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Assessment of Heavy Metal Contamination in Agricultural Soils with Organic and Inorganic Production Systems in Cunduacán, Tabasco, Mexico
Evaluación de la Contaminación por Metales Pesados en Suelos Agrícolas con Sistemas de Producción Orgánicos e Inorgánicos en Cunduacán, Tabasco, México

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SUMMARY

Cocoa cultivation is the main economic source for small and large farmers in Tabasco. However, cocoa production has decreased recently due to financial, edaphic, and nutritional factors. Therefore, this study aimed to measure the concentration of heavy metals (HM) in agricultural soil. To achieve this, two polygons (P1 and P2) were selected to evaluate the environmental impact of the agricultural production system used in each polygon. The pH (hydrogen potential), OM (organic matter), apparent density (AD), real density (RD), porosity (PO), clay (C), silt (ST), sand (S), and field capacity (FC) of the examined regions were also determined. In addition, a solid waste landfill (SWLF) was included as a third sampling site (P3). This is because it is a source of contamination of the surrounding cocoa-growing areas (P1 and P2). According to Mexican standards NOM-147-SEMARNAT and NOM-021-SEMARNAT-2000, the heavy metals that exceeded the permissible limits were Cd > Ni > V for P1, Cd for P2, and Cd for P3, with significant differences between polygons. The highest level of Cd was determined in P3; therefore, the concentration of Cd in P1 and P2 is associated with the use of agrochemicals and the dragging of soil particles due to the topographic position of P3.

Index words: *agrochemicals, cocoa, edaphology, fertility, leaching.*

RESUMEN

El cultivo de cacao es la principal fuente económica para pequeños y grandes productores en Tabasco. Sin embargo, la producción de cacao ha disminuido recientemente debido a factores financieros, edáficos y nutricionales. Por lo tanto, el objetivo de este estudio fue medir la concentración de metales pesados (MP) en suelos agrícolas. Para ello, se seleccionaron dos polígonos (P1 y P2) para evaluar el impacto ambiental del sistema de producción agrícola utilizado en cada polígono. Asimismo, se determinaron el pH (potencial de hidrógeno), MO (materia orgánica), densidad aparente (DA), densidad real (DR), porosidad (PO), arcilla (Ar), limo (Li), arena (A) y capacidad de campo (CC) de las regiones examinadas. Además, se incluyó un relleno sanitario de residuos sólidos (RSRS) como un tercer sitio de muestreo (P3), debido a que constituye una fuente de contaminación para las áreas cacaoteras circundantes (P1 y P2). De acuerdo con las normas mexicanas NOM-147-SEMARNAT y NOM-021-SEMARNAT-2000, los metales pesados que excedieron los límites permisibles fueron Cd > Ni > V en P1, Cd en P2 y Cd en P3, con diferencias

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significativas entre polígonos. El mayor contenido de Cd se determinó en P3; por lo tanto, la concentración de Cd en P1 y P2 se asocia con el uso de agroquímicos y el arrastre de partículas del suelo debido a la posición topográfica de P3.

Palabras clave: *agroquímicos, cacao, edafología, fertilidad, lixiviación.*

INTRODUCTION

Cocoa (*Theobroma cacao L.*) is a tropical fruit that small producers in the Chontalpa region of Tabasco have cultivated using various production systems (Brechelt, 2004; Córdova-Avalos, Mendoza, Vargas, Izquierdo, and Ortiz, 2008; Priego-Castillo, Galmiche, Castelán, Ruiz, and Ortiz, 2009; Sbarbati-Nudelman, 2011; Tadeo-Sánchez and Tolentino, 2020). It has been established that the use of agrochemicals in the inorganic production system results in higher levels of toxic metals in agricultural soils (Franco Cabrera and Scaldaferro, 2017; Londoño-Franco, Londoño-Muñoz, and Muñoz, 2016). These metals can affect human health by being transferred from soil to fruit, besides causing harm to the environment (Brechelt, 2004; Laribi *et al*., 2023). Ramos-Mejía (2022[1]) cocoa cultivation study demonstrated that Mg, Ca, Sr, Zn, Cd, and Cu can be transported from the soil to the leaves and from the soil to the cocoa beans. It has also been reported that this contaminant can cause plant metabolic damage, decreasing fertility and crop production (Hernández-Caricio *et al*., 2022). In addition to the above, the research conducted by Tun-Canto, Álvarez, Zapata, and Sosa (2017) determined the distribution of heavy metals in the sugarcane area of the Hondo River basin, located in the south of Quintana Roo, Mexico. They found that the detected concentrations of Hg, Cd, and Cu come from anthropogenic sources, where the factor that determines the distribution of heavy metals is the soil particle drag caused by runoff. Therefore, soil quality and agricultural sustainability are related to land use, topographic, and geomorphological variations (Derakhshan-Babaei, Nosrati, Mirghaed, and Egli, 2021; Meitasari, Hanudin, and Purwanto 2024). Due to the mentioned reasons, the identification and quantification of chemical elements in agricultural soils have become crucial (Franco-Cabrera and Scaldaferro, 2017[1]). This research aims to quantify chemical elements in agricultural soils with different agrarian production systems identified as polygons. In the first polygon (P1), an inorganic production system was used, while in the second polygon (P2), an organic production system was used. In addition, a solid waste landfill (SWLF) was included as a third sampling site (P3). The collection of samples followed Mexican Official Standard NOM-147-SEMARNAT/SSA-1-2004 (2007). The physical and chemical properties of the samples collected were obtained according to the Mexican Official Standard NOM-021-SEMARNAT-2000 (2002). The total petroleum hydrocarbon fractions (TPH) present in the municipal solid waste landfill (SWLF) were determined using the SARA method (Saturated, Asphalt, Resinous, and Aromatic). The leached in the extracts using the Toxic Contaminant Extraction Process (TCEP). The concentration of heavy metals was obtained by inductively coupled plasma spectroscopy (ICP-OES) under the specifications of the Mexican Official Standard NOM-147-SEMARNAT/SSA-1-2004 (2007).

MATERIALS AND METHODS

The obtained data was also subjected to a variance analysis (ANOVA) and Tukey's test for multiple comparisons of means with a significance level of p-value ≤ 0.05. The Shapiro-Wilks test was used to determine the data's normality.

Study Area

The study area is in the municipality of Cunduacán, Tabasco, geographically situated between parallels 17° 56′ and 18° 14′N; 93° 01′ and 93° 25′ W; and an altitude range between 0-100 m. (Figure 1). The study areas are represented by polygons P1, P2, and P3 in Figure 1, located in the Piedra 2da community. The DEM (Digital Elevation Model) map and surface runoff of the study areas according to the topographic elevation (Figure 2).

[1] Ramos-Mejía, C. (2022). *Sostenibilidad del cultivo de cacao (Theobroma cacao) en el distrito minero de Ponce Enríquez*. Master´s Degree. Universidad Andina Simón Bolívar, Ecuador. Retrieved from http://hdl.handle.net/10644/8953

[2] Franco-Cabrera, A., & Scaldaferr, Ruiz, K. (2017). *Determinación de plaguicidas y metales pesados en sedimentos superficiales del embalse el Guájaro como consecuencia de la actividad agrícola en el Distrito de riego Repelón, Atlántico.* [Tesis de grado]. Corporación Universidad de la Costa, CUC. Facultad de Ingeniería. Programa de Ingeniería Ambiental.

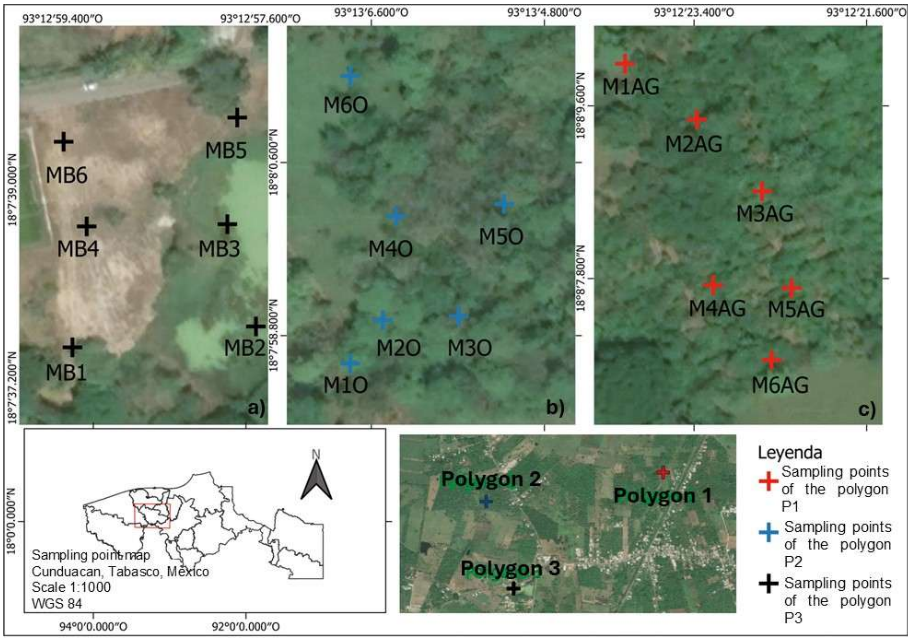

Figure 1. Study Area. a) puntos de extracción de muestras del P3, b) puntos de extracción de muestras del P3 y c) puntos de extracción de muestras del P1.

Edaphology and Soil Use

To analyze the spatial information of the study area and the site data, the QGIS Desktop 3.26.3 Software was used (QGIS.org, 2022). For the vector layer, the Digital Elevation Model (DEM) was used (INEGI, 2025). The edaphology (INIFAP and CONABIO, 1995) and land use (INEGI, 2013) were studied using information provided by institutions of the Tabasco state government. Subsequently, a slope map was prepared to analyze the conditions of the study area and identify the geomorphological units (slopes): upper, middle, and lower (Rivas-Domínguez and Escuintla, 2021).

