layers in landfills. Notably, the mixture with 30% sludge addition was identified as the best for application in base and cover layers. Samples of this mixture achieved the required permeability coefficient for landfill applications and exhibited the highest unconfined compressive strength among all samples.

Knierim et al. (2023) conducted a technical feasibility analysis of using WTP sludge-soil mixtures from Santa Maria - RS in landfill layers, based on minimum permeability coefficient values established by various standards. The authors concluded that the mixture incorporating 15% WTP sludge performed best, as it met the most stringent permeability requirements, making it suitable for application in landfill base and cover layers.

Scapin (2021) analyzed samples of WTP sludge-soil mixtures from Santa Maria - RS under chemical, physical, and biological parameters. The author constructed experimental cells with municipal solid waste and, after analyzing the waste mass inside the cells and the generated leachate, concluded that the sludge did not increase environmentally harmful parameters. Scapin (2021) concluded that the sludge could be used in base and cover layers in landfills, with 15% sludge incorporated into the layers.

This paper presents the initial results of the characterization of WTP sludge obtained from the WTP located in the city of Pinhais, in the state of Paraná, Brazil, aiming to contribute to the technical literature by employing a sludge that has not been studied so far for applications of this nature. It is noteworthy that the research focused on the use of the raw material for geotechnical applications without the need for pre-processing. For the characterization of the material, tests commonly used in soil characterization were employed.

2. Materials and methods

The research comprised three stages, according to the following flowcharts. In the first stage, the soil was characterized (Figure 1); in the second stage, the sludge was characterized (Figure 2) and in the third stage tests were carried out with the soil, sludge, and mixtures in the percentages in terms of 97.5% soil - 2.5% sludge (raw) and 95% soil – 5% sludge (raw) (Figure 3). The proportions were defined

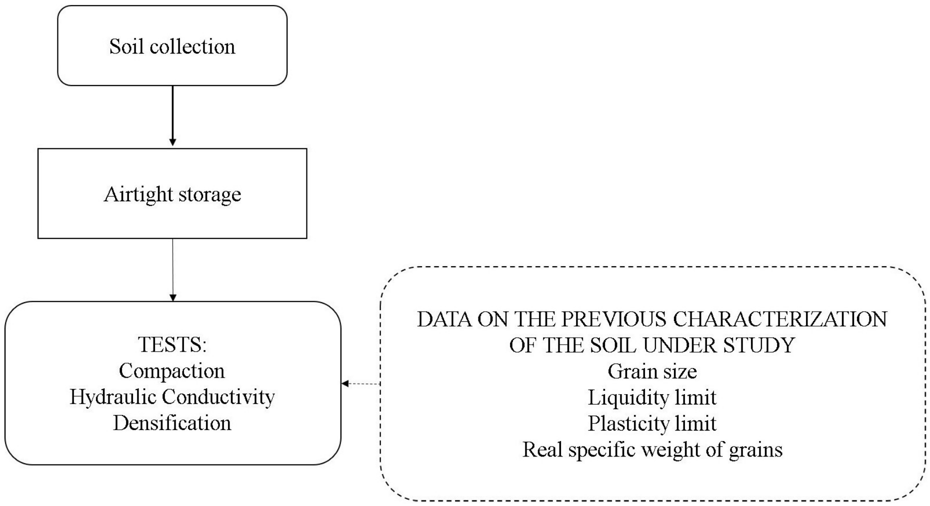

Figure 1. Soil research flowchart.

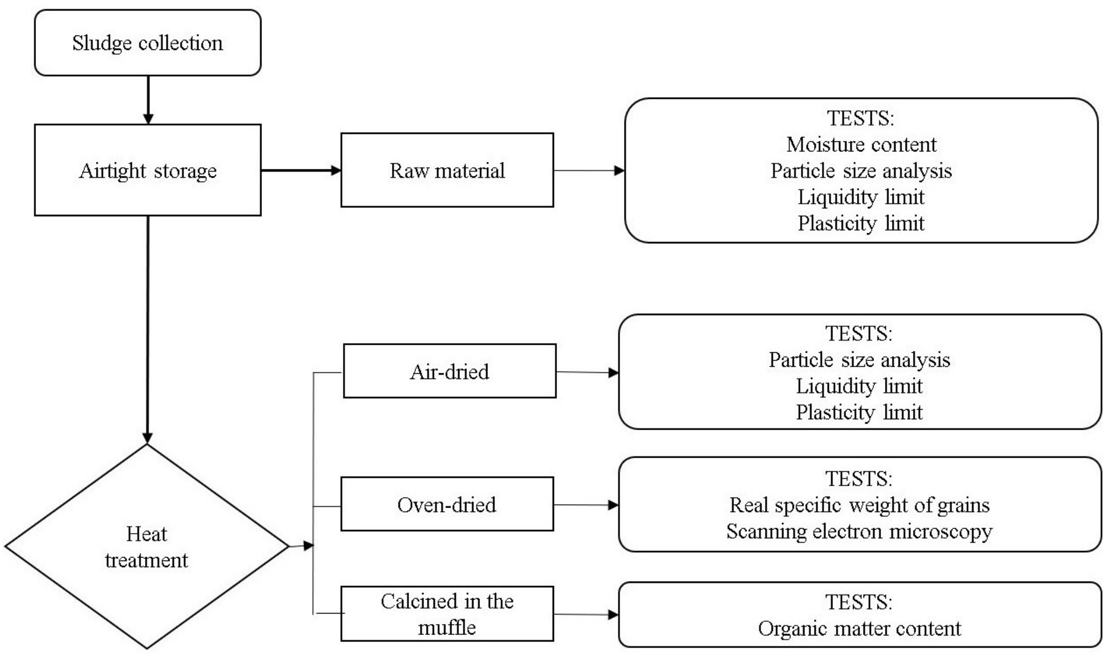

Figure 2. Sludge research flowchart.

