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Impact of Leachates from the Chupaca Landfill on Agricultural Soil Quality

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ABSTRACT

This study assesses the impact of leachates from Chupaca's municipal landfill on the physical, chemical, and biological properties of nearby agricultural soils. Given their high concentration of contaminants, these leachates pose a critical risk to soil fertility and agricultural productivity. A quasi-experimental design was employed, comparing soil samples from contaminated and non-contaminated areas. Key parameters such as pH, electrical conductivity, organic matter content, and soil fauna were analyzed. The findings reveal a significant decrease in pH, indicating increased soil acidification, along with a reduction in essential nutrients such as potassium and magnesium. Conversely, elevated levels of phosphorus and calcium were observed, potentially affecting plant development. From a biological perspective, the total absence of earthworms in contaminated soils highlights severe ecological degradation. Predictive modeling using COMSOL Multiphysics indicates that, over the next 20 years, contaminants may extend up to 300 meters from the source, further compromising agricultural areas. These findings underscore the urgent need for enhanced waste management policies and soil remediation strategies to mitigate environmental, economic, and agricultural risks.

1. INTRODUCTION

Currently, at the municipal dump in the province of Chupaca, inadequate solid waste management results in leachate generation, constituting a significant environmental issue, thus constituting a significant environmental problem which negatively affects the diverse ecosystems and thereby damaging agricultural soils [1]. The generation of leachate is the main cause of this impact, since its components have high levels of contaminants which negatively alter the physical, chemical and, above all, biological properties of the soil [2]. This problem has become very relevant for this province, since one of its main sources of economic income and support for its population is agriculture. There are many studies which point out the harmful effects that improper management of leachate has on soils, where initially they can contribute positively by increasing nutrients in them, however, when these are not controlled they can introduce high concentrations exceeding optimal levels, thereby generating high degrees of toxicity, which negatively impacts the properties of the soil, resulting in the alteration of agricultural productivity and the general health of all surrounding ecosystems [3, 4]. Previous studies in Peru point out that existing correlations have been reported between the presence of leachate from landfills and high levels of heavy metals in agricultural soils, which emphasizes the urgency of having the need to be able to investigate this problem in provinces such as the Chupaca [5, 6].

In this context, this study integrates field and laboratory analyses with computational modeling to evaluate the transport of contaminants over a 20-year period using COMSOL Multiphysics. A quasi-experimental approach was applied, incorporating rigorous statistical methods, including t-tests to compare soil properties between contaminated and uncontaminated sites, as well as linear regression models to predict pH variations.

Although previous research has examined the effects of leachate on soil quality, significant knowledge gaps remain, especially in agricultural regions like Chupaca, Peru. This study addresses these gaps by integrating physicochemical and biological assessments with predictive modeling, providing a comprehensive understanding of contaminant migration and its long-term effects. The disappearance of earthworms, a key biological indicator of soil health, serves as direct evidence of soil degradation, underscoring the ecological impact of leachates. Thus, this research not only advances knowledge on leachate contamination in the Andean region but also provides crucial insights for developing mitigation strategies and soil conservation policies, ensuring agricultural sustainability and environmental protection.

The central research question guiding this study is: *What is the impact of leachates from the Chupaca landfill on the physicochemical and biological properties of agricultural soils?*

Accordingly, the general objective is to analyze and determine the extent to which leachate from the Chupaca landfill influences the physicochemical and biological properties of agricultural soils.

To address this, the following specific objectives are proposed: (a) Analyze the impact of leachates on soil physical properties, including bulk density, porosity, and water retention capacity; (b) Evaluate their influence on chemical properties, such as pH, electrical conductivity, and nutrient concentrations; (c) Examine their effects on biological properties, particularly microbial activity and the presence of macrofauna, such as earthworms; and (d) Model the transport dynamics of leachates within the soil profile using COMSOL Multiphysics, predicting their long-term behavior.

The hypothesis is that leachates from the Chupaca municipal landfill significantly alter the physical, chemical, and biological properties of adjacent agricultural soils. Specifically, these leachates are expected to cause soil acidification, nutrient imbalances, and a reduction in biological activity, as evidenced by the disappearance of earthworms. Such changes could jeopardize soil fertility and agricultural productivity, emphasizing the urgent need for effective mitigation strategies.

By integrating these analyses, this study enhances the understanding of leachate-induced contamination and contributes to the development of evidence-based mitigation strategies to preserve agricultural soil quality and long-term productivity.

2. MATERIALS AND METHODS

2.1 Study area

The selection of the Chupaca municipal landfill as the study site is based on its environmental and socioeconomic impact in a region where agriculture is one of the main productive activities. This landfill lacks an adequate waste management system, which facilitates the infiltration of leachates into the surrounding agricultural soils, affecting their quality and productivity.

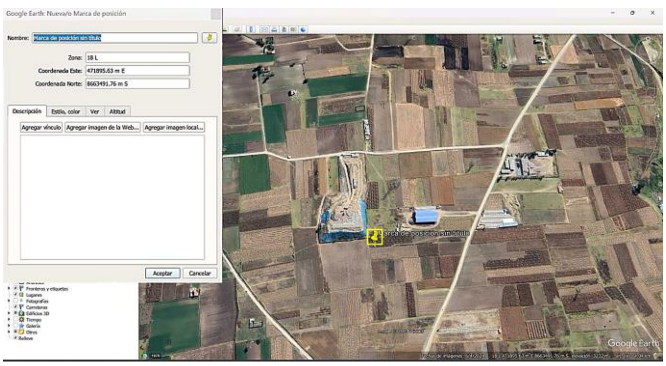

Figure 1. Coordinates of the Chupaca study area

Figure 2. Chupaca dump site

Table 1. Locations and coordinates of sampling sites and study area

Location	Category	Coord. (Lat, Lon)
Study Area	General	12°5'20.7"S, 75°15'31.65"W
Zone A	Cont. Soil	12°5'20.34"S, 75°15'33.42"W
Zone B	Cont. Soil	12°5'22.68"S, 75°15'33.0"W
Zone C	Non-Cont. Soil	12°5'17.4"S, 75°15'23.94"W
Zone D	Non-Cont. Soil	12°5'17.34"S, 75°15'24.24"W

Moreover, previous studies in Peru have identified a correlation between landfill leachates and the presence of heavy metals in cultivated soils, yet there is a lack of specific research in this province. The site's location, its proximity to agricultural land, and the absence of proper control measures make this study essential for understanding the long-term effects of leachates on soil health and for proposing mitigation strategies based on scientific evidence.

