Vol 28 (1)

Ingeniería y Competitividad
Vol 28 (1) 2026 doi: 10.25100/iyc.v28i1.15329

ISSN
0123-3033
e- 2027-8284

Original Article

Remediation of Andisols Contaminated by Whey Through the Application of Organic Fertilizer

Remediación de Andisoles Contaminados con Suero de Leche mediante la Aplicación de Fertilizantes Orgánicos

Jenny L. Huertas Delgado[1] Juan S. Garzón Quiñonez [1] Angela M. Sánchez Madroñero[1]
Lisbeth C. Rodríguez Patichoy[1]

[1]Grupo de investigación Ambiental (GIA), Universidad Mariana, Programa de Ingeniería Ambiental, Universidad Mariana, Pasto, Nariño, Colombia.

How to cite?

Garzón JS, Sánchez AM, Rodríguez LC, Huertas JL. Remediation of Andisols Contaminated by Whey Through the Application of Organic Fertilizer. Ingeniería y Competitividad, 2026, 28(1)e-20715329

https://doi.org/10.25100/iyc.v28i1.15329

Received: 10/07/25
Revised: 22/01/26
Accepted: 02/02/26
Online: 24/02/26

Correspondence

hgrubianos@ut.edu.co

Spanish version

Abstract

Introduction: Soil contamination by agro-industrial waste, such as whey, poses a significant threat to ecosystem sustainability and agricultural productivity.
Objetive: This study evaluated the effectiveness of organic fertilizer as a bioremediation strategy for Andisols contaminated with whey in Villa Moreno, Buesaco (Nariño).
Metodology: The impact on key physicochemical properties such as pH, electrical conductivity (EC), organic matter (OM), cation exchange capacity (CEC), bulk density, and porosity was analyzed. A randomized block design was implemented with treatments of control soil, contaminated soil, and soil contaminated with two different doses of organic fertilizer (500 g and 1000 g per 3 kg of soil).
Results: The results indicated that the addition of whey slightly acidified the soil and significantly increased its salinity. The application of organic fertilizer effectively neutralized the pH, improved the organic matter content and CEC, and reduced the bulk density, increasing porosity. Although both fertilizer doses were effective, the higher dose showed faster neutralization but also a higher risk of salinization.
Conclusions: It is concluded that organic fertilizer is a viable and sustainable alternative for the remediation of soils contaminated by whey, although careful management of the dose is required to balance fertility recovery and salinity control.

Keywords: Bioremediation, soil contamination, liquid whey, organic fertilizer, physicochemical properties, Andisols.

Resumen

Introducción: La contaminación del suelo por residuos agroindustriales, como el suero de leche, representa una amenaza significativa para la sostenibilidad de los ecosistemas y la productividad agrícola.
Objetivo: Este estudio evaluó la efectividad del fertilizante orgánico como estrategia de biorremediación para Andisoles contaminados con suero de leche en Villa Moreno, Buesaco (Nariño).
Metodología: Se analizó el impacto sobre propiedades fisicoquímicas clave como pH, conductividad eléctrica (CE), materia orgánica (MO), capacidad de intercambio catiónico (CIC), densidad aparente y porosidad. Se implementó un diseño de bloques al azar con tratamientos de suelo control, suelo contaminado y suelo contaminado con dos dosis diferentes de fertilizante orgánico (500 g y 1000 g por 3 kg de suelo).
Resultados: Los resultados indicaron que la adición de suero de leche acidificó ligeramente el suelo y aumentó significativamente su salinidad. La aplicación de fertilizante orgánico neutralizó eficazmente el pH, mejoró el contenido de materia orgánica y la CIC, y redujo la densidad aparente, incrementando la porosidad. Aunque ambas dosis de fertilizante fueron efectivas, la dosis más alta mostró una neutralización más rápida, pero también un mayor riesgo de salinización.
Conclusiones: Se concluye que el fertilizante orgánico es una alternativa viable y sostenible para la remediación de suelos contaminados con suero de leche, aunque se requiere un manejo cuidadoso de la dosis para equilibrar la recuperación de la fertilidad y el control de la salinidad.

Palabras clave: Biorremediación, contaminación del suelo, suero de leche líquido, fertilizante orgánico, propiedades fisicoquímicas, Andisoles.

Why was it carried out?
The disposal of untreated whey can disrupt soil chemical balance (acidification and salinization) and impose a high organic load. This issue is particularly relevant in municipalities of Nariño (Colombia), where adequate treatment processes for this type of wastewater are often limited. In addition, Andisols—common in volcanic regions of the area—exhibit distinctive physical and chemical properties (high organic matter, high cation exchange capacity, strong sorption capacity, and the influence of amorphous minerals) that can govern solute mobility, contaminant retention, and the soil response to amendments, making them a key system for remediation research. Therefore, we evaluated whether the organic amendment ABONISSA could rapidly restore soil chemical functionality and promote early attenuation of n-hexane extractable material (HEM) under controlled microcosm conditions.
Most relevant results
Over 7–15 days, ABONISSA treatments showed: (i) acidity neutralization (pH increase), (ii) significant increases in organic matter and cation exchange capacity (CEC), (iii) decreases in HEM relative to the whey-contaminated soil, and (iv) physical improvements (lower bulk density and higher porosity). However, EC increased markedly, especially at the high dose (REM1), indicating a risk of secondary salinization.
What do they contribute?
The results support ABONISSA as a promising early-stage management option for whey-affected Andisols, while emphasizing that the assessment captures an initial response rather than definitive soil remediation. The study also demonstrates a dose-dependent salinity risk, highlights the need for EC mitigation/monitoring, and recommends longer-term (greater than 60 days) and field validation to confirm sustainability and potential impacts on agricultural productivity. In addition, these findings open the possibility of considering more integrated treatment approaches for this type of wastewater, in which Andisols, due to their distinctive physical and chemical properties, could function as controlled receiving media and regulatory filters, contributing to contaminant retention/attenuation and organic-load reduction in combined soil–amendment treatment schemes (e.g., ex situ systems or integrated processes), provided that appropriate management, monitoring, and safeguards are implemented to prevent secondary impacts such as salinization.

Graphical Abstract

doi: 10.25100/iyc.v28i1.15329

Introduction

Soil contamination has emerged as a formidable and escalating global environmental crisis, casting a long shadow over the sustainability of our planet's ecosystems and the productivity of its agricultural lands (1). Within rural landscapes characterized by intensive agro-industrial operations, such as the Nariño region of Colombia, the inadequate management of dairy byproducts, most notably whey, has been identified as a primary driver of this environmental degradation. Whey, despite its rich organic composition, triggers a cascade of adverse physicochemical alterations when discharged into the soil without proper control. These detrimental effects include significant soil acidification, increased salinization, and a diminished capacity for retaining essential nutrients and water. Such changes directly compromise soil fertility and disrupt the delicate balance of essential microbial communities (2,3). The repercussions of this degradation extend beyond the immediate threat to agricultural yields a cornerstone of local economies as they can also precipitate the leaching of nitrates and phosphates into groundwater. This nutrient runoff exacerbates the eutrophication of adjacent water bodies, thereby endangering the quality of water resources vital for both human consumption and agricultural irrigation (4).

The remediation of soils degraded by agro-industrial waste is an imperative for safeguarding environmental health and securing the global food supply. Within this framework, bioremediation, particularly through the strategic application of organic fertilizers, is increasingly recognized as a highly promising and environmentally sustainable solution. These fertilizers, derived from the controlled decomposition of plant and animal materials, not only supply a rich profile of essential nutrients but also stimulate the activity of beneficial microorganisms. This microbial enhancement is key to facilitating the breakdown of organic pollutants and improving the overall physical and chemical structure of the soil (5). A substantial body of previous research has validated the capacity of organic amendments to increase the Cation Exchange Capacity (CEC), stabilize pH levels, and significantly improve water retention in compromised soils (6).

Despite this progress, a critical knowledge gap persists regarding the specific efficacy and optimal application rates of organic fertilizers for the remediation of Andisols—a soil type prevalent in tropical regions like Villa Moreno, Buesaco (Nariño)—that are specifically contaminated with whey. Andisols, while possessing good drainage, are inherently limited in their ability to retain water and nutrients, which makes them exceptionally vulnerable to the impacts of contamination (7). This vulnerability necessitates a rigorous and systematic evaluation to quantify the effects of varying doses of organic fertilizer on the soil's key physicochemical properties. A comprehensive analysis of pH, electrical conductivity (EC), organic matter (OM), CEC, bulk density, and porosity is essential to develop and optimize effective soil recovery strategies.

This research directly confronts this knowledge deficit by systematically evaluating the use of organic fertilizer as a bioremediation tool for whey-contaminated Andisols in Villa Moreno. Our findings indicate that while whey contamination leads to soil acidification and increased salinity, the application of organic fertilizer effectively counteracts these effects. It successfully

doi: 10.25100/iyc.v28i1.15329

neutralizes pH, enriches the soil with organic matter, boosts CEC, and reduces bulk density, thereby enhancing porosity. Although both tested fertilizer doses were beneficial, the higher dose provided faster neutralization but also introduced a heightened risk of salinization. Consequently, this investigation is guided by the following central research question:

To what precise extent can the application of organic fertilizer remediate Andisols contaminated by whey in Villa Moreno, Buesaco, Nariño, while simultaneously optimizing the recovery of soil fertility and maintaining effective control over salinity?

Materials and Methods

Study Area

The research was conducted in La Florida, a municipality situated in the department of Nariño in the southwestern Andean region of Colombia. This mountainous area is characterized by a temperate climate and a diverse topography of mountains, valleys, and rivers, which collectively foster a conducive environment for a range of agricultural pursuits. Dairy production stands out as a cornerstone of the local economy. The whey utilized as the contaminating agent in this investigation was procured from Lácteos Figueroa, a prominent dairy enterprise that is representative of the region's productive sector. The main administrative center of La Florida is located at an elevation of 2,077 meters above sea level (m.a.s.l.), experiencing an average annual temperature of approximately 17°C and receiving nearly 2,500 mm of annual precipitation. The municipality spans three distinct thermal zones: cold, temperate, and the high-altitude páramo (Figure 1).