considering the objective of analyzing the behavior of the soil with lower sludge incorporations, aiming to observe the influence of the addition of sludge on the properties of the natural soil in quantities lower than those usually reported in the literature on the subject. As observed by Montalvan (2016) and Gonçalves et al. (2017), similar studies using proportions ranging from 15% to 100% were observed in the literature. It is important to emphasize that the proportions used in the mixtures were calculated in terms of the dry mass of the components, but that the incorporation of sludge into the soil occurred in the raw state, leading to the use of larger masses of waste due to the high moisture content intrinsic to the sludge in the disposal state.

The collected soil was mixed with the sludge to form a waterproofing layer for the embankment, and its behavior was analyzed through laboratory tests. The soil samples studied were provided by the Experimental Field for Geotechnical Studies in Ponta Grossa (*Campo Experimental de Estudos Geotécnicos de Ponta Grossa*), which is predominantly silty-clay and typically found in the Campos Gerais region. Its characterization has been reported in recent publications for different geotechnical applications (Anibele et al., 2020;

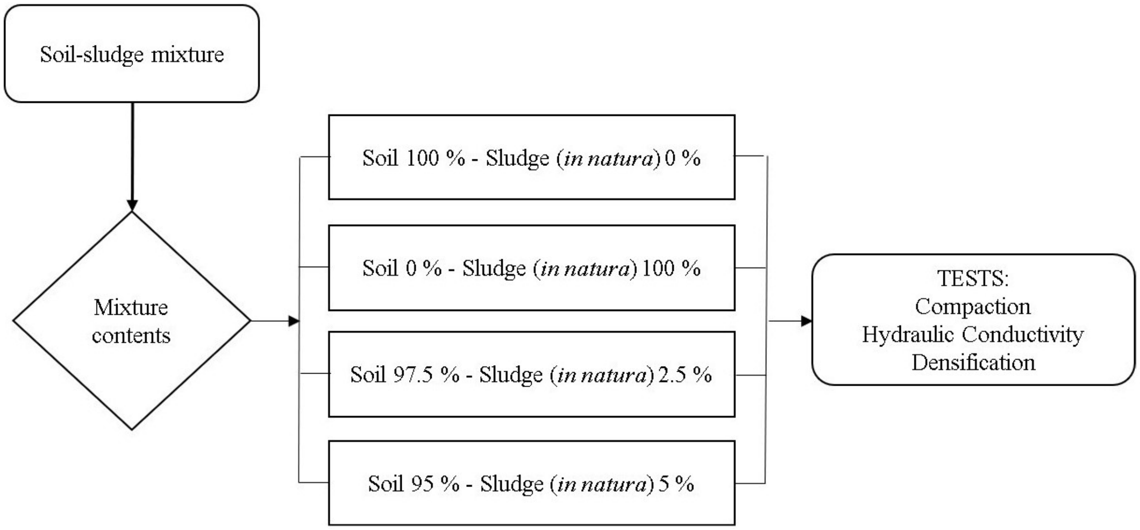

Figure 3. Flowchart of research on soil-sludge mixtures.

Figure 4. Experimental Field for Geotechnical Studies in Ponta Grossa location.

Pereira & Vargas, 2019; Tonus et al., 2022). The geotechnical tests conducted to characterize the natural soil followed the guidelines of NBR 6457: Soil Samples - Preparation for Compaction Tests and Characterization Tests (ABNT, 2016a).

Centrifuged sludge from the Iraí WTP, located in the municipality of Pinhais, Paraná, was used in this study (Figure 4). This plant supplies water to over 1 million inhabitants of the city of Curitiba and the metropolitan region (Oliveira, 2010). At this WTP, the raw water undergoes complete treatment through a process that includes flotation, coagulation, flocculation, filtration, disinfection, pH correction, and chlorination. The decanters have been replaced by floto-filtration, which is a physical separation process based on the dissolved air flotation process. In this process, water saturated with air is mixed with the flocculated water in an expansion chamber that precedes the floto-filters (flotation in the top layer of the filters).

The sludge is scraped from the surface and dehydrated through centrifugation. The resulting sludge used in the research had an average solids content of 22.58% and was in a pasty state. It underwent physical-chemical and geotechnical characterization to determine its potential as a substitute for dry matter when mixed with soil. The geotechnical characterization included moisture content tests (NBR 6457/2016), granulometric analysis (ABNT, 2016d), actual specific weight (DNER-ME 093/1994), Atterberg limits (liquidity and plasticity limits) (NBR 6459/2016 and 7180/2016), and organic matter content (ABNT, 2022). To determine the moisture content and specific weight of the grains, the sludge underwent drying in an oven at 60 ± 5 °C and 105 ± 5 °C. This allowed for observation of variations in these parameters while considering the possible presence and influence of organic matter. Atterberg limits tests were conducted on sludge samples prepared under three conditions: air-dried, oven-dried at 60 ± 5 °C, and unprocessed.

Particle size analysis of the sludge was conducted on two samples: raw sludge and dried sludge using the Bettersizer 2600 Particle Size Analyzer. Chemical characterization was performed on three crumbled and dried sludge samples in an oven at 60 ± 5 °C, using Scanning Electron Microscopy (SEM) to obtain images and point chemical analysis through Energy Dispersive Spectroscopy (EDS).