Figures 1 and 2 indicate that the study area covered approximately 49 hectares and was carried out at the landfill located in the Chupaca district, Chupaca province, Junín department. This site is located at an altitude of 3,263 meters above sea level and is geographically located at the coordinates indicated in Table 1.

2.2 Materials

The materials used included 1 measuring tape, 2 medium transparent containers, 4 resealable plastic bags of 2 kg capacity for filling the samples, a small shovel for excavation, disposable gloves, a lab coat, safety glasses, 1 pen, 10 bond sheets for labeling the samples, 1 packing tape (for labeling the samples), 1 shopping bag for transporting the samples, and a double-layered plastic sheet or tarp of 2 meters to homogenize the extracted sample.

2.3 Sampling

2.3.1 Sampling at the contaminated site

Soil sampling was conducted at depths ranging from 0 to 30 cm within a standardized area of 25 cm × 25 cm per sampling point. To ensure methodological rigor, two sampling points were randomly selected within the contaminated area, maintaining a 20-meter distance between them. The selection of sampling sites followed a quasi-experimental design, wherein contaminated and uncontaminated zones were identified based on their relative proximity to the landfill. Contaminated sites were situated in close proximity to the landfill, where visible evidence of leachate infiltration was observed. In contrast, uncontaminated sites were located 800 to 1000 meters away, serving as a reference for background soil conditions. Within each designated zone, the random selection of two sampling points was implemented to minimize selection bias and enhance the reliability of comparative analyses.

2.3.2 Sampling at the uncontaminated site

Uncontaminated agricultural land nearby (at a distance of 800 to 1000 m from the contaminated site) was sampled for soil at depths of 0 to 30 cm within an area of 25 cm × 25 cm. For each sampling point, a total of 2 sampling points were randomly selected (with a distance of 20 m between them).

Simultaneously with the soil sampling, earthworms (at a depth of 0 to 30 cm) must be collected at both the contaminated and uncontaminated sites. During the excavation, remove stones, plastic, and other objects that may be present in the extracted soil.

The samples from each extraction point must be placed on a tarp or double-layered plastic, thoroughly mixed, and 1 kg of sample should be taken and placed in a transparent resealable plastic bag.

2.3.3 Sample identification

Label the materials with the identification of each sampling point (points 1 and 2 correspond to the contaminated site, while points 3 and 4 correspond to the uncontaminated site), and georeferencing must be performed. Finally, a comparison of means test should be applied to analyze the earthworm count.

The materials used included 1 measuring tape, 2 medium transparent containers, 4 resealable plastic bags of 2 kg capacity for filling the samples, a small shovel for excavation, disposable gloves, a lab coat, safety glasses, 1 pen, 10 bond sheets for labeling the samples, 1 packing tape (for labeling the samples), 1 shopping bag for transporting the samples, and a double-layered plastic sheet or tarp of 2 meters to homogenize the extracted sample.

2.4 Type and level of research

2.4.1 Type of research

Based on the description of the study, the type of research that best fits is quasi-experimental research. This type of research involves the manipulation of an independent variable under controlled conditions but without the random assignment of participants or subjects to treatment groups [7]. In this case, the effects of leachates from the Chupaca dump site on agricultural soil properties are analyzed, which involves manipulating the presence or absence of these leachates in different sampling sites. However, there is no full control over all variables that might affect the results.

2.4.2 Level of research

The level of research for this study can be defined as explanatory. This level of research focuses on understanding the causal relationships between variables, i.e., it seeks to explain why certain phenomena occur or how one variable affects another [8].

In this case, the study aims to explain how the presence of leachates from the Chupaca dump site affects the physical, chemical, and biological properties of agricultural soil. Authors have contributed to defining this level of research as one that goes beyond the mere description of phenomena, seeking to understand the relationships between variables and provide causal explanations [7, 9].

3. EXPERIMENTAL PROCEDURE

3.1 Determination of pH

The electrometric procedure for measuring soil pH begins with sample preparation, where 20 grams of fine agricultural soil, air-dried, and sieved through a No.10 mesh (2 mm nominal size), are mixed with 50 ml of distilled water. The resulting suspension is stirred for 15 minutes and left to rest for another 10 minutes.

This step ensures proper homogenization and allows complete interaction between the soil and water. The potentiometer is then calibrated using buffer solutions with pH values of 4, 7, and 10. Figure 3 indicates that the electrode must be cleaned and dried after each measurement to avoid cross contamination. The electrodes are also dipped into the suspension without directly touching the soil, and the pH value is recorded.

Figure 3. Electrometric pH measurement

3.2 Determination of conductivity

The procedure for measuring soil conductivity starts with sample preparation, where 20 grams of fine agricultural soil, air-dried, and sieved through a No.10 mesh, are mixed with 50 ml of distilled water. The resulting suspension is stirred for 15 minutes and left to rest for another 10 minutes. This step ensures proper homogenization and allows complete interaction between the soil and water.

Conductivity is then measured, and the electrode must be cleaned and dried after each measurement to prevent cross-contamination. Finally, the electrodes are immersed in the suspension without directly touching the soil, and the conductivity value is recorded.