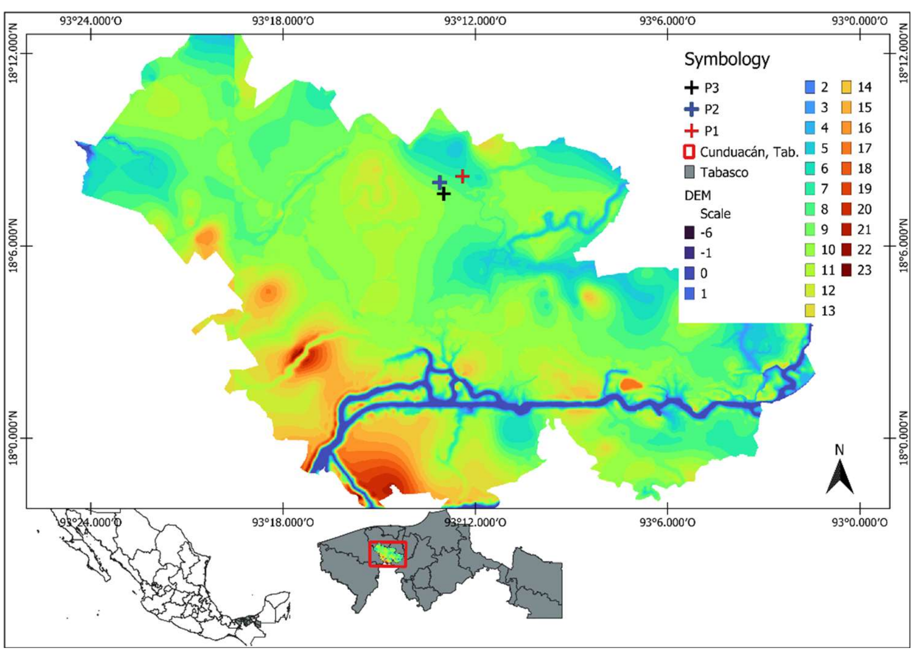

Figure 2. DEM map and surface runoff of the study areas, created using QGIS Desktop 3.26.3 software (QGIS.org, 2022). Own design.

Sampling Plan

Before collecting samples, a field visit was conducted to identify the area, and interviews were conducted with agricultural producers (Ramos-González, Lunagómez, and Pérez, 2024). The distribution of the sampling points (Figure 1) was punctual and directed as indicated in the NMX-AA-132-SCFI-2016 (SEMARNAT, 2016), establishing that the number of samples to be extracted was 6 per 0.5 hectare. Samples were collected from each horizon until reaching the water table (about 40-60 cm deep) and their respective soil profiles. P1 (inorganic production system) and P2 (organic production system) were chosen because both areas correspond to the same variety of cocoa plants and have similar plantation ages, between 30-32 years. The third polygon (P3) was included because it could be a potential source of contamination for P1 and P2, as it is located 1 kilometer away and its topographical position affects this, given that there was an urban solid waste dump in that location, which has been inactive for 15 years. The soil sampling time was between November and December, as these months coincide with the rainy season. The samples were collected during the rainy season, as this period can highlight the differences in PM retention or mobilization between polygons with different agricultural production systems (organic and chemical), more clearly showing the effects of soil management.

Determination of Soil Fertility

The methodologies used in the Mexican Official Standards were used to determine the physical and chemical parameters in the soil samples. The pH was determined using AS-02/NOM-021-SEMARNAT-2000 (SEMARNAT, 2002), with a soil-water ratio of 1:2, and a potentiometer HANNA HI 9813-6. A Collman column and AS-05/NOM-021-SEMARNAT-2000 (SEMARNAT, 2002) were utilized to determine the percentage of saturation or field capacity (FC). For real density (RD), AS-04/NOM-021-SEMARNAT-2000 (SEMARNAT, 2002) was considered. Method AS-09/NOM-021-SEMARNAT-2000 (SEMARNAT, 2002) was used for the texture. AS-03/NOM-021-SEMARNAT-2000 (SEMARNAT, 2002) was utilized to determine the apparent density (AD). Porosity (PO) was obtained according to the methodology reported by Palma-López et al., and the equation 1 (Palma-López, Cisneros, Moreno, and Rincón, 2007). Finally, the content of organic matter (OM) was obtained by oxidation with H_2O_2, as indicated by Solis-Pérez et al. (Solís-Pérez *et al*., 2019).

$$\%PO = \left(\frac{RD - AD}{RD}\right)100 \qquad (1)$$

Assessing toxic Contaminants in SWLF Soil Samples

The evaluation of pollutants in the municipal solid waste dump (SWLF) was conducted as follows: a) Using Soxhlet equipment that contained 5 g of soil and 90 mL of dichloromethane, a continuous solid-liquid extraction process for 6 hours was carried out to evaluate total petroleum hydrocarbons (TPH) (Martínez-Chávez, Morales, and Alor, 2017). The solvent type varied for SARA fractions according to the fraction to be determined (Marín-García, Adams, and Hernández, 2015).

b) Determination of content of polar components by FtIR: HTP extracts were analyzed using the Infrared with Fourier Transform (FtIR), model Nicole is50 ZNSE with ID7 Air Diamond detector from Thermo Scientific brand, operated with the Omnic Spectra Software Falcón service (Guzmán-Osorio *et al*., 2020).

Metal Quantification Using Inductive Coupling Plasma Spectroscopy (ICP-OES)

The soil samples were digested according to the Mexican Official Standard NOM-147-SEMARNAT/SSA-1-2004 (2007). A mixture of 0.5 g of soil, 3 ml of HCl (71.30%, JT Baker), and 9 mL of HNO_3 (65.80%, JT Baker) was placed in an MLS-1200 MEGA microwave oven (Milestone) for 20 minutes. Afterward, the digested sample was placed in centrifuge tubes and diluted in 45 mL of deionized water. The diluted samples were allowed to settle for 24 hours before reading in the ICP-OES equipment. Sample analysis was performed on a Perkin Elmer Optima Avio 500 ICP-OES using high-purity Argon gas (80-120 PSI), nitrogen (30-120 PSI), and dry air (80-120 PSI). Calibration was performed according to the equipment manufacturer's recommendations by adding multielement standards S7A (Quality Control Standard, TruQ) and S21 (Quality Control Standard, TruQ) and ASTM Type 1 deionized water. The calibration curve was made using standards at concentrations of 0.1, 0.5, 1.0, 5.0, and 10.0 mg L^{-1}.

The analysis sequence was as follows: The first step was to analyze the blank measurement (deionized water) and the standards at the concentrations mentioned. In addition, the blank and the 0.5 mg L^{-1} standard were read every 15 samples. The blank was used to wash the system for a minute between each sample reading. To obtain the recovery percentage, the Montana I, certified soil from the National Institute of Standards and Technology of the U.S.A. was used (National Institute of Standards y Technology, 2018).

The following elements were determined: (As), silver (Ag), barium (Ba), beryllium (Be), cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), potassium (K), manganese (Mn), nickel (Ni), lead (Pb), selenium (Se), thallium (Tl), and vanadium (V). The coefficient of determination (r^2) of the calibration curve, the method detection limit (MDL), and the SD obtained for each chemical element (Table 1) indicate that the data points are clustered closely around the mean, or central tendency (Barzallo, Vera, Gavin y Lazo, 2021).

The recovery percentage was calculated to assess the method's ability to quantify the concentration of metals in the soil (Table 2). For this, a certified reference material "Montana I" and an ICP-OES equipment were used to measure the concentration of recovered metals. The recovery percentages obtained were in the range of 71% to 95% and the %RSD was %, which means that the analytical method used is acceptable (Barzallo *et al*., 2021; Gillings *et al*., 2020).

RESULTS AND DISCUSSION

Edaphology and Soil use

All data was analyzed using STATGRAPHICS Centurion statistical software (Statgraphics Technologies, 2024). The information reported by government institutions on the edaphology of the study areas (INEGI, 2010, 2013, 2025; INIFAP and CONABIO, 1995) shows that P1 is integrated into soils with Gleysol-vertic classification, while P2 and P3 are constituted by Mollic-Gleysols soils. However, during the field visit and taxonomic characterization, soil P1 showed marked dilation and contraction behaviors in conditions of drought and humidity, which are characteristic of Vertisol. On the other hand, P2 was affected by the water table, a characteristic observed in Gleysol (Morales-Ramos, Estrada, Alor, Méndez, and Morales, 2022), and P3 had a thicker texture, which indicates that it is integrated by Arenosol (Morales-Ramos *et al*., 2022; Palma-López *et al*., 2007). Regarding land use in the areas of study, it primarily consists of temporary and permanent agriculture.

Table 1. Validation parameters for the determination of chemical elements by ICP-OES.

Elements	CV (r^2)	Slope	SD	DLM (mg kg^{-1})
As	0.9996	1349.9870	0.0087	2.3556
Ag	0.9985	31883.4826	0.0032	0.8640
Ba	0.9997	140475.4820	0.0002	0.0540
Be	0.9999	264358.8670	0.0002	0.0540
Cd	0.9999	43624.2547	0.0009	0.2430
Cr	0.9997	21721.7688	0.0017	0.4590
Cu	0.9999	22001.0398	0.0035	0.9352
Fe	0.9998	54958.0956	0.0006	0.1620
K	0.9999	208789.5180	0.0013	0.3510
Mn	0.9995	465038.3950	0.0001	0.0271
Ni	0.9999	3477.8169	0.0021	0.5670
Pb	0.9999	3065.4527	0.0077	2.0858
Se	1.0000	1080.0782	0.0175	4.7250
Tl	1.0000	1098.8320	0.0061	1.6470
V	0.9998	57112.0661	0.0016	0.4320

SD = standard deviation; DLM = detection limit of the method; CV = coefficient of variation.