The soil and sludge samples were characterized individually before being mixed in two different proportions: 97.5% soil - 2.5% sludge (raw) and 95% soil – 5% sludge (raw). The purpose of this study was to investigate the effect of sludge addition levels on the geotechnical behavior of the mixtures. Compaction, hydraulic conductivity, and oedometric consolidation tests were conducted for both percentages of soil-sludge mixture, as well as for samples of sludge alone.

The objective of this phase was to compare the characteristics of the soil-sludge mixtures with those specified for landfill-cover soils.

3. Analysis and results

Tests carried out on samples taken at different depths, according to DNER-ME 093 (DNER-ME, 1994), revealed that the actual specific weight of soil grains ranges from 26.3 to 28.5 kN/m³. The consistency characteristics, obtained through tests defined by NBR 6459 (ABNT, 2016b) and NBR 7180 (ABNT, 2016c), shows in the Table 1, indicate that the soil's liquidity limit (LL) falls between 31% and 43%, characterizing it as a non-plastic soil due to the lack of a plasticity index (Anibele et al., 2020).

After characterizing the soil, we proceeded to analyze the WTP sludge. As sludge is composed of suspended solids from raw water treatment, it is expected to contain a certain percentage of organic matter. Therefore, we dried sludge samples in an oven at 60 ± 5 °C and 105 °C ± 5 °C to compare the results. Regarding moisture content, the sample yielded values of 342.87% when dried in an oven for 24 hours at 60 ± 5 °C and 368.66% when dried in an oven for 24 hours at 105 ± 5 °C.

As there was a variation in moisture content between the two drying temperatures, it is considered that there is an organic matter content being volatilized at higher temperatures. Since the aim of the study was to use natural sludge without undergoing a drying process, the moisture content value of 60 °C ± 5 °C drying, applicable to soils with organic matter according to NBR 6457/2016, was adopted.

The specific gravity values of the grains were 20.51 kN/m³ for samples dried in an oven at 60 ± 5 °C and 21.10 kN/m³ for samples dried in an oven at 105 ± 5 °C. This difference in moisture content and the low specific gravity values, when compared to soils, may indicate the presence of a higher amount of organic matter, which is susceptible to volatilization at higher temperatures. This point is reinforced when evaluating the result of the organic matter content test, which indicated 51.72% when the samples were dried in a muffle oven at 700 °C for 2 hours. The obtained data at this stage of the characterization is consistent with previous studies by Roque et al. (2021), Montalvan (2016), and Scapin (2021).

O'Kelly (2016) found that the specific mass of WTP sludge solids decreases with an increase in organic matter content. Therefore, a high percentage of organic matter leads to a decrease in the specific mass value. Furthermore, it is expected that higher temperatures will result in greater solubilization of organic matter. The values obtained for the sludge from the Iraí WTP are consistent with the expected behavior found in the literature.

Particle size analysis was performed using a Bettersizer 2600 particle size analyzer with two samples of sludge: raw and dried at room temperature. The curves for these two types of samples were chosen to better visualize the impact of drying on waste particle size (Figure 5).

The granulometry curve of the dried sludge shows a shift to the right compared to the raw sludge. This reaction may be due to the sludge's behavior during water loss. As the sludge dries, its particles agglutinate, forming larger, strongly cemented lumps, resulting in a granular texture (Montalvan, 2016).

Regarding the consistency limits of the sludge, both tests were conducted using raw sludge and sludge dried at room temperature. The LL values obtained were 100% for sludge dried at room temperature and crumbled, and 487% for raw samples.

Regarding the plasticity limit (LP), only the raw sample exhibited plasticity with an LP value of 392%. This indicates a Plasticity Index of 95%, which indicates that the raw sludge is highly plastic. These values are comparable in magnitude to those found in other studies of sludge in this state, such as Roque et al. (2021). Plastic properties are influenced by moisture content, particle shape, particle size, and the chemical and mineralogical composition of the material. According to Scapin (2021), the sludge loses its plastic characteristics during the drying process, indicating changes in other factors besides moisture content.

Table 1. Results of characterization tests carried out in the soil (Anibele et al., 2020).

Sample	Actual specific weight (kN/m³)	Liquidity limit (%)	Plasticity limit (%)	Plasticity index (%)
Soil	26.3 - 28.50	31 - 43	-	NP

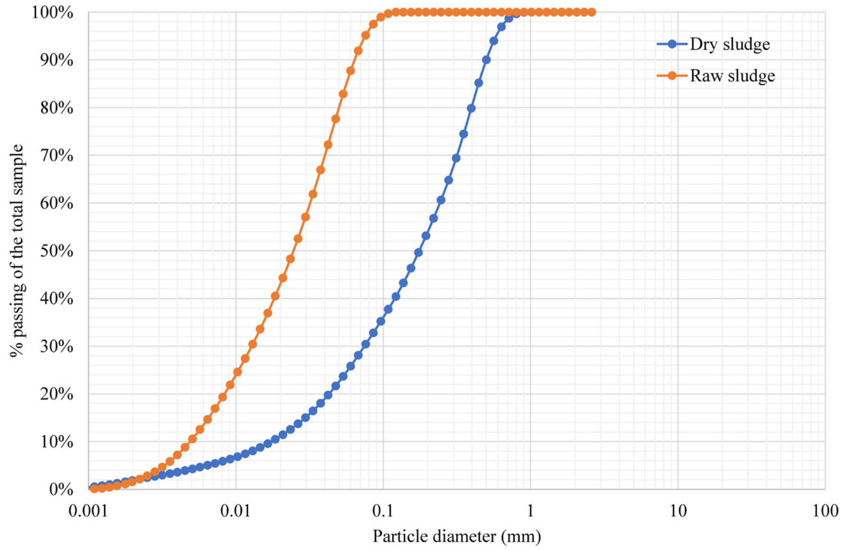

Figure 5. Particle size curves of dry and raw sludge.

