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Determination of Soil Contamination Due to the Influence of Cemeteries for the Surrounding Land and People in Central Ecuador—Worldwide Implications

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Abstract: Human decomposition processes generate pulses of nutrients, such as carbon (C) and nitrogen (N) in the form of ammonium and nitrate (NO_3^-), which are released into the surrounding environment. The little exploration related to the potential of cadaveric leachate to influence the physical chemistry and biology of the soil makes it difficult to obtain data and scientific evidence, and subsequently the predominant objective of the current study was to determine soil contamination through the analysis of parameters of physical chemistry that included organic matter (OM), NO_3^-, texture, humidity, and pH. Soil samples were taken at different depths in two temporary trials (the dry and rainy seasons) in central Ecuador. The Kruskal–Wallace and ANOVA statistical analyses determined significant differences in relation to the sampling sections and by categories, while there were no significant differences in the inter-season analysis; therefore, the study was based on the data obtained in the dry season. The results indicate a tendency towards contamination in cemeteries categorized as critical, that is, moderate, light, and not suitable due to the high values of OM and humidity measured. On the contrary, the soils that corresponded to the cemeteries classified as suitable yielded low values of the analyzed parameters, which corroborates their capacity for the present and future location of cemeteries. Monitoring and managing soil health is crucial to ensure sustainable environmental practices and protect public health; nonetheless, additional research is suggested to confirm the findings of the current study.

Keywords: soil pollution; cemeteries pollution; corpse leachate; ANOVA analysis

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1. Introduction

Soil plays a fundamental role in the interaction between land, air, water, and the biosphere, providing essential ecosystem services to sustain life on the planet [1–4]. Humans interact with soil in a variety of ways, including its use as a site for solid waste disposal, wastewater treatment, and as a foundation for the construction of cities and towns [1,3,5]. The main function of a cemetery is to provide a physical space for the burial of corpses, stillbirths, anatomical remains, and human bones, as well as the placement of ashes resulting from cremation [6–8], being perceived in a spiritual and cultural context as a place that provides a space for the commemoration and final rest of the deceased [6,9,10].

However, cemeteries not only serve as the final resting place of corpses, but also as a repository for chemicals and materials related to funerary practices, including ornaments, shrouds, coffins, and caskets used for the burial of remains [9,11]. Therefore, these burial sites have been compared to diluted and dispersed municipal landfills [12–14]. This aspect, together with the generation of pollutants by leachates from cadaveric decomposition, underlines the importance of careful design and management of these spaces for the correct execution of their functions [15–17].

A carcass is a complex resource containing a high microbial load in the form of enteric and dermal communities, a significant proportion of water (60–80%), a relatively high concentration of lipids and proteins, and a close carbon (C) to nitrogen (N) ratio [18,19]. The decomposition of a body in the ground, particularly in the context of traditional burial practices, follows a sigmoidal pattern [18,20] and is able to be divided into five stages [21–26], with varying durations, namely, fresh, bloated, active decomposition, advanced decomposition, and dry decomposition. This process ideally takes place during the usual resting period of 15 to 25 years, leading to complete skeletonization of the body [27,28].

During the putrefaction process, a leachate overflow occurs that seeps into the soil and transmits contaminants derived from the body's own decomposition [29]. The leachate generated has a grayish and brownish color, with an acidic taste, and is mainly composed of 60% water; 30% mineral salts; and 10% complex substances, such as putrescine and cadaverine, with a repulsive odor [8,29]. This liquid has a high degree of toxicity and pathogenicity, is quite soluble in water at a pH between 5 and 9, and has a temperature between 23 °C and 28 °C [30–33]. With a density greater than that of water with an average value of 1.23 g/cm^3 and, therefore, acquiring good dispersion and mobility, facilitating its passage to underground wells, thus extending to wider regions of contamination [8,29,34].

The environment surrounding a corpse is called cadaver decomposition island (CDI), which changes over time in terms of its lateral and vertical extent due to the physicochemical composition of the corpse [18]. The CDI receives more N from the body, mainly in the form of ammonia (NH_3), which is converted to nitrate (NO_3^-), but it is not the only chemical element that increases. Some people accumulate other chemical compounds inside themselves that have their effect when released into the environment, for example, if the victim consumed certain supplements or medications or in the case of chemicals such as formaldehyde from embalming practices [32,35–37]. Other contaminants are those elements that make up a coffin, such as wood or metal, sealants, and varnishes, as these are able to corrode or degrade and become harmful toxins [11,38].

The degree to which carcasses laterally and vertically influence the surrounding environment (soil) depends on several factors, such as size and physical properties of the soil. According to Keenan et al., 2018 [39], decomposition products migrate laterally through the soil up to approximately 1 m away. Decomposition products have also been shown to remain in the soil for months after carcasses disintegrate [36]. During carcass decomposition, CDIs receive pulses of organic matter (OM), creating ephemeral hotspots of increased nutrient cycling and microbial activity, which generates changes in soil biogeochemistry at these hotspots, including pH, electrical conductivity (EC), organic and inorganic carbon (C), and speciation as well as nitrogen (N) cycling and soil oxygen (O_2) [40], directly affecting soil health.

