Review article

https://revistas.unal.edu.co/index.php/refame

Revista Facultad Nacional de Agronomía

Cadmium in soil and cacao beans of Peruvian and South American origin

Cadmio en suelos y granos de cacao de origen peruano y sudamericano

https://doi.org/10.15446/rfnam.v74n2.91107

Nelino Florida Rofner[1]*

ABSTRACT

Keywords:
Bioaccumulation
Cadmium levels
European Union regulations
Geo-distribution
Treatment technologies

Cadmium tends to bioaccumulate in different parts of cacao plant and its consumption can lead to serious health complications; due to this, the European Union (EU) established limits for tolerable concentrations of cadmium in cacao products as a preventive measure, which took effect as of January 2019. In South America and Peru, a sustained growth in cacao production has been recorded over the last 10 years, but scientific studies reveal that in some areas the cadmium levels of the soil and cacao beans exceed those established by the EU, thus, jeopardizing marketing and export possibilities to the EU. With this in mind, the purpose of this review was to compile information on the cadmium that is available in the soil, its accumulation in cacao beans, and the advances in treatment technologies; as well as to analyze the potential effects this has on cacao exports of South American origin, using Peru as a case analysis.

RESUMEN

Palabras clave:
Bioacumulación
Niveles de cadmio
Reglamento de la Union Europea
Geo distribución
Tecnologías de tratamiento

El cadmio tiende a bioacumularse en distintas partes de la planta de cacao y su consumo puede conducir a graves complicaciones de salud; por ello, como medida preventiva, la Unión Europea (UE) estableció concentraciones tolerables de cadmio a productos derivados del cacao, el cual entró en vigencia desde enero del 2019. En Sudamérica y el Perú la producción de cacao registra un crecimiento sostenido en los últimos 10 años y estudios científicos revelan que algunas zonas presentan niveles de cadmio en suelos y granos que superan lo establecido por la UE, poniendo en riesgo sus posibilidades de comercialización y exportación hacia la UE. En ese sentido, el propósito de esta revisión fue compilar información sobre el cadmio disponible en suelos y su acumulación en granos de cacao, los avances en tecnologías de tratamiento y analizar los potenciales efectos en las exportaciones del cacao de origen sudamericano, tomando Perú como análisis de caso.

---

[1] Universidad Nacional Agraria de la Selva, Huánuco, Peru. nelinof@hotmail.com
*Corresponding author

Received: January 26, 2021; Accepted: February 24, 2021
Rev. Fac. Nac. Agron. Medellín 74(2): 9499-9515. 2021

ISSN 0304-2847 / e-ISSN 2248-7026

INTRODUCTION

Cadmium is a heavy metal with no known biological function, the physicochemical properties of which are between Zn and Hg (Antoine *et al*., 2017). It was discovered in Germany in 1817 by Friedrich Stromeyer as an impurity in zinc carbonate ($ZnCO_3$) (Pérez and Azcona 2012); its various applications in the industry started 50 years ago (Pérez and Azcona, 2012; Gunnar, 2013). However, it is currently causing a number of complications in vital organs such as lungs, kidneys, liver and bones either by inalation or ingestion, becoming in a potential threat to human health (Reyes *et al*., 2016; Ali *et al*., 2020). Despite being in low concentrations when compared to other metals, the impact on health, due to its high mobility and bioaccumulative power is alarming (Reyes *et al*., 2016; Engbersen *et al*., 2019). Even at trace levels cadmium can cause serious health complications (Maddela *et al*. 2020).

There was an incident in Japan in the 1950s where the people living on the banks of the Jintsu River were affected by the consumption of rice from crops that were contaminated with cadmium from mining (Reyes *et al*., 2016; Hernández-Baranda *et al*., 2019). From there, a series of studies was initiated which lead to cadmium, as well as lead, mercury, and chromium, to be considered as the elements most dangerous to human health (Casteblanco, 2018; Engbersen *et al*., 2019); particularly, because of their cumulative nature which can cause a series of damages to one's health (Prieto *et al*., 2009; Reyes *et al*., 2016; Maddela *et al*., 2020).

Soil generally has a low cadmium content (Kabata-Pendias, 2010), but regardless of the level and origin, the dynamics of the metal depend on its chemical form and the characteristics of the soil (Bravo *et al*., 2014; Díaz *et al*., 2018; Scaccabarozzi *et al*., 2020). This limits or contributes to the mobilization and uptake of cadmium from cacao plants (Gramlich *et al*. 2017; Zug *et al*. 2019); in some plant structures it is accumulative (Hernández-Baranda *et al*., 2017; Tantalean and Huauya, 2017; Casteblanco, 2018), and reaches concentrations that are higher than in the soil itself (Chávez *et al*., 2015; Díaz *et al*., 2018; Oliva *et al*., 2020). Due to this, the EU and some other countries have implemented standards to classify agricultural soil. Also, the EU has established tolerable limits for cacao beans and its by-products that are imported.

Taking into account the studies that warn of high levels of cadmium in cacao beans and processed cacao products of South American origin (Chávez *et al*., 2015; Lanza *et al*., 2016; Arévalo-Gardini *et al*., 2017; Gramlich *et al*., 2017; Díaz *et al*., 2018; Argüello *et al*., 2019), the recent EU provision, Regulation No. 488/2014, which entered into effect in 2019, sets tolerable values to be between 0.1 and 0.80 µg g^{-1} for products derived from cacao (EU, 2014; Jiménez, 2015). This will put the quality and export possibilities of cacao from Latin America at risk, and in particular those coming from Peru, whose main market is the EU, which makes up 76% of their exports (MINAGRI, 2019).

Therefore, the objective of this document was to evaluate, through the interpolation of data, the presence of cadmium available in the soil, its bioaccumulation in cocoa beans, and the technological advances for controlling it; as well as to analyze the potential effects on Latin America exports volumes, using Peru as a case analysis.