The behavior of dry sludge differed significantly from other types. The liquidity limit was found to be 100%. Upon testing for plasticity limit, the dry sludge was classified as non-plastic.

Based on the granulometric analysis and Atterberg limits, it was determined that raw sludge is classified as an organic clay (OH) within the Unified Soil Classification System (SUCS) due to its high organic matter content and non-plasticity after drying (Roque et al., 2021). Dry sludge, however, has a different classification as it contains less than 50% fines. Based on the SUCS classification, dry sludge is classified as silty sand (SM).

The EDS analyses revealed that the sludge contains an average of 22.05% Carbon (C), 33.59% Oxygen (O), 21.54% Aluminium (Al), 6.82% Silicon (Si), 1.09% Sulphur (S), and 14.91% Iron (Fe). The micrographs show that, even at the highest magnification, the sludge components still occur in an agglomerated form, with fragments in the colloidal range, confirming the material's extremely fine nature.

Compaction tests were conducted for all variations of soil-sludge mixtures (0%, 2.5%, and 5%) using raw sludge. A compaction test was not performed on the pure sludge sample due to its semi-solid state and high moisture content, which made it impossible to compact.

Soil and sludge mixtures were created using the aforementioned soil. Compaction tests were conducted following the Normal Proctor energy method as per NBR 7182 (ABNT, 2016e). Different combinations of sludge were incorporated to replace the dry mass portion of the soil, including fresh sludge at two levels (2.5% and 5% of solids content) and dried and crumbled sludge (5% of solids content). Figure 6 displays the compaction curves of the amended materials in comparison to the compaction curve of the pure soil (soil-sludge 0%) and includes the saturation curves.

It can be observed that the inclusion of raw sludge has modified the position of the compaction curve, resulting in an increase in the optimum moisture content and a decrease in the dry apparent specific weight. This behavior is expected for soils with higher clay content (Pinto, 2006). When sludge was used in its dry and crumbled state, the curve changed very little, remaining close to the curve of the original soil. This behavior is consistent with the differences observed in the consistency tests carried out on raw samples and dry and crumbled samples. The former shows high plasticity indexes, while the latter shows non-plastic behavior, indicating the influence of the sludge preparation processes on the mixture behavior.

The results of the soil compaction tests indicate that the maximum dry apparent specific weight value of the soil under Normal Proctor conditions, governed by NBR 7182 (ABNT, 2016e), was 14.9 kN/m^3, associated with an optimum moisture content of 24.6%. These values were crucial in defining the three compaction variations studied. The Table 2 shows the optimum moisture content and maximum apparent dry weight for each case.

For this study, tests were conducted on the application of sludge in low-permeability layers. To incorporate raw sludge into the soil mass, quantities of 2.5% and 5% were evaluated in the compaction tests. This option was deemed optimal because it allows for the sludge to be delivered directly to the WTP without requiring pre-treatment. Additionally, it leads to compaction of the soil, creating an impermeable layer suitable for use with clay materials.

The hydraulic conductivity test was conducted using a rigid-wall permeameter with a variable load, following the guidelines of NBR 14545 (ABNT, 2021), based on the results of previous tests.

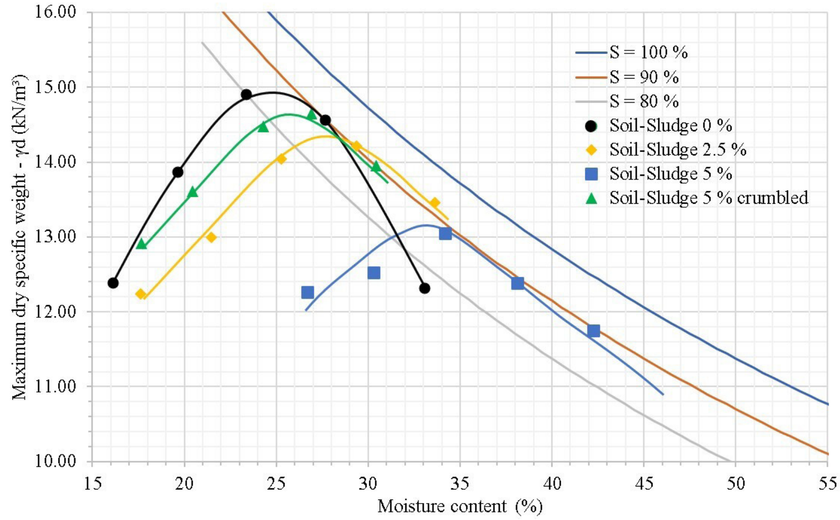

Figure 6. Compaction curves of soil-sludge mixtures.

Table 2. Optimum compaction values for pure soil and soil-sludge mixtures.

Variable	Sample evaluated		
	Pure Soil	Soil-Sludge 2.5%	Soil-Sludge 5%
Optimum moisture (%)	24.6	28.2	34.2
Maximum apparent dry unit weight (kN/m^3)	14.98	14.28	13.05

Table 3. Hydraulic conductivities obtained for pure soil and soil-sludge mixtures.