Increased rates of microbial respiration and mineralization of nitrogen and carbon from biomass beneath carcasses have been observed. Although microbes are responsible for recycling carcass-derived organic matter, surprisingly little is known about the microbial communities responsible [36]. Furthermore, microbes associated with humans have been demonstrated to persist in soils for surprisingly long periods of time. Their low abundance in natural soils and significant increases during decomposition make them adequate candidates as bioindicators [40]. Microorganisms present in soil play a crucial role in the degradation of contaminants, through dissolution and degradation processes or immobilization and mobilization mechanisms contributing to the decomposition of

harmful substances, such as solid waste leachates, as well as to the restoration of soil health [41,42].

Factors such as the microclimate surrounding the corpse (both indoors and outdoors), the presence of clothing covering the body, the physical trauma suffered by the corpse, the body weight, and the embalming process to which they were subjected influence the rate and process of cadaveric decomposition [6,43–47]. The more separation there is between the body and the ground, by means of coffins, shrouds, or plastic sheets, the longer the decomposition time will be [12,48].

Soil characteristics such as texture and structure influence its potential to act as a filter for buried waste or discarded products and, in turn, affect the infiltration rate of contaminants, both gaseous and volatile emissions and liquids and solutes from decomposing bodies [12,45,49,50]. In general, coarse-textured (sandy) soils with low moisture content promote desiccation and gas diffusion through the soil matrix. These soils allow easy water infiltration and rapid removal of transformation products from bodies and coffins [45,51]. In contrast, fine-textured (clayey) soils inhibit the decomposition of bodies due to their low gas diffusion rate [50,51].

The slope of the terrain can also affect the rate of penetration of contaminants. On steep terrain, water tends to flow rapidly through the soil, which can increase the rate of penetration of contaminants [52–54]. In terms of infiltration, it is fundamental to consider the interaction between gravity and capillary action, as they are factors that influence the movement of fluids in the soil [55]. Capillary action is able to draw water into porous materials against gravity, allowing it to penetrate small spaces. However, the rate and extent of absorption can be affected by factors such as soil texture, as clay soils have a greater capillary rise than sandy soils [56]. Another factor to consider is the percolation of fluids in the pore structure of the soil to describe and predict the migration of contaminants to groundwater or other subsurface environments [57].

Little is known about the effect of soil pH on the decomposition of carcasses, but conclusions may be drawn from other disciplines. The onset of the active decomposition stage brings with it an expansion of the CDI because at this stage there is greater tissue loss and, therefore, greater leaching of the decomposition liquid into the soil. As a result, the pH of the soil adjacent to the carcass indicates low values, reaching a minimum of 5.8 according to the study conducted by [40]. However, it is important to note that these values may vary depending on different factors and environmental conditions.

As scientific evidence of the contamination generated by cemeteries, there are the cases of studies realized in Europe (Paris and Berlin) where cases of groundwater contamination near cemeteries have been recorded, with the presence of bacteria, ammonium ions (NH_4^+), nitrite (NO_2^-), and other contaminants. These cases of contamination are related to the processing of OM and bacterial proliferation [38]. In Colombia, a study focused on analyzing the impact of leachates on soil quality by collecting soil samples from cemeteries and surrounding areas. Evaluating pH, EC, total nitrogen, nitrates, acidity, current humidity, and equivalent humidity, these analyses allowed a final diagnosis to be made and the incidence of leachates on soil contamination to be analyzed [58].

In Ecuador, very few advanced studies have been carried out to demonstrate whether cemeteries are a source of contamination for the population. In the research performed by [59], environmentally unsuitable areas for the location of cemeteries were identified in the cantons of Mejía, Quito, and Rumiñahui in the province of Pichincha, central Ecuador. Conversely, in the study realized by [54], empirical environmental indices are established based on variables that describe the morphology of the terrain of a cemetery. These indices allow for the finding of the best conditions for the location of treatment and final disposal sites in the management of human corpses in the study area.

Therefore, the current research focused on the analysis of physicochemical parameters of the soil matrix, including OM, NO_3^-, texture, humidity, and pH in two temporal tests (dry and rainy season). The predominant objective has been to determine the susceptibility to contamination caused by the location of cemeteries in the cantons of Quito, Mejía, and

Rumiñahui. A statistical analysis was used to verify the suitability of the cemetery location areas, using the data obtained in the characterization of the analyzed soil samples. The soil samples were characterized to identify the differences in the concentrations of the parameters measured at the three sampling points, as well as to indicate any significant variation in the behavior of the concentrations between the cemeteries sampled in different categories and thus determine if there is contamination.

2. Materials and Methods

The present research was conducted in six distinct phases. The first phase consisted of a thorough analysis of the available bibliographic information on the study area. The second phase involved the determination of the sample using the Saaty matrix, integrating data from geographic information tools and considering environmental, legal, and accessibility criteria. In the third phase, field investigations were carried out to verify the geographic conditions and determine suitable locations for collecting soil samples. In phase four, the sampling was carried out. In phase five, the physicochemical tests were carried out both in the laboratory of the University of the Armed Forces ESPE and in an accredited laboratory. In the last phase, the Kruskal–Wallace method and ANOVA were used for the statistical analysis of the results. The field and laboratory phases were carried out during the dry season (August) and the rainy season (November) in Ecuador, in order to provide a complete perspective of the behavior of the soil against the action of leachates from the decomposition of corpses at different times of the year.