Cadmium in the soil

The U.S. Environmental Protection Agency (USEPA) established 0.43 µg g^{-1} to be a critical level of total cadmium in agricultural soil (USEPA, 2002). On the other hand, the EU through the Kelley Directive, indicated that the typical values in uncontaminated soil with cadmium are between 0 and 1 µg g^{-1} (Acevedo *et al*., 2005) and the recent supreme decree issued by the Peruvian Ministry of Environment, DS N° 011-2017 (MINAM, 2017) approved environmental quality standards (EQS) for soil, setting 1.4 µg g^{-1} as the maximum limit for the cadmium values of agricultural soil.

The natural average level of cadmium in agricultural soil fluctuates between 0.01 to 7 µg g^{-1} (Bohn *et al*., 1993); although more specific studies have found it to be between 0.07 and 1.1 µg g^{-1}, with a natural base level of 0.5 µg g^{-1} (Kabata-Pendias, 2010). In addition, rock composition can elevate the cadmium levels in soil (Argüello *et al*., 2019); generally following the natural order of their evolution, with the lowest values being found in the most evolved soils, which have an acidic pH, low cation exchange capacity values and thick textures (Pérez and Azcona, 2012). Also, alluvial soil has been shown to have higher levels of available cadmium when compared with residual cadmium (Tantalean and Huauya, 2017; Scaccabarozzi *et al*., 2020); and the contribution of natural processes to the cadmium contamination of the soil is three to ten times less than in anthropogenic sources (He *et al*., 2015).

Naturally, soils have varing levels of cadmium, and the availability is subject to their physicochemical and biological properties; studies reveal relationships between cadmium and pH (Arévalo-Gardini *et al*., 2016; Florida *et al*., 2018). The higher the pH level of the soil, the greater the cadmium retention and the lower the cadmium contamination in cacao beans, according to the Kelley Directive (Acevedo *et al*., 2005). In addition, the cadmium concentration and mobility are influenced by the percentage of clay, the presence and type of organic matter (Bravo *et al*., 2014), the available cadmium (Sánchez *et al*., 2011; Gramlich *et al*., 2018), the cation exchange capacity, and the amount of mangnesium and zinc (Degryse *et al*., 2009; He *et al*., 2015; Arévalo-Hernández *et al*., 2017; Argüello *et al*., 2019; Zug *et al*., 2019). These authors suggest that the aforementioned indicators have a direct effect on the plant's absorption.

Geo-distribution of available cadmium soil

There are reports of high levels of cadmium in the soil of Latin America. Table 1 shows the average of the sampling work that is carried out at regional levels and even at national levels in some countries. The results reveal that on average, South America has 0.42 µg g^{-1}, being categorized as having soil that is not contaminated by cadmium, according to the USEPA (0.43 µg g^{-1}), which has the most stringent regulations established so far for agricultural soil.

Table 1. Available cadmium in the soil of some cacao-producing countries of South America.

References	Country	Samples	Cd Level (µg g^{-1})
Araujo-Abad *et al.* (2020)	Ecuador	--	0.304
Argüello *et al*. (2019)	Ecuador	560	0.44
Barraza *et al*. (2019)	Ecuador	145	0.20
Barraza *et al*. (2017)	Ecuador	113	0.44
Chávez *et al*. (2015)	Ecuador	76	0.85
Mite *et al*. (2010)	Ecuador	568	0.49
Chambi (2010)	Bolivia	18	0.39
Gramlich *et al*. (2017)	Bolivia	--	0.20
Aguirre-Forero *et al.* (2021)	Colombia	--	0.02
Silva (2019)	Colombia	--	0.096
Charrupi and Martínez (2017)	Colombia	--	1.15
Marrugo-Negrete *et al.* (2017)	Colombia	--	0.04
Almeida (2016)	Brasil	50	0.705
*	Peru	160	0.33
Total Samples		1727	
Average			0.40

* Calculated by the author (Table 2). -- Not specified.

Peru is considered megadiverse country due to its bioclimates and the fact that is possesses coastal, mountain and tropical soil (Pulgar, 2014). In addition, it is the center of the origin of the greatest diversity of cacao in the world (Motamayor *et al*., 2008); thus, it is a good representation of a caco producing country in South America for the case analysis. Table 2 shows Peruvian scientific reports from the different districts, provinces and regions of the country.

Table 2. Available cadmium in the soil of different cacao producing areas within Peru.