Variable	Sample evaluated		
	Pure Soil	Soil-Sludge 2.5%	Soil-Sludge 5%
Hydraulic conductivity (m/s)	8.5 x 10^{-8}	1.8 x 10^{-8}	4.9 x 10^{-9}

The samples for the hydraulic conductivity test were prepared with maximum compaction, meaning that compaction energy was applied to reach the γ_d and $\omega_{optimum}$ values. The hydraulic conductivity of the material was affected by the variation in the percentage of sludge applied to the mixtures. The raw sludge used in the tests has a high percentage of fines, as seen in the particle size curve. This portion of waste in the colloidal range helped to reduce the pore size between grains in the mixture, thus reducing the hydraulic conductivity coefficients. As a result, the mixtures were less permeable when compared to pure soil (Ferreira et al., 2011).

The results indicated that the addition of sludge maintained (2.5%) or improved (5%) the permeability characteristics of the residual soil under investigation. In the best condition, the hydraulic conductivity was approximately 10-9 m/s, making it ideal for waterproofing applications, such as mineral barriers in landfills. Table 3 displays the results of the tests conducted on the pure soil and with the raw sludge additions.

The deformability study of the soil, sludge, and soil-sludge mixtures was conducted through oedometer compression tests on compacted specimens, following the recommendations of NBR 7182 (ABNT, 2016e). The samples were molded with the incorporation of raw sludge to verify the feasibility of using the material without prior treatment, apart from that already carried out at the WTP, as this would allow for the conservation of natural resources and add value to the waste. The oedometer compression tests were performed following the recommendations of NBR 16853 (ABNT, 2020), which included two preloading stages, six loading stages, and three unloading stages. The stresses applied at each stage are presented in Table 4. The stress level adopted as the limit for the tests (400 kPa) was determined based on the maximum expected surcharge values for the evaluated scenario of application in sanitary landfills.

For the execution of the test, displacement stabilizations between loading increments were observed. The acquisition time interval was defined so that the time intervals between each acquisition follow an exact square root sequence, as indicated by ASTM D 2435M-11 (ASTM, 2011). The samples were prepared within a circular mold with a diameter of 50.5 mm and a height of 20 mm, with mass control to achieve the maximum dry bulk density values for each sample. With the mold integrated into the consolidation cell and positioned at the center of the equipment base, the material sample was saturated for the test execution.

For the calculation of the compression coefficients (C_c), related to soil compression under load during the primary consolidation phase, and recompression coefficients (C_r), related to the deformability of the soil when reloaded after being unloaded, the Equation 1 was used for both calculations.

$$C_{c,r} = \frac{e_2 - e_1}{log_{10} p_2 - log_{10} p_1} \tag{1}$$

where: e_1 e e_2 area the void ratios corresponding to two arbitrary points on the recompression or virgin compression lines; p_1 and p_2 are the pressures associated with the void ratios e_1 and e_2.

Table 5 presents the physical properties of the specimens. The pure sludge was tested in its raw condition, while the soil-sludge mixtures were tested under optimum compaction conditions. Figures 7 and 8 display the consolidation curves of the soil, sludge, and soil-sludge mixtures obtained in this test.

The soil-sludge samples molded under the optimum moisture conditions have a higher initial void ratio, as indicated by the maximum dry specific weight (γ_d) obtained in the compaction curve. This leads to greater variations in the void ratio under the same loading stages compared to the sample without the addition of soil sludge. Although compressibility is higher in mixtures with a higher sludge content, hydraulic conductivity is lower in these cases. This indicates that, after consolidation by densification, the hydraulic conductivity of the mixture tends to decrease over time. This is a desirable characteristic for waterproofing layer materials in landfills.

For soil compacted under optimum conditions, the compaction index (C_c) was 0.046 and the recompression index (C_r) was 0.028. For the 2.5% soil-sludge mixture, the C_c increased to 0.051 and the C_r to 0.039. The 5% soil-sludge mixture showed the highest values, with C_c of 0.080 and C_r of 0.060. The compression and recompression results for both soil-sludge compositions were found to be higher than for pure soil, indicating that the mixtures are more compressible than pure soil compacted to the optimum moisture level. This is supported by the high compressibility of the pure sludge, which is unable to be compacted in the oedometrtic ring due to its consistency. This is evidenced by the C_c value of 1.399 and the C_r value of 0.691 (Table 6).

When analyzing the results from Table 6 and Figures 7 and 8, it is observed that the incorporation of WTP sludge influenced the C_c values of the soil-sludge mixtures. This trend was also noted by Boscov et al. (2021), where the authors concluded that sludge could increase the compressibility of the sample. Additionally, the sludge sample itself presented a C_c value approximately 30 times greater than that of the soil. This characteristic can be considered undesirable for applications in landfill layers that need to maintain their initial thicknesses. Preserving the geometry is important for maintaining other geotechnical characteristics, such as impermeability and strength, when subjected to progressive overloads caused by landfill height increases.

In Figure 7, both C_c and C_r increased progressively as the sludge percentage increased, with the difference between C_c and C_r values growing closer to that of the raw sludge sample. Observing this behavior corroborates the interpretation that higher sludge additions lead to greater compressibility and a higher tendency for compression after stress relief. Furthermore, the sludge exhibited a C_r value approximately 24 times greater than the residual soil. This trend is consistent when compared to C_c, as recompression shows a smaller void ratio variation, considering the elastic nature of the compressibility curve.

The high compressibility of the raw sludge sample (Figure 8) is justified by the inability to compact it in the consolidation ring due to its consistency. The C_c value of

Table 4. Loads applied in the consolidation test stages.

Step	Stage	Applied load (kPa)
Preload	1º	2
	2º	5
Load	1º	12
	2º	25
	3º	50
	4º	100
	5º	200
	6º	400
Unloading	1º	200
	2º	50
	3º	12

Table 5. Initial physical properties of the samples for the consolidation tests.