2.1. Selection of Cemeteries to Sample

In previous studies by Guayasamín (2021) [60], as well as studies by Crisanto-Perrazo et al. (2022) [54,59], criteria are defined for the categorization of the areas where the seventy cemeteries of the Quito, Rumiñahui, and Mejía cantons are located in Pichincha, Ecuador. In the present study, those implanted in the completely adequate (2) and very adequate (14) areas were classified as suitable. Conversely, those implanted in the moderately adequate (18), slightly adequate (30), and not adequate (6) areas were classified as critical. Through the panel of experts, it was decided that the number of cemeteries per category would be three, in order to mark a trend in the data and obtain relevant information for the analysis. Hereby, in the described context, a ranking analysis was used using the method used in the research by Ponce-Arguello et al. (2022) [61] that consists of performing a hierarchical analysis (AHP) with Saaty and the weighted linear sum (WLC) for sample selection [62–65].

The variables considered were accessibility, in terms of ease of taking samples; distance to the population; the affected population; the number of graves; the form of burial; and the years of service or operation. Each variable had various categories and in turn qualitative–quantitative criteria. This generated the need to carry out a normalization in order to standardize the variables. The values on which it was weighted were obtained from the research of Crisanto-Perrazo et al. (2022) [54]. They were subsequently assigned a weighting on a scale of 1 to 9, as listed in Table 1.

In order to encounter the degree of importance of each variable with respect to the others, AHP was performed using Saaty where the panel of experts assigned an importance value on a scale from 1 to 9 to each variable [66,67]. The coefficients for each parameter were generated using the pairwise comparison matrix presented in Table 2.

To choose the cemeteries that will constitute the sample, the WLC was formed with the factors w_i of each parameter, obtaining Equation (1).

$$\begin{aligned}\text{Value assigned to the cemetery} = {} & 0.17 \times \text{accessibility} + 0.03 \times \text{distance to the population} \\ & + 0.14 \times \text{affected population} + 0.22 \times \text{buried population} + 0.25 \times \text{form of burial} \\ & + 0.19 \times \text{years of service or operation.}\end{aligned} \quad (1)$$

Table 1. Variable weighting.

Variable	Category	Values/Data	Weighing
Accessibility	Low	-	1
	Average	-	5
	High	-	9
Distance to the population (m)	Low	>301	1
	Average	201–300	5
	High	0–200	9
Affected population	Very low	0–2	1
	Low	3–20	3
	Average	21–80	5
	High	81–160	7
	Very high	>160	9
Buried population	Very low	0–1000	1
	Low	1001–5000	3
	Average	5001–25,000	5
	High	25,001–50,000	7
	Very high	>50,001	9
Burial form	Low	Niches	1
	Average	Land-niches	5
	High	Land	9
Years of service or operation	Very low	<1833	1
	Low	1833–1933	3
	Average	1933–1983	5
	High	1983–2008	7
	Very high	2008–2023	9

Note: Adapted with permission from Crisanto-Perrazo et al. (2022) [53].

Table 2. Pairwise comparison matrix and WLC coefficients.

	Accessibility	Distance to the Population	Affected Population	Buried Population	Burial Form	Years of Service or Operation	=	w_i
Accessibility	1	6.00	1.20	0.75	0.67	0.86	=	0.17
Distance to the population	0.17	1	0.20	0.13	0.11	0.14	=	0.03
Affected population	0.83	5.00	1	0.63	0.56	0.71	=	0.14
Buried population	1.33	8.00	1.60	1	0.89	1.14	=	0.22
Burial form	1.50	9.00	1.80	1.13	1	1.29	=	0.25
Years of service or operation	1.17	7.00	1.40	0.88	0.78	1	=	0.19

From the values obtained from Equation (1) and according to the categorization of the location areas, three cemeteries were selected per category that achieved the highest score. Given that the completely appropriate category consists of two cemeteries, a total of 13 cemeteries were obtained to be sampled, distributed in the study area as indicated in Figure 1.