Table 2. Recovery percentages.

Certified value		λ	Experimental value ()	RSD	Recovery
- - - - - - - - - - mg kg^{-1} - - - - - - - - - -		nm	mg kg^{-1}		%
As	1540	188.979	1287.3534 ± 4.9036	0.3729	83.5944
Cu	3420	327.393	2725.1081 ± 29.7542	1.0918	79.6815
Fe	43200	238.196	40899.1781±134.5717	0.3290	94.6740
Mn	2140	257.61	1726.3707±4.0914	0.2370	80.6715
Pb	5520	220.355	4465.4363±63.2164	1.4157	80.8956
Ba	792	233.524	564.8799±7.8799	1.2404	71.3232
Cd	12.3	226.502	37.0706±0.0268	0.0723	78.0217

λ= wavelength; RSD = relative standard deviation.

Physicochemical Parameters

Table 3 (Polygon 1), Table 4 (Polygon 2), and Table 5 (Polygon 3) contain the results of the physical parameters and chemicals of the soil in the three study polygons. The ANOVA test revealed significant statistical differences between the polygons, except for organic matter (OM). Consequently, the Tukey test indicated that there are significant differences between some group means.

The FC percentage was between 46-76% for P1 and 29-60% for P2. The highest percentage obtained for P1 indicates that it has a higher water content, which makes it favorable for plant development. This characteristic is typical of soil that contains silt and clay particles. However, their capacity to hold more water can lead to flooding when they reach the saturation point. In the case of P1, due to a depression in the earth's surface compared to P2 and P3, the water remains stagnant for long periods.

Table 3. Physical and chemical parameters of P1 samples.

ID	pH	FC	OM	AD	RD	PO	C	S	ST
M1AGH1	4.87 ± 0.06 a	60.55 ± 0.10 a	2.72 ± 0.14a	1.25 ± 0.02 c	1.86 ± 0.08 a	32.46 ± 3.49 a	39.99 ± 4.16 a	0	59.33 ± 4.16 a
M1AGH2	5.07 ± 0.06 b	71.36 ± 0.01 b	2.56 ± 0.13a	1.31 ± 0.02 d	1.87 ± 0.02 a	30.15 ± 1.29 a	39.33 ± 2.00 a	0	60.67 ± 2.00 b
M2AGH1	5.03 ± 0.06 b	73.90 ± 0.02 b	5.66 ± 0.28b	1.18 ± 0.03 c	1.86 ± 0.14a	36.45 ± 5.33 a	35.46 ± 2.13 a	0	64.54 ± 2.13 b
M2AGH2	5.10 ± 0.10b	55.95 ± 0.01 a	3.17 ± 0.16a	1.24 ± 0.04 c	1.66 ± 0.02 a	25.43 ± 3.41 c	39.80 ± 5.03 a	0	60.20 ± 5.03 b
M3AGH1	4.83±0.06a	46.02 ± 0.06 a	4.15 ± 0.21a	1.22 ± 0.01 c	1.75 ± 0.09 a	30.04 ± 3.51 c	50.71 ± 1.15 b	0	49.33 ± 1.15 a
M3AGH2	5.33 ± 0.12c	64.51 ± 0.05 a	3.33 ± 0.17a	1.28 ± 0.04 d	1.75 ± 0.02 a	26.66 ± 2.59 c	42.66 ± 6.11 b	0	56.67 ± 6.11 a
M4AGH1	5.43 ± 0.06 d	59.19 ± 0.09 a	3.20 ± 0.16a	1.22 ± 0.02 c	1.79 ± 0.08 a	31.79 ± 2.78 c	42.71 ± 3.06 b	0	57.29 ± 3.06 a
M4AGH2	5.63 ± 0.06 c	75.83 ± 0.02 b	2.52 ± 0.13a	1.25 ± 0.01 c	1.73 ± 0.09 a	27.95 ± 3.46 c	31.57 ± 4.02 a	0	68.43 ± 4.02 b
M5AGH1	5.10 ± 0.00b	54.82 ± 0.08 a	6.56 ± 0.33b	1.11 ± 0.02 a	2.01 ± 0.10 b	44.52 ± 2.45 b	32.04 ± 3.46 a	0	67.96 ± 3.46 b
M5AGH2	5.10 ± 0.00 b	49.26 ± 0.06 a	4.00 ± 0.20a	1.20 ± 0.00 c	1.70 ± 0.08a	28.96 ± 3.56 c	33.94 ± 1.15 a	0	66.06±1.15 b
M6AGH1	5.37 ± 0.06 c	53.28 ± 0.03 a	3.64 ± 0.18a	1.31 ± 0.05 d	1.74 ± 0.04 a	24.96 ± 3.23 c	37.86 ± 1.57 a	0	62.14±1.57 b
M6AGH2	5.67±0.06d	67.92 ± 0.30 a	2.65 ± 0.13a	1.05 ± 0.01 a	1.79 ± 0.08 a	41.62 ± 2.15 b	31.09 ± 3.65 a	0	68.91±3.65 b
SWc	0.94	0.97	0.94	0.94	0.94	0.94	0.95	NA	0.95
P valor	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	NA	< 0.05
HSD	0.18	24.25	2.41	0.08	0.23	9.55	10.21	NA	10.21

a, b, c, d indicate significant statistical differences ($p \leq 0.05$); SWc = Shapiro Will calculated; HSD = honestly significant difference; pH = hydrogen potential; OM = organic matter; AD = apparent density; RD = real density; PO = porosity; C = clay; ST = silt; S = sand; FC = field capacity.

Table 4. Physical and chemical parameters of P2 samples.

ID	pH	FC	OM	AD	RD	P	S	C	ST
M1OH1	4.87 ± 0.06 d	58.84 ± 2.94	3.88 ± 0.19 b	1.03 ± 0.02 a	1.79 ± 0.02 a	42.63 ± 1.19 a	58.95 ± 1.01 c	0	41.05 ± 1.01 a
M1OH2	4.80 ± 0.00 c	49.23 ± 2.46	1.43 ± 0.07 a	1.16 ± 0.01 c	1.68 ± 0.09 a	30.70 ± 4.25 b	49.27 ± 2.31 b	0	48.61 ± 2.31 a
M2OH1	4.90 ± 0.00 d	59.93 ± 3.00	1.10 ± 0.05 a	1.08 ± 0.01 b	1.82 ± 0.06 a	40.47 ± 2.62 a	49.94 ± 1.15 b	0	50.06 ± 1.15 b
M2OH2	4.87 ± 0.06 d	54.67 ± 2.73	9.39 ± 0.47 c	1.08 ± 0.01 b	1.71 ± 0.09 a	36.71 ± 3.99 a	47.65 ± 3.31 b	0	52.35 ± 3.31 b
M3OH1	4.60 ± 0.00 a	57.83 ± 2.89	0.83 ± 0.04 a	1.12 ± 0.03 b	1.73 ± 0.10 a	35.25 ± 4.63 a	51.51 ± 1.01 b	0	48.49 ± 1.01 a
M3OH2	4.60 ± 0.00 a	45.68 ± 2.28	1.77 ± 0.09 a	1.12 ± 0.02 b	1.76 ± 0.05 a	36.21 ± 1.74 a	36.47 ± 3.16 a	0	63.53 ± 3.16 c
M4OH1	4.90 ± 0.00 d	57.24 ± 2.86	2.75 ± 0.14 b	1.12 ± 0.01 b	1.82 ± 0.10 a	38.12 ± 3.85 a	46.90 ± 4.07 b	0	53.15 ± 4.07 b
M4OH2	4.60 ± 0.00 a	29.71 ± 1.49	1.68 ± 0.08 a	1.22 ± 0.04 c	1.79 ± 0.11 a	31.48 ± 2.31 b	58.71 ± 3.06 c	0	41.29 ± 3.06 a
M5OH1	4.80 ± 0.00 c	46.25 ± 2.31	3.11 ± 0.16 b	1.17 ± 0.02 c	1.79 ± 0.02 a	34.37 ± 1.82 b	53.99 ± 1.15 b	0	46.01 ± 1.15 a
M5OH2	4.70 ± 0.00 b	41.95 ± 2.10	2.06 ± 0.10 a	1.16 ± 0.02 c	1.75 ± 0.03 a	33.78 ± 2.74 b	54.47 ± 1.41 b	0	44.85 ± 1.41 a
M6OH1	4.90 ± 0.00 d	46.47 ± 2.32	3.32 ± 0.17 b	1.11 ± 0.00 b	1.93 ± 0.12 b	42.64 ± 3.51 a	44.23 ± 1.57 a	0	55.57 ± 1.57 b
M6OH2	5.00 ± 0.00 e	42.57 ± 2.13	2.49 ± 0.12 b	1.16 ± 0.01 c	1.95 ± 0.11 b	43.08 ± 3.31 a	37.33 ± 5.29 a	0	62.72 ± 5.29 c
SWc	0.94	0.99	0.94	0.98	0.94	0.98	0.95	N/A	0.95
Valor *p*	< 0.05	> 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	N/A	< 0.05
HSD	0.07	35.16	1.54	0.06	0.25	9.35	8.03	N/A	8.03

a, b, c, d, e indicate significant statistical differences (p value ≤ 0.05); SWc = Shapiro Will calculated; HSD = honestly significant difference; pH = hydrogen potential; OM = organic matter; AD = apparent density; RD = real density; PO = porosity; C = clay; ST = silt; S = sand; FC = field capacity.