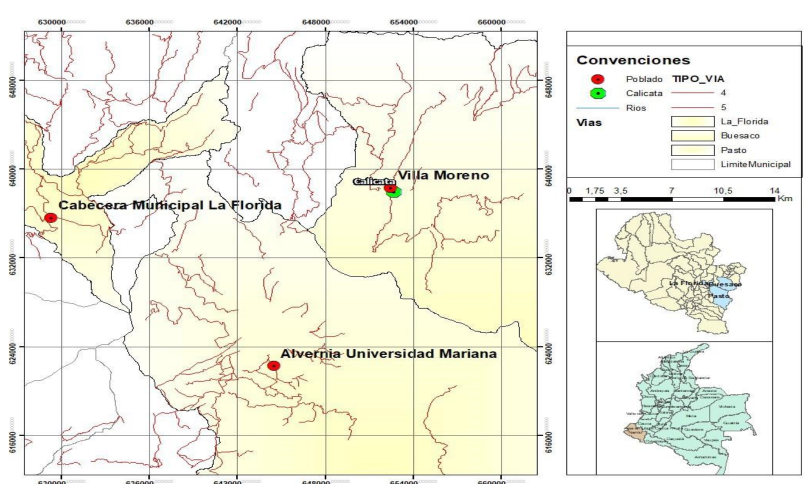

Figure 1. Map of key locations in the investigation Source: Adapted from IGAC and Colombia en Mapas

The specific experimental site was located in Villa Moreno, a sub-district within the municipality of Buesaco, also in Nariño. Buesaco is nestled in the Andean highlands, with its municipal center at an average altitude of 1,959 m.a.s.l., while the Villa Moreno sub-district can reach elevations approaching 2,200 m.a.s.l. (8). The municipality is renowned for its favorable climate, often

doi: 10.25100/iyc.v28i1.15329

cited as one of the "best climates in the nation," with average temperatures around 20°C in certain areas, making it ideal for agriculture (8). While precipitation in this part of the Andes is variable, it is generally adequate to support a diversity of crops. Historically, Buesaco has been a territory of significant agricultural importance, with a peasant economy founded on traditional production systems where coffee and corn are the most notable crops (8).

Descripción de metodologías

A representative plot within the study area was selected for the excavation of a soil pit (calicata) to facilitate a detailed morphological analysis. The in-situ description of the soil profile involved identifying distinct horizons and meticulously documenting their visual and tactile characteristics. A comprehensive set of parameters was recorded, including soil color (determined using the Munsell color chart), texture assessed by feel, soil structure (categorized by type, size, and grade), consistency (evaluated in wet, moist, and dry states), the presence and abundance of plant roots, the existence of mottling, visible porosity, and any other distinguishing features such as hardened pans or carbonate accumulations. This thorough characterization provided a critical baseline understanding of the initial soil properties and their potential influence on the subsequent contamination and remediation dynamics.

To quantitatively evaluate the changes in the soil's physicochemical properties, samples were systematically collected at key stages: prior to any treatment (control soil), following contamination with whey, and after the application of varying doses of ABONISSA organic fertilizer, as dictated by the experimental design. These samples underwent a battery of laboratory analyses to determine a range of physicochemical properties. The specific analytical methods employed for each parameter are detailed in Table 1.

Table 1. Laboratory methods for the analysis of soil physicochemical properties.

Test	Method	Instruments	Reagents
Organic Matter	Walkley and Black	Spectrophotometer; Erlenmeyer flask	Potassium dichromate ($K_2Cr_2O_7$); Sulfuric acid (H_2SO_4)
CEC (Cation Exchange Capacity)	Titration (Ammonium acetate)	Burette; beaker; Erlenmeyer flask	Ammonium acetate (CH_3COONH_4); Sodium hydroxide ($NaOH$); Formaldehyde (CH_2O)
True Density	Pycnometer method	Pycnometer; balance; syringe	Distilled water (H_2O)
Bulk Density	Graduated cylinder (Clod method)	Graduated cylinder; balance	–
pH	Potentiometry (saturated paste)	pH meter; glass jars	Buffer solutions
Electrical Conductivity	Conductometry (saturation extract)	Conductivity meter; beaker	Distilled water (H_2O)
Soil Texture	Hydrometry (Bouyoucos)	Hydrometer; dispersing cup; graduated cylinder	Sodium hexametaphosphate ($(NaPO_3)_6$); Sodium carbonate (Na_2CO_3); Distilled water (H_2O)

doi: 10.25100/iyc.v28i1.15329

Porosity	Indirect calculation	True and bulk density data	–
Moisture	Gravimetry (oven drying)	Oven; balance; crucibles	–

To quantify the reduction of fats and oils across the different treatments (CONT, REM1, REM2) and sampling intervals, the standardized procedure for determining n-Hexane Extractable Material (HEM), as outlined in the NMX-AA-134-SCFI-2006 standard (9), was strictly followed. A soil subsample (approximately 10 g), which was pre-mixed with anhydrous sodium sulfate if necessary to remove excess moisture, was subjected to an extraction process using n-hexane as the solvent. This was performed with a sonication device (an ultrasonic disruptor with a submersible horn) under the conditions specified by the standard (30 mL of n-hexane, sonication at 100% power with a 50% pulse for 3 minutes, with the extraction repeated). The resulting extract was carefully separated from the soil matrix via centrifugation or filtration. Subsequently, the solvent from the pooled extract was evaporated in a pre-weighed round-bottom flask containing boiling chips, using a water or steam bath. A distillation apparatus was used as needed to recover the solvent until the residue was completely dry. The flask containing the HEM residue was then dried in an oven at 125°C for one hour, cooled in a desiccator, and weighed repeatedly until a constant weight was achieved. The concentration of HEM—which, according to definition 4.5 of the standard, includes fats, oils, non-volatile hydrocarbons, and waxes—was calculated gravimetrically and expressed based on the dry mass of the soil.

Experimental Design

To rigorously pursue the study’s objectives, a quantitative Randomized Block Experimental Design was meticulously implemented. This robust design was chosen to systematically evaluate the efficacy of the organic fertilizer as a remediation agent for whey-contaminated soil. Furthermore, this experimental structure ensures the statistical validity of the results by effectively minimizing the influence of variability arising from external, uncontrolled factors.

Treatments

The experimental treatments were structured as follows:

T1: Uncontaminated Control Soil (CTR). This treatment consisted of pots filled with 3 kg of uncontaminated soil, to which neither whey nor organic fertilizer was applied. It served as the critical baseline, representing the natural physicochemical state of the soil and providing a benchmark against which the impacts of contamination and remediation could be accurately measured.

T2: Whey-Contaminated Soil (CONT). In this treatment, 750 ml of whey was applied to pots containing 3 kg of soil, with no subsequent addition of organic fertilizer. This allowed for the direct assessment of whey’s impact on soil properties, establishing a clear baseline of the negative effects of the contamination.

T3: Contaminated Soil with High-Dose Remediation (REM1). This treatment involved applying 750 ml of whey along with a 1000 g dose of organic fertilizer (compost or vermicompost) to

doi: 10.25100/iyc.v28i1.15329

pots containing 3 kg of soil. Its purpose was to investigate the remediation potential of a higher application rate of the organic amendment.

T4: Contaminated Soil with Low-Dose Remediation (REM2). This treatment consisted of applying 750 ml of whey along with a 500 g dose of organic fertilizer to pots with 3 kg of soil. It was designed to evaluate whether a lower, more moderate dose of the organic amendment could still achieve a significant and effective remediation outcome.

To isolate the effects of the treatments, a uniform watering regime was applied to all experimental units throughout the duration of the study. Specifically, 140 ml of water was administered at intervals corresponding to the sampling schedule (7 days before the first sampling, M1, and 15 days before the second sampling, M2), in accordance with the established experimental protocol (2).

Response Variables

The efficacy of the treatments was assessed through a series of response variables directly linked to the physicochemical parameters measured in the laboratory and field:

- Soil pH
- Soil Texture
- Bulk density
- Particle density
- Moisture content
- Porosity
- Electrical conductivity
- Cation Exchange Capacity (CEC)
- Organic matter content
- Fat and oil content

Statistical Analysis

The empirical data generated from this experiment will be subjected to a rigorous statistical analysis using a two-way Analysis of Variance (ANOVA). This powerful statistical method is ideal for evaluating the main effects of multiple factors (treatment type and time) and their potential interactions. The ANOVA will facilitate a detailed comparison of the mean values of the various physicochemical soil properties, not only across the different treatment groups (CTR, CONT, REM1, REM2) but also between the two distinct sampling points in time (M1 at 7 days and M2 at 15 days).

doi: 10.25100/iyc.v28i1.15329

Morphological Characterization of the Soil

An in situ morphological characterization of the soil was conducted to establish a baseline of its properties prior to the application of the experimental treatments. To this end, a soil pit was excavated to a depth of 52 cm and four horizons (H1–H4) were described, recording visual and tactile parameters such as soil color, texture, roots, moisture, and consistency. This information is crucial because it controls processes such as infiltration, water retention, aeration, and solute mobility, which in turn govern whey dynamics and the soil's response to the organic amendment. Overall, this baseline enables more accurate interpretation of subsequent changes and a more robust assessment of the effectiveness of the proposed remediation design.

Soil characterization revealed a profile with four horizons (0–52 cm) (Table 2). The surface horizons H1 (0–14 cm) and H2 (14–26 cm) showed a sandy loam texture, dark colors, subangular blocky structure, mottling, and hardened layers (3.4 and 2.8 cm), with a predominance of fine roots. In contrast, the deeper horizons H3 (26–38 cm) and H4 (38–52 cm) shifted to a loamy sand texture, with relatively lighter colors, no mottling, and thinner hardened layers (2.1 and 1.7 cm); root abundance also decreased with depth and was absent in H4.

Table 2. Data from the morphological characterization of the soil.