3.3 Determination of organic matter

The modified Walkley-Black method for the determination of organic matter in soils is a well-established and widely used procedure due to its accuracy and reliability. The procedure involves weighing 1 g of the sample, which is then transferred to a 500 ml container. Subsequently, 10 ml of 1N potassium dichromate is added, and the mixture is stirred manually in a circular motion.

Then, 20 ml of sulfuric acid is added, followed by manual stirring (to ensure complete contact of the reagent with the soil). The mixture is left to rest for approximately 30 minutes and then diluted to 200 ml with distilled water. The sample is extracted into the reading cells, and the transmittance is measured at 660 nm.

3.4 Determination of Ca

Weigh 2 g of soil and add 50 ml of ammonium acetate solution. Stir the mixture for 5 minutes. The resulting solution is filtered, and a 5 ml aliquot is extracted into an Erlenmeyer flask. Dilute the aliquot to approximately 25 ml with distilled water, then add 5 drops of NaOH and approximately 50 mg of ammonium purpurate as an indicator. Titrate with 0.01 N ethylenediaminetetraacetic acid (EDTA) solution using a burette. The color change is from orange-red to purple.

3.5 Determination of Mg

Weigh 2 g of soil and add 50 ml of ammonium acetate solution. Stir the mixture for 5 minutes. The resulting solution is filtered, and a 5 ml aliquot is extracted into an Erlenmeyer flask, then diluted to 150 ml with water. Adding a buffer solution to adjust the pH to 10, followed by 1 ml of potassium cyanide solution and six drops of Eriochrome Black T indicator. Titrate with the EDTA solution until the color changes from wine red to blue.

3.6 Determination of phosphorus

This method quantitatively determines phosphorus (P) extracted by the solution using a colorimetric technique. The Bray method is employed because it provides better efficiency for neutral and acidic soils. Weigh 2 g of soil in a 100 ml flask, add 20 ml of Bray solution, stir for 15 minutes, and filter using Whatman No.42 filter paper.

From the filtrate, extract a 3 ml aliquot and transfer it to a 20 ml test tube. Add 10 ml of RT solution (1 g of ascorbic acid in 1 L of ammonium molybdate solution) and let it rest for approximately 30 minutes to develop the blue color. Measure the transmittance (T%) using a spectrophotometer at a wavelength of 660 nm. A blank reference is run for this analysis.

Figure 4. Soil analysis

Figure 4 illustrates the laboratory procedures involved in soil analysis, where multiple soil samples undergo chemical evaluation. The presence of glass containers with soil suspensions of varying coloration suggests the assessment of key physicochemical properties such as pH, electrical conductivity, and organic matter content. The filtration equipment and reagent bottles ensure standardized analytical techniques for accurate soil composition quantification, enabling a precise comparison between contaminated and uncontaminated samples to assess landfill leachate impacts.

3.7 Determination of potassium

The Peech method is used, which analyzes the potassium content in the extract by turbidimetry in the presence of sodium cobaltinitrite as the main reagent. In a flask, weigh 5 g of soil sample and add 20 ml of extracting solution.

Shake for 30 minutes and filter with Whatman filter paper to obtain a minimum of 15 ml of extract in a beaker. Extract a 5 ml aliquot and add 0.5 ml of sodium cobaltinitrite reagent. Stir the mixture constantly to prevent precipitation and ensure a uniform suspension.

Allow the solution to rest for 6 hours. The turbidity formed is an indicator of the potassium in the solution. Measure the transmittance at a wavelength of 660 nm using a spectrophotometer and run a blank reference.

3.8 Determination of bulk density

Weigh 25 g of fine agricultural soil, air-dried, and sieved through a No.10 mesh. Transfer the soil into a 50 ml graduated cylinder, gently tap until the soil is compacted, and record the volume displaced by the soil.

3.9 Determination of particle density

Weigh 25 g of fine agricultural soil, air-dried, and sieved through a No.10 mesh. Transfer the soil into a 50 ml graduated cylinder, add 25 ml of distilled water, and use a glass rod to eliminate air spaces in the soil.

Air bubbles emerging from the bottom of the cylinder indicate the removal of voids. Continue until no more air bubbles are observed, and record the volume displaced by the soil

3.10 Soil color

Take a portion of the sample (approximately 2 g of fine agricultural soil, air-dried, and sieved through a No.10 mesh), and place it on a clean, neutral surface, preferably white. Observe the color of the sample carefully and compare it with the color charts from the Munsell Color Chart.

Figure 5. Soil color - Munsell chart

Figure 5 provides a series of standard color chips that include a combination of letters, numbers, and colors to describe the hue, value, and chroma of the soil color. Identify the color that best matches the soil sample on the Munsell chart, and record the complete Munsell notation that accurately describes the soil sample's color.

4. METHODOLOGY

4.1 T-test

The application of the t-test in this study is essential for comparing soil properties between contaminated and non-contaminated areas, determining whether observed differences are statistically significant or attributable to random variation. This test is particularly relevant for evaluating key variables such as pH, electrical conductivity, organic matter content, and earthworm abundance, all of which are influenced by leachate exposure. By assessing the statistical significance of these changes, the t-test provides critical insights into their impact on soil health and agricultural productivity.

Moreover, the t-test enables rigorous hypothesis testing regarding the effects of leachates. The null hypothesis posits no significant differences between contaminated and non-contaminated soils, while the alternative hypothesis suggests measurable variations. The results facilitate the acceptance or rejection of these hypotheses, offering robust statistical evidence to support the study's conclusions. This analytical approach is fundamental for understanding the extent of soil degradation caused by leachates and for designing targeted mitigation strategies to protect agricultural ecosystems in the Chupaca district.