Sample	Maximum dry specific weigth	Optimum moisture	Void ratio
	γ_d (kN/m³)	$w_{optimum}$ (%)	e_i
Sludge	2.39*	342.87*	7.828*
Soil-Sludge 0%	15.15	24.55	0.761
Soil-Sludge 2.5%	14.22	28.20	0.871
Soil-Sludge 5%	12.90	34.20	1.058

*Data from the raw sludge used to carry out the test. It was not possible to compact it due to its consistency.

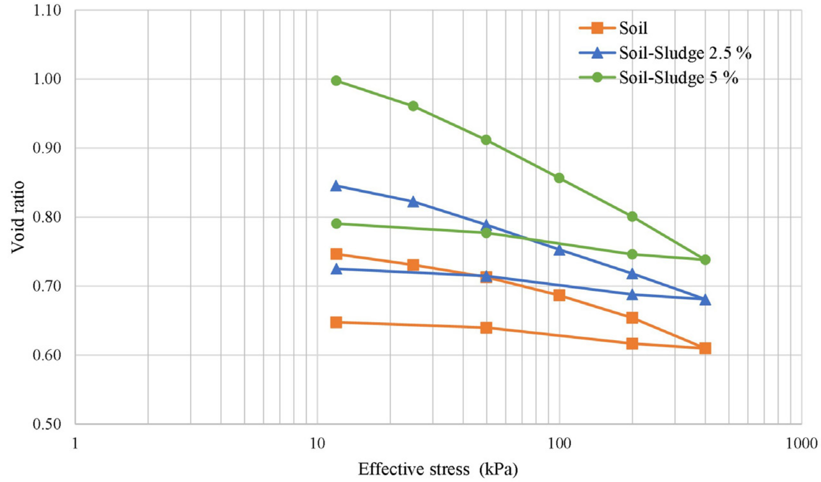

Figure 7. Consolidation curves - Soil and soil-sludge mixtures.

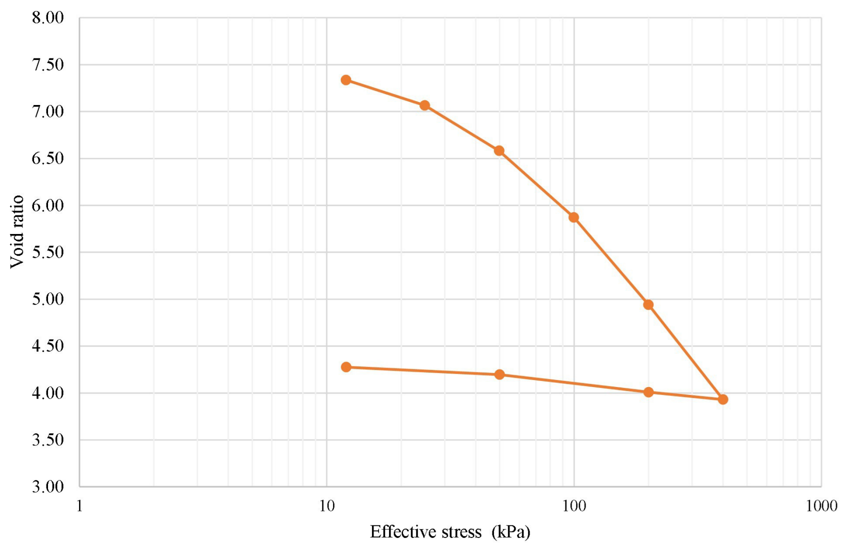

Figure 8. Consolidation curve - Sludge.

Table 6. Evolution and recompression index of soil, sludge and soil-sludge sample.

Sample	Compression index (C_c)	Recmpression index (C_r)
Sludge	1.399	0.691
Soil-Sludge 0%	0.046	0.028
Soil-Sludge 2.5%	0.051	0.039
Soil-Sludge 5%	0.080	0.060

1.399 is considered compatible with those found by O'Kelly (2016). The soil-sludge mixtures exhibited C_c and C_r values closer to those of the soil, despite showing the previously mentioned trend of increasing coefficients as the sludge percentage in the mixture increased.

The compression index results were lower than those obtained by Montalvan (2016) in his study incorporating 16.7%, 20%, and 25% sludge into sandy soil, where compression index values ranged from 0.13 to 0.19, and recompression index values ranged from 0.02 to 0.03. This result indicates that, in mixtures with a low percentage of WTP sludge, the soil characteristics are more dominant.

4. Conclusion

The study seeks to contribute to environmental sustainability concerning the proper disposal of waste generated in WTPs, using it as an addition to soil for waterproofing layers in landfills. The inclusion of WTP sludge in a semi-solid state, in mixtures with soil, demonstrated the technical feasibility of using the waste in civil engineering applications, such as landfill sites. The findings indicated that it is viable from the point of view of hydraulic conductivity, with values suitable for applications in waterproofing layers, and from the point of view of consolidation, indicating variations in void ratio that will further reduce permeability, with a compression coefficient in soil-sludge mixtures much lower than that of pure sludge.

The use of sludge as a substitute for soil (sludge in a semi-solid state) is a beneficial practice as it not only conserves natural resources such as water and soil, but also adds value to the waste, which has the potential to be used as a construction material in waterproofing layers in landfills where it would be disposed of, or even in the manufacture of products with a high production volume, such as road embankments, because it has acceptable hydraulic conductivity for waterproofing layer material.