Horizon	1	2	3	4
Depth (cm)	0 – 14	14 – 26	26 – 38	38 – 52
Texture	Sandy Loam	Sandy Loam	Loamy Sand	Loamy Sand
Munsell Color	10YR 3/2	7.5YR 3/2	10YR 3/3	10YR 4/4
Structure	Subangular Blocks	Subangular Blocks	Subangular Blocks	Subangular Blocks
Mottling	Yes	Yes	No	No
Consistency (Moist)	Friable	Very Friable	Very Friable	Very Friable
Plasticity	Non-Plastic	Slightly Plastic	Slightly Plastic	Non-Plastic
Adhesiveness	Slightly Adherent	Slightly Adherent	Slightly Adherent	Slightly Adherent
Roots	Fine	Fine	Fine	Not found
Abundance	Very Abundant	Scarce	Scarce	Not found

Mottling in H1–H2 suggests periodic moisture fluctuations and alternating saturation/oxidation conditions (10), whereas the dark surface coloration is consistent with higher organic matter accumulation and biological activity (11). The transition from sandy loam to loamy sand may be related to a lithological discontinuity or differential pedogenetic processes (12) and generally implies better drainage but also greater susceptibility to leaching and lower water and nutrient retention at depth (13). The slight stickiness observed is consistent with the role of clay and organic matter as binding agents that promote aggregation (14). Finally, the absence of roots in H4 may be explained by greater depth and/or less favorable physical conditions (lower water-

doi: 10.25100/iyc.v28i1.15329

holding capacity or local barriers) that restrict root penetration and development (13).

Evaluation of Changes in Physicochemical Properties of Contaminated Soil Following the Application of ABONISSA Organic Fertilizer

This section provides a detailed assessment of the shifts in the physicochemical properties of the soil that was previously contaminated with whey. This evaluation was conducted following the application of a bioremediation treatment centered on the use of ABONISSA, a powdered organic amendment specifically formulated for direct soil application. Its composition is based on a blend of animal and plant-derived materials, including poultry manure, sugarcane dust, and sawdust, and it was selected for its recognized properties as a restorer of edaphic characteristics. The production of this fertilizer involved a carefully controlled process of composting and maturation. The guaranteed chemical analysis of Abonissa revealed a substantial contribution of macronutrients, containing 1.5% total nitrogen (N), 4% available phosphorus (P2O5), and 3.5% soluble potassium (K2O). Furthermore, its high content of oxidizable organic carbon (19%) and its distinctly alkaline nature, with an initial pH of 8.2, were notable features (15).

The contaminating agent, whey, is a major byproduct of the cheese manufacturing industry. Its improper disposal is a significant environmental concern due to its high biochemical oxygen demand and organic load. Previous physicochemical analyses have classified this type of byproduct as sweet whey, characterized by an average pH of 5.7. This pH is higher than that of acid wheys and directly influences its interaction with the soil matrix. Lactose was identified as its primary component, with a reported concentration of approximately 5.1%. The whey's composition also included a protein fraction of about 0.71% and a fat content of 0.5%. While these components have nutritional value, they are the main contributors to its high pollution potential when mismanaged (16).

pH Analysis

Soil pH, a measure of its acidity or alkalinity, is a master variable in soil science, exerting a profound influence on the bioavailability of nutrients for plants, the activity and diversity of microbial ecosystems, and the overall efficiency of remediation processes (17). n this investigation, the control soil (CTR), which received no whey or organic fertilizer, exhibited a stable and near-neutral pH, with an average of 6.80 at the 7-day mark (M1) and 6.81 at 15 days (M2).

doi: 10.25100/iyc.v28i1.15329

These pH values fall squarely within the slightly acidic to neutral range as defined by the FAO classification system (Table 3). This is highly consistent with the known characteristics of Andisols, which are soils derived from volcanic ash. These soils frequently display a pH in this range due to their unique mineralogy and typically high concentration of organic matter. During decomposition, this organic matter can release various organic acids, which contributes to the soil's natural acidity (12,18).

Table 3. Soil pH classification according to the FAO. Fuente: Adaptado de FAO (2006).

pH Range	Classification
< 4.5	Extremely acid
4.5 - 5.0	Very strongly acid
5.1 - 5.5	Strongly acid
5.6 - 6.0	Moderately acid
6.1 - 6.5	Slightly acid
6.6 - 7.3	Neutral
7.4 - 7.8	Slightly alkaline
7.9 - 8.4	Moderately alkaline
8.5 - 9.0	Strongly alkaline
> 9.0	Very strongly alkaline

The introduction of whey (CONT treatment) induced a noticeable, albeit slight, acidification of the soil. The pH dropped to 6.695 at M1 and was 6.781 at M2. This acidifying effect is directly attributable to the presence of organic acids, such as lactic acid, within the whey (19,20). Statistical analysis (Figure 2) confirmed that the pH of the CONT M1 treatment was significantly lower than that of the other treatments at the M1 sampling and also significantly lower than its own value at the M2 sampling.

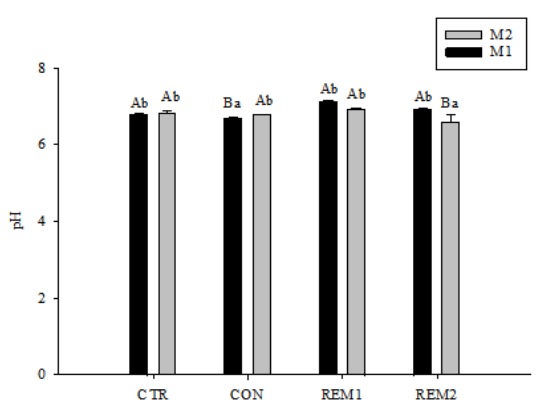

Figure 2. pH in Soil Subjected to Different Treatments.

doi: 10.25100/iyc.v28i1.15329

The application of the ABONISSA organic fertilizer in the REM1 (1000 g) and REM2 (500 g) treatments demonstrated a potent alkalinizing, or neutralizing, effect. The REM1 treatment achieved a pH of 7.120 at M1 and 6.920 at M2, while the REM2 treatment recorded a pH of 6.920 at M1 and 6.589 at M2 (Figure 2). This increase in pH is attributed to two primary mechanisms: the inherent alkalinity of the fertilizer itself (with a starting pH of 8.2) and the release of basic cations during its decomposition (21,22). The ANOVA results were particularly revealing, indicating that the pH of REM1 M1 was significantly higher ($p=0.040$) than that of CONT M1. This suggests that the higher fertilizer dose led to a more effective and rapid neutralization of the whey-induced acidity. Interestingly, while there were no significant pH differences between M1 and M2 for the REM1 treatment, there was a significant decrease in pH over time for the REM2 treatment.

This downward trend in pH observed in REM2 M2, and the slight reduction in REM1 M2, could be explained by the production of organic acids during the more advanced stages of the fertilizer's decomposition, or perhaps by the gradual neutralization of the fertilizer's initial alkalinity by the soil's buffering capacity (23,24). Previous studies, such as the one by Mendoza-Hernández et al. (2020), have similarly shown that alkaline organic amendments are effective at stabilizing the pH of contaminated soils. In the context of this study, the REM1 treatment demonstrated superior efficacy in the short term, successfully counteracting the acidification from the whey and re-establishing a pH level close to neutral, which is highly favorable for the soil's overall biological activity.

Conductivity Analysis

Electrical conductivity (EC) serves as a direct measure of soil salinity, a critical parameter that can significantly impact both plant growth and the activity of soil microorganisms (17). The control soil (CTR) consistently exhibited low EC values, with averages of 0.559 mS/cm at M1 and 0.542 mS/cm at M2 (Figure 3). These values are characteristic of non-saline Andisols and were significantly lower than those recorded in all other treatments (12,18).

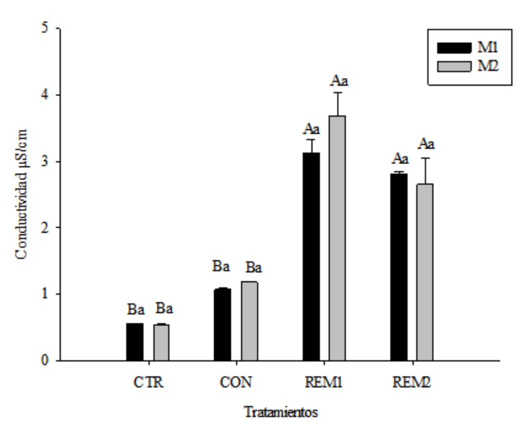

Figure 3. Electrical Conductivity (µS/cm) in Soil Subjected to Different Treatments

The addition of whey (CONT treatment) led to a marked increase in EC, with values rising to 1.075 mS/cm at M1 and 1.182 mS/cm at M2. This increase is a direct consequence of the soluble

doi: 10.25100/iyc.v28i1.15329

salts and other ionizable compounds inherent in the whey (19,25). Despite this increase, the EC of the CONT treatment remained significantly lower than that of the fertilizer-amended treatments, and there were no statistically significant differences between its two sampling times.

The most dramatic increases in EC were observed in the treatments amended with ABONISSA fertilizer (REM1 and REM2), as shown in Figure 3. The REM1 treatment averaged 3.120 mS/cm at M1 and rose further to 3.675 mS/cm at M2. Similarly, the REM2 treatment averaged 2.810 mS/cm at M1 and was 2.645 mS/cm at M2. This substantial rise in salinity is due to the combined release of ions from both the organic fertilizer (particularly from its poultry manure component) and the whey (21,22). All REM treatments displayed EC values that were significantly higher than both the CTR and CONT treatments. The ANOVA results confirmed the magnitude of this effect, showing that the EC of REM1M2 (3.675 mS/cm) was significantly greater than that of CTRM2 (0.542 mS/cm) ($p < 0.001$) and CONTM1 (1.075 mS/cm) ($p < 0.001$).

The additive effect of whey and the organic amendment on soil electrical conductivity (EC) is unmistakable. Although this increase may reflect greater nutrient availability for plants, it also entails a significant risk. EC values approaching or exceeding the 4 mS/cm threshold—as observed in one replicate of REM1M2—may induce osmotic stress, lowering soil water potential and hindering root water uptake even when soil moisture is adequate. This can result in reduced germination, slower vegetative growth, restricted root development, and yield losses, particularly in salt-sensitive species or at early crop stages (6,17). Moreover, sustained elevation of EC can promote nutrient imbalances through ionic antagonisms (e.g., interference with Ca^{2+}, Mg^{2+}, and K^{+} uptake), increase the risk of salt-induced phytotoxicity, and constrain the activity of key microorganisms involved in mineralization and the degradation of organic compounds (26,27).