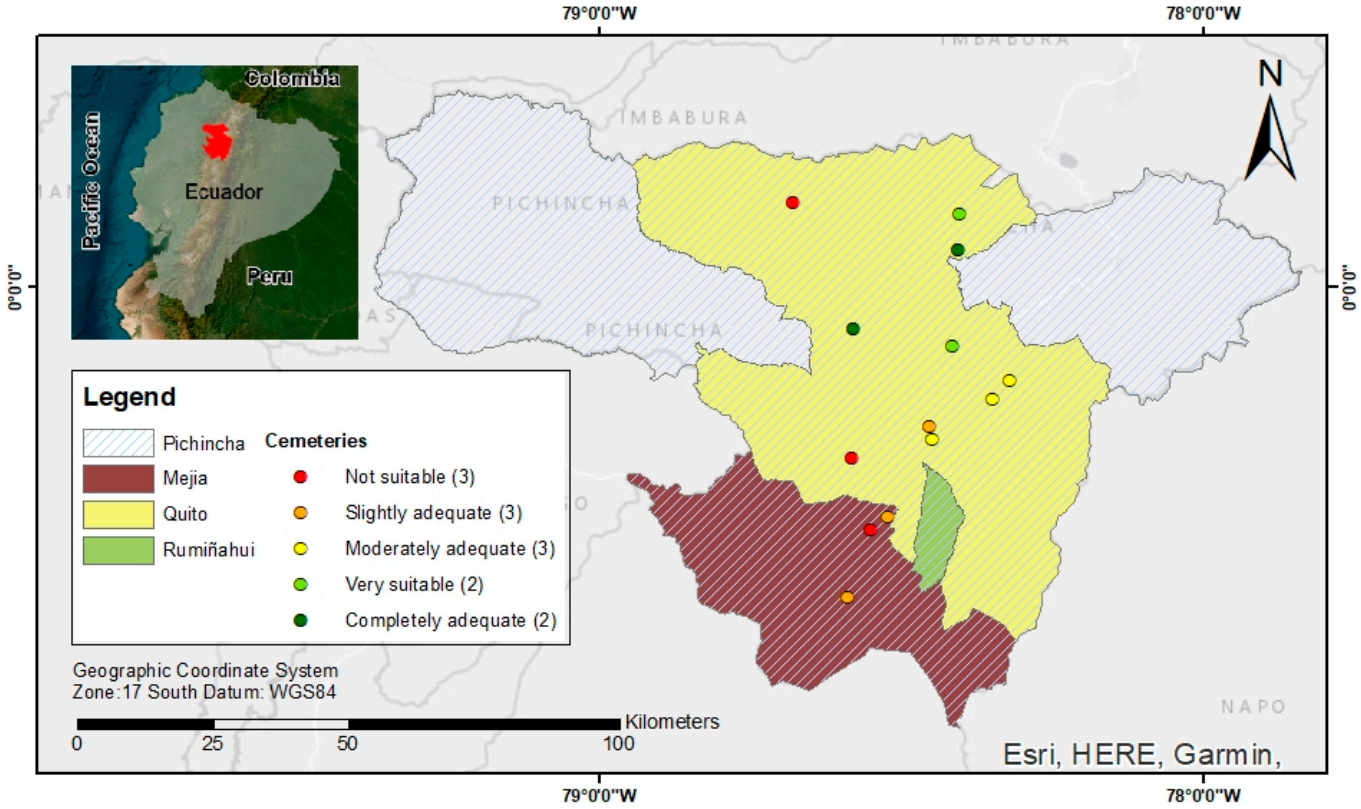


Figure 1. Location of the sampled cemeteries.

2.2. Geographic Conditions and Definition of Soil Sampling Sites

For the selected sample, three sampling points per cemetery were chosen, considering the topography of the place. These include a start point (before), a midpoint (adjacent to a grave between the years 2015 and 2023), and an end point (after), taking into consideration the slope of the cemetery. Although there are no standard guidelines regarding the depth to bury a body, both local laws and international regulations were taken into account. In the case of Ecuador, the burial depth is 2.5 m [68]. Organizations such as the Pan American Health Organization, the World Health Organization, the International Committee of the Red Cross, and the International Federation of Red Cross and Red Crescent Societies suggest a depth between 1.5 and 3 m [69,70]. Therefore, three samples were collected at different depths: superficial (2.00 m), medium (2.50 m), and deep (3.00 m), in order to obtain repeatability of the sampling points for statistical analysis. In total, nine soil samples were obtained per cemetery, considering the possible influence of capillarity and percolation [55,57,71,72].

The standard penetration test (SPT) was applied under the ASTM D1586 standard to extract the samples to the aforementioned depths [73,74]. Subsequently, the samples were carefully packaged in Ziploc-type plastic bags to guarantee their correct storage and transportation to the laboratory. Due to physical limitations in certain cemeteries, such as terrain and infrastructure, sampling of some soils was difficult. Therefore, the dry season test included thirteen cemeteries, while the rainy season test was realized in twelve.

2.3. Analysis of Physicochemical Parameters of the Soil Matrix in the Laboratory

The analysis of parameters such as pH, texture, and soil humidity were conducted in the laboratories of the University of the Armed Forces ESPE in Sangolquí, Ecuador. Meanwhile, the analysis of OM content was limited to the least critical cemeteries, with cemeteries classified as slightly suitable and not suitable being analyzed in the certified laboratory of the Center for Environmental Research and Control (CICAM), belonging to

the Escuela Politécnica Nacional, Ecuador. Additionally, all categories were examined for NO_3^- in the CICAM. This allocation was implemented to optimize the use of resources.

Gravimetric moisture was calculated from mass loss after oven drying for 24 h at 105 °C according to ASTM D2216 [75,76]. To determine the pH, the AS-02 method of the Mexican standard NOM-021-SEMARNAT-2000 was used [77]. The Hach HQ40d multiparametric equipment was used, along with the properly calibrated probe of the same brand, model PHC101.

The granulometric analysis of soils by sieving is a method used to determine the distribution of particle sizes in a soil sample. In this case, the standard ASTM D422 was used [78]. Once the values of the granulometric analysis were obtained, the textural triangle method based on the USDA system was used to determine the textural class of each of the soil profiles based on the size of the particles, their characteristics, and their composition. Based on the methodology recommended by the Standard Methods for the analysis of water and wastewater, the SM 2540 E/Gravimetric method was used to determine the OM. For the analysis of nitrates, the SM 4500-NO3-B/UV Spectrophotometry method was used [79].

2.4. Statistical Analysis

To evaluate the tendency towards contamination, the groupings were subjected to graphic and statistical analysis. Three types of analyses were performed. Initially, the difference between sampling times was compared, followed by comparison by sampling sections (before, inside, and after), and finally by category. ANOVA analysis was used for data that satisfied the assumptions of normality and homoscedasticity, generating Tukey–Kramer multiple comparison tests [80–82]. Differences with a p value less than 0.05 were considered statistically significant. For data that did not meet the assumptions, the non-parametric Kruskal–Wallace test was used, and a post hoc pairwise.wilcox.test test was applied in the RStudio software version 4.3.2, considering a p value < 0.05 [83–85]. International standards predominantly do not present maximum permitted limits for contaminants in soil depending on its use, so limit values were calculated according to the "completely adequate" category because this segment represents conditions close to ideal for the location from a cemetery [54,59].