Table 5. Physical and chemical parameters of P3 samples.

ID	pH	AD	RD	P	S	C	ST
MB1H1	7.85 ± 0.03 a	1.39 ± 0.00 b	1.63 ± 0.04	14.44 ± 1.91 b	91.89 ± 0.00 c	0.11 ± 0.00 a	8.00 ± 0.00 a
MB1H2	7.82 ± 0.01 a	1.40 ± 0.01 b	1.62 ± 0.09	13.63 ± 5.30 b	74.56 ± 1.15 b	0.11 ± 0.00 a	25.33 ± 1.15 c
MB2H1	7.70 ± 0.02 d	1.36 ± 0.03 b	1.63 ± 0.07	16.54 ± 1.75 b	71.22 ± 1.15 a	1.44 ± 1.15 a	27.33 ± 1.15 c
MB2H2	7.75 ± 0.02 a	1.35 ± 0.04 b	1.67 ± 0.06	18.89 ± 4.82 b	75.22 ± 1.15 b	0.11 ± 0.00 a	24.67 ± 1.15 c
MB3H1	7.88 ± 0.02 a	1.32 ± 1.50 b	1.65 ± 0.08	19.97 ± 4.35 b	83.89 ± 0.00 c	0.11 ± 0.00 a	16.00 ± 0.00 b
MB3H2	7.70 ± 0.02 d	1.36 ± 0.03 b	1.63 ± 0.07	16.54 ± 1.75 b	70.22 ± 1.15 a	2.44 ± 1.15 b	27.33 ± 1.15 c
MB4H1	7.82 ± 0.01 a	1.22 ± 0.04 a	1.66 ± 0.03	19.10 ± 1.87 b	69.22 ± 1.15 a	0.78 ± 1.15 a	30.00 ± 2.00 d
MB4H2	7.76 ± 0.04 a	1.34 ± 0.01 b	1.70 ± 0.15	20.57 ± 7.59 b	75.03 ± 1.03 b	0	25.52 ± 1.35 c
MB5H1	7.17 ± 0.06 c	1.23 ± 0.03 a	1.78 ± 0.02	30.63 ± 1.67 a	70.66 ± 1.15 a	0	29.28 ± 2.00 d
MB5H2	7.35 ± 0.02 b	1.20 ± 0.02 a	1.63 ± 0.03	26.09 ± 0.40 a	75.03 ± 1.03 b	0	26.00 ± 1.11 c
MB6H1	7.82 ± 0.01 a	1.19 ± 0.06 a	1.62 ± 0.02	26.16 ± 3.78 a	91.22 ± 1.15 c	0	9.33 ± 1.15 a
MB6H2	7.69 ± 0.14 d	1.32 ± 0.02 b	1.65 ± 0.03	19.95 ± 2.49 b	74.56 ± 1.15 b	0.11 ± 0.00 a	25.33 ± 1.15 c
SWc	0.94	0.96	0.94	0.96	0.97	0.98	0.94
Valor *p*	<0.05	<0.05	>0.05	<0.05	<0.05	<0.05	<0.05
HSD	0.14	0.08	0.20	10.92	3.34	2.48	4.42

a, b, c, d indicate significant statistical differences (p value ≤ 0.05); SWc = Shapiro Will calculated; HSD = honestly significant difference; pH = hydrogen potential; OM = organic matter; AD = apparent density; RD = real density; PO = porosity; C = clay; ST = silt; S = sand; FC = field capacity.

According to the classification established by NOM-021-SEMARNAT 2000 (SEMARNAT, 2002), the pH of the soils in P1 (pH 4.83 and 5.67) and P2 (pH 4.60 and 5.0) fluctuated between strongly acidic and moderately acidic. In P3, the pH (7.17 and 7.88) was characteristic of neutral to moderately alkaline soils (SEMARNAT, 2002). Orozco and Thienhaus (1997) reported that acidic soils decrease the adsorption of some elements and favor the toxicity caused by iron and aluminum; additionally, they contribute to the deficiency of calcium, magnesium, and potassium. According to Arévalo-Gardini *et al*. (2016), uncontaminated acidic soils should have a pH range between 6.0 to 7.0, while slightly contaminated soils can lead to a pH decrease between 5.0 and 5.9. Hence, acidic conditions can lead to the retention of contaminants. In most cases, acidic soils show phytotoxicity in plants caused by HM, which causes damage to the growth and formation of lateral and secondary roots during their development (Bravo-Realpe, Arboleda, and Martín, 2014), *(Theobroma cacao L.)* decreasing the harvest every year (Cepeda and Jhon, 2022). Therefore, the decrease in productivity of cocoa plants in P1 and P2 may be related to the aforementioned factors. The pH of soil in P3 was typical of neutral to moderately alkaline soils. It has been reported that alkaline soils with a pH between 7.0-8.0 are not contaminated by HM (Arévalo Gardini *et al*., 2016). However, according to the visual assessment conducted, solid residues of HM and hydrocarbon waste, among others, were found at the site. In addition, no signs of biological activity or growth of vegetation cover were found in this polygon, which indicates that the soil is affected by contamination and the conditions are not suitable for agricultural land use.

Organic matter (OM) analysis was only performed for P1 and P2 because P3 is a solid waste landfill (SWLF) with no biological activity or vegetation cover growth. Hence, the transformation of organic matter into vermicompost humus derived from vegetation is non-existent. The ANOVA test showed no statistically significant differences between the two polygons with a p-value > 0.05. For P1, the classification of reactivity with H_2O_2 was medium to high in all profiles and their horizons, and very low for reactivity with CH_3COOH and HCl. For P2, it was low to medium reactivity with H_2O_2, and null to very low with CH_3COOH and HCl. In the soils, OM was determined up to 5.66 ± 0.28 and 9.39 ± 0.47 for P1 and P2, respectively; considered as medium-high according to the classification of NOM-021-SEMARNAT-2000 (SEMARNAT, 2002). The highest value of OM in one of the horizons of P2 is due to the greater presence of earthworms (*Lumbricus terrestris*), indicating greater biological activity in the area due to increased soil fertility. These characteristics are typical of agricultural soils in which an organic production system is used (Orozco and Thienhaus, 1997). However, it has been mentioned that soils containing high values of OM can adsorb more Cd than soils that have large amounts of 2:1 type clay (Bravo-Realpe *et al*., 2014). The low amount of organic matter (OM) in P1, where an inorganic production system is used, is associated with low soil and biological activity.

The main problems in soils where tillage is carried out, which cause changes in the size distribution of aggregates, are high apparent density (AD), surface sealing, hardening of the soil during the dry season, compaction, low infiltration rates, and continuity of the pore space. Additionally, all these factors decrease the water storage capacity, root penetration, and growth (Amezquita, 1999; Le Bissonnais, 2016; Morales-Ramos *et al*., 2022). These conditions are supposed to be present in P1, as intense soil tillage is carried out on this site. However, the results are contradictory: in P1, high AD values are observed, but the FC percentage is high; in P2, lower AD is found, but the FC percentage is lower.

The range of the percentage of porosity (PO) obtained for P1 was 24.96 ± 3.23 - 44.52 ± 2.45%, for P2 it was 31.48 ± 2.31 - 42.64 ± 3.51% and for P3 it was 13.63 ± 5.30 - 30.63 ± 1.67%. In polygon 1, the highest percentage of PO is related to the high percentage of FC (Table 3). In P2, the lowest percentage of PO is related to lower percentages of FC (Table 4). In this same sense, the low porosity of P3 could be explained.

For sands (S), the ANOVA determined that the three polygons have significant statistical differences with a p-value < 0.05. However, the percentage of clays (C) in the three groups of samples was almost zero and equal. Therefore, the analysis was performed with the sum of the percentage of silts (ST) and clays (C). The ANOVA showed that P1, P2, and P3 have significant statistical differences. Regarding edaphology and soil textural classes; the factors that influence the growth and good performance of cocoa plants are soils of alluvial origin, rich in OM, clay loam texture, pH of 6 to 7 (optimal 6.5), and well-drained (Francisco-Santiago, Palma, Sánchez, Obrador, and García, 2023). However, the favorable pH range was not found in any of the three polygons. Despite the above, P1 has a clayey-loam texture suitable for cocoa cultivation, but it is affected by the inorganic production system used on the site since this textural class has a greater capacity to absorb HM. In addition, the soil structure in P1 has an increased number of cracks due to the presence of more silt and clay than in P2.

Determination of TPH and SARA Fractions in P3

The determination of TPH and SARA fractions was only carried out in P3 because it is a solid waste landfill (SWLF) in which hydrocarbon residues were observed. Table 6 displays the results of TPH quantification and SARA analysis for polygon 3 (6 samples). Regarding the TPH results, concentrations above 4400 mg/kg were detected, which exceed the maximum limit set by NOM-138-SEMARNAT/SSA1-2012 (SEMARNAT, 2012). The multiple comparison of means of the TPH for MB1 and MB4 was statistically significant. The highest concentration of TPH in MB1 is because MB4 is located within a water stream that is in the SWLF. This water effluent is directed towards lower altitude areas during the rainy season. MB4 is situated at a higher topographic altitude; therefore, it does not benefit from soil erosion that carries contaminants to low-lying areas. Hydrocarbon-contaminated soil causes changes in soil properties, and these effects are permanent, as the weathering of hydrocarbons can persist for a long time. Alor-Chávez, Morales, Álvarez, and Méndez (2022) reported that TPH in the soil causes changes in pH from moderately acidic to neutral, changes in textural classification, increased density, and reduced porosity, which contribute to low hydraulic conductivity and poor plant rooting. In this same sense, Adams, ZaVala, and Morales (2008) and Marín-García *et al*. (2016) report that hydrocarbons have a greater affinity with clayey soils, resulting in aggregates of higher molecular weight.