In this context, the EC increase observed in REM1 constitutes a warning signal of potential secondary salinization associated with the combined management of the dairy residue and the organic amendment (28). Although this effect was assessed over a short period (7–15 days), its implications for future agricultural productivity justify monitoring salinity dynamics over time, particularly under field conditions where leaching, drainage, and ion-exchange processes may vary. Therefore, while ABONISSA showed positive effects on fertility indicators (pH, OM, and CEC), its use should be accompanied by careful dose management, salinity-mitigation strategies (e.g., split applications, controlled leaching, or the use of lower-salinity materials), and evaluation of local crop responses to ensure agronomic sustainability.

Moisture Analysis

Soil moisture content is a dynamic property that plays a crucial role in regulating biological processes, nutrient availability, and the physical characteristics of the soil (29). In this study, the CTR treatment had an average moisture content of 4.415% at M1, which increased to 5.600% at M2 (Figure 4). Andisols are generally known for their high water retention capacity (30,31), so the relatively low initial moisture levels in the CTR may have been due to the specific antecedent conditions before the experiment began. The significant increase in moisture from M1 to M2 in the CTR treatment is likely a direct result of the controlled irrigation applied. The addition

doi: 10.25100/iyc.v28i1.15329

of whey (CONT treatment) elevated the moisture content to 5.755% at M1 and 5.660% at M2, a logical consequence of the high water content of the whey itself (25). The CONT treatment exhibited significantly higher moisture than the CTR at M1, with no significant difference between its own two sampling times.The REM1 and REM2 treatments, which received both whey and organic fertilizer, displayed the highest moisture contents overall (Figure 4). The REM1 treatment averaged 7.045% moisture at M1 and 6.580% at M2, while the REM2 treatment averaged 5.490% at M1 and 6.380% at M2. This is attributable to the combined effect of the water introduced with the whey and the enhanced water-holding capacity provided by the organic fertilizer (32). All REM treatments consistently maintained moisture levels that were significantly higher than the CTR and were similar to or higher than the CONT treatment. The ANOVA further highlighted this, showing that REM1M1 (7.045%) had a significantly higher moisture content than CTRM1 (4.415%) ($p = 0.020$).

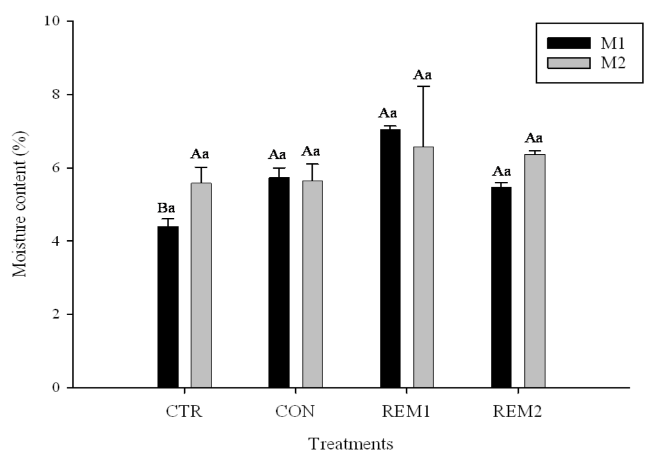

Figure 4. Moisture (%) in Soil Subjected to Different Treatments

The immediate impact of the water added via the whey and the fertilizer is clearly demonstrated. While the organic matter in the fertilizer is known to improve long-term water retention by enhancing soil structure (33), within the short timeframe of this study, the directly added water was the predominant factor. The notable variability observed in the replicates of the REM1M2 treatment (ranging from 4.94% to 8.22%) suggests a degree of heterogeneity in the soil-amendment mixture. Over a longer period, it is expected that the organic matter would more fully integrate with the soil, leading to a more stable and uniform increase in water retention capacity and an overall improvement in soil structure.

Bulk Density Analysis

Bulk density (BD) is a key physical indicator of soil compaction and, inversely, its porosity (29). The control (CTR) treatment exhibited average BD values of 0.8700 g/cm³ at M1 and 0.8956 g/cm³ at M2 (Figure 5). These values are typical for Andisols, which are known for their low bulk densities, generally ranging from 0.5 to 1.0 g/cm³, a characteristic attributed to their high porosity and well-developed structure (30,31).

doi: 10.25100/iyc.v28i1.15329

No significant differences in BD were observed between the two sampling times for the CTR treatment, which consistently showed the highest (most compact) values among all treatments. The application of whey (CONT treatment) led to a significant decrease in BD to 0.7439 g/cm³ at M1, which then partially rebounded to 0.8345 g/cm³ at M2. This initial reduction in density is due to the incorporation of low-density organic matter from the whey and the stimulation of microbial activity, which enhances soil aggregation and creates pore space. The CONT M1 treatment had a significantly lower BD than the CTR.

The REM1 and REM2 treatments, which included the organic fertilizer, successfully maintained low bulk densities (Figure 5). The REM1 treatment averaged 0.7410 g/cm³ at M1 and 0.8045 g/cm³ at M2, while the REM2 treatment averaged 0.7670 g/cm³ at M1 and 0.7456 g/cm³ at M2. The intrinsically low density of the fertilizer itself contributed significantly to this effect. At the M1 sampling, both REM treatments had lower BD values than the CTR. By M2, the REM2 treatment had a significantly lower BD than the CTR. The ANOVA results provided strong statistical support for these observations, showing that the CTRM2 value (0.8956 g/cm³) was significantly higher than those of REM1M1 (0.7410 g/cm³, p=0.030), CONTM1 (0.7439 g/cm³, p=0.040), and REM2M2 (0.7456 g/cm³). This confirms that both the whey and the organic fertilizer were effective in reducing soil bulk density. A reduction in BD is highly beneficial for soil health, as it implies greater porosity, improved aeration, and enhanced conditions for root growth (34). These findings are consistent with research by Cabrera Lobelo & Unibio Salcedo (2019) (35) who also reported significant decreases in BD (to 0.62-0.70 g/cm³) in diesel-contaminated soils following remediation with organic materials. Although the contaminants differ, the underlying principle—that the addition of organic matter tends to decrease soil bulk density—is clearly demonstrated. The rapid biodegradation of the whey and the resulting improvement in soil aggregation, coupled with the physical contribution of the low-density organic fertilizer, appear to be the key mechanisms driving this positive change.

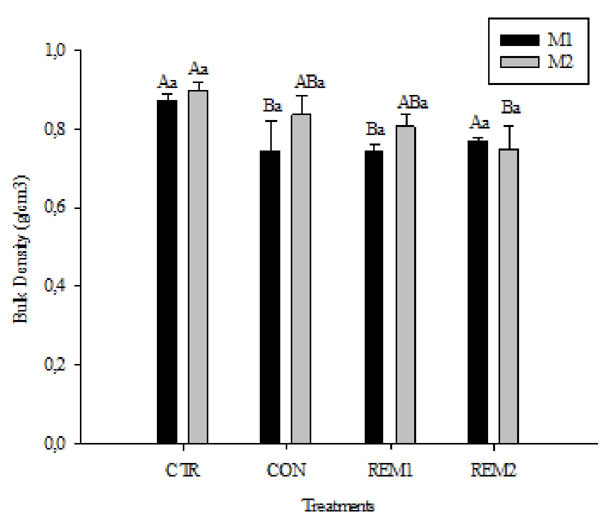

Figure 5. Apparent Density (g/cm³) in Soil Subjected to Different Treatments

doi: 10.25100/iyc.v28i1.15329

Particle Density Analysis

In contrast to bulk density, particle density (PD) refers to the density of the soil solid particles (excluding pore space) and is governed primarily by mineralogical composition and, to a lesser extent, by organic matter content (29).

In the control soil (CTR), particle density (PD) was 2.27 g/cm³ at M1 and 2.15 g/cm³ at M2 (Figure 6), values consistent with the expected range for Andisols, where the presence of low-density minerals (e.g., allophane) and high organic matter contents can reduce PD relative to typical mineral soils (30,31).

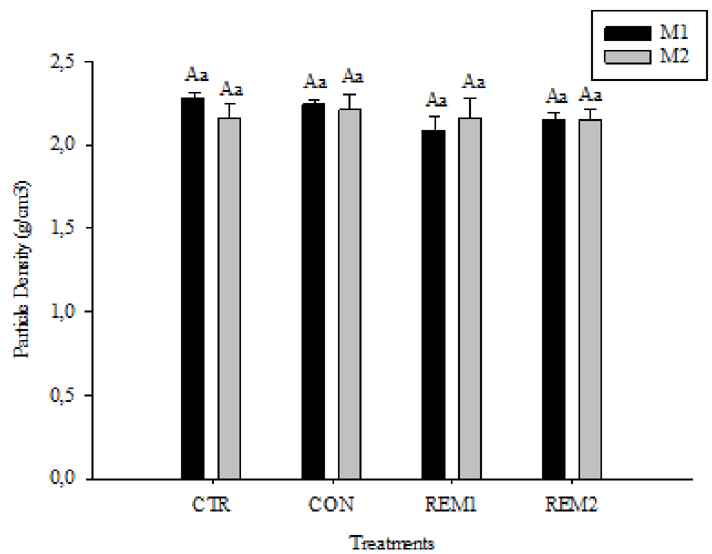

Figure 6. Particle Density (g/cm3) in Soil Subjected to Different Treatments

Overall, no significant differences in PD were detected among treatments or between sampling times ($p > 0.05$), as reflected by the uniform statistical lettering in Figure 6. The whey-contaminated treatment (CONT) showed PD values of 2.24 g/cm³ (M1) and 2.20 g/cm³ (M2), which were statistically indistinguishable from the control. Similarly, the ABONISSA-amended treatments exhibited slightly lower mean values (REM1: 2.08 g/cm³ at M1 and 2.15 g/cm³ at M2; REM2: 2.15 g/cm³ at M1 and 2.14 g/cm³ at M2), but without significant differences. Although, in theory, the incorporation of lower-density organic materials could decrease PD, these results suggest that over the short term (7–15 days) the composition of the soil solid phase did not change detectably, or that any effect was too subtle relative to the inherent variability of the measurement. In summary, the stability of PD indicates that the changes observed in other physical variables (e.g., bulk density and porosity) are mainly attributable to modifications in soil structure and pore arrangement rather than to changes in the density of the mineral particles.