4.2 Linear regression

The linear regression analysis plays a crucial role in understanding how soil physicochemical properties, particularly electrical conductivity and organic matter content, influence pH levels. This approach provides a robust quantitative framework for assessing key variables and identifying significant patterns that affect soil chemical balance. Additionally, it enables precise estimation of the impact of each factor, establishing clear causal relationships between leachate contamination and changes in soil properties. The model's capacity to predict pH variations under different conductivity and organic matter scenarios is particularly valuable, as it allows for early identification of contamination risks and the development of timely remediation strategies to restore soil quality and ensure long-term sustainability.

Furthermore, linear regression facilitates the comparison of results with previous studies, reinforcing the validity of the findings. Complementary analyses, such as Quantile-Quantile (Q-Q) plots and normality tests, ensure the model adheres to classical regression assumptions, enhancing its reliability. The predictive capability of the model provides critical insights into potential contamination scenarios, essential for designing evidence-based mitigation strategies. In this context, linear regression emerges as a fundamental tool for assessing leachate-induced soil degradation and guiding effective interventions to preserve agricultural productivity in the Chupaca district.

4.3 Interface modeling

The COMSOL Multiphysics software will be used, which analyzes the transport capacity of leachate through the flow in porous media, which makes possible the circulation of water, gases and air, in this specific case being the transfer of leachate. through the soils, performing multiple analyses. These projections are essential to be able to know long-term scenarios and thus be able to implement prevention and/or soil recovery strategies.

5. RESULTS

5.1 T-test result

The results obtained in this study demonstrate that solid waste leachates have a significant impact on the chemical, physical, and biological properties of agricultural soil. These findings align with previous research documenting how contaminants present in leachates substantially alter soil characteristics, affecting its fertility and structure [10].

Table 2. Significance analysis of chemical parameters

Variable	Soil Type	Mean	t	d.f.	P-Value
P	Cont. Non-Cont	25.54 1.47	11.01	3	0.0016
K	Cont. Non-Cont	1.11 0.9	4.04	3	0.027
Mg	Cont. Non-Cont	3.8 4.0	-9.84	3	0.0022
Ca	Cont. Non-Cont	9.1 5.8	-15.35	3	0.0006
Al	Cont. Non-Cont	47.3 96.9	-11.01	3	0.0016
N	Cont. Non-Cont	33.48 26.88	-4.04	3	0.0273
pH	Cont. Non-Cont	6.56 7.81	-51.31	3	0.00001
Organic Matter	Cont. Non-Cont	1.3 1.0	6.47	3	0.0075
Conductivity (uS/cm)	Cont. Non-Cont	160 73	-5.45	3	0.0121

Table 2 shows that the presence of leachates caused significant changes in the chemical properties of the soil. A notable increase was recorded in the levels of phosphorus (P) and calcium (Ca), which are essential nutrients for plants. However, a decrease in potassium (K) and magnesium (Mg) levels was observed, indicating a nutritional imbalance in contaminated soils. Additionally, a slight reduction in nitrogen (N) concentration was detected, which could hinder proper crop development. This nutrient imbalance may negatively affect agricultural productivity, as it impairs the availability of essential elements needed for optimal plant growth.

Table 2 shows that the significance values for all the analyzed parameters are below 5%, indicating that the presence of leachates has a statistically significant impact on the properties of agricultural soils.

The pH of the contaminated soil showed a significant decrease, from 7.81 to 6.56, indicating a more acidic environment. Soil acidity can negatively affect nutrient availability and microbial activity, reducing soil fertility [11, 12]. This acidification may result from the decomposition of organic matter present in the leachates, which releases organic acids into the soil [13, 14].

Organic matter also showed a significant increase in contaminated soils due to the accumulation of organic material that does not fully decompose due to the toxicity of the leachates. The leachate from the Chupaca landfill contains high levels of phosphorus, a nutrient that could stimulate plant and microbial growth, thereby increasing the amount of organic matter in the soil.

Electrical conductivity increased, which could indicate the presence of leachate salts and a notable impact on the soil's ability to conduct electricity caused by contamination.

Regarding physical properties, a slight increase in the porosity of contaminated soils was observed, although this change was not statistically significant. This increase might be related to the aggregation of particles caused by organic matter from the leachates, promoting greater separation between soil particles [15]. Bulk density showed a significant decrease in contaminated soils due to the amount of organic matter generated by the presence of leachates.

Table 3 presents the results of the significance analysis of soil physical properties, showing that leachates have a moderate impact on porosity and real density, although these effects are not statistically significant ($p > 0.05$).

On the other hand, a significant effect is observed on bulk density, as the significance value is below 5%. This suggests that leachates significantly alter this property from a statistical perspective.

These results align with previous studies that have demonstrated that contaminants can alter soil structure, reducing its ability to support crops and resist erosion [16-18]. Real density showed no significant differences between contaminated and non-contaminated soils, suggesting that the mineral composition of the soil has not been considerably altered.

Table 3. Significance analysis of physical parameters

Variable	Soil Type	Mean	t	d.f.	P-Value
Porosity	Non-Cont Cont.	50.7 47.8	2.40	3	0.0959
Bulk Density	Non-Cont Cont.	2.6 2.5	1.17	3	0.3250
Apparent Density	Non-Cont Cont.	1.26 1.31	-5.45	3	0.0121

Table 4 shows that the analysis of soil biological properties has a critical impact on leachates, evidenced by the total absence of earthworms in contaminated soils compared to an average of 16 earthworms in uncontaminated soils.

Table 4. Significance analysis of biological parameters

Variable	Soil Type	Mean	t	d.f.	P-Value
Earthworm Count	Cont. Non-Cont	0 16	-18.00	6	0.0000

This result, with an extremely low significance level below 1%, suggests that leachates create a highly toxic and unfavorable environment for biological life [19]. The t-test yielded a value of -18.00, statistically confirming the negative effect of leachates on soil fauna, thereby compromising essential ecological processes in agricultural soils.