3. Results

3.1. Laboratory Analysis

After analyzing the soil samples from the selected places, considering various depths and sections, the results were obtained for the dry and rainy seasons. These results are listed in Table 3, which highlights the critical values of each variable by cemetery.

The values presented correspond to the critical values of each variable for each cemetery, considering the soil samples within and after having a direct influence of the leachates from cadaveric decomposition.

Table 3. Results obtained from laboratory analyses in dry and rainy seasons.

Category	Cemetery	Latitude	Longitude	Season	OM (%)	NO_3^- (mg.kg^{-1})	Humidity (%)	pH	Textural Class
Not suitable	Tambillo	0°24′17.0006″ S	78°32′57.8845″ W	dry rainy	5.4 4.7	18 13	29 26	7.02 6.53	Clay
	La Libertad de Chillogallo	0°17′6.1401″ S	78°34′47.3232″ W	dry rainy	5.9 5.4	10 4	27 26	6.12 6.17	Sandy clay loam
	Nanegal	0°8′22.0378″ N	78°40′37.1893″ W	dry rainy	9.4 8.9	53 4	50 49	6.93 5.97	Sandy clay loam
Slightly adequate	Aloasí	0°30′59.7751″ S	78°35′14.5372″ W	dry rainy	3 2.8	75 24	17 17	7.88 8.05	Sandy clay loam
	Lumbisí	0°13′55.1394″ S	78°27′8.8344″ W	dry rainy	4.0 4.1	10 24	22 23	7.79 7.65	Sandy clay loam
	Uyumbicho	0°22′55.6563″ S	78°31′18.7682″ W	dry rainy	4.2 4.8	15 22	25 27	5.32 5.54	Sandy clay loam

Table 3. *Cont.*

Category	Cemetery	Latitude	Longitude	Season	OM (%)	NO_3^- (mg.kg^{-1})	Humidity (%)	pH	Textural Class
Moderately adequate	Guangopolo	0°15′20.4411″ S	78°26′59.6962″ W	dry rainy	8 4.8	14 11	25 23	7.62 7.31	Sandy clay loam
	Tababela	0°11′14.4457″ S	78°20′56.2596″ W	dry rainy	3.4 5.4	23 19	18 15	8.23 7.79	Sandy clay loam
	Yaruquí	0°9′21.1911″ S	78°19′8.2484″ W	dry rainy	4.9 -	19 -	16 -	8.56 -	Sandy clay loam
Very suitable	Descanso Eterno	0°5′54.8324″ S	78°24′55.3176″ W	dry rainy	2.3 2.8	12 14	5 5	8.81 8.22	Sandy clay loam
	Puellaro	0°3′44.2347″ N	78°24′14.2151″ W	dry rainy	2.2 2.1	34 30	4 4	9.16 9.90	Sandy loam
Completely adequate	Chavezpamba	0°7′19.7715″ N	78°24′12.6394″ W	dry rainy	4.1 3.1	12 13	17 18	5.65 7.40	Sandy clay loam
	Nono	0°4′9.0194″ S	78°34′43.7041″ W	dry rainy	4.3 5.8	10 10	23 21	7.64 6.06	Loamy sand

3.2. Statistical Analysis of Results

3.2.1. Inter-Season Differences in Soils

The content of OM, NO_3^-, and humidity did not yield significant differences between the test conducted in the dry and rainy season (Kruskal–Wallace, $p < 0.05$). However, pH did present a significant difference (ANOVA, $p < 0.05$), as detailed in Table 4.

A significance level of * $p < 0.05$ indicates that there is less than a 5% probability that the observed results are random. On the other hand, a level of ** $p < 0.01$ indicates that the probability of the results occurring by chance is less than 1%, which provides stronger evidence and suggests that the results are more reliable. Furthermore, a significance level of *** $p < 0.001$ indicates that the probability that the results are the product of random variation is less than 0.1% [86].

Table 4. Differences between inter-season tests.

Variable	Dry	Rainy	X^2	*p*	Statistical Test
OM (%)	3.64 ± 1.85	3.39 ± 1.64	0.9283	0.3353	Kruskal–Wallace
NO_3^- (mg.kg^{-1})	14.0 ± 13.1	11.7 ± 7.6	0.2786	0.5976	Kruskal–Wallace
Humidity (%)	17.5 ± 9.30	17.3 ± 8.89	0.0657	0.7977	Kruskal–Wallace
pH	7.47 ± 0.79	7.16 ± 0.84	---	0.00508 **	ANOVA

The means of the samples taken in the dry season (n = 112) and the rainy season (n = 107) plus the standard deviation are presented along with the results (X^2 and the *p* value) of the Kruskal–Wallace test.

After establishing that there are no significant differences between the seasonal tests, a comparison was made by section using exclusively the data obtained in the dry season sampling. This decision is based on the fact that, environmentally, during this time, there is a higher concentration of pollutants.

3.2.2. Differences between Sampling Sections

The analysis using the Kruskal–Wallace test reveals that the OM and humidity variables did not present significant differences between sections. However, NO_3^- concentrations did demonstrate significant variation. The ANOVA analysis for pH also indicates a significant difference between the sampling sections, as listed in Table 5 and shown in Figure 2.