Porosity Analysis

Soil porosity, defined as the volume of void spaces between solid particles, is a fundamental physical property that dictates the soil's capacity for water and air retention and movement. It also defines the habitat available for plant roots and essential soil microorganisms (29). n

doi: 10.25100/iyc.v28i1.15329

this study, the control soil (CTR) initially exhibited an average porosity of 61.4443% at 7 days (M1), which then decreased to 57.9055% by 15 days (M2) (Figure 7). This high initial porosity is characteristic of Andisols, which are well-known for their total porosity often exceeding 60%, a feature attributed to their well-developed structure and the low bulk density of their constituent particles (30,31).

The statistically significant decrease in porosity observed in the CTR treatment from M1 to M2 is likely due to a slight natural consolidation or settling of the soil within the experimental pots over time, accelerated by the watering regime. In stark contrast, the addition of whey (CONT treatment) led to a remarkable increase in porosity. At day 7 (M1), the average porosity surged to 66.5523% and remained elevated at 62.7101% on day 15 (M2) (Figure 7).

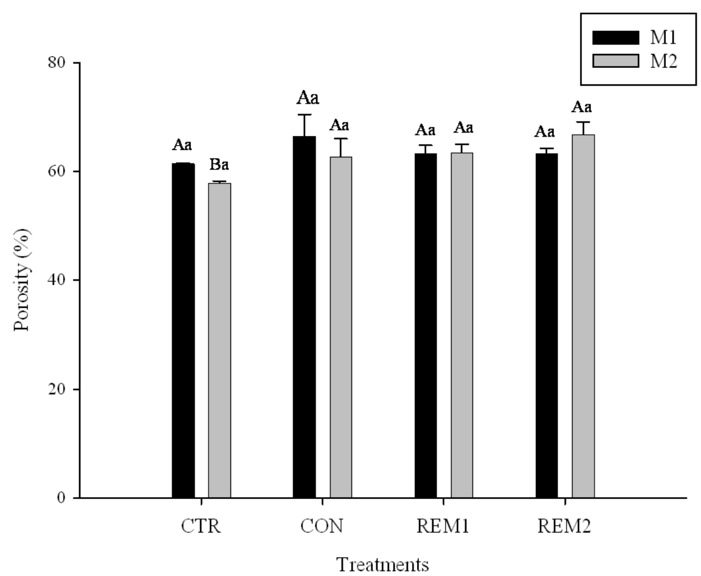

Figure 7. Porosity (%) in Soil Subjected to Different Treatments

This enhancement in porosity is directly and inversely correlated with the decrease in bulk density observed in the same treatment. It can be explained by two primary factors: the physical incorporation of organic matter from the whey and, more significantly, the stimulation of microbial activity which promotes the formation of stable soil aggregates, thereby creating new and larger pore spaces. The graphical representation in Figure 7, where both CONT bars are labeled "Aa," indicates that the porosity in this treatment was significantly higher than in the CTR at M2.

The treatments that included ABONISSA organic fertilizer (REM1 and REM2) either maintained or further increased the high porosity levels seen in the contaminated soil (Figure 7). In the REM1 treatment, the average porosity was 63.3324% at M1 and remained stable at 63.4760% at M2. For the REM2 treatment, the average porosity was 63.3899% at M1 and increased to 66.8229% at M2. The incorporation of organic matter from the fertilizer, especially from the poultry manure and plant residues, is a well-documented method for improving soil structure and increasing porosity (21,34). The "Aa" labels on all REM1 and REM2 bars indicate that these

doi: 10.25100/iyc.v28i1.15329

treatments sustained a significantly high porosity, comparable to or greater than the CONT treatment and significantly higher than the CTR at M2.

The two-way ANOVA confirmed these observations, revealing significant differences among the treatments. For instance, the REM2M2 treatment (average porosity 66.8229%) had a significantly higher porosity than the CTRM2 treatment (average porosity 57.9055%) (a difference of 8.917%, p = 0.020). Similarly, the CONTM1 treatment (average porosity 66.5523%) also had a significantly higher porosity than CTRM2 (a difference of 8.647%, p = 0.020). These results provide strong evidence that both the whey contamination and the subsequent application of organic fertilizer led to a beneficial increase in soil porosity. Enhanced porosity is highly desirable in soil remediation, as it facilitates crucial processes like aeration, drainage, water infiltration, and nutrient transport, and provides a more favorable environment for root development and the biodegradation of contaminants (29). The improvement of porosity is, therefore, one of the most significant benefits of using organic amendments in soil remediation programs.

Cation Exchange Capacity (CEC) Analysis

Cation exchange capacity (CEC) is a critical measure of a soil's ability to retain positively charged ions (cations), which include essential plant nutrients like calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), and ammonium (NH_4^+). This retention occurs on the negatively charged surfaces of clay particles and organic matter, making CEC a cornerstone of soil fertility and nutrient availability (29). In this study, the control soil (CTR) demonstrated an average CEC of 33.3672 meq/100g at 7 days (M1), which increased to 38.3224 meq/100g by 15 days (M2) (Figure 8).

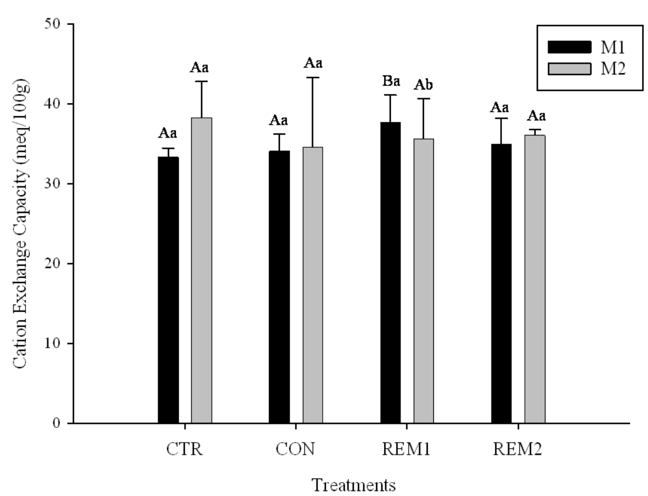

Figure 8. CIC (meq/100g) in Soil Subjected to Different Treatments

Andisols are known to have a variable CEC that is strongly influenced by pH as well as the content and type of organic matter and clay minerals present. CEC values between 20 and 50 meq/100g are common for this soil type. A key characteristic is that their CEC tends to increase with rising pH, due to the pH-dependent charge of minerals like allophane and of the organic matter itself (30,31). The graphical representation in Figure 8, where both CTR bars are labeled "Aa," indicates that there were no statistically significant differences in the CEC of the control soil between the two sampling times.

doi: 10.25100/iyc.v28i1.15329

The addition of whey (CONT treatment) resulted in CEC values that were similar to or slightly higher than the control at M1, with an average of 34.1485 meq/100g. By M2, the average CEC was 34.6027 meq/100g (Figure 8). While whey contains proteins and other organic compounds that could theoretically provide some exchange sites, its direct impact on the mineral soil's CEC is typically limited in the short term, unless it causes significant shifts in pH or leads to the formation of new, stable organic matter. The "Aa" labels on the CONT bars suggest that, overall, there were no significant differences compared to the control or between its own sampling times, although a high degree of variability was noted in the CONTM2 samples.

The most substantial and consistent increases in CEC were observed in the treatments amended with ABONISSA organic fertilizer (REM1 and REM2), as shown in Figure 8. In the REM1 treatment, the average CEC was 37.7698 meq/100g. For the REM2 treatment, the average CEC was 35.0186 meq/100g at M1 and increased to 36.1298 meq/100g at M2. This significant boost in CEC is primarily attributed to the high content of stable, humified organic matter present in the composted fertilizer (especially from the poultry manure). This organic matter possesses a high density of negatively charged functional groups (carboxyl and phenol groups) that are highly effective at retaining cations (21,22). nterestingly, the graph shows that for REM1, the M1 bar ("Aa") is slightly higher than the M2 bar ("Ba"), suggesting a possible minor decrease over time, though both values remain elevated. For REM2, both bars are labeled "Aa," indicating a consistently high CEC.

The comprehensive ANOVA and Tukey's test revealed complex interactions. While one comparison indicated that CTRM2 had a significantly higher CEC than REM1M1, other comparisons showed that the average CEC of REM2M2 (36.1298 meq/100g) was significantly higher than that of REM1M1 ($p=0.003$), and that CONTM1 (34.1485 meq/100g) was significantly lower than REM1M1 ($p < 0.001$). Taken together, these comparisons suggest that the treatments with organic fertilizer (REM) were more effective at increasing the CEC than either the whey alone (CONT) or the control (CTR), with the high dose (REM1) showing a particularly strong initial effect. An increase in CEC is a clear and positive indicator of enhanced soil fertility and an improved capacity to retain essential nutrients, thereby preventing their loss through leaching (34).