Earthworms are considered important indicators of soil quality due to their role in organic matter decomposition and soil aeration [20]. The absence of earthworms in contaminated soils indicates severe degradation of the soil ecosystem, which can have negative repercussions on agricultural productivity and long-term sustainability [21].

The findings of this study align with previous research documenting the adverse effects of solid waste leachates on soils. For example, Yeilagi et al. [22] found that leachates reduce the availability of essential nutrients and alter soil structure, consistent with our observations. Additionally, Rashid et al. [23] highlighted that soil contamination negatively impacts soil biodiversity, as evidenced in our study by the significant decline in earthworm counts.

Figure 6 illustrates the impact of leachate contamination on soil properties, comparing contaminated and non-contaminated areas. In contaminated soil, porosity decreases slightly (47.77% vs. 50.73%), while bulk and real density show minimal variation, suggesting moderate structural alteration. Chemically, pH drops significantly (6.56 vs. 7.81), indicating acidification that may reduce nutrient availability and microbial activity. Phosphorus (25.5 mg/kg) and calcium (9.1 mg/kg) levels increase, whereas potassium and magnesium decline slightly, reflecting a nutrient imbalance. Biologically, the absence of earthworms in contaminated soils, compared to 16 recorded in non-contaminated soils, highlights severe degradation, compromising biodiversity and long-term soil fertility.

The results indicate that leachates from the solid waste landfill have a significant impact on the physicochemical properties of adjacent agricultural soils.

The acidity of the soil (low pH) and elevated levels of electrical conductivity suggest that leachates contribute to soil salinization and acidification, which can inhibit crop growth and alter the availability of essential nutrients. The high organic matter content found in soils near the landfill is a consequence of leachate contamination.

5.2 Linear regression results

We present the results of the linear regression analysis applied to the updated data from the study on the impact of leachates from the Chupaca landfill on soil properties. Additionally, residual plots from the model are included to assess its validity.

The linear regression analysis aims to determine the relationship between conductivity and organic matter as predictors of soil pH. The model results show a highly significant fit, with a coefficient of determination (R^2) of 0.992, indicating that 99.2% of the variability in pH can be explained by the independent variables included in the model. Furthermore, the F-statistic value is 326.2, with an associated probability of 5.04e-06, confirming that the observed relationship between the variables is statistically significant and not due to chance.

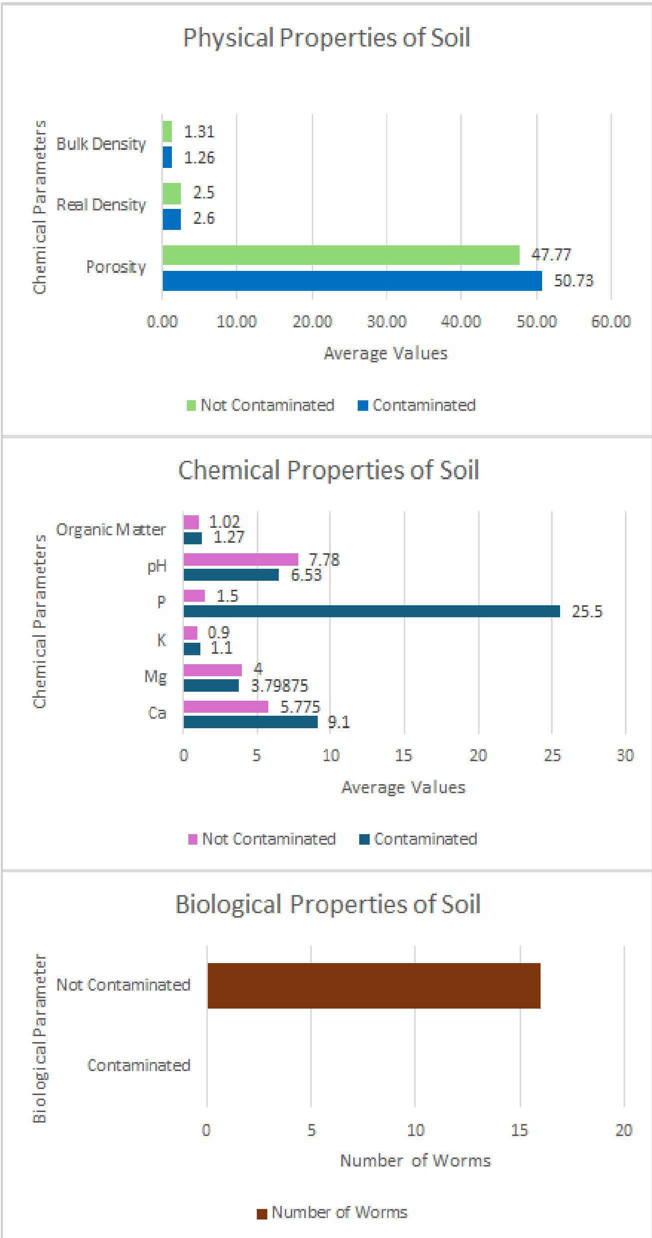

Figure 6. Properties of soil

Table 5. Model coefficients

Variable	Coefficient	SE	t	P-Value
Intercept	7.1519	0.244	29.325	0.000
Conductivity	-0.0201	0.001	-17.715	0.000
Organic Matter	2.0665	0.306	6.760	0.001

Table 5 shows the interpretation of the coefficients in the linear regression model, highlighting the impact of each independent variable on soil pH.

The intercept (7.1519) represents the pH value when conductivity and organic matter are equal to zero. The conductivity coefficient (-0.0201) indicates that for each 1-unit increase in conductivity, soil pH decreases by 0.0201 units, suggesting that an increase in soil salinity contributes to its acidification. On the other hand, the organic matter coefficient (2.0665) shows that for each additional unit of organic matter, pH increases by 2.0665 units, reflecting an alkalizing effect of this variable on the soil.