Zone	Region	Province	References	Cd Level (μg g^{-1})	UTM Coordinates
North	Tumbes	Tumbes	4	0.50	562379E-9606058N
			4	0.26	556998E-9604790N
	Piura	Piura	4	0.48	538295E-9427857N
		Huancabamba	4	0.14	672373E-9422057N
		Morropón	4	0.53	592923E-9436422N
		San Ignacio	4	0.01	720769E-9431431N
	Amazonas	Bagua	4	0.11	773547E-9376440N
		Bagua	7	1.46	--
		Condorcanqui	4	0.01	783829E-9364136N
	San Martin	San Martin	1	0.27	354517E-9278816N
		Bellavista	4	0.20	324522E-9219718N
			1	0.32	326533E-9215295N
		El Dorado	1	0.27	313538E-9268407N
		Lamas	1	0.22	332615E-9290811N
		Huallaga	4	0.29	304650E-9231329N
		Mariscal Cáceres	1	0.28	312023E-9205915N
			4	0.21	300970E-9192099N
		Moyobamba	1	0.16	286619E-9329588N
		Picota	1	0.33	352976E-9235603N
		Rioja	1	0.22	261893E-9329417N
		Tocache	1	0.23	332630E-9092486N
		Bambamarca-Tocache	5	0.24	647657E-9097795N
		Tananta-Tocache	5	0.16	326325E-9102289N
		Nvo. Progreso-Tocache	5	0.19	354326E-9065466N
Center	Junín	Satipo	4	0.10	539354E-8755739N
	Huánuco	Rupa Rupa	6	0.53	394588E-8978855N
			3	0.63	391952E-8966760N
			5	0.45	395116E-8982497N
		Supte San Jorge	5	0.54	393951E-8971537N
		Pueblo Nuevo	3	0.41	383134E-8994796N
		Puerto Ángel	5	0.18	382690E-8996783N
		Castillo Grande	3	0.29	386765E-8978110N
			3	0.82	388995E-8976876N
		J. Crespo y Castillo	3	0.41	383134E-8994796N
			3	0.16	389956E-8988252N
		San José Pucate	5	0.26	374175E-9014524N
		Marona	3	0.26	396097E-8979819N
		Dámaso Beraun	3	0.40	395359E-8959585N
		Aalto Sanjuan	5	0.30	411020E-8961339N
		Bella-Monzón	5	0.29	385888E-8969250N
		Paraíso	5	0.32	347572E-9059513N
		Venenillo	5	0.22	379875E-8993949N
	Ucayali	Callería	5	0.37	546513E-9071823N
		Irazola	5	0.86	444682E-9001025N
		A. Bon Humbolt	5	0.29	498145E-9027812N
		Padre Abad	2	0.23	445791E-9015463N
		Nuevo Horizonte	5	0.28	470854E-9022059N
		Nuevo Tahuantinsuyo	5	0.26	459718E-9013764N
South	Cusco	La Convención	4	0.01	747811E-8577789N
Average				0.33±0.18	

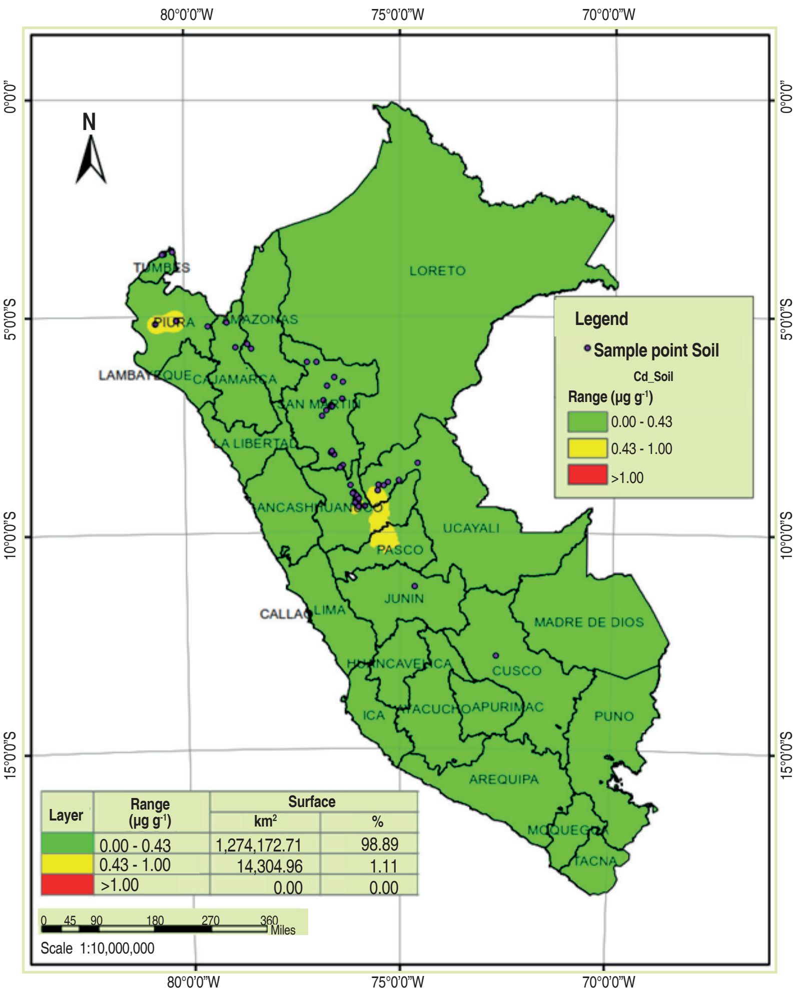
-- Not specified. Data of four regions (Madre de Dios, Ucayali, San Martín and Amazonas) were not considered in the geo-distribution.
Source: 1 GRSM (2019); 2 Florida *et al.* (2019); 3 Florida *et al.* (2018); 4 Arévalo-Hernández *et al.* (2017); 5 COPAIN (2014); 6 Huamani *et al.* (2012); 7 Oliva *et al.* (2020).

Using these data of averages, a spatial analysis was performed through interpolation with the inverse distance weighting (IDW) extension in ArcGIS, version ArcMap10.5, to determine the geo-distribution of the available cadmium in the terirritory of Peru (Figure 2).

Figure 1, through interpolation, shows the geo-distribution of the levels of available cadmium in soil and that it is determined that 100% of the territory is below the tolerable limit for agricultural soil, as set by Peruvian regulations and only 1.11% approach, but do not exceed EU limits (Kelley Directive); therefore, according to the interpolation, Peru has soil which is intended for cacao production and is not contaminated by cadmium.

Cadmium in cacao beans

The EU with Regulation No. 488/2014, established tolerable limits on cacao and chocolate derivatives: for milk chocolate with cacao solids less than 30%, 0.1 µg g^{-1}; for chocolate with cacao solids of less than 50% and milk chocolates with cacao solids greater than or equal to 30%, 0.3 µg g^{-1}; for chocolates with cacao solids greater than or equal to 50%, 0.8 µg g^{-1}; and for cocoa powder, 0.6 µg g^{-1} (EU, 2014).