Table 5. Differences between sampling sections.

Variable	Before	Inside	After	X^2	*p*	Statistical Test
OM (%)	3.83 ± 2.13	3.68 ± 1.82	3.42 ± 1.58	0.40043	0.8186	Kruskal–Wallace
NO_3^- ($mg.kg^{-1}$)	19.8 ± 14.4	11.7 ± 9.1	10.9 ± 13.4	17.104	0.0001932	Kruskal–Wallace
Humidity (%)	17.2 ± 9.14	17.8 ± 9.51	17.5 ± 9.51	0.67759	0.7126	Kruskal–Wallace
pH	7.67 ± 0.79	7.52 ± 0.77	7.20 ± 0.76	---	0.0315 *	ANOVA

The means and standard deviations of the samples from the before (n = 38), inside (n = 37), and after (n = 37) sections are shown, along with the results (X^2 and *p* value) of the Kruskal–Wallis test.

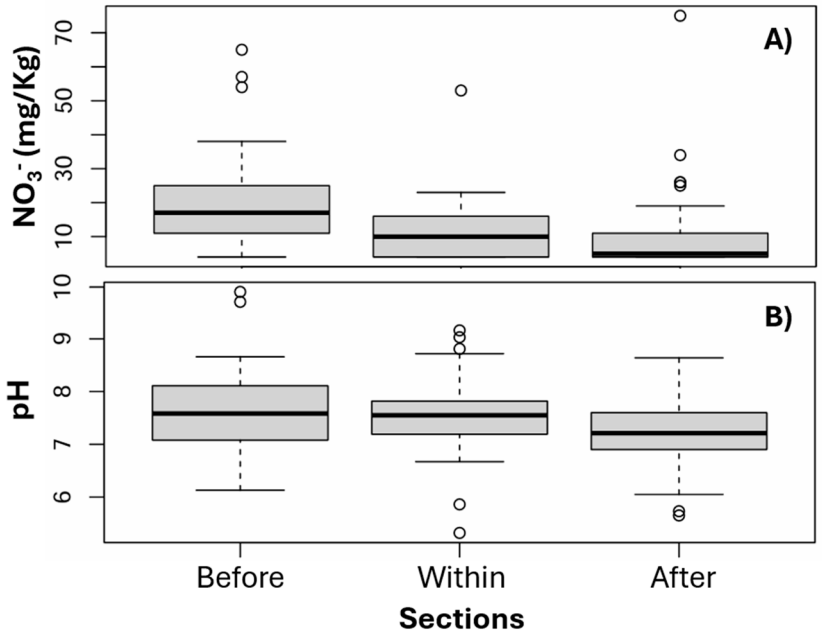


Figure 2. Changes in physicochemical parameters depending on the sampling sections. (**A**) illustrates the distribution of NO_3^- concentrations in the three sampling sections; (**B**) shows the distribution of pH values in the three sampling sections.

After a multiple comparison test for the variable NO_3^- using pairwise.wilcox.test, statistically notable differences were detected in the Before–Inside (0.00470) and Before–After (0.00063) sections. The Tukey test ran for the pH values highlighted the Before–After comparison as the most significant, with a value $p = 0.0272377$, as illustrated in Figure 2. Subsequently, after confirming significant differences between sampling sections, a categorical comparison was performed using only the data obtained during dry season sampling and specifically from the sections located within and after each cemetery. This decision was based on the fact that these soils are directly affected by leachate resulting from cadaveric decomposition.

3.2.3. Differences between Categories

To examine the differences between the categories, the Kruskal–Wallace test was used on the four variables, since the pH did not meet the assumptions necessary to apply ANOVA, after eliminating the data from the control soils. The existence of significant differences between categories was confirmed for all variables, as detailed in Table 6.

Therefore, post hoc tests were applied to identify the groups that present the greatest differences between themselves.

Table 6. Differences between categories, with the Kruskal–Wallace statistical test.

Variable	Not Suitable	Slightly Adequate	Moderately Adequate	Very Suitable	Completely Adequate	X^2	*p*
OM (%)	4.92 ± 1.92	3.27 ± 0.79	4.34 ± 1.39	1.95 ± 0.22	2.43 ± 1.43	36.29	<0.001 ***
NO_3^- ($mg.kg^{-1}$)	10.4 ± 11.7	10.7 ± 17.0	13.7 ± 5.6	15 ± 9.9	6.5 ± 2.8	14.59	0.005639
Humidity (%)	27.3± 9.13	19.3 ± 4.32	17.6 ± 2.97	2.58 ± 1.08	15.5 ± 3.59	48.93	<0.001 ***
pH	7.03 ± 0.41	7.05 ± 0.83	7.65 ± 0.43	8.35 ± 0.6	6.95 ± 0.65	31.59	<0.001 ***

The means and standard deviations of the samples from the categories not suitable (n = 18), slightly adequate (n = 18), moderately adequate (n = 15), very suitable (12), and completely adequate (n = 11) are displayed, along with the results (X^2 and *p* value) of the Kruskal–Wallis test.

Multiple comparisons demonstrate that humidity is the variable with the largest number of groups that present significant differences (7), followed by OM and pH, both with six groups, and finally NO_3^- with two groups, as seen in Table 7 and Figure 3.

Table 7. Comparison between categories.