Regarding the results of the SARA analysis, the determination was carried out according to what was reported by Lache-García *et al*. (2011) y Martínez-Chávez *et al*. (2017). In the repellent fraction (Resins + Asphaltene), a ($p < 0.05$) was obtained, indicating a significant statistical difference between the meaning of the samples with a confidence level of 95.0%. The statistical differences between the MB3 and the MB6 samples are significant. This is because the MB3 sampling point is situated in an area with a higher accumulation of urban waste residue, high sand content, and organic matter derived from hydrocarbons. Point MB6 was taken near the road, where there were fewer remains of urban solid waste.

Torre-Vaamonde (2016[3]) mentioned that hydrophobicity in the soil is most frequently manifested when it has a coarse texture, and an excessive accumulation of organic matter derived from hydrocarbons. In addition to the above, resins and asphaltene fractions tend to cause water repellency in the soil, which has negative effects on the water storage capacity and contributes to poor plant development (Marín-García *et al*., 2016). The samples from Polygon 3 that show repellency are MB1, MB2, MB3, MB4, and MB5. They contain a percentage of resins and asphaltene that is greater than 70%. To avoid soil hydrophobicity, solid waste landfills should be established in a geographic depression covered by an impermeable lower membrane with a leachate collection system, a gas collection system, and an upper cover (Pomposiello, Dapeña, Boujon, and Favetto, 2009). These topographic

Table 6. TPH and SARA fractions of polygon P3.

ID	TPH	SARA Fractions				Toxic	Repellent
		Saturate	Aromatic	Resin	Asphaltene		
	mg kg^{-1}	% w/w of the extract					
MB1	11598.84 ± 579.94 a	3.46	4.31	3.81	88.42	7.77 ± 0.39 b	92.23 ± 4.61 a
MB2	10700.00 ± 540.00	15.72	3.70	2.88	77.70	19.60 ± 0.97 a	80.40 ± 4.03 b
MB3	11517.08 ± 572.93	1.38	0.00	0.00	98.62	1.07 ± 0.07 c	98.93 ± 4.93 a
MB4	10600.00 ± 530.00 b	27.32	2.83	1.92	67.93	29.21 ± 1.51 d	70.79 ± 3.49 c
MB5	11393.16 ± 569.66	17.65	0.88	0.71	80.76	18.53 ± 0.93 a	81.47 ± 4.07 b
MB6	11398.88 ± 569.94	98.25	0.00	0.00	1.75	99.12 ± 4.91 e	0.88 ± 0.09 d
SWc	0.85	N/A	N/A	N/A	N/A	0.62	0.83
p value	< 0.05	N/A	N/A	N/A	N/A	< 0.05	< 0.05
HSD	1062.59	N/A	N/A	N/A	N/A	993.58	397.85

a, b, c, d, indicate significant statistical differences (p < 0.05); SWc = shapiro Will calculated; HSD = honestly significant difference.

[3] Torre-Vaamonde, S. D. L. (2016). Mitigación de la repelencia al agua en suelos quemados empleando polímeros orgánicos. Masters´s degree.vUniversidade da Coruña, España. Retrieve from http://hdl.handle.net/2183/17224

conditions are not met in polygon P3 because its geographic location is above P2 and P1, and it also lacks the conditions. Meitasari *et al*. (2024) determined that the soil quality index is related to geographic elevation and dynamic properties, which can change due to anthropogenic and biological activities. In this same sense, Valcarce-Ortega and Jiménez (2016), demonstrated in their research that high slopes favor surface runoff and reduce the infiltration of contaminants. However, the lower the slope of the land, the greater the impact on the aquifer, which could cause contaminants in P3 to migrate to P1 and P2, increasing contamination in these sites.

The results of the toxic fraction (Aromatic + Saturated) indicate a statistically significant difference, with a confidence level of 95.0%. The results of sample MB6 are significantly different from all other samples because the sampling point MB6 is located on a lower topographic slope. However, weed growth was found near the road in the area. In MB1, MB2, MB3, MB4, and MB5, a lower toxic fraction was found than in MB6. The transfer of contaminants from the soil to different places by runoff could be absorbed by the soil in MB6 Simbaña-Cazar (2016[4]). Since only sample MB6 showed a high concentration of the toxic fraction, contamination and damage caused by this type of hydrocarbons in the area are ruled out. On the other hand, this confirms the soil repellency to water in the entire study polygon.

Fourier Transform Infrared Spectroscopy (FtIR)

The FtIR analysis results (Figure 3) confirm that the extracts exhibit signals from polar and saturated functional groups. The bands corresponding to the functional groups are observed: carbonyl-aromatic (ArCOR) in ~1728 cm^{-1}, sulfonyl (O=S=O) in ~1088 cm^{-1}, ethers (COC) in ~1018 cm^{-1}, Sat1 in ~1358 cm^{-1}, Sat2 in ~1431 cm^{-1}, Sat3 in ~2854 cm^{-1}, and Sat4 in ~2920 cm^{-1}; which coincide with the reports of some investigations (Guzmán-Osorio *et al*., 2020; Melendez, Lache, Orrego, Pachón, and Mejía, 2012; Morales-Bautista, Adams, Hernández, Lobato, and Torres, 2016). These results were confirmed by FtIR analysis.

Determination of heavy metals (HM) by ICP-OES

Table 8-10 shows the HM values per sampling point and their horizons. These values were compared with current national and international standards to estimate the level of contamination and its potential effects (Table 7). These national and international standards belong to countries where cocoa plants are grown and have soils with similar textural characteristics to P1, P2, and P3.

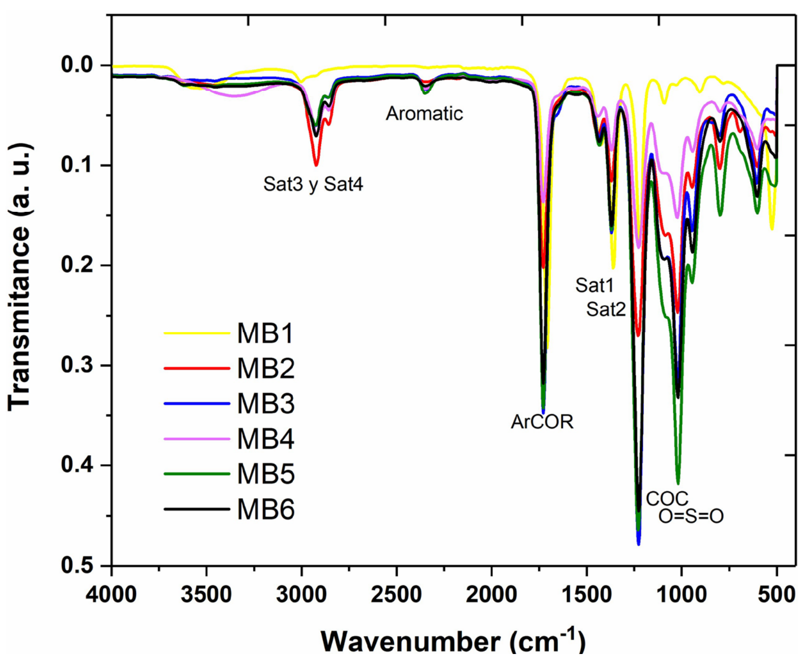

Figure 3. IR spectrum of samples P3.

[4] Simbaña-Cazar, C. J. (2016). *Biorremediación de suelos contaminados con hidrocarburos de la Parroquia Taracoa en Francisco de Orellana, mediante el hongo Pleurotus ostreatus* (Tesis de pregrado). Escuela Superior Politécnica de Chimborazo, Riobamba, Ecuador.

Table 7. National and international standards and their maximum permissible limits in soils.

	NOM 147-SEMARNAT (NOM-147-SEMARNAT/SSA-1-2004, 2007)	NOM 021-SEMARNAT-2000 (SEMARNAT, 2002)		Ecuadorian Standard	ECA for soils from Peru
	Agricultural, residential, and commercial land use	Micronutrients	Polluting metals	Agricultural land use	Agricultural land use
	mg kg^{-1}				
As	22	-	-	12	50
S	-	-	-	500	-
Ba	5400	-	-	750	750
Be	150	-	-	-	-
Cd	37	-	3-5	2	1.4
Cr	280	-	-	0.4	0.4
VI	-	-	-	-	-
Cu	-	Deficiente <2.5	-	-	-
Sn	-	-	-	5	-
Fe	-	Deficiente <1.0	-	-	-
Mn	-	Deficiente <0.2	-	-	-
Hg	23	-	-	0.8	6.6
Ni	1600	-	100	50	-
Ag	390	-	-	-	-
Pb	400	-	100-300	100	70
Se	390	-	-	2	-
Tl	5.2	-	-	1	-
V	78	-	-	130	-
Zn	-	Deficiente <0.5	-	200	-

Ecuadorian Standard = environmental quality standard for soil resources and criteria for contaminated soils; ECA for soils in Peru = environmental quality standards (ECA) for soils in Peru.

Table 8. Elements exceeding the maximum permissible limits of polygon P1.