Layer	Range (µg g^{-1})	Surface	
		km^2	%
🟩	0.00 - 0.43	1,274,172.71	98.89
🟨	0.43 - 1.00	14,304.96	1.11
🟥	>1.00	0.00	0.00

Figure 1. Geo-distribution of available cadmium in the soil of the Peruvian territory

According to some countries, such as the United States, Food and Drug Administration (FDA) gives specifications for cadmium levels in bottled water, up to 0.005 mg L^{-1} according to the Code of Federal Regulations, 2013, Sec. 165.110. Title 21 of the Federal Code for Food and Medicines, chapter 163, details the different specifications for cacao products; there are no established levels for pollutants in this document, specifically for cadmium. In the case of Peru, there is no specific standard for cadmium levels in cacao, which is similar to other countries in the region, such as Chile (Food Health Regulations, title IV referring to pollutants), Bolivia (National Directorate of Standardization), Ecuador (NTE INEN 621: 2010) and Venezuela (La COVENIN 50: 1995 standard). It is important to note that the United States, Russia, Canada and Japan do not have limits for tolerable amounts of cadmium in cacao derivatives (Jiménez, 2015); thus, these could be alternative destinations for exports that exceed EU limits.

In this context, the soil has a low cadmium content, referring to both Peru (Figure 1), and the reports available for South American (Table 1), but research warns that cacao beans can capture cadmium and reach concentrations that are higher than the soil itself (Chávez *et al*., 2015; Díaz *et al*., 2018; Engbersen *et al*., 2019; Oliva *et al*., 2020). Moreover, most agree that bioaccumulation is higher in roots, leaves, pods and beans, with or without shell (Ramtahal *et al*., 2019; Barraza *et al*., 2017; Gramlich *et al*., 2017; Oliva *et al*., 2020), which is an aspect that can be analyzed.

Geo-distribution of cadmium in beans

Table 3 shows the average of the work that was done at regional levels in South American countries. The results reveal that, on average, the cadmium levels of cacao exceed those established by EU Regulation No. 488/2014 (maximum 0.8 μg g^{-1} cadmium). The results also show that beans have 2.1 times more cadmium in relation to the cadmium available in soil. This shows the bioaccumulation capacity of cacao and the potential impact on the possibilities of marketing this product to the EU, the main export market for cacao produced in Latin America.

Table 3. Total cadmium in cacao beans from some cacao-producing countries of South America.

References	Country	Samples	Cadmium levels (μg g^{-1})
Argüello *et al*. (2019)	Ecuador	560	0.9
Barraza *et al*. (2019)	Ecuador	145	0.4
Barraza *et al*. (2017)	Ecuador	113	1.12
Chávez *et al*. (2015)	Ecuador	76	0.94
Mite *et al*. (2010)	Ecuador	803	0.84
Romero-Estévez et al. (2019)	Ecuador	--	0.75
Lanza *et al*. (2016)	Venezuela	NE	1.62
Oliveira *et al*. (2019)	Brasil	61	0.129
Aguirre-Forero *et al*. (2021)	Colombia	NE	0.66
Niño (2015)	Colombia	NE	1.62
Gramlich et al. (2017)	Bolivia	NE	0.21
*	Perú	160	0.91
Total samples		1973	
Average			0.84

* Calculated by the author.

-- Not specified

Table 4 shows the results of research throughout Peru and among different cacao genotypes; data was statistically analyzed with the Stata program (R) 15.1, to create box diagrams (Figures 2A), using the Minitab * 18.1 program, in order to determine interquartile ranges (Figure 2B).

Figure 2A, shows that the average concentration of cadmium in Peruvian soil used for cacao production is 0.29±0.18 μg g^{-1} and in the beans it is 0.91±0.48 μg g^{-1}, this latter is 3.13 times higher than the value calculated for South America (2.1 times more cadmium in relation to the available cadmium in the soil). Also, when looking at the interquartile range (Figure 2B), 50% of the cadmium in the soil is between 0.02 and 0.23, while in the beans it is between 0.18 and 1.52 μg g^{-1}.

Table 4. Total cadmium in cacao beans from different areas of production in Peru.

Zone	Region	Province	References	Cd levels (μg g^{-1})	UTM Coordinates
North	Tumbes	Tumbes	4	1.78	559145E- 9608347N
	Piura	Piura	4	1.55	558018E- 9608353N
		Jaén	4	0.75	743205E- 9379500N
	Amazonas	Bagua	4	0.80	746080E- 9370593N
		Imaza	3	0.41	778456E- 9444312N
	San Martin	San Martin	4	0.78	791650E- 9278816N
		Santa Cruz-Tocache	5	1.41	354517E- 9054092N
		Shapaja-Tocache	5	1.11	358296E- 9082526N
		Tananta-Tocache	5	0.93	350341E- 9102541N
		Bambamarca	5	0.96	326715E- 9103226N
Center	Junín	Satipo	4	0.45	322870E- 8766373N
	Huánuco	Rupa Rupa	2	1.42	533950E- 8966760N
			2	1.93	391952E- 8982497N
		Bella	5	1.01	395116E- 8969187N
		Supte San Jorge	2	0.30	386028E- 8973837N
		Marona	1	0.27	403663E- 8979819N
		Marona Baja	5	1.00	396097E- 8978419N
		Pueblo Nuevo	2	1.37	396680E- 8995909N
		Pueblo Nuevo	5	1.47	383426E- 8994796N
		San José Pucate	5	1.63	383134E- 9015205N
		San Miguel La Cocha	5	1.03	373995E- 8989834N
		Castillo Grande	2	0.61	385389E- 8995243N
		Castillo Grande	2	0.18	380328E- 8976876N
		Castillo Grande	2	0.52	388995E- 8975440N
		J. Crespo y Castillo	2	0.43	389173E- 8998273N
		La Morada	5	0.95	375599E- 9020745N
		Palo de Acero-Huamalíes	5	1.24	358621E- 8978570N
		Merced de Locro	5	1.23	380266E- 8985796N
		Dámaso Beraun	2	1.52	383365E- 8959585N
	Ucayali	Callería	5	0.61	395359E- 9071823N
		Padre Abad	5	0.66	546513E- 9001025N
		Padre Abad	1	0.31	444682E- 9015463N
		Irazola	2	0.53	445791E- 9023025N
		Bajo Shiringal	5	0.64	471720E- 9022636N
		Nuevo Tahuantinsuyo	5	1.47	470935E- 9013764N
		Balle Sagrado	5	0.84	459718E- 9026534N
		Huacamayo	5	0.92	455921E- 9005300N
South	Cusco	La Convención	4	0.20	447599E- 8576210N
Average				0.91±0.48	