Compared Categories		*p*			
		OM (%)	NO_3^- ($mg.kg^{-1}$)	Humidity (%)	pH
Completely adequate	Very suitable	0.57512	0.251	**0.00028**	**0.00040**
Completely adequate	Moderately adequate	**0.02313**	**0.022**	0.23299	**0.03475**
Completely adequate	Slightly adequate	0.57512	1.000	0.08518	0.77388
Completely adequate	Not suitable	**0.00407**	1.000	**0.00037**	0.96411
Very suitable	Moderately adequate	**0.00012**	1.000	**<0.001** ***	**0.02583**
Very suitable	Slightly adequate	**0.00058**	0.251	**<0.001** ***	**<0.001** ***
Very suitable	Not suitable	**0.00047**	0.451	**<0.001** ***	**0.00046**
Moderately adequate	Slightly adequate	0.09932	**0.031**	0.23299	0.37056
Moderately adequate	Not suitable	0.57512	0.196	**0.00016**	**0.00127**
Slightly adequate	Not suitable	**0.00444**	1.000	**0.00584**	0.50579

Pairwise.wilcox.test test results compared the cemetery site categories. Significant differences between categories are in bold ($p < 0.05$).

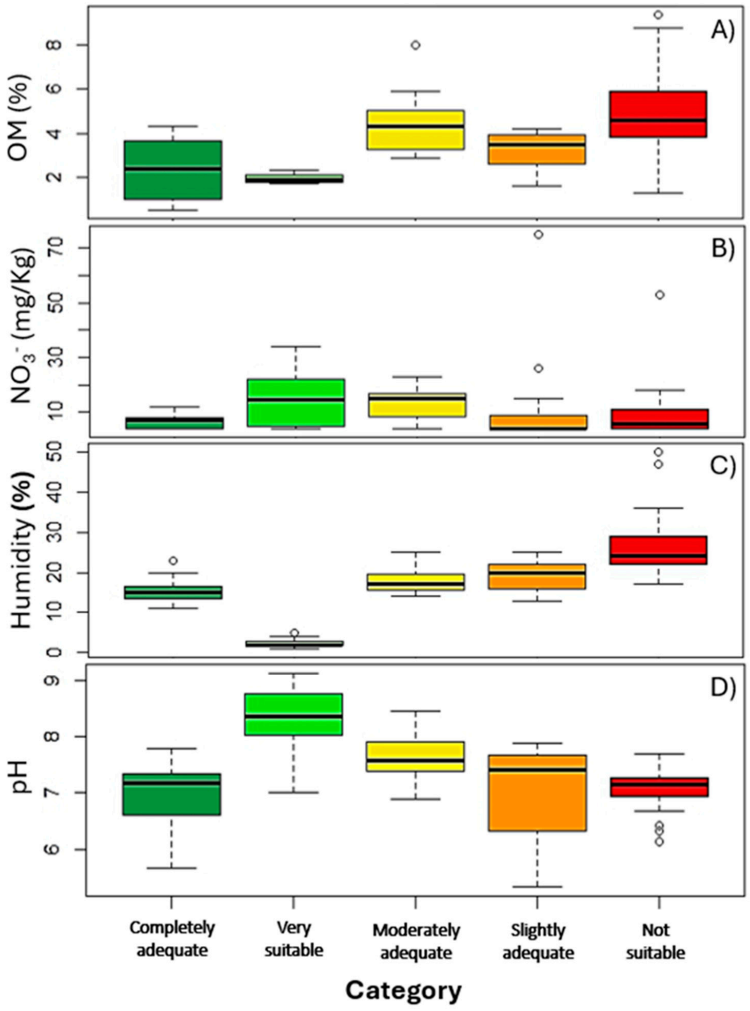


Figure 3. Analysis of leachate contamination from sampled cemeteries by category. Comparison between the categories corresponding to the optimal areas for the location of study cemeteries for (**A**) OM (%), (**B**) NO_3^- (mg/Kg), (**C**) humidity (%) and (**D**) pH.

4. Discussion

This study evaluated the trend of soil contamination attributed to cemeteries on a set of variables, which included both pulses of nutrients released during cadaveric degradation found in significant quantities OM and NO_3^- [36], as well as physicochemical indicators of decomposition in soils (humidity and pH). Soil texture was included due to its influence on the mobility of contaminants through it [12,45,49,50].

Statistical tests were performed to corroborate the existence of significant differences between temporal trials (Table 4). However, no empirical evidence was found to demonstrate this hypothesis for the variables of OM, NO_3^-, and humidity, which can be attributed to the presence of the El Niño phenomenon in Ecuador. El Niño usually brings droughts, extreme temperatures, torrential rains, and floods, with important implications for ecosystems, biodiversity, and human health [87–89]. In the second half of 2023, a significant activation of the El Niño phenomenon was detected as stated by the US Department of Commerce, NOAA (2023) [90], which caused a rainfall deficit between −100% and −51% of the usual reception in the Inter-Andean Region of Ecuador [91]. This rainfall deficit in the study area generated a similar behavior between seasons (dry and rainy) that significantly impacted the measured parameters. Despite this result, it cannot be concluded that the concentration of pollutants is the same in both the dry and rainy seasons. Studies have indicated that rainfall generates an environment that reduces the cadaveric decomposition

process, which leads to a considerable decrease in pollutants [92], and in addition, there is the possibility of dilution of these compounds [93].