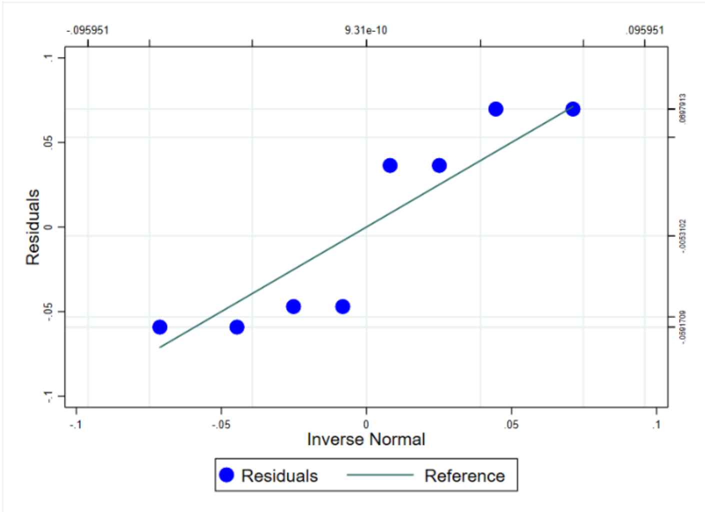

Figure 7. Quantile-Quantile (Q-Q) plot of residuals

Figure 7 presents a Quantile-Quantile (Q-Q) plot of the residuals, used to assess the normality of the residual distribution in the regression model. In this graph, the points represent the observed quantiles of the residuals, while the diagonal line indicates the expected values under a theoretical normal distribution. The alignment of the points with the line suggests that the residuals follow an approximately normal distribution, which is a key assumption for the validity of the applied statistical models. However, some deviation is observed at the extremes, which could indicate the presence of outliers or a slight departure from normality in the distribution tails.

Despite the slight dispersion at the extremes, most of the residuals follow a pattern close to the reference line, suggesting that the distribution does not exhibit a severe violation of normality. This supports the reliability of the statistical inferences made in the study, as many statistical procedures, such as linear regression and parametric tests, assume that the residuals are normally distributed.

We used the Jarque-Bera (JB) test to assess whether the residuals of the regression model follow a normal distribution. The results show a JB statistic of 1.096 and a p-value of 0.578. Since the p-value is significantly greater than the commonly used significance level of 5%, the null hypothesis, which assumes that the residuals have a normal distribution, is not rejected. This indicates that the residuals of the model are approximately normally distributed, further reinforcing the validity and reliability of the applied regression model.

Below are the pH predictions for new values of conductivity and organic matter.

Table 6. pH predictions based on conductivity and organic matter

Conductivity (uS/cm)	Organic Matter (%)	Predicted pH
100	0.9	7.27
150	1.2	6.66
200	1.5	6.33

Table 6 and Figure 8 illustrate the predicted relationship between soil electrical conductivity and pH, showing a clear inverse correlation. As conductivity increases from 100 to 200 µS/cm, pH declines from approximately 7.2 to 6.4, indicating that higher salinity contributes to soil acidification. This trend suggests that leachate contamination, which elevates soil conductivity through dissolved salts and organic compounds, may significantly disrupt soil chemical balance. The reduction in pH can negatively impact nutrient availability and microbial activity, potentially impairing soil fertility and crop productivity. These findings highlight the need for effective leachate management to mitigate acidification and preserve soil health in agricultural areas.

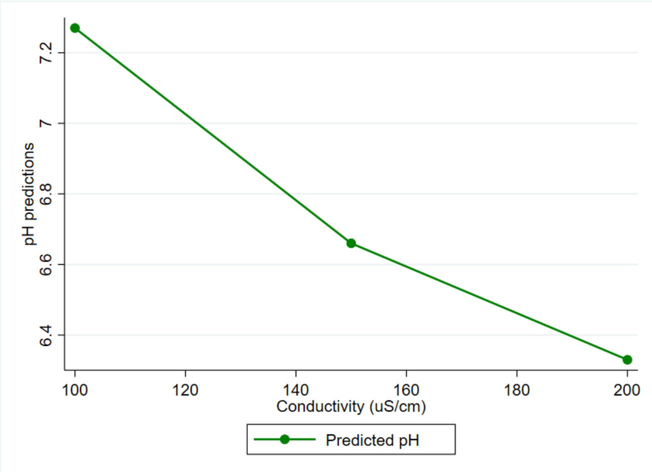

Figure 8. pH prediction based on conductivity

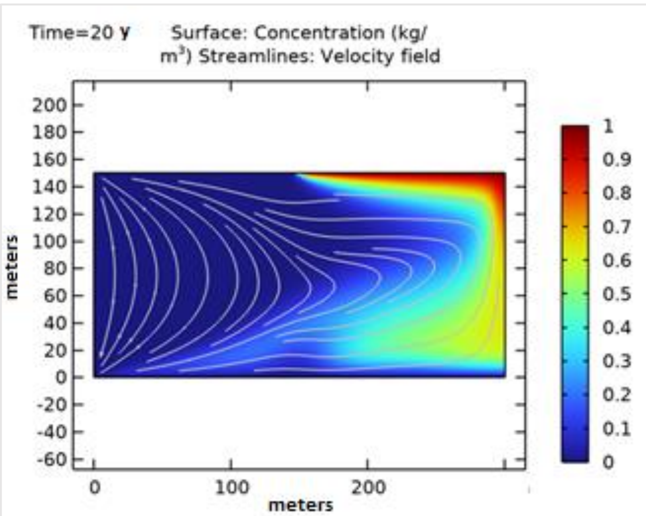

Figure 9. Concentration behavior and flow dynamics

Figure 9 illustrates the concentration behavior and flow dynamics of contaminants over a 20-year period, highlighting the spatial distribution of leachate migration through the soil. The color gradient represents contaminant concentration, with higher values (red and orange) concentrated near the source and gradually decreasing towards the periphery (blue and green), indicating progressive dilution. Streamlines depict the velocity field, showing the direction and intensity of flow, which follows a predominantly horizontal trajectory with minor vertical dispersion. This pattern suggests that contaminant transport is influenced by both advection and diffusion processes, with a notable accumulation at approximately 200 meters from the source. These results emphasize the long-term impact of leachate infiltration, underscoring the necessity for proactive containment and remediation strategies to prevent further degradation of surrounding agricultural soils and water resources.