		As	Pb	Cd	Ba	Be	Cu	Tl	Ag	Ni	Se	V	Cr	K	Fe	Mn
ID	LOD	2.35	2.08	0.24	0.05	0.05	0.93	1.64	0.86	0.56	4.72	0.43	0.45	0.35	0.16	0.02
M1AGH1	Concentration (mg kg^{-1})	N/D	N/D	7.27	262.22	0.37	42.85	N/D	<LOD	101.58	N/D	75.65*	153.29	9317.56	N/D	654.56
M1AGH2		N/D	N/D	N/D	278.63	N/D	27.04	N/D	<LOD	N/D	N/D	68.90	N/D	9951.32	38709.02	847.40
M2AGH1		N/D	N/D	7.25	184.92	N/D	52.27	<LOD	<LOD	89.61	N/D	60.62	121.22	5317.37	32804.40	728.42
M2AGH2		N/D	N/D	7.79	180.85	N/D	33.89	N/D	<LOD	67.17	N/D	61.36	128.38	3980.88	35124.96	620.97
M3AGH1		4.2020	7.70	7.55	238.22	0.2565	48.07	<LOD	<LOD	84.69	N/D	68.97	143.82	9326.91	34725.04	410.12
M3AGH2		4.8632	N/D	7.75	180.72	N/D	31.50	N/D	<LOD	51.35	<LOD	58.34	126.49	3746.68	34601.66	463.56
M4AGH1		N/D	6.42	7.41	252.27	0.2204	35.381	N/D	<LOD	76.08	N/D	73.30	153.84	10290.94	36372.34	551.38
M4AGH2		N/D	3.81	7.88	251.92	N/D	31.42	N/D	<LOD	39.79	N/D	75.41*	159.40	9571.36	N/D	737.49
M5AGH1		N/D	N/D	7.35	177.70	N/D	57.49	<LOD	<LOD	73.48	N/D	57.36	120.89	5061.54	32537.74	430.33
M5AGH2		N/D	N/D	8.30	270.98	<LOD	39.35	N/D	<LOD	N/D	N/D	80.22	163.59	10690.62	39058.85	510.80
M6AGH1		N/D	N/D	8.01	227.30	N/D	30.70	N/D	<LOD	52.41	<LOD	67.95	145.96	9611.44	35589.68	522.94
M6AGH2		N/D	6.08	8.32	184.40	<LOD	30.32	<LOD	<LOD	39.26	N/D	70.69	148.72	5322.21	38793.95	674.04

LOD = less than the detection limit; N/D = not determined; * = close to the maximum permitted limit; λ = wavelength.

Table 9. Elements exceeding the maximum permissible limits of polygon P2.

		As	Pb	Cd	Ba	Be	Cu	Tl	Ag	Ni	Se	V	Cr	K	Fe	Mn
ID	LOD	2.35	2.08	0.24	0.05	0.05	0.93	1.64	0.86	0.56	4.72	0.43	0.45	0.35	0.16	0.02
M1OH1		7.58	N/D	7.40	186.58	<LOD	35.67	<LOD	<LOD	N/D	N/D	57.20	114.30	7001.17	28634.85	362.33
M1OH2		N/D	N/D	7.552	150.26	<LOD	21.13	N/D	<LOD	<LOD	N/D	62.06	112.01	4784.19	31521.18	371.43
M2OH1		N/D	N/D	7.36	139.38	<LOD	43.61	N/D	<LOD	9.53	N/D	50.87	95.74	4602.53	27240.82	362.03
M2OH2		8.03	N/D	7.35	143.7193	<LOD	22.95	N/D	<LOD	<LOD	N/D	58.22	112.60	4200.27	30406.46	397.26
M3OH1		N/D	N/D	7.55	195.10	<LOD	32.25	<LD	<LOD	<LOD	N/D	63.92	133.52	7688.47	31952.48	381.47
M3OH2		8.17	N/D	7.25	128.49	<LOD	19.85	N/D	<LOD	N/D	N/D	56.20	107.98	2896.77	31412.40	433.30
M4OH1	Concentration (mg kg^{-1})	8.26	N/D	7.15	160.52	<LOD	ND	N/D	<LOD	N/D	N/D	57.77	108.82	6173.66	27041.75	302.95
M4OH2		7.58	N/D	7.22	125.61	<LOD	17.32	N/D	<LOD	<LOD	N/D	52.41	97.46	2032.47	30561.53	476.61
M5OH1		N/D	N/D	7.03	155.10	<LOD	30.40	N/D	<LOD	N/D	N/D	54.91	106.66	6757.42	26115.24	275.46
M5OH2		8.91	N/D	7.21	166.08	<LOD	20.30	N/D	<LOD	N/D	N/D	65.28	131.2836	5916.25	30817.56	392.01
M6OH1		N/D	N/D	7.03	120.40	<LOD	38.80	N/D	<LOD	11.65	N/D	45.83	90.5599	3054.73	26085.58	323.81
M6OH2		N/D	N/D		138.45	<LOD	19.32	N/D	<LOD	N/D	N/D	56.12	107.00	N/D	N/D	N/D

LOD = less than the Detection Limit; N/D = not determined. * = close to the maximum permitted limit; λ = wavelength.

Of the fifteen chemical elements found in the soil samples, only three (Cd, Ni, and V) exceeded regulatory limits. In polygon P1, levels of cadmium (Cd), nickel (Ni), and vanadium (V) were elevated. Their presence is primarily associated with phosphate fertilizers and surface runoff processes, which mobilize pollutants. In contrast, in polygons P2 and P3, only Cd was detected. This is linked to anthropogenic sources, such as urban solid waste (MSW). According to NOM-021-SEMARNAT-2000 (SEMARNAT, 2002), the exposure limit for cadmium in agricultural soils is 3 to 5 mg kg^{-1}. The Cd values found in the three polygons exceed the regulatory range, indicating potential health risks associated with using contaminated soils for agriculture.

The concentration of Cd in each polygon followed the following trend P3<P2<P1. This trend could be linked to the contribution of pollutants from stormwater runoff coming from high areas (P3) to low areas (P2 and P1).

Table 10. Elements exceeding the maximum permissible limits of polygon P3.

		As	Pb	Cd	Ba	Be	Cu	Tl	Ag	Ni	Se	V	Cr	K	Fe	Mn
ID	LOD	2.35	2.08	0.24	0.05	0.05	0.93	1.64	0.86	0.56	4.72	0.43	0.45	0.35	0.16	0.02
MB1H1		4.71	N/D	5.82	43.56	<LOD	8.19	<LOD	<LOD	<LOD	N/D	50.92	42.97	897.35	19727.70	259.60
MB1H2		5.32	N/D	4.92	38.15	<LOD	7.23	N/D	<LOD	N/D	N/D	24.07	32.86	672.73	11158.86	165.77
MB2H1		5.10	N/D	5.71	88.65	<LOD	12.59	N/D	<LOD	N/D	N/D	41.51	46.78	2156.74	18843.93	260.28
MB2H2		N/D	12.07	6.15	286.63	<LOD	14.90	N/D	<LOD	<LOD	N/D	47.86	65.85	2783.58	21933.45	306.54
MB3H1		N/D	N/D	6.17	90.66	<LOD	13.75	N/D	<LOD	<LOD	N/D	51.49	57.56	2133.73	22428.58	297.45
MB4H1	Concentration (mg kg^{-1})	7.98	N/D	6.23	100.43	<LOD	13.82	N/D	<LOD	<LOD	N/D	48.01	86.06	2294.50	24889.18	353.38
MB4H2		N/D	N/D	5.31	57.25	<LOD	22.02	N/D	<LOD	<LOD	N/D	38.49	40.32	1994.25	17338.79	223.32
MB5H1		N/D	N/D	6.20	78.58	<LOD	16.84	N/D	<LOD	<LOD	N/D	47.82	63.23	2049.75	23163.61	355.28
MB5H2		N/D	N/D	5.43	61.80	<LOD	10.92	N/D	<LOD	<LOD	N/D	47.76	39.97	1941.75	19915.01	287.09
MB6H1		N/D	N/D	6.63	115.20	<LOD	16.48	N/D	<LOD	<LOD	N/D	49.84	101.96	2331.96	29095.15	431.52
MB6H2		N/D	N/D	5.58	69.71	<LOD	9.25	<LOD	<LOD	N/D	N/D	37.46	42.19	2240.35	16858.38	231.65

LOD = less than the detection limit; N/D = not determined; * = close to the maximum permitted limit; λ = wavelength.

According to the previously obtained pH, soils P1 and P2 were classified as strongly acidic to moderately acidic. This means that soil acidification improves the bioavailability of Cd in cocoa plants in P1 and P2 (Haider *et al*., 2021; Lux, Martinka, Vaculík, and White, 2011; Sarwar *et al*., 2010). However, organic amendments used in the organic production system decrease the availability of Cd in cocoa plants, even in soils with a high content of this toxic element (Sohail *et al*., 2019), as occurs in P2. The transport and accumulation of Cd in the soil cause this chemical element to enter the roots of plants, affect the root system, and contaminate the harvest (Hasan, Ali, Hayat, and Ahmad, 2007; Kubier and Pichler, 2019). To reduce the presence of this toxic metal, we must emphasize the importance of avoiding chemical products in agricultural production soils. This increases nutrients in the soil, benefiting crops and the environment (Díaz-José, Porras, and Aguilar, 2013; Triano-Sánchez, Palma, Salgado, Lagunes, and Córdova, 2016). Cadmium does not perform any metabolic function in cocoa cultivation, but in very low concentrations, it can cause toxic complications for the health of humans, plants, and animals (Ordoñez-Araque, Lopez, Casa, Landines, and Fuentes, 2020)

Nickel is a metal that is abundant on the earth's surface; therefore, it tends to be naturally present in cocoa in low concentrations (Ordoñez-Araque *et al*., 2020). However, the official Mexican standard NOM-021-SEMARNAT-2000 (SEMARNAT, 2002) considers a metal as a contaminant starting at 100 mg kg^{-1}, so only point M1AGH1 of P1 exceeded the permitted limits. Ecuadorian regulations establish the maximum permissible limit for Ni at 50 mg kg^{-1}; in this regard, 8 (66.66%) of the 12 sampling points at P1 exceeded this international standard. These concentrations of nickel could cause allergies, abdominal pain, increased red blood cells, bronchitis, liver-related pathologies, and, in the most serious cases, lung cancer. In P2 and P3, no presence of this contaminating metal was found.