In the comparison of the sampled sections, a decrease in the concentrations of NO_3^- and pH levels (Table 5, Figure 2) was observed in the soils exposed to decomposition (inside), in contrast to the control soils (before). The limited NO_3^- levels initially result from the decomposition of soft tissues of mammals [92]. Conversely, other studies have demonstrated that the decrease in soil pH is due to the influence of human decomposition and an increase by animal decomposition [18,39,92].

The comparison between categories related to the optimal areas for the location of burial sites presented relevant differences (Table 6, Figure 3). The OM indicated a tendency to decrease as the suitability of the soil increased, for example, with the moderately, slightly, and not suitable soils, there was a higher concentration. Although the presence of OM in the soil is not directly associated with the presence of contaminants, it can be inferred as an indicator of contamination attributed to the decomposition of human remains in sites where the use of the soil is directed to the burial of corpses [18,19,40]. Significant differences are observed between the categories "very suitable" and "moderately suitable", "very suitable" and "slightly suitable", and "very suitable" and "not suitable" (Table 7). This suggests that the amount of OM can vary significantly depending on the suitability of the soil.

As for NO_3^- content, an increase in concentration was observed as soil suitability increased, except for the "completely suitable" category where it decreased (Table 6, Figure 3). This suggests that these sites have an environment that significantly slows down decomposition and preserves bodies for longer periods than usual [92]. Although no significant differences were found between categories, this does not rule out nitrate concentrations as a potential factor in soil suitability, suggesting the possibility of optimal levels, based on the values obtained in the "completely suitable" category.

Moisture demonstrated a general decrease with soil suitability, except in "fully suitable" soils (Table 6, Figure 3). This suggests the importance of moisture in soil categorization and contamination, considering that there is an optimal level of moisture that favors the decomposition of corpses [27,48,94]. Burying a corpse in a moist, fine-textured soil may reduce cadaveric disintegration, since the rate of O_2 exchange with carbon dioxide (CO_2) may not be sufficient to meet the aerobic microbial demand. This creates reducing conditions in which anaerobic microorganisms dominate decomposition [18,27,48,95].

The pH indicated a tendency to increase with soil suitability until reaching "very suitable", where it decreased (Table 6, Figure 3). In the vast majority of categories, there are significant differences, except between "completely suitable–slightly suitable" and "completely suitable–not suitable" (Table 7). The tendency for pH to increase by categories is due to the conditions of the sampling sites. In its natural state, the pH of soils tends to be alkaline, but in the presence of compounds derived from cadaveric decomposition, the values tend to become acidic, although there are studies that have reported mixed results regarding pH [36], and this can have a significant effect on the decomposition of corpses or vice versa [50,96–98]. A very acidic or very alkaline environment will inhibit bacterial growth and, therefore, decomposition [99]. Studies suggest that a buried corpse initially creates an alkaline environment, followed by the formation of an acidic environment [18]. Variability in soil pH is important because it controls not only soil chemistry but is also a key driver of overall bacterial community structure, which ultimately influences the composition of the decomposer community [92,98] and is therefore an indicator of the tendency for contamination due to leachate from carcasses.

The performed analyses for the different variables revealed significant differences between categories, demonstrating that, given the variability of the soil, geographic, environmental, and social conditions in which each of these sites used for the burial of corpses are located, there will be a minor or major impact [54,59]. It was proven that cemeteries located in the unsuitable category yielded a greater tendency towards soil contamination. Długozima 2022 [15] and Flores Gómez et al. 2022 [100] stated that management policies

should be applied according to the nature and environmental, geographic, and social characteristics of each cemetery, proposing environmental and territorial solutions. The results of their research indicated a tendency towards contamination in the cemeteries studied.

5. Conclusions

The exhaustive analysis of soil samples from the various cemeteries and sections provides an understanding of the conditions and composition of the soil. The high content of organic matter and moisture, as well as low levels of pH (acidity) and NO_3^-, indicate the tendency towards soil contamination compared to control soils in cemeteries categorized as moderately, slightly, and not suitable. Despite not indicating statistically significant differences in the sampling periods, this study demonstrates that the characteristics of the soil in these areas contribute to the diffusion of the analyzed contaminants resulting from cadaveric decomposition. A direct comparison between categories has yielded that the impacts on the soils in this study are not identical. Given the variability of the edaphic, geographic, environmental, and social conditions in which each of these sites used for the burial of corpses are found, there was a minor or major impact depending on the category in which the cemetery is located. Furthermore, this study validates the hypothesis that soils in sites suitable for the location of cemeteries (completely and very suitable) have little susceptibility to contamination and could therefore be used as a reference for the current and future location of cemeteries and final waste disposal sites.

6. Recommendations

The scarce bibliographic information related to contamination by cadaveric decomposition and its effect on soil biogeochemistry made it difficult to obtain data and scientific evidence to better support this research. The high costs of sample extraction and laboratory analysis of the parameters studied limited the scope of this study, so it is recommended to expand the sample to other latitudes, climates, and variables in order to have more evidence of contamination due to cemeteries.

It is suggested that cemeteries that are considered suitable (fully and highly suitable) be constantly monitored to ensure the control of contamination of the surrounding soils and maintain a low environmental impact, thereby protecting public health. It is fundamental that decision-makers promote legislation for the regulation and management of corpses with less environmentally aggressive forms of burial and observing the type of land on which cemeteries or other final waste disposal sites are located.

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