The maximum dry specific weight values decreased, and the optimum moisture content increased as the percentage of sludge in the mix increased. Additionally, the hydraulic conductivity coefficient values decreased, indicating greater impermeability of the system and the possibility of applying the mixture in landfill layers from a hydraulic point of view. Although the values of the geotechnical parameters of the mixtures with 2.5 and 5 percent sludge incorporated into the soil are acceptable, it is necessary to consider their greater deformability than when compared to the use of soil alone.

The anticipated advantages include the provision of a viable solution for the disposal of WTP waste, a reduction in the consumption of natural raw materials and the sustainable use of waste that commonly occupies valuable space in landfills. This waste can be disposed of in an environmentally appropriate, socially responsible, and economically viable way.

The obtained data also indicate that the variability in the properties of WTP sludge, determined by factors such as the origin and quality of the raw water, requires specific geotechnical characterization for each application to ensure that soil-sludge mixtures meet the desired quality and performance standards.

In general, waste management policies and practices can benefit from the adoption of soil-sludge mixtures reinforced with geosynthetics, providing a practical solution for utilizing WTP sludge, adding value to the waste without the need for prior processing, and promoting environmental sustainability in infrastructure projects.

To further research on using WTP sludge in landfill impermeable layers, it is suggested to study the behavior of soil-sludge mixtures with the addition of geosynthetic barriers, analyze the economic and financial feasibility of this alternative, and monitor landfill cells to understand the long-term behavior of compressibility and settlement.

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Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors’ contributions

Daiana Tatiele Fiedler: conceptualization, data curation, visualization, investigation, writing – original draft. Maitê Milléo Almeida: conceptualization, data curation, visualization, investigation, writing – original draft. Carlos Emmanuel Ribeiro Lautenschläger: formal analysis, funding acquisition, investigation, methodology, project administration, resources, software, supervision, validation, writing – review & editing.

Data availability

Research data is only available upon request.

Declaration of use of generative artificial intelligence

This work wasn´t prepared with the assistance of generative artificial intelligence. The authors assume full responsibility for the content of the publication, which did not have the help of GenAI.

List of symbols and abbreviations

e_i	Void ratio
$w_{ótimo}$	Optimum moisture
C_c	Compaction index
C_r	Recompression index
γ_d	Maximum dry specific weigth
NP	Non-plastic soil

References

ABNT NBR 6457. (2016a). *Solo: preparação de amostras para ensaios de compactação, caracterização e determinação de teor de umidade.* ABNT - Associação Brasileira de Normas Técnicas, Rio de Janeiro, RJ (in Portuguese).

ABNT NBR 6459. (2016b). *Solo: determinação do limite de liquidez.* ABNT - Associação Brasileira de Normas Técnicas, Rio de Janeiro, RJ (in Portuguese).

ABNT NBR 7180. (2016c). *Solo: determinação do limite de plasticidade.* ABNT - Associação Brasileira de Normas Técnicas, Rio de Janeiro, RJ (in Portuguese).

ABNT NBR 7181. (2016d). *Solo: análise granulométrica.* ABNT - Associação Brasileira de Normas Técnicas, Rio de Janeiro, RJ (in Portuguese).

ABNT NBR 7182. (2016e). *Solo: ensaio de compactação.* ABNT - Associação Brasileira de Normas Técnicas, Rio de Janeiro, RJ (in Portuguese).

ABNT NBR 16853. (2020). *Solo: ensaio de adensamento unidimensional.* ABNT - Associação Brasileira de Normas Técnicas, Rio de Janeiro, RJ (in Portuguese).

ABNT NBR 14545. (2021). *Solo: determinação do coeficiente de permabilidade de solos argilosos a carga variável.* ABNT - Associação Brasileira de Normas Técnicas, Rio de Janeiro, RJ (in Portuguese).

ABNT NBR 13600. (2022). *Solo: determinação do teor de matéria orgânica por queima a 440 °C.* ABNT - Associação Brasileira de Normas Técnicas, Rio de Janeiro, RJ (in Portuguese).

American Water Works Association – AWWA. (1978). Committee report: water treatment plant sludges – an update of the state of the art: part 1. *Journal - American Water Works Association*, 70(9), 498-503. http://doi.org/10.1002/j.1551-8833.1978.tb04216.x.

Anibele, R., Halitski, E.R., Tonus, B.P.D.A., & Lautenschläger, C.E.R. (2020). Análise em modelo de laboratório da substituição de filtro de areia por geocomposto em barragens de terra. In *XX Congresso Brasileiro de Mecânica dos Solos e Engenharia Geotécnica (COBRAMSEG)*, São Paulo (in Portuguese). http://doi.org/10.4322/cobramseg.2022.0192.

ASTM D2435/D2435M-AA. (2011). *Standard test methods for one-dimensional consolidation properties of soils using incremental loading.* ASTM International, West Conshohocken, PA. http://doi.org/10.1520/D2435-04.

Boscov, M.E.G., Tsugawa, J.K., & Montalvan, E.L.T. (2021). beneficial use of water treatment sludge in geotechnical applications as a sustainable alternative to preserve natural soils. *Sustainability (Basel)*, 13(17), 9848. http://doi.org/10.3390/su13179848.

Castilhos Junior, A., Prim, E., & Pimentel, F. (2012). Utilização de lodo de ETA e ETE como material alternativo de cobertura de aterro sanitário. *Estudos Tecnológicos em Engenharia*, 7(2), 86-97. http://doi.org/10.4013/ete.2011.72.02.

Daniel, D.E., & Koerner, R.M. (1993). *EPA/600/R-93/182: quality assurance and quality control for waste containment facilities*. Cincinnati: U.S. EPA.