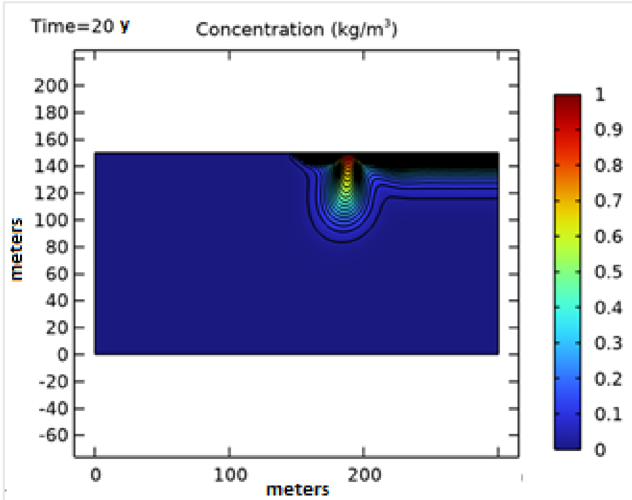

Figure 10. Soil concentration distribution

Figure 10 illustrates the spatial distribution of contaminant concentration in the soil over a 20-year period. The highest concentration (red zone) is localized near the contamination source, gradually decreasing outward (blue areas), indicating diffusion and dispersion over time. The confined spread suggests limited vertical migration, likely due to soil properties restricting downward infiltration. This pattern highlights the persistence of contaminants near the source, emphasizing the need for targeted remediation strategies to prevent long-term soil degradation and groundwater contamination.

6. DISCUSSION

The results of this study highlight the significant impact of leachates from the municipal landfill of Chupaca on the physical, chemical, and biological properties of nearby agricultural soils. The t-test results revealed substantial changes in nutrient levels in contaminated soil, including a significant increase in phosphorus (P) and calcium (Ca) and a decrease in potassium (K) and magnesium (Mg). These findings align with those researchers [24, 25], who documented how leachates alter the availability of essential nutrients. This imbalance could negatively affect agricultural productivity by impacting the absorption of critical nutrients for plant growth.

The pH of the contaminated soil showed a significant decrease, from 7.81 to 6.56, indicating a more acidic environment. Soil acidity can negatively affect nutrient availability and microbial activity, reducing soil fertility [11, 12]. This acidification may result from the decomposition of organic matter present in the leachates, which releases organic acids into the soil [13, 14].

The soil acidification observed in this study is a direct consequence of leachate infiltration from the Chupaca municipal landfill. This phenomenon is driven by the release of organic acids from the decomposition of organic matter in waste, which lower soil pH by increasing proton concentration in the soil solution. Additionally, the presence of heavy metals, such as aluminum, exacerbates this effect through hydrolysis processes and the displacement of essential cations like calcium and magnesium, weakening the soil's buffering capacity. The reduction in pH limits nutrient availability and disrupts beneficial microbial activity, ultimately affecting soil fertility and agricultural productivity. These findings highlight the need for effective remediation strategies to mitigate acidification and preserve soil chemical stability.

A critical finding was the total absence of earthworms in contaminated soils, compared to an average of 16 earthworms in non-contaminated soils. This result, with an extremely low significance level ($p < 0.01$), suggests a highly toxic environment for biological life. Earthworms, considered key bioindicators, play a vital role in organic matter decomposition and soil aeration [26]. Their absence implies severe degradation of the soil ecosystem, consistent with study by Chen et al. [27].

Regarding physical properties, the changes observed in porosity and real density were not statistically significant, whereas bulk density showed a significant decrease in contaminated soils. This change may be related to the increase in organic matter, which reduces soil compaction. These findings support those reported by Gomiero [28], who emphasized how contaminants affect soil structure, diminishing its ability to support crops and resist erosion.

The linear regression analysis confirmed that conductivity and organic matter are significant predictors of soil pH, explaining 99.2% of its variability ($R^2 = 0.992$). This high degree of fit supports the robustness of the model used and enables future scenario predictions. Furthermore, numerical simulation with COMSOL indicated that, over 20 years, contaminants could be transported up to 300 meters from the landfill, emphasizing the need for mitigation measures.

The findings underscore the urgency of implementing sustainable waste management strategies and soil remediation programs. Soil acidification and salinization could be addressed through the use of organic amendments and phytoremediation, while biological rehabilitation could focus on the reintroduction of earthworms and other beneficial organisms.

While this study provides a comprehensive analysis of the impact of leachates from the Chupaca municipal landfill on agricultural soils, it has certain limitations. The analysis was conducted over a specific period, without accounting for seasonal variations that could alter leachate composition and its effects on the soil, particularly during rainy or dry seasons. Additionally, although key chemical and biological properties were evaluated, the study did not thoroughly assess the presence of heavy metals, whose accumulation could intensify contamination and affect soil biota. Furthermore, the computational modeling predicts the long-term migration of contaminants but does not incorporate the influence of agricultural practices or fertilizer applications. These limitations highlight the need for future research to expand the temporal and analytical scope, providing a more precise understanding of leachate dynamics and optimizing remediation strategies.