Another element that exceeded the permissible limit was vanadium, which can be attributed to residues of humic and fulvic acids. Thus, when organic matter degrades, this metal is incorporated into the soil (Simbaña-Cazar, 2016[3]). Vanadium is considered toxic to plants in concentrations greater than or equal to 10 mg kg^{-1} (Alvarado-Gámez, 2016[5]). The Mexican Official Standard NOM-147-SEMARNAT/SSA1-2004 (2007) sets 78 mg kg^{-1} of vanadium as the permissible limit in agricultural, residential, and commercial soil. Therefore, point M5AGH2 exceeded the limit allowed by current regulations. Consequently, these concentrations at the P1 sampling points indicate that cocoa plants could be overexposed to this element. Hence, there is a risk of phytotoxicity in these crops. In this context, it is recommended to use organic products for soil restoration.

CONCLUSIONS

This study demonstrated that agronomic management and geomorphological conditions significantly influence the distribution and accumulation of heavy metals in soils used for agricultural purposes. The results show significant differences in soil acidity between the organic and inorganic production systems. In polygon P1 (an inorganic production system), intensive phosphate fertilizer application decreased the pH. This reduction in pH limited nutrient availability but favored retention of heavy metals such as Cd, Ni, and V. These conditions increase the risk of heavy metal contamination in agricultural soils, compromising both soil quality and long-term productivity. In contrast, polygon P2, associated with an organic system, exhibited a more stable pH. Organic fertilizers in P2 promoted acidity neutralization and maintained nutrient availability. However, lower organic matter content in P2 may be tied to organic management practices typical of Cunduacán, Tabasco.

Both polygons, P1 and P2, share topographic and geomorphological traits. These features make them accumulation zones for surface runoff from the urban solid waste disposal area (P3). As a result, the pollutant load increases, particularly with heavy metals.

From a soil and environmental perspective, these factors highlight the need to systematically evaluate the agricultural production system (organic or inorganic) when assessing the risk of heavy metal contamination. Specifically, the organic system in polygon P2 presents more favorable conditions for sustainable agriculture, particularly for crops like cacao. These conditions include lower particulate matter (PM) accumulation, balanced soil pH, and favorable physical and chemical soil attributes. Therefore, adopting organic practices in regions like polygon P2 can enhance both the sustainability and safety of agricultural production.

[5] Alvarado Gámez, A. L. (2016). Determinación electroquímica de vanadio y tungsteno en aguas con electrodos serigrafiados modificados con nanomateriales y enzimas. [Tesis Doctoral]. Universidad de Burgos. Departamento de Química. Área de Química Analítica.

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The authors declare that they have no conflict of interest.

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REFERENCES

Adams, R. H., ZaVala-Cruz, J., & Morales-García, F. (2008). Concentración residual de hidrocarburos en suelo del trópico. II: afectación a la fertilidad y su recuperación. *Interciencia, 33*(7), 483-489.

Alor-Chávez, M. de J., Morales-Bautista, C. M., Álvarez-Jiménez, M. F., & Méndez-Olán, C. (2022). Cambios en las propiedades de un suelo contaminado con petróleo crudo pesado después de un periodo de intemperización. En *Memorias del Congreso Mesoamericano de Investigación* (pp. 40-45). Tuxtla Gutiérrez, Chiapas, México: Universidad Autónoma de Chiapas.

Amezquita, E. (1999). Propiedades físicas de los suelos de los Llanos Orientales y sus requerimientos de labranza. *Palmas, 20*(1), 73-86.

Arévalo-Gardini, E., Obando-Cerpa, M. E., Zúñiga-Cernades, L. B., Arévalo-Hernández, C. O., Baligar, V., & He, Z. (2016). Metales pesados en suelos de plantaciones de cacao (*Theobroma cacao* L.) en tres regiones del Perú. *Ecología Aplicada, 15*(2), 81–89. https://doi.org/10.21704/rea.v15i2.747

Barzallo, D., Vera, H., Gavin, C., & Lazo, R. (2021). Determinación simultánea de metales traza en muestras de suelo mediante espectrometría de emisión atómica con plasma de acoplamiento inductivo (ICP-OES). *Ecuadorian Science Journal, 5*(4), 130–139. https://doi.org/10.46480/esj.5.4.176

Bravo-Realpe, I. D. S., Arboleda-Pardo, C. A., & Martín-Peinado, F. J. (2014). Efecto de la calidad de la materia orgánica asociada con el uso y manejo de suelos en la retención de cadmio, en sistemas altoandinos de Colombia. *Acta agronómica, 63*(2), 164-174.

Brechelt, A. (2004). *El manejo ecológico de plagas y enfermedades. Red de Acción en Plaguicidas y sus Alternativas para América Latina* (RAP-AL), Santiago de Chile, Chile: Fundación Agricultura y Medio Ambiente (FAMA).

Cepeda, M., & Jhon, D. (2022). *Los micronutrientes y su importancia en el cultivo de cacao* (*Theobroma cacao* L.). Babahoyo, Ecuador: Universidad Técnica de Babahoyo.

Córdova-Avalos, V., Mendoza-Palacios, J. D. D., Vargas-Villamil, L., Izquierdo-Reyes, F., & Ortiz-García, C. F. (2008). Participación de las asociaciones campesinas en el acopio y comercialización de cacao (*Theobroma cacao* L.) en Tabasco, México. *Universidad y Ciencia, 24*(2), 147-158.

Derakhshan-Babaei, F., Nosrati, K., Mirghaed, F. A., & Egli, M. (2021). The interrelation between landform, land-use, erosion and soil quality in the Kan catchment of the Tehran province, central Iran. *Catena, 204*, 105412.

Díaz-José, Ó., Porras-Umaña, V. H., & Aguilar-Ávila, J. (2013). Colección Trópico Húmedo. El cacao (*Theobroma cacao* L.): avances y retos en la gestión de la innovación. Texcoco, Estado de México, México: Universidad Autónoma Chapingo

Francisco-Santiago, S. P., Palma-López, D. J., Sánchez-Hernández, R., Obrador-Olán, J. J., & García-Alamilla, P. (2023). Fertilidad edáfica y nutrición en el cultivo de cacao (*Theobroma cacao* L.) en tres suelos de Tabasco, México. *Terra Latinoamericana, 41*, 1-18. https://doi.org/https://doi.org/10.28940/terra.v41i0.1116

Gillings, N., Todde, S., Behe, M., Decristoforo, C., Elsinga, P., Ferrari, V., ... & Patt, M. (2020). EANM guideline on the validation of analytical methods for radiopharmaceuticals. *EJNMMI Radiopharmacy and Chemistry, 5*(1), 7.

Guzmán-Osorio, F. J., Adams, R. H., Domínguez-Rodríguez, V. I., Lobato-García, C. E., Guerrero-Peña, A., Barajas-Hernández, J. R., & Baltierra-Trejo, E. (2020). Alternative method for determining API degrees of petroleum in contaminated soil by FtIR. *Egyptian Journal of Petroleum, 29*(1), 39-44. https://doi.org/10.1016/j.ejpe.2019.10.002

Haider, F. U., Liqun, C., Coulter, J. A., Cheema, S. A., Wu, J., Zhang, R., ... & Farooq, M. (2021). Cadmium toxicity in plants: Impacts and remediation strategies. *Ecotoxicology and Environmental Safety, 211*, 111887. https://doi.org/10.1016/j.ecoenv.2020.111887

Hasan, S. A., Ali, B., Hayat, S., & Ahmad, A. (2007). Cadmium-induced changes in the growth and carbonic anhydrase activity of chickpea. *Turkish Journal of Biology, 31*(3), 137-140.

Hernández-Caricio, C., Ramírez, V., Martínez, J., Quintero-Hernández, V., Baez, A., Munive, J. A., & Rosas-Murrieta, N. (2022). Los metales pesados en la historia de la humanidad, los efectos de la contaminación por metales pesados y los procesos biotecnológicos para su eliminación: el caso de Bacillus como bioherramienta para la recuperación de suelos. *AyTBUAP, 7*(27), 1-68. http://doi.org/10.5281/zenodo.7091407

INEGI (Instituto Nacional de Estadística y Geografía). (2025). Continuo de Elevaciones Mexicano (CEM). El Continuo de Elevaciones Mexicano 3.0. Instituto Nacional de Estadística y Geografía. Consulted on September 15, 2025, retrieve from https://www.inegi.org.mx/app/geo2/elevacionesmex/

INEGI (Instituto Nacional de Estadística y Geografía). (2010). Compendio de información geográfica municipal 2010 Cunduacán Tabasco. Consulted on September 15, 2025, retrieve from www.inafed.gob.mx/wb2/ELOCAL/ELOC_Enciclopedia

INEGI (Instituto Nacional de Estadística y Geografía). (2013). Uso de suelo y vegetación. Cartografía y diccionario de datos de uso del suelo y vegetación: Escala 1:250, 000; Versión 3. Consulted on September 15, 2025, retrieve from. https://www.inegi.org.mx

INIFAP (Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias) & CONABIO (Comisión Nacional para el Conocimiento y Uso de la Biodiversidad). (1995). *Edafología*. Catálogo de Metadatos Geográficos. D.F., México: INIFAP- CONABIO.

Kubier, A., & Pichler, T. (2019). Cadmium in groundwater— A synopsis based on a large hydrogeochemical data set. *Science of the Total Environment, 689*, 831-842.

Lache-García, A., Meléndez-Correa, L. V, Orrego, J. A., Mejía-Ospino, E., Pachón, Z., & Cabanzo, R. (2011). Predicción del análisis sara de crudos colombianos por métodos quimiométricos utilizando espectroscopia infrarroja-ATR. *Revista Colombiana de Física, 43*(3), 643.