Dixon, D.A., Graham, J., & Gray, M.N. (1999). Hydraulic conductivity of clays in confined tests under low hydraulic gradients. *Canadian Geotechnical Journal*, 36(5), 815-825. http://doi.org/10.1139/t99-057.

DNER-ME 093. (1994). Solo: determinação da densidade real. DNER – Departamento Nacional de Infraestrutura de Transportes, Brasília, DF (in Portuguese).

Ferreira, S.R.M., Oliveira, J.T.R., Messias, A.S., Silva, H.A., Nascimento, A.E., & Feitosa, M.C.A. (2011). Hydraulic conductivity and soil-sewage sludge interactions. *Revista Brasileira de Ciência do Solo*, 35(5), 1569-1577. http://doi.org/10.1590/S0100-06832011000500011.

Gonçalves, F., Souza, C.H.U., Tahira, F.S., Fernandes, F., & Teixeira, R.S. (2017). Incremento de lodo de ETA em barreiras impermeabilizantes de aterro sanitário. *Revista Dae*, 65(205), 5-14. http://doi.org/10.4322/dae.2016.018.

Katayama, V.T. (2012). *Quantificação da produção de lodos de estação de tratamento de água de ciclos completo: uma análise crítica* [Master's dissertation]. University of São Paulo (in Portuguese).

Kaza, S., Yao, L.C., Bhada-Tata, P., & van Woerden, F. (2018). *What a waste 2.0: a global snapshot of solid waste management to 2050.* Washington, D.C.: World Bank.

Knierim, L.S., Delongui, L., & Pinheiro, R.J.B. (2023). Estudo do comportamento mecânico e hídrico do uso do lodo de estação de tratamento de água em misturas com solo argiloso laterítico. *Revista Dae*, 71(240), 51-64. http://doi.org/10.36659/dae.2023.021.

Mazzutti, E., Klamt, R., & Faro, V. (2023). Study of the hydro-mechanical behavior of a stabilized soil with water treatment plant sludge for application in sanitary landfills. *Soils and Rocks*, 46(1), e2023011222. http://doi.org/10.28927/SR.2023.011222.

Montalvan, E.L.T. (2016). *Investigação do comportamento geotécnico de misturas de solo arenoso com lodo de tratamento de água do município de Cubatão, SP* [Master's dissertation]. University of São Paulo (in Portuguese).

O'Kelly, B.C. (2016). Geotechnics of municipal sludges and residues for landfilling. *Geotechnical Research*, 3(4), 148-179. http://doi.org/10.1680/jgere.16.00013.

Oliveira, N.S. (2010). *Estudo da secagem de lodo de estação de tratamento de água* [Master's dissertation]. Federal University of Paraná (in Portuguese).

Ou, Y., Tian, G., Chen, J., Chen, G., Chen, X., Li, H., Liu, B., Huang, T., Qiang, M., Satyanaga, A., & Zhai, Q. (2022). Feasibility studies on the utilization of recycled slag in grouting material for tunneling engineering. *Sustainability*, 14(17), 11013. http://doi.org/10.3390/su141711013.

Pereira, E.V., & Vargas, M.C. (2019). *Estudo de dosagem para misturas de solo-cimento e resíduos de construção e demolição mediante ensaio de compressão simples*

[Course completion work]. State University of Ponta Grossa (in Portuguese).

Pinto, C. S. (2006). *Curso básico de mecânica dos solos.* São Paulo: Oficina de Texto.

Rahardjo, H., Satyanaga, A., Leong, E.-C., & Noh, O. (2017). Performance of residual soil as cover system for a sanitary landfill in Singapore. *Journal of Performance of Constructed Facilities*, 31(1), D4016004. http://doi.org/10.1061/(ASCE)CF.1943-5509.0000926.

Rahardjo, H., Gofar, N., & Satyanaga, A. (2018). Effect of concrete waste particles on infiltration characteristics of soil. *Environmental Earth Sciences*, 77(9), 347. http://doi.org/10.1007/s12665-018-7530-3.

Rangel, M.L. (2005). A influência da urbanização na qualidade da água: Barragem Mãe D'água - Porto Alegre - RS. In *Anais do X Encontro de Geógrafos da América Latina*, São Paulo (in Portuguese).

Rodrigues, L.P., & Holanda, J.N.F. (2013). Influência da incorporação de lodo de estação de tratamento de água (ETA) nas propriedades tecnológicas de tijolos solo-cimento. *Cerâmica*, 59(352), 551. http://doi.org/10.1590/S0366-69132013000400010.

Roque, A., Montalvan, E.L.T., & Boscov, M.E.G. (2021). Caracterização mineralógica, química e geotécnica do lodo da estação de tratamento de água Taiaçupeba. *Geotecnia*, 151(151), 33-52. http://doi.org/10.24849/j.geot.2021.151.03.

Scapin, J. (2021). *Avaliação da utilização de mistura de solo e lodo de estação de tratamento de água como material de cobertura e de fundo em células experimentais de resíduos sólidos urbanos* [Doctoral thesis]. Federal University of Santa Maria (in Portuguese).

Sharma, H.D., & Reddy, K.R. (2004). *Geoenvironmental engineering: Site remediation, waste containment and emerging waste management technologies.* New York: Wiley.

Tonus, B.P.A., Lautenschläger, C.E.R., Vieira, A.F., Faro, V.P., & Tsuha, C.H.C. (2022). Site characterization for a study on shallow geothermal energy exploitation in southern Brazil. *Soils and Rocks*, 45(1), 1-13. http://doi.org/10.28927/SR.2022.078221.