Source: Prepared by the author using data from 1 Florida *et al.* (2019); 2 Florida *et al.* (2018); 3 Llatance *et al.* (2018); 4 Arévalo-Hernández *et al.* (2017); 5 COPAIN (2014).

Figures 3 and 4 shows the geospatial analysis using data interpolation with the IDW extension of ArcGIS, version ArcMap10.5, software created in the USA.

The high bioacummulation capacity of cadmium in the cacao beans (Figure 2A and 2B) is relevant and suggests that current standards should take into account the natural level of cadmium in the soil as well as cacao genotipes, in order to establish average levels of cadmium, allowing the categorization of agricultural soil not contaminated with cadmium. In addition, it should not be confused with tolerable limits for derived or processed products in the commercialization of cacao beans (Pastor, 2017). Under current regulatory criteria, cadmium concentrations should be reformulated to classify soil, according to the cacao absorption capacity and the criteria proposed by Meter *et al.* (2019), who calculated a tolerable maximum limit for cadmium value in dry beans or raw cacao mass at 1.1 μg g^{-1}.

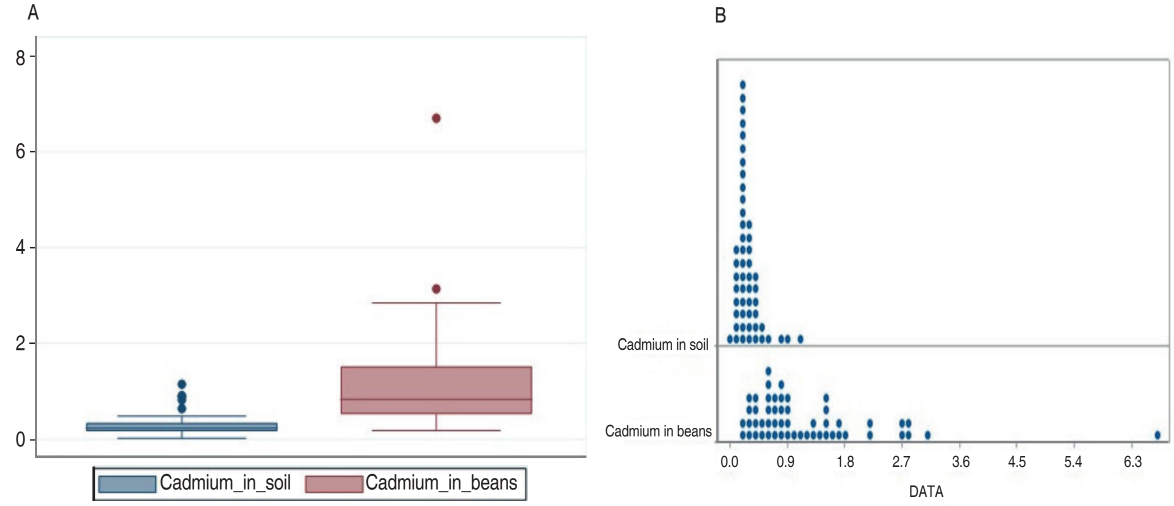


Figure 2. The dispersion of the available cadmium levels in the soil and the total cadmium in the cacao beans of the Peruvian territory. Diagram (A) and interquartile range (B).

Therefore, in the case of Peru, an uncontaminated soil should have a maximum of 0.36 μg g^{-1}; far below the limits set by the current USEPA standards (<0.43 μg g^{-1}), EU (<1 μg g^{-1}) and by the Peruvian Ministry of Environment (<1.4 μg g^{-1}) (Acevedo *et al.*, 2005; Jiménez, 2015; Pastor, 2017). This would jeopardize the availability of areas for cacao production; however, it would prevent cacao production in heavily contaminated soils (Zug *et al.*, 2019).