Organic Matter (OM) Analysis

Soil organic matter (OM) is a cornerstone of soil health, acting as a crucial component that profoundly influences soil fertility, physical structure, and the intensity of biological activity. In this study, the control soil (CTR) presented an average OM content of 6.7826% at 7 days (M1) and 7.1285% at 15 days (M2) (Figure 9). These levels are entirely consistent with the characteristics of Andisols, which are known to accumulate substantial quantities of OM. This accumulation is due to the formation of highly stable complexes between the organic matter and the unique minerals found in these soils, such as allophane and imogolite, which significantly retards the rate of decomposition (30,31).

doi: 10.25100/iyc.v28i1.15329

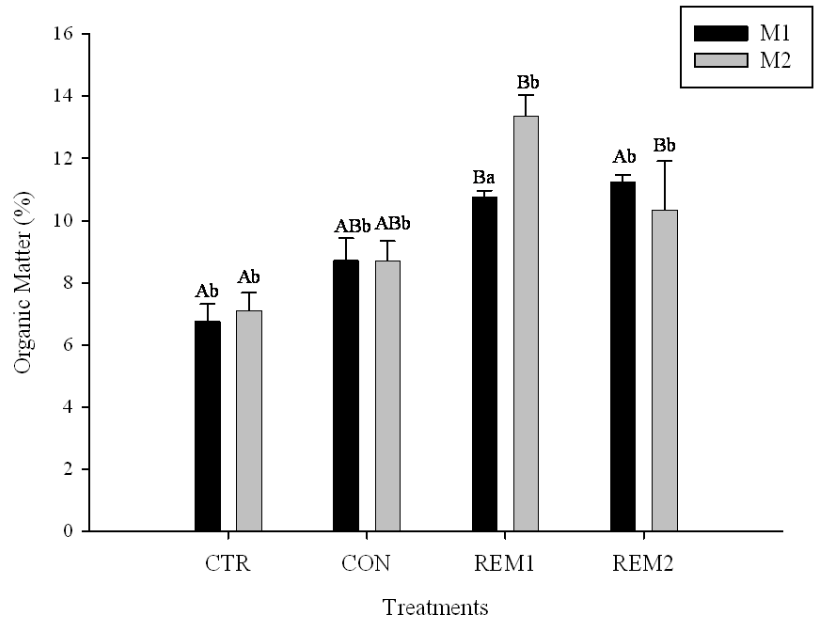

Figure 9. Organic Matter (%) in Soil Subjected to Different Treatments

As depicted in Figure 9, both the CTR M1 and CTR M2 data points are labeled “Ab.” This notation signifies that there were no statistically significant differences in the OM content of the control soil between the two sampling times, and that these values represent the lowest baseline level of OM among all the experimental treatments. The addition of whey (CONT treatment) led to a notable increase in OM content, with an average of 8.7399% at M1 and 8.7182% at M2 (Figure 9). This increase is a direct and predictable consequence of the contribution from the intrinsic organic components of the whey itself.

The figure further shows that both data bars for the CONT treatment are labeled “ABb.” This indicates that the OM content in this treatment was significantly higher than in the CTR (which belongs to group “A”), but it was not as elevated as in some of the remediated treatments (which fall into group “B”). The lowercase “b” for both time points indicates that there were no significant changes in the OM content of the CONT soil between the two sampling times.

The most substantial and impactful increases in OM content were observed in the treatments amended with ABONISSA organic fertilizer (REM1 and REM2), as shown in Figure 9. The REM1 treatment averaged an impressive 10.7724% OM at M1, and this value increased significantly to 13.3733% by M2. This temporal increase in OM within the REM1 treatment is statistically significant, as denoted by the different lowercase letters (“a” for M1 and “b” for M2). The REM2 treatment showed an OM content of 11.2687% at M1, with a slight, though statistically significant, decrease to 10.3606% at M2.

This marked overall increase in OM in the REM treatments is directly attributable to the substantial input of stabilized, carbon-rich organic matter from the composted fertilizer (36,37).

doi: 10.25100/iyc.v28i1.15329

The two-way ANOVA and subsequent Tukey's test confirmed that the differences in OM content among the treatments were highly significant ($p < 0.001$). To illustrate, the REM1M2 treatment (with an average OM of 13.3733%) had a significantly higher OM content than the CTRM1 treatment (average OM of 6.7826%), with a difference of 6.591% ($p < 0.001$). The addition of this organic matter is fundamental for improving a wide range of soil properties and for stimulating the microbial activity that is essential for the degradation of contaminants.

Texture Analysis

Soil texture, which is defined by the relative proportions of sand, silt, and clay particles, is a fundamental and relatively stable physical property of soil. It exerts a profound influence on a wide array of soil functions, including water retention, aeration, workability (tilth), the capacity to supply nutrients, and susceptibility to erosion (13). As a result, a true change in textural class is not expected over short periods (7–15 days) following the addition of organic amendments; therefore, the differences observed among sampling times and treatments should be interpreted as variations in "apparent texture" or as limitations of the hydrometer (Bouyoucos) method, particularly in Andisols and soils with high organic matter (OM) content (38,40). In this study, organic matter was not removed prior to analysis using H_2O_2, which may have promoted incomplete dispersion of fine particles and the formation of microaggregates, thereby affecting the estimation of sand, silt, and clay fractions. Thus, the results primarily reflect changes in aggregation and methodological sensitivity rather than actual modifications of the soil's mineral texture (41).

As shown in Table 3, both the control soil and the whey-contaminated soil fall within the sandy clay loam textural class in both M1 and M2, which is consistent with the expected stability of the mineral fraction. The ABONISSA-amended treatments were classified as sandy loam in M1, followed by a shift to loam (REM1 in M2) and sandy loam (REM2 in M2). These variations do not indicate a true change in mineral texture, but rather differences in aggregation state and/or dispersion efficiency during the analysis (41,42).

Table 3. Percentages of mineral fractions

Sample	% Sand	% Clay	% Silt	Total	Textural Class
Control (M1)	54	36	10	100	Sandy clay loam
Contaminated (M1)	57	30	13	100	Sandy clay loam
Remediated 1 (M1)	60	11	29	100	Sandy loam
Remediated 2 (M1)	55	11	34	100	Sandy Loam
Control (M2)	51	34	15	100	Sandy clay loam
Contaminated (M2)	55	35	10	100	Sandy clay loam
Remediated 1 (M2)	47	13	40	100	Loam
Remediated 2 (M2)	51	11	38	100	Sandy loam

doi: 10.25100/iyc.v28i1.15329

The Bouyoucos method assumes complete particle dispersion; however, under high organic matter (OM) conditions—and especially after adding an organic amendment—OM can act as a cementing agent, promoting the formation of stable aggregates and microaggregates. Under these conditions, part of the clay fraction may not fully disperse and may settle as larger units, leading to a relative overestimation of coarser fractions and an apparent underestimation of clay (41,43). This effect is relevant for interpreting the differences in measured textural class between M1 and M2 in amended soils.

In addition, Andisols commonly contain amorphous minerals (e.g., allophane/imogolite) and organo–mineral complexes that promote strong microaggregation and hinder clay dispersion. Therefore, even when chemical dispersants are used, hydrometer results may partially reflect the aggregation state rather than the true mineral particle-size distribution (44). In this sense, the results in Table 3 should be discussed as indirect evidence of rapid physical changes induced by the amendment (aggregation/structural stability), not as changes in mineral texture.

Analysis of the Reduction of Fats and Oils in the Contaminated Soil Following the Application of Organic Fertilizer as a Remediation Method

The quantification of n-Hexane Extractable Material (HEM) serves as an essential indicator for determining the concentration of fats, oils, and other lipid-based compounds within the soil. This measurement is critical for both assessing the magnitude of contamination and evaluating the efficacy of the implemented remediation strategies. In this study, the control soil (CTR), which represents the baseline condition without any added contaminants or amendments, exhibited an average HEM content of 949.25 mg/kg in the first sampling at 7 days (M1), as shown in Figure 10. It is important to recognize that soils, even in the absence of direct industrial contamination, naturally contain a lipid fraction derived from the decomposition of plant and animal residues as well as from the metabolic activity of the native soil microbial community (45). In this context, the presence of a detectable baseline level of HEM in the control soil is expected and does not necessarily indicate residual contamination. Moreover, the NMX-AA-134-SCFI-2006 standard defines HEM broadly as the material extracted with n-hexane, including not only fresh fats and oils but also waxes, hydrophobic compounds associated with organic matter, and other non-volatile hydrocarbons. Accordingly, the control soil was used as a reference for the natural content of hexane-extractable material, and treatment effects were interpreted relative to this baseline. Thus, the measured HEM values reflect both the soil's natural lipid fraction and the extractable fraction associated with soil–amendment dynamics, avoiding an overestimation of residual contamination based solely on the presence of HEM (9).

doi: 10.25100/iyc.v28i1.15329

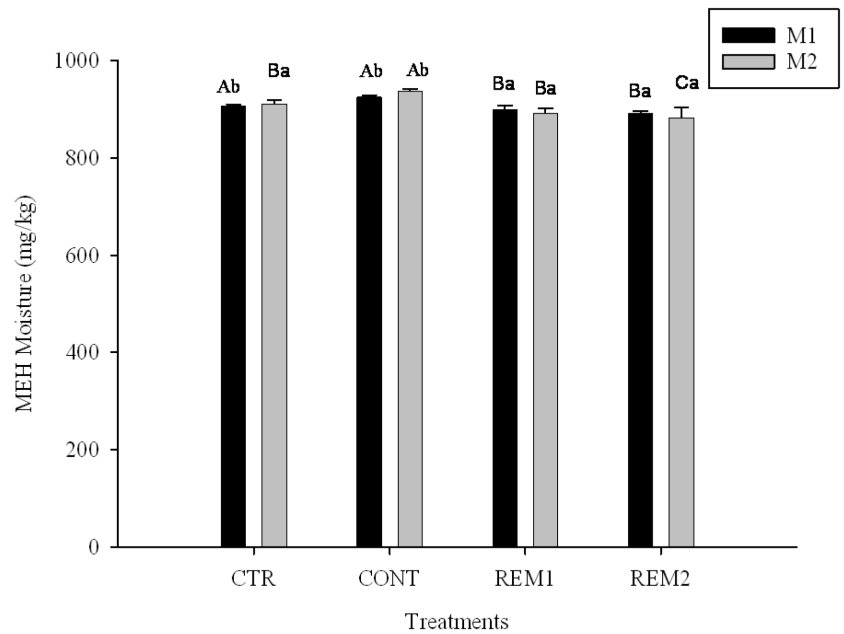

Figure 10. Fats and oils (mg/kg) in different treatments

Initially, the control soil (CTR) had an average HEM content of 907.3 mg/kg (Figure 10). This basal concentration is consistent with the natural lipid fraction found in soils that have a notable organic matter content, originating from the decomposition of various biological residues and the soil's own microbial biomass.

Following the application of the contaminant, the treatments with whey (CONT) showed a discernible increase in HEM content, reaching average values of 925.3 mg/kg in the first sampling and 937.4 mg/kg in the second. This increase is directly attributable to the intrinsic fat fraction present in the whey. Although this fraction is a minor component of whey's overall composition, it contributes measurably to the total lipid load in the soil (9). The treatments amended with ABONISSA organic fertilizer (REM1 and REM2) demonstrated the most significant and positive effects. The remediated soils exhibited HEM concentrations that were consistently and substantially lower than those of the contaminated soil, with average values dropping to as low as 882.5 mg/kg. Remarkably, these values were not only lower than those of the contaminated treatment but, in some instances, were even lower than the background levels of the control soil.