7. CONCLUSIONS

The results of this research were able to show that the leachates from the municipal landfill of the province of Chupaca managed to negatively and significantly impact the physical, chemical and also biological properties of the soils, and also managed to alter the properties of the soils that were found in the surroundings where it is currently located, these results being evidence that better sustainable practices must be implemented immediately for better control of the soils of this province.

Being more specific with each negative impact generated by leachates, we will begin with the alterations suffered in the chemical properties of the soils, where a negative deterioration was evident in the decrease in PH from 7.81 to 6.56, thereby leading to a higher degree of acidity. in the soil and the environment. This type of event brings with it negative effects on the correct availability of soil nutrients and also negatively alters microbial activity, thus compromising soil fertility, turning them into sterile lands [1]. The decomposition of the organic matter found in the leachates brings with it the release of organic acids in the soils, which increase the chemical balance in the soil in an uncontrolled manner [2]. These alterations being the main causes of significant negative consequences in a long-term period in the productivity and stability of agricultural soils and the ecosystem in general.

In reference to the biological properties of the soils, it was also evident that they were severely damaged, demonstrated by the complete elimination of worms within the contaminated soils, unlike the non-contaminated soils where several were found. These types of results demonstrate that leachates negatively disturb soils, transforming highly toxic and harmful conditions for both flora and fauna [3]. Earthworms are considered essential bioindicators of soil quality and health, due to their fundamental role in the nutrient cycle, the decomposition of organic matter and also aeration [4]. The lack of these earthworms indicates a profound degradation of the ecosystem, which if not adequately controlled could endanger the proper sustainability of agricultural activities in this province.

Regarding the physical properties of the soils, the study managed to demonstrate a notable reduction in the apparent density of the soils, with which, being altered, their properties lose their ability to retain water and in addition to being able to support the roots of the plants, which is attributed exclusively to the accumulation of leachate [5]. Although it should be noted that statistically significant changes were not highlighted in relation to the real density of the soils, however these results also suggest that soils with mineral contamination from leachate could undergo significant changes.

These results are consistent with previous research showing how leachate contamination alters soil composition, reducing its capacity to support agricultural activities and increasing its susceptibility to erosion. The observed impacts on its physical, chemical and biological properties highlight the close interdependence between ecosystems and the adverse effects of contamination.

Using COMSOL Multiphysics software, simulations were performed to project the migration of contaminants from leachates over a period of up to 20 years. The results indicate that these contaminants could disperse up to 300 meters, increasing the risk of soil degradation in agricultural areas and the potential impact on nearby water resources. This study provides significant scientific evidence on the dynamics of leachate dispersion in agricultural soils, integrating a multidisciplinary approach that combines physicochemical, biological and computational modeling analyses. Given the limited research on this phenomenon in the Andean region, the findings represent a substantial contribution to understanding pollution processes and their long-term impact on productive ecosystems. They also highlight the need to establish public policies focused on soil remediation and efficient waste management, particularly in vulnerable rural areas where agriculture plays a crucial role in the local economy.

Therefore, we conclude that it is imperative to implement mitigation measures, prioritizing the development and application of advanced waste management systems and effective soil recovery strategies to minimize contamination risks. Moreover, these results provide a solid foundation for future research aimed at the characterization of heavy metals and the evaluation of sustainable technologies for the rehabilitation of degraded soils, ensuring the long-term sustainability of agricultural ecosystems and environmental security.

8. RECOMMENDATIONS

The study highlights the need to be able to put into practice suitable strategies for the correct management and treatment of leachate in the dumpsite of the province of Chupaca, with the objective of preventing its infiltration into peripheral agricultural soils. Likewise, it is proposed to be able to develop some remediation proposals that manage to incorporate the use of organic correctives and make use of techniques such as plant bioremediation, which would be capable of reducing the effects of soil acidification and salinization.

Ecological restoration must be prioritized through the biological restoration of the soil, such as worms, in order to restore biological balance and vital ecological cycles. On the other hand, it is considered essential to be able to establish a permanent monitoring strategy which is capable of carrying out constant evaluations of the type of soil quality and can also immediately and continuously report the presence of all types of possible contaminants in those agricultural areas. peripherals.

While this study provides evidence of the impact of leachates on agricultural soil quality, future research should address complementary aspects to further characterize and mitigate this issue. First, a more detailed analysis of the heavy metals present in leachates and their bioaccumulation in crops is necessary to assess risks to human health and food safety. Additionally, long-term studies that incorporate seasonal variations in leachate composition would provide a more accurate understanding of their dynamics and cumulative effects on the soil. From a mitigation perspective, exploring bioremediation strategies based on microorganisms and organic amendments, as well as designing leachate treatment systems to reduce their toxicity before soil infiltration, is recommended. Finally, advanced modeling with geospatial data and hydrodynamic simulations would allow for better predictions of contaminant migration, facilitating the development of more effective environmental management policies.

Finally, more rigorous regulatory measures are required for proper management of solid and leachate waste, and at the same time, the adoption of better sustainable agricultural practices should be promoted. Future research should focus on analyzing other types of components that are present in the leachate, such as the various types of metals and their impact or possible impact of these components on the different types of agricultural land, thus making it possible to formulate and develop more solutions. holistic and precise in order to effectively guarantee the recovery of damaged agricultural ecosystems.

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NOMENCLATURE

P	Phosphorus level (mg/kg)
K	Potassium level (mg/kg)
Mg	Magnesium level (mg/kg)
Ca	Calcium level (mg/kg)
Al	Aluminum level (mg/kg)
N	Nitrogen level (mg/kg)
pH	Hydrogen potential (dimensionless)
OM	Organic matter (% weight)
EC	Electrical conductivity (uS/cm)
AP	Apparent porosity (%)
BD	Bulk density (g/cm^3)
RD	Real density (g/cm^3)

Greek symbols

μ	Dynamic viscosity (Pa.s)

Subscripts

Cont.	Contaminated soil
Non cont.	Non-contaminated soil