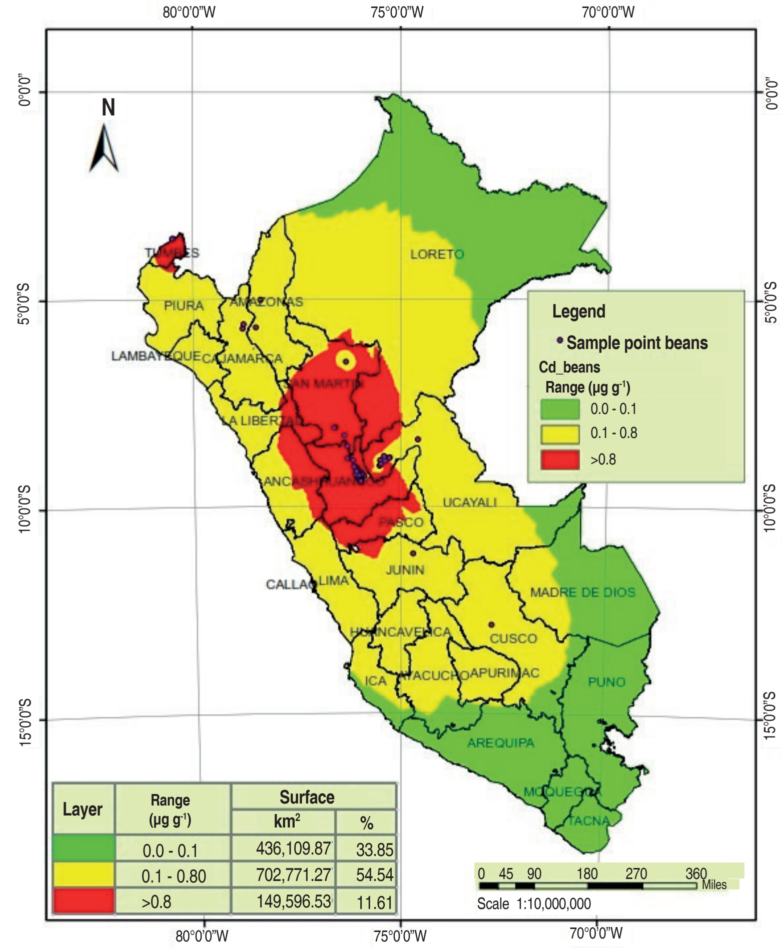
Data interpolation shows that the San Martin, Huánuco, Ucayali and Junín (central zone) and Tumbes (northern zone) regions have areas that exceed the tolerable limits as set by the EU; these areas represent 11.61% of the national territory (Figure 3). According to MINAGRI (2019) (acronym in Spanish) the Tumbes, Ancash and Pasco regions, together with other regions, contribute to only 3% of domestic production; therefore, they are not part of the calculations to measure the effects on future exports.

In addition, Figure 4 confirms the warnings of some researchers (Huamani *et al.*, 2012; Arévalo-Hernández *et al.*, 2017; Florida *et al.*, 2018; Zug *et al.*, 2019), since in central Peru, in 78.27% of San Martin, 87.74% of Huánuco, 6.49% of Ucayali, and 8.45% of the Junín region, there are areas with plantations that exceed the tolerable limits of cadmium, according to the EU, and these regions contribute to 79.2% of the domestic production (MINAAGRI, 2019); basic information for determining the effects on future exports.

Figure 4 shows geo-distribution by interpolating the total cadmium levels of beans from central Peru: in the San Martin region 78.27% of the total production areas have levels that exceed the limits that are tolerated by the EU, in Huánuco 87.74%, Junín 8.45% and Ucayali 6.49%.

Technologies for reducing cadmium levels in cacao beans

The geo-distribution (Figures 3 and 4) confirms that part of the Peruvian territory (central and northern zone) has beans with cadmium levels, which exceed the limits established by the EU, and similar to Peru, high levels



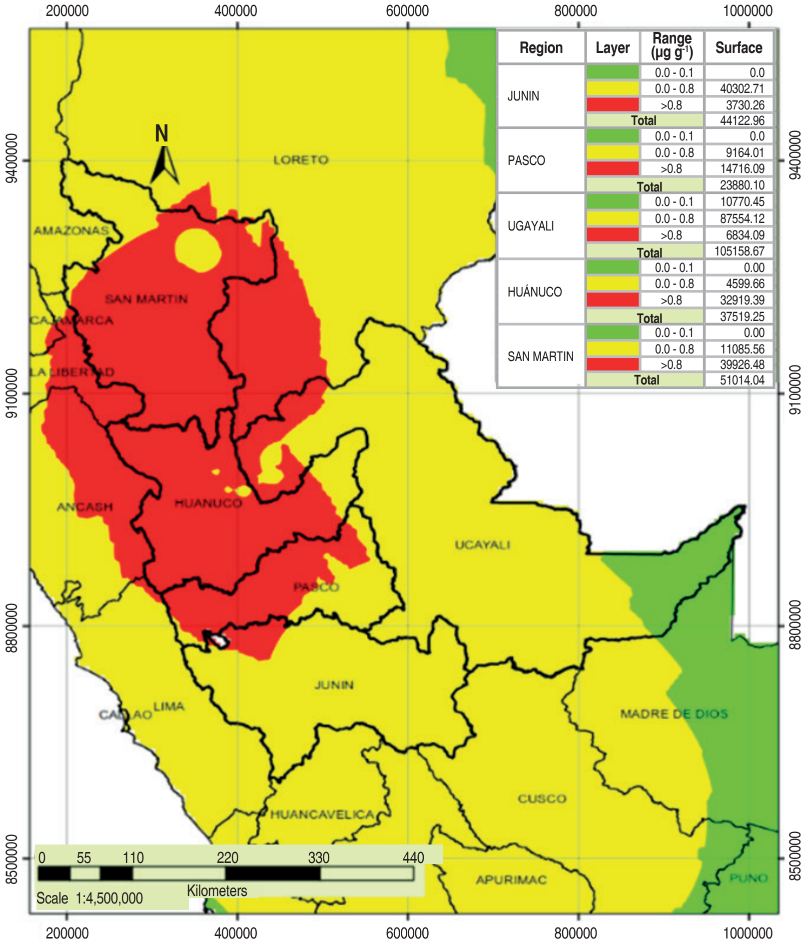
Layer	Range (µg g⁻¹)	Surface	
		km²	%
🟩	0.0 - 0.1	436,109.87	33.85
🟨	0.1 - 0.80	702,771.27	54.54
🟥	>0.8	149,596.53	11.61

Figure 3. Geo-distribution of the cadmium in beans of the Peruvian territory.

have also been reported in parts of Ecuador (Mite *et al*., 2010; Chávez *et al*., 2015; Diaz *et al*., 2018; Argüello *et al*., 2019; Barraza *et al*., 2019), Venezuela (Sánchez *et al*., 2011; Lanza *et al*., 2016) , Colombia (Bravo *et al*., 2014; Jiménez, 2015; Rodríguez *et al*., 2019), Brazil (Oliveira *et al*., 2019) and Bolivia (Gramlich *et al*., 2017) . These countries contributed to world production with 12% in 2012 and 17% in 2019 (Morales *et al*., 2012; MINAGRI, 2016; Arvelo *et al*., 2017; Antolinez *et al*., 2020).