A rigorous statistical analysis confirmed this trend with a high degree of certainty, revealing statistically significant differences between the contaminated and the remediated treatments ($p < 0.05$). For instance, the comparison between the CONT2 treatment and the REM2_2 treatment yielded a p-value of less than 0.001, which provides robust validation of the treatment's efficacy in reducing the concentration of lipids.

This pronounced remedial effect is attributed to a process of biostimulation. The addition of the ABONISSA organic fertilizer, which is rich in essential nutrients and stabilized carbon, acted as a catalyst, promoting the growth and metabolic activity of the native microbial community. These

doi: 10.25100/iyc.v28i1.15329

microorganisms, finding themselves in a nutritionally enriched environment, were able to utilize the lipid compounds as a readily available substrate and energy source, thereby accelerating their degradation. This is a fundamental principle of bioremediation for soils contaminated with organic compounds, where stimulating the indigenous microbiota is often a more effective strategy than introducing external microbial strains (46).

To place the magnitude of this impact in context, it is pertinent to note that the initial contaminant load in this study (close to 1000 mg/kg) is considerably lower than the concentrations of total petroleum hydrocarbons (TPH) often reported in other bioremediation studies, which can range from 10,000 to 50,000 mg/kg. This lower initial load likely facilitated a more rapid and efficient remediation process by the soil microbiota, which was not inhibited by excessive toxicity and was thus able to metabolize the contaminant effectively (47).

The temporal dynamics of the process revealed an accelerated microbial response, as no statistically significant differences were found between the samplings conducted at 7 and 15 days ($p > 0.05$). This suggests that the microbial community, stimulated by the addition of the fertilizer, began the degradation of the lipids almost immediately. This rapid onset of degradation is in stark contrast to the remediation of more recalcitrant contaminants, which often require prolonged periods of acclimatization before any significant reduction is observed (48). The biodegradation of complex lipids is a process that requires time and the concerted action of diverse microbial populations, and this study effectively demonstrates that biostimulation with a suitable organic fertilizer can significantly optimize this process, even from its earliest stages (9).

Conclusions

The main objective of this study was to comprehensively assess the feasibility of applying the organic amendment ABONISSA as a management strategy for Andisols affected by whey contamination in La Florida (Nariño). The in situ morphological characterization established a baseline, revealing a stratified soil profile with textural variability and features such as mottling and hardened layers, which influence hydrological behavior and condition both contaminant mobility and the soil's response to the amendment.

Physicochemical evaluation confirmed that the application of untreated whey produces undesirable alterations, particularly slight acidification and a marked increase in electrical conductivity, highlighting its potential to induce salinization processes in the soil environment. Although favorable physical changes were observed—such as reduced bulk density and increased porosity—the overall balance indicates that whey can compromise soil quality and supports the need for corrective measures.

Over the short evaluation period (7–15 days), the application of ABONISSA in treatments REM1 and REM2 produced an immediate, favorable response in key variables of the whey-contaminated soil, notably the neutralization of acidity and significant increases in organic matter and cation exchange capacity (CEC). These results suggest that the amendment can act as a rapid agent for restoring soil chemical functionality, promoting conditions conducive

doi: 10.25100/iyc.v28i1.15329

to microbial activity and fertility recovery. However, it is important to emphasize that this timeframe corresponds primarily to an initial stage or early response; therefore, the findings represent short-term effects rather than definitive soil remediation.

Despite the improvements observed, a critical challenge associated with the combined use of whey and the organic amendment was identified: the marked increase in electrical conductivity (EC), particularly at the highest dose (REM1). This represents a potential agronomic risk due to osmotic stress and possible effects on certain microbial groups; thus, any real-scale application should incorporate salinity management strategies and monitoring over time.

Dose comparison (REM1: 1000 g vs. REM2: 500 g per 3 kg of soil) showed that, although REM1 tended to induce faster and more pronounced changes, it also posed the greatest risk of salinization. In contrast, REM2 achieved significant improvements in most evaluated parameters with a smaller increase in EC, suggesting that a moderate dose may provide a better balance between physicochemical recovery and salinity risk. Nevertheless, it must be acknowledged that the REM1 dose is high and may be difficult to implement directly under field conditions; therefore, these assays can be interpreted as an ex situ approach (conditions comparable to a biopile), aimed at assessing immediate responses under a high-intensity treatment, while scalability validation remains pending.

Additionally, ABONISSA showed potential to reduce the soil lipid fraction in the short term, as evidenced by decreases in n-hexane extractable material (HEM) relative to the contaminated soil. This outcome suggests an initial biotransformation process associated with biostimulation of the native microbiota; however, the complete biological degradation of fatty compounds typically requires longer periods. Accordingly, extending the monitoring period (weeks to months) is recommended to confirm the persistence and stability of the observed effect.

In summary, ABONISSA represents a promising alternative for improving the physicochemical conditions of whey-affected Andisols at early stages, but its practical applicability requires longer-term studies—preferably under field conditions—to assess salinity dynamics over time, crop responses, and the overall sustainability of the treatment.

CrediT authorship contribution statement

Conceptualization - Ideas: Juan Sebastián Garzon Quiñonez Lisbeth Carolina Rodríguez Patichoy Angela María Sánchez Madroñero. Data curation: Juan Sebastián Garzon Quiñonez Lisbeth Carolina Rodríguez Patichoy Angela María Sánchez Madroñero. Analisis formal: Juan Sebastián Garzon Quiñonez Lisbeth Carolina Rodríguez Patichoy Angela María Sánchez Madroñero Investigation: Juan Sebastián Garzon Quiñonez Lisbeth Carolina Rodríguez Patichoy Angela María Sánchez Madroñero,Jenny Lucia Huertas Delgado. Methodology: Juan Sebastián Garzon Quiñonez Lisbeth Carolina Rodríguez Patichoy Angela María Sánchez Madroñero Jenny Lucia Huertas Delgado. Project Management: Juan Sebastián Garzon Quiñonez Lisbeth Carolina Rodríguez Patichoy Angela María Sánchez Madroñero Jenny Lucia Huertas Delgado. Resources: Juan Sebastián Garzon Quiñonez Lisbeth Carolina Rodríguez Patichoy Angela María Sánchez Madroñero Jenny Lucia Huertas Delgado. Supervision: Jenny Lucia Huertas Delgado. Validation: Jenny Lucia Huertas Delgado. Writing - original draft - Preparation: Juan Sebastián

doi: 10.25100/iyc.v28i1.15329

Garzon Quiñonez Lisbeth Carolina Rodríguez Patichoy Angela María Sánchez Madroñero Jenny Lucia Huertas Delgado. Writing - revision and editing -Preparation: Juan Sebastián Garzon Quiñonez Lisbeth Carolina Rodríguez Patichoy Angela María Sánchez Madroñero Jenny Lucia Huertas Delgado.

Financing: does not declare. Conflict of interest: does not declare. Ethical aspect: does not declare.

References

1. Patiño-Burbano RE, Jiménez-Velásquez SDC, Cabrera-Cabreta SL, Guerrero-Narvaez EM, Montes-Vergara JC, Castro-Rincón E, Rodríguez-Bautista JL, Parra-Arango JL. Caracterización higiénico-sanitaria de la leche bovina del departamento de Nariño. Rev MVZ Córdoba. 2023;28:e2895. https://doi.org/10.21897/rmvz.2895

2. Cabrera M, Salazar C. El cultivo de hortalizas de clima cálido [Internet]. Agrosavia.co; 2004. Availabre from: http://hdl.handle.net/20.500.12324/17559

3. Muñoz D, López M. Implementación de un mecanismo de aprovechamiento de los residuos sólidos orgánicos para el hogar infantil personitas de Tunja (Boyacá) [Internet]. Edu.co; 2018. Availabre from: https://repository.unad.edu.co/bitstream/handle/10596/26433/jmlopez1.pdf;jsessionid=4F842BDD78C7ADB2FC8DBF7FE389E9B0?sequence=1

4. Cotrina-Cabello VR, Alejos-Patiño IW, Cotrina-Cabello GG, Córdova-Mendoza P, Córdova-Barrios IC. Efecto de abonos orgánicos en suelo agrícola de Purupampa Panao, Perú. [Internet]. Cent agríc; 2020;47(2). Availabre from: http://ref.scielo.org/862pr8

5. Lainez AM, López Iglesias E. EL SECTOR LÁCTEO EN ESPAÑA [Internet]. Vacapinta.com; 2022. Availabre from: https://vacapinta.com/media/files/fichero/monografias-44-sector-lacteo.pdf

6. Bauder TA, Waskom RM, Davis JG. Irrigation Water Quality Criteria [Internet]. Irrigationtoolbox.com; 2014. Availabre from: https://irrigationtoolbox.com/ReferenceDocuments/Extension/Colorado/00506.pdf

7. Moreno Reséndez A, Briceño Contreras EA, Núñez V, Manuel L, Hernández Herrera JA. Capítulo VI: Abonos orgánicos: una alternativa sustentable en la agricultura [Internet]. Researchgate.net. 2019. Availabre from: https://www.researchgate.net/publication/341358160_Capitulo_VI_Abonos_organicos_una_alternativa_sustentable_en_la_agricultura

8. Bolaños Martinez A. Buesaco Territorio y memoria [Internet]. Gov.co; 2015. Availabre from: https://www.buesaco-narino.gov.co/biblioteca-municipal/buesaco-territorio-y-memoria-por-arturo-bolanos-martinez-494201

9. NMX-AA-134-SCFI-2006. Suelos–Hidrocarburos fracción pesada por extracción y gravimetría–Método de prueba [Internet]. México, D.F.; 2006. Availabre from: http://104.209.210.233/gobmx/repositorio/FRACCION_I/NMX134SCFI2006IDROCARBUROSPESADO.pdf

doi: 10.25100/iyc.v28i1.15329

10. Dane JH, Topp GC, editors. Methods of soil analysis. Part 4, Physical methods [Internet]. Madison (WI): Soil Science Society of America; 2002. Availabre from: https://acsess.onlinelibrary.wiley.com/doi/book/10.2136/sssabookser5.4