Laribi, A., Shand, C., Wendler, R., Mouhouche, B., Hillier, S., & Colinet, G. (2023). Ambient background and quality reference values for trace metals in soils from Algeria. *Soil and Water Research, 18*(1), 33-42. https://doi.org/10.17221/143/2021-SWR

Le Bissonnais, Y. (2016). Aggregate stability and assessment of soil crustability and erodibility: I. Theory and methodology. *European Journal of Soil Science, 67*(1), 11-21. https://doi.org/10.1111/ejss.4_12311

Londoño-Franco, L. F., Londoño-Muñoz, P. T., & Muñoz-García, F. G. (2016). Los riesgos de los metales pesados en la salud humana y animal. *Biotecnología en el sector Agropecuario y Agroindustrial, 14*(2), 145-153. https://doi.org/10.18684/bsaa(14)145-153

Lux, A., Martinka, M., Vaculík, M., & White, P. J. (2011). Root responses to cadmium in the rhizosphere: a review. *Journal of Experimental Botany, 62*(1), 21-37.

Marín-García, D. C., Adams, R. H., & Hernández-Barajas, R. (2016). Effect of crude petroleum on water repellency in a clayey alluvial soil. *International Journal Of Environmental Science And Technology, 13*(1), 55-64. https://doi.org/10.1007/s13762-015-0838-6

Martínez-Chávez, C. G., Morales-Bautista, C. M., & Alor-Chávez, M. D. J. (2017). Extracción de hidrocarburo pesado en suelo arenoso. *Avances en Ciencias e Ingeniería, 8*(1), 9-16.

Meitasari, R., Hanudin, E., & Purwanto, B. H. (2024). Comparison of two soil quality assessment models under different land uses and topographical units on the southwest slope of Mount Merapi. *Soil & Water Research, 19*(2), 77-89. https://doi.org/10.17221/76/2023-SWR

Melendez, L. V., Lache, A., Orrego-Ruiz, J. A., Pachón, Z., & Mejía-Ospino, E. (2012). Prediction of the SARA analysis of Colombian crude oils using ATR–FtIR spectroscopy and chemometric methods. *Journal of Petroleum Science and Engineering, 90*, 56-60. https://doi.org/10.1016/j.petrol.2012.04.016

Morales-Bautista, C. M., Adams, R. H., Hernández-Barajas, J. R., Lobato-García, C. E., & Torres-Torres, J. G. (2016). Characterization of fresh and weathered petroleum for potential impacts to soil fertility. *International Journal Of Environmental Science And Technology, 13*(11), 2689-2696. https://doi.org/10.1007/s13762-016-1097-x

Morales-Ramos, P. C., Estrada-Andrade, L. F., Alor-Chávez, M. D. J., Méndez-Olán, C., & Morales-Bautista, C. M. (2022). Condiciones de fertilidad de un suelo en Comalcalco, Tabasco, México. *Journal of Basic Sciences, 8*(23), 85-95.

National Institute of Standards and Technology. (2018). *Standard Reference Material® 2710a: Montana I Soil*. Gaithersburg, MD, USA: National Institute of Standards and Technology.

NOM-147-SEMARNAT/SSA-1-2004 (Norma Oficial Mexicana). (2007). Que establece criterios para determinar las concentraciones de remediación de suelos contaminados por arsénico, bario, berilio, cadmio, cromo hexavalente, mercurio, níquel, plata, plomo, selenio, talio y/o vanadio. publicada el 2 de marzo de 2007. *Diario Oficial de la Federación*. México, D. F.: SEGOB.

Ordoñez-Araque, R., Lopez-Cortez, A., Casa-Lopez, F., Landines-Vera, E., & Fuentes, E. (2020). Análisis de cadmio, plomo, níquel y arsénico en plantas de cacao y derivados: Industria Alimentaria. CienciAmérica: *Revista de Divulgación Científica de la Universidad Tecnológica Indoamérica, 9*(4), 107-114. https://doi.org/10.33210/ca.v9i4.351

Orozco, M., & Thienhaus, S. (1997). Efecto de la gallinaza en plantaciones de cacao (*Theobroma cacao* l.) en desarrollo. *Agronomía Mesoamericana, 8*(1), 81-92.

Palma-López, D. J., Cisneros, D. J., Moreno, C. E., & Rincón-Ramírez, J. A. (2007*). Suelos de Tabasco: su uso y manejo sustentable*. Villahermosa, Tabasco, México: Colegio de Postgraduados.

Pomposiello, C., Dapeña, C., Boujon, P., & Favetto, A. (2009). Tomografías eléctricas en el basurero municipal Ciudadde Gualeguychú, provincia de Entre Ríos: evidencias de contaminación. *Revista de la Asociación Geológica Argentina, 64*(4), 603-614.

Priego-Castillo, G. A., Galmiche-Tejeda, A., Castelán-Estrada, M., Ruiz-Rosado, O., & Ortiz-Ceballos, A. (2009). Evaluación de la sustentabilidad de dos sistemas de producción de cacao: estudios de caso de unidades de producción rural en Comalcalco, Tabasco. *Universidad y Ciencia, 25*(1), 39-57.

QGIS.org (2021). *QGIS Geographic Information System. User´s Guide. Version 3.26.3*. Grüt, Switzerland: QGIS Association.

Ramos-González, B. C., Lunagómez-Rocha, M. A., & Pérez-Vidal, H. (2024). Contaminación y deficiencia de la calidad por uso de suelos agrícolas: una revisión cualitativa. *Journal of Basic Sciences, 10*(27), 58-64.

Rivas-Domínguez, M. R., & Escuintla-Morán, J. J. (2021). Procedimientos en QGIS: extracción de curvas de nivel, mapa de pendientes, modelo 3D, índice de vegetación mejorado y clasificación semiautomática (2ª ed.). San Salvador, El Salvador: Universidad Doctor Andrés Bello.

Sarwar, N., Saifullah, Malhi, S. S., Zia, M. H., Naeem, A., Bibi, S., & Farid, G. (2010). Role of mineral nutrition in minimizing cadmium accumulation by plants. *Journal of the Science of Food and Agriculture, 90*(6), 925-937.

Sbarbati-Nudelman, N. (2011). Uso sustentable de agroquímicos: Debates a nivel nacional e internacional. *Anales de la Academia Nacional de Agronomía y Veterinaria, 65*, 471-482.

SEMARNAT (Secretaría de Medio Ambiente y Recursos Naturales). (2002). Norma Oficial Mexicana NOM-021 SEMARNAT-2000 antes NOM-021-RECNAT-2000. Que establece las especificaciones de fertilidad, salinidad y clasificación de suelos. Estudio, muestreo y análisis. *Diario Oficial de la Federación*. D. F., México: SEGOB.

SEMARNAT (Secretaría de Medio Ambiente y Recursos Naturales). (2012). Norma oficial mexicana NOM-138-SEMARNAT/SSA1-2012. Límites máximos permisibles de hidrocarburos en suelos y lineamientos para el muestreo en la caracterización y especificaciones para la remediación. *Diario Oficial de la Federación*. D. F., México: SEGOB.

SEMARNAT (Secretaría de Medio Ambiente y Recursos Naturales). (2016). Norma mexicana NMX-AA-132-SCFI-2016. Muestreo de suelos para la identificación y la cuantificación de metales y metaloides, y manejo de la muestra. *Diario Oficial de la Federación*. D. F., México: SEGOB.

Sohail, M. I., Arif, M., Rauf, A., Rizwan, M., Ali, S., Saqib, M., & Zia-ur-Rehman, M. (2019). Organic manures for cadmium tolerance and remediation. In M. Hasanuzzaman & K. Nahar (Eds.). *Cadmium tolerance in plants: Agronomic, molecular, signaling, and omic approaches* (pp. 19-67). London, United Kingdom: Academic Press.

Solís-Pérez, Y. Y., Gómez-Mellado, A. Y., Morales-Bautista, C. M., Méndez-Olán, C., Lobato-García, C. E., & Peña-Morán, O. A. (2019). Factibilidad ecológica de dos técnicas de remediación según las propiedades de un suelo aluvial contaminado con aguas congénitas. *Journal of Basic Sciences, 5*(15), 1-19.

Statgraphics Technologies (2024). *Statgraphics Centurion Version 19 User´s Manual*. The Plains, VA, USA: Statgraphics Inc.

Tadeo-Sánchez, J. M., & Tolentino-Martínez, J. M. (2020). El cacao Grijalva de Tabasco: dinámicas socio territoriales en torno a su producción. Estudios sociales. *Revista de Alimentación Contemporánea y Desarrollo Regional, 30*(56), 15.

Triano-Sánchez, A., Palma-López, D. J., Salgado-García, S., Lagunes-Espinoza, L. C., & Córdova-Ávalos, V. (2016). Nutrición orgánica en plantaciones de cacao (*Theobroma cacao* L.) en Tabasco, México. *Agro Productividad, 9*(12), 39-44.

Tun-Canto, G. E., Álvarez-Legorreta, T., Zapata-Buenfil, G., & Sosa-Cordero, E. (2017). Metales pesados en suelos y sedimentos de la zona cañera del sur de Quintana Roo, México. *Revista Mexicana de Ciencias Geológicas, 34*(3), 157-169. https://doi.org/10.22201/cgeo.20072902e.2017.3.433

Valcarce-Ortega, R. M., & Jiménez-Reyes, R. (2016). Vulnerabilidad y riesgo de contaminación de la cuenca Dolores-Sagua la Chica, Cuba. *Ingeniería Hidráulica y Ambiental, 37*(1), 03-14.