Cadmium in cacao is a challenge to overcome in the short term (Antolinez *et al*., 2020), therefore, appropriate technologies are needed to reduce cadmium levels in the beans and protect the product quality, as well as consumer health (Casteblanco, 2018; Engbersen *et al*., 2019; Maddela *et al*., 2020). In addition, the availability of the cadmium in the soil and its bioaccumulation in beans is influenced by natural concentration (Argüello *et al*., 2019), physical, and chemical factors of the soil, which can maintain control of metal mobilization and bioaccumulation (Prieto *et al*., 2009; Sanchez *et al*., 2011; Bravo *et al*., 2014; Arévalo-Gardini *et al*., 2017; Pereira *et al*., 2017; Florida *et al*., 2019) as well as the genotype of cacao grown (Arévalo-Hernández *et al*., 2017; Chupillon-Cubas *et al*., 2017; Barraza *et al*., 2019; Engbersen *et al*., 2019).

In this context, this research suggests that the most promising strategies to reduce cadmium in cacao beans its absorption by trees, adding soil amendments to alter soil characteristics, thus reducing the bioavailability of cadmium (Argüello *et al*., 2019; Meter *et al*., 2019). These agronomic techniques offer advantages because of their low cost and minimal environmental impact as compared to other remediation procedures (Mohamed *et al*., 2017). Moreover, these techniques have shown favorable results along with the application of organic, inorganic, and combined fertilizers. In this regard, at the laboratory level was demonstrated, that the retention and mobility factor of cadmium depend on the quality of organic matter. In Colombia, Bravo *et al*. (2014) found significant effect in these processes, in addition, a better quality causes a lower cadmium mobility, avoiding contamination and toxicity through bioaccumulation. Furthermore, Ramtahal *et al*. (2019) applied biochar and lime *in vitro* and found that the two amendments were complementary in their action and they can be used to reduce cadmium bioaccumulation. There are already successful experiences, including Florida *et al*. (2019) in Padre Abad, Peru, who applied compost and NPK and found a significant reduction in cadmium levels of soil for cacao production, as well as the beans. Also, in Venezuela, Sánchez *et al*. (2011) applied phosphorus doses and the amount of available cadmium decreased because of the phosphorus effect.



Region	Layer	Range (µg g^{-1})	Surface
JUNIN	🟩	0.0 - 0.1	0.0
	🟨	0.0 - 0.8	40302.71
	🟥	>0.8	3730.26
	Total		44122.96
PASCO	🟩	0.0 - 0.1	0.0
	🟨	0.0 - 0.8	9164.01
	🟥	>0.8	14716.09
	Total		23880.10
UGAYALI	🟩	0.0 - 0.1	10770.45
	🟨	0.0 - 0.8	87554.12
	🟥	>0.8	6834.09
	Total		105158.67
HUÁNUCO	🟩	0.0 - 0.1	0.00
	🟨	0.0 - 0.8	4599.66
	🟥	>0.8	32919.39
	Total		37519.25
SAN MARTIN	🟩	0.0 - 0.1	0.00
	🟨	0.0 - 0.8	11085.56
	🟥	>0.8	39926.48
	Total		51014.04

Figure 4. Regional area which exceeds the EU's tolerable limits.

The use of amendments from organic and mineral origin, together with efficient microorganisms, showed better results. In Colombia, Cáceres and Torres (2017) found changes in the diversity of the microbial community of the soil associated with cacao cultivation, as well as, potential cadmium tolerant strains that can be used in on-site bioremediation programs or microorganisms can be used in order to produce biotechnological products. Revoredo and Hurtado (2017) evaluated the bioremedial activity of 3 strains of Streptomyces: *Streptomyces variabilis* (AB5 and X) and *Streptomyces* sp. (C2) in cacao plants using concentrations of 100 and 200 µg g^{-1} of Cd. The C2 strain showed bioremedial activity and reduced absorption by 39.67%. Also, Guerra-Sierra *et al*. (2014) found that the *Aspergillus* and *Trichoderma* genres have high percentages of cadmium biosorption in a liquid culture medium of 98.6% and 96%, respectively. These potential capabilities were studied by Mohamed *et al*. (2017) who used organic amendments, compost, and microorganisms (bacteria, fungi, mycorrhizae) and demonstrated that the integration of compost and microorganisms has a positive effect on reducing the bioavailability of cadmium in the soil.

Agroforestry systems have also demonstrated positive influences on the decrease of cadmium in cacao beans. In this context, Gramlich *et al*. (2017) found lower cadmium contents in agroforestry systems than in monocultures, further noting that specific absorption capacities of crops are related to the genotype and age of the plants. In Huánuco, Peru, Zug *et al*. (2019) assessed the influence of land management and the diversity of nearby vegetation; the increased biodiversity of plant species was positively correlated with the cadmium content in cacao, which may make them promising measures to counteract cadmium contamination in regions with high cadmium content in the soil.