11. Porta Casanellas J, López-Acevedo Reguerín M, Roquero de Laburu C. Edafología para la agricultura y el medio ambiente [Internet]. 3a ed. Madrid: Ediciones Mundi-Prensa; 2003. Availabre from: https://es.scribd.com/document/601573424/Edafologia-Para-La-Agricultura-y-El-Medio-Ambiente-3era-Edicion-2003-J-Porta-C-M-Lopez-Acevedo-R-C-Roquero-L

12. IUSS Working Group WRB. World Reference Base for Soil Resources: international soil classification system for naming soils and creating legends for soil maps [Internet]. 4th ed. Vienna (AT): International Union of Soil Sciences (IUSS); 2022. Availabre from: https://files.isric.org/public/documents/WRB_fourth_edition_2022-12-18.pdf

13. Soil Science Division Staff. Soil survey manual [Internet]. (Agriculture Handbook No. 18). Washington (DC): United States Department of Agriculture; 2017. (Minor amendments Feb 2018). Availabre from: https://www.nrcs.usda.gov/sites/default/files/2022-09/The-Soil-Survey-Manual.pdf

14. Oades JM. Soil organic matter and structural stability: mechanisms and implications for management. Plant Soil. 1984;76:319-337. doi: 10.1007/BF02205590.

https://doi.org/10.1007/BF02205590

15. AGROACTIVO. FICHA-TECNICA-ABONISSA.pdf [Internet]. 2022. Available from: https://agroactivocol.com/producto/nutricion-vegetal/enmiendas-y-acondicionadores/organicas/abono-organico-abonissa

16. López-Barreto RE, Becerra-Jiménez ML, Borrás-Sandoval LM. Caracterización físico-química y microbiológica del lactosuero del queso Paipa. Cien Agri. 2018;15:99-106. https://doi.org/10.19053/01228420.v15.n2.2018.8565

17. Brady NC, Weil RR. The nature and properties of soils [Internet]. 15th ed. Columbus (OH): Pearson; 2016. Availabre from: https://www.researchgate.net/publication/301200878_The_Nature_and_Properties_of_Soils_15th_edition.

18. Nanzyo M, Shoji S, Dahlgren R. Chapter 7 Physical Characteristics of Volcanic Ash Soils. Developments in Soil Science [Internet]. Elsevier; 1993 [cited 2025 Aug 20]. p. 189-207. https://doi.org/10.1016/S0166-2481(08)70268-X

19. Panesar P, Kennedy J, Gandhi D, Bunko K. Bioutilisation of whey for lactic acid production. Food Chemistry. 2007;105:1-14. doi: 10.1016/j.foodchem.2007.03.035. https://doi.org/10.1016/j.foodchem.2007.03.035

20. Akay A, Sert D. The effects of whey application on the soil biological properties and plant growth. EURASIAN JOURNAL OF SOIL SCIENCE (EJSS). 2020;9:349-355. doi: https://doi.org/10.18393/ejss.785380

doi: 10.25100/iyc.v28i1.15329

21. Agegnehu G, Srivastava AK, Bird MI. The role of biochar and biochar-compost in improving soil quality and crop performance: A review. Applied Soil Ecology. 2017;119:156-170 https://doi.org/10.1016/j.apsoil.2017.06.008

22. Whalen JK, Chang C, Clayton GW, Carefoot JP. Cattle Manure Amendments Can Increase the pH of Acid Soils. Soil Science Soc of Amer J. 2000;64:962-966. https://doi.org/10.2136/sssaj2000.643962x

23. Hue NV, Licudine DL. Amelioration of Subsoil Acidity through Surface Application of Organic Manures. J of Env Quality. 1999;28:623-632 https://doi.org/10.2134/jeq1999.00472425002800020028x

24. Magdoff F. Building Soils for Better Crops: Organic Matter Management. Soil Science. 1993;156:371 https://doi.org/10.1097/00010694-199311000-00014

25. Prazeres AR, Carvalho F, Rivas J. Cheese whey management: A review. Journal of Environmental Management. 2012;110:48-68. https://doi.org/10.1016/j.jenvman.2012.05.018

26. Zhang T, Wang T, Liu KS, Wang L, Wang K, Zhou Y. Effects of different amendments for the reclamation of coastal saline soil on soil nutrient dynamics and electrical conductivity responses. Agricultural Water Management. 2015;159:115-122 https://doi.org/10.1016/j.agwat.2015.06.002

27. Yan N, Marschner P, Cao W, Zuo C, Qin W. Influence of salinity and water content on soil microorganisms. International Soil and Water Conservation Research. 2015;3:316-323. https://doi.org/10.1016/j.iswcr.2015.11.003

28. Pessoa LGM, Freire MBGDS, Green CHM, Miranda MFA, Filho JCDA, Pessoa WRLS. Assessment of soil salinity status under different land-use conditions in the semiarid region of Northeastern Brazil. Ecological Indicators. 2022;141:109139. https://doi.org/10.1016/j.ecolind.2022.109139

29. Hillel D. Environmental soil physics. San Diego, CA: Academic Press; 1998.

30. FAO, editor. World Reference Base for Soil Resources. International soil classification system for naming soils and creating legends for soil maps [Internet]. LCC MAKS Press; 2024 [cited 2025 Aug 19]. Available from: https://docs.soilsociety.ru/Мировая%20реферативная%20база%20почвенных%20ресурсов_эл.pdf

31. Dahlgren RA, Saigusa M, Ugolini FC. The Nature, Properties and Management of Volcanic Soils. Advances in Agronomy [Internet]. Elsevier; 2004 [cited 2025 Aug 19]. p. 113-182. https://doi.org/10.1016/S0065-2113(03)82003-5

32. Minasny B, McBratney AB. Estimating the Water Retention Shape Parameter from Sand and Clay Content. Soil Science Soc of Amer J. 2007;71:1105-1110. https://doi.org/10.2136/sssaj2006.0298N

33. Abiven S, Menasseri S, Chenu C. The effects of organic inputs over time on soil aggregate stability - A literature analysis. Soil Biology and Biochemistry. 2009;41:1-12. https://doi.org/10.1016/j.soilbio.2008.09.015

doi: 10.25100/iyc.v28i1.15329

34. Six J, Bossuyt H, Degryze S, Denef K. A history of research on the link between (micro) aggregates, soil biota, and soil organic matter dynamics. Soil and Tillage Research. 2004;79:7-31. https://doi.org/10.1016/j.still.2004.03.008

35. Lobelo LMC, Salcedo MTU. Evaluación de la remoción de grasas y aceites en suelo contaminado con diésel b10 y biodiésel aplicando la tecnología OSE II implementada por EOM CONSULTING SAS. (tesis). 2019. https://repository.uamerica.edu.co/server/api/core/bitstreams/93e1850a-bffc-46b0-a844-dd8131ae01a9/content

36. Diacono M, Montemurro F. Long-term effects of organic amendments on soil fertility. A review. Agron Sustain Dev. 2010;30:401-422. https://doi.org/10.1051/agro/2009040

37. Larney FJ, Hao X. A review of composting as a management alternative for beef cattle feedlot manure in southern Alberta, Canada. Bioresource Technology. 2007;98:3221-3227. https://doi.org/10.1016/j.biortech.2006.07.005

38. Matisic M, Dugan I, Bogunovic I. Challenges in Sustainable Agriculture-The Role of Organic Amendments. Agriculture. 2024;14:643. https://doi.org/10.3390/agriculture14040643

39. Stöcker CM, Bamberg AL, Stumpf L, Monteiro AB, Cardoso JH, de Lima ACR. Short-term soil physical quality improvements promoted by an agroforestry system. Agroforestry Systems. 2020;94:2053-2064. https://doi.org/10.1007/s10457-020-00524-3

40. Dong L, Zhang W, Xiong Y, Zou J, Huang Q, Xu X, Ren P, Huang G. Impact of short-term organic amendments incorporation on soil structure and hydrology in semiarid agricultural lands. International Soil and Water Conservation Research. 2022;10:457-469. https://doi.org/10.1016/j.iswcr.2021.10.003

41. Mwendwa S. Revisiting soil texture analysis: Practices towards a more accurate Bouyoucos method. Heliyon. 2022;8:e09395. https://doi.org/10.1016/j.heliyon.2022.e09395

42. Beretta AN, Silbermann AV, Paladino L, Torres D, Bassahun D, Musselli R, García-Lamohte A. Soil texture analyses using a hydrometer: modification of the Bouyoucos method. Cienc Inv Agr. 2014;41:25-26. https://doi.org/10.4067/S0718-16202014000200013

43. Jensen JL, Schjønning P, Watts CW, Christensen BT, Munkholm LJ. Soil texture analysis revisited: Removal of organic matter matters more than ever. Paz-Ferreiro J, editor. PLoS ONE. 2017;12:e0178039. https://doi.org/10.1371/journal.pone.0178039

44. Clunes J, Dörner J, Bravo A, Jara R, Zúñiga F. DID WE UNDERESTIMATE SILT AND CLAY CONTENT IN THE TEXTURAL ANALYSIS? Chil j agric anim sci. 2022;38:94-103 https://doi.org/10.29393/CHJAAS38-9DWJF50009

45. Marín Velásquez TD. Crecimiento de plantas de maíz (Zea mays) en un suelo contaminado con petróleo y remediado con extracto de cáscaras de naranja (Citrus sinensis). Enfoque UTE. 2016;7:1-13. https://doi.org/10.29019/enfoqueute.v7n3.101

46. Anza Cruz HG, Orantes Calleja PD, González Herrera R, Ruíz Marín A, Espinoza Medinilla E, Martínez Salinas RI, et al. Biorremediación de suelos contaminados con aceite automotriz usados

mediante sistema de biopilas. 5(12) https://doi.org/10.31644/IMASD.12.2016.a04

47. Vásquez MC, Guerrero Figueroa JT, Quintero ADP. Biorremediación de lodos contaminados con aceites lubricantes usados. Rev Colomb Biotecnol. 2010;12(1):141-157. Availabre from: https://www.redalyc.org/pdf/776/77617786014.pdf

48. Marín Velásquez TD, Gota Díaz CN, Ortiz Pinto TC. Evaluación del extracto obtenido como lixiviado de fibra de coco (Cocos nucifera) como bioestimulante en la remediación de un suelo contaminado con petróleo. Enfoque UTE. 2018;9:180-193. https://doi.org/10.29019/enfoqueute.v9n4.303