The selection of cacao genotypes that have low bioaccumulation capacities for use in cadmium contaminated soils is another alternative (Engbersen *et al*., 2019). In Ecuador, Barraza *et al*. (2019) found differences in isotopes 114 and 110 of cadmium for three different cacao genotypes. In the same country, Barraza *et al*. (2017) found average values of 1.21±0.87 and 0.89±0.64 µg g^{-1} for the CCN51 genotype and other Ecuadorian national varieties. In the San Martin, Peru, region, Chupillon-Cubas *et al*. (2017) found that the absorption of cadmium for six cacao genotypes could be used as a pattern, and thus, found differences in absorption levels for both the aerial and root parts of the plants, with mean values for the EET-400 genotype being 13.18 and 6.55, common cacao (12.98 and 2.81), CCN-51 (11.89 and 3.31), POUND-12 (10.30 and 3.38), SCA-6 (9.57 and 5.92), and IMC-67 (6.78 and 2.12 µg g^{-1}). Also, Lanza *et al*. (2016) found different mean values for the genotypes: HNF (2.09), PNF (1.9), PF (1.82), PFC (1.76), HF (1.74), PFM (1.57), HFC (1.1), and HFM with 0.95 µg g^{-1}. The use of genotypes with low heavy metal accumulation capacities could be an alternative in order to avoid bioaccumulation problems. Therefore, it is necessary to study the genotype indicative of each cacao producing region.

Phytoremediation with plant species that have the ability to accumulate and tolerate high concentrations of cadmium in harvestable tissue (Tariq and Ashraf, 2016) is another alternative to remove metal contaminants such as cadmium; through phytofiltration, phytostabilization, phytoextraction, phytolatization, and phytotransformation (Casteblanco, 2018). In this regard, some plant species with hyperaccumulative capacities have been identified, including sunflowers (*Helianthus annuus*), which are a hyperaccumulator for cadmium (Tariq and Ashraf, 2016); soybeans when up to 300 mg kg^{-1} of TiO_2 nanoparticles are added to the soil, obtained up to 400% µg of cadmium per plant (Singh and Byeong, 2016). However, the process can be optimized if plant species are combined with microorganisms. According to Ahemad (2015), endophytic bacteria associated with hyperaccumulating plant species promote the efficiency of the process through three mechanisms: increasing the root surface area and root hair production; increasing the availability of metals; and increasing the transfer of soluble metals from the rhizosphere to the plant. Guarino and Sciarrillo (2017) used *Acacia saligna*, *E. camaldulensis*, rhizobacteria and mycorrhizals, and they found that phytostabilization can occur in the soil with lead, cadmium and zinc. Also, Hashem *et al*. (2016) found that the arbuscular mycorrhizals *Glomus mosseae*, *Glomus intraradices*, *Glomus etunicatum* and *Bassia indica* can be used to decrease the dispersion of cadmium in the soil.

Effect on exports

Global cacao production increased from 2005-2018 by approximately 800 thousand t; it reached almost 4.6 million (Cunha, 2018). Meanwhile, Ecuador produced, in the same period, 118 to 260 thousand t and went from making up 3% to 6% of the world´s production, becoming fourth among cacao-producing countries, showing an annual growth of 9.8% (Cunha, 2018). Peru also showed sustained growth in cacao, with it being the sixth largest crop, in terms of area, that is harvested in 16 regions, 57 provinces and 259 districts (INEI, 2017).

According to Table 5, in the last 10 years the cultivated area has had an annual growth of 10.45%, so that by 2020 it is forecasted to reach an area of 219.8 thousand ha. Also, domestic production has had an annual growth rate of 14% and by 2020 it is forecasted to reach 169.86 thousand t, with a projected yield of 840 kg ha^{-1}; the latter is due to the sustained increase (5%) of the performance, which increased from 555 in 2010 to 820 kg ha^{-1} in 2019. This is a very positive aspect for Peruvian production, which contributes to approximately 2% of the world´s production and ranks nineth in the world (MINAGRI, 2019).

Table 5. Area and performance of Peru in cacao production.

Year	Cultivated area (thousand ha)	Growth of cultivated area (%) *	National production (thousand t)	National production growth(%) *	Performance (kg ha^{-1})
2009	66.3[b]		36.8[b]		
2010	77.2[b]	16.44	46.6[b]	26.63	555[b]
2011	84.2[b]	9.07	56.5[b]	21.24	604[b]
2012	91.5[b]	8.67	62.5[b]	10.62	671[b]
2013	97.6[b]	6.67	71.8[b]	14.88	683[b]
2014	106.6[b]	9.22	81.7[b]	13.79	736[b]
2015	121.3[b]	13.79	87.3[b]	6.85	766[b]
2016	125.58[b]	3.53	107.9[b]	23.60	720[b]
2017	143[a]	13.87	121.8[a]	12.88	759[a]
2018	160[a]	11.89	135.3[a]	11.08	800[a]
2019	199[a]	24.38	149[a]	10.13	820[a]
2020	219.8*		169.86*		840*
	Average	10.45*		14*	

* Calculated by the author. Source: [a] MINAGRI (2019); [b] MINAGRI (2016)

Table 6 shows that in the last 10 years the price has remained relatively steady (ICO, 2020) and Peruvian exports have grown on average by 11%, from 145.86 million in 2010 to 348.66 million in 2019 and a record 421 million can be reached by the end of 2020, as long as prices in the first months of 2020 remain stable (ICO, 2020), despite the validity of the pandemic.

Table 6. Behaviour of Peruvian cacao exports through 2020.

Year	National production (thousand t)	Average international price ($)	Exports (Millions $) *	Export growth (%) *
2010	46.6[c]	3.13	145.86	
2011	56.5[c]	2.98	168.37	15.43
2012	62.5[c]	2.39	149.38	-11.28
2013	71.8[c]	2.44	175.19	17.28
2014	81.7[c]	3.06	250	42.70
2015	87.3[c]	3.14	274.12	9.65
2016	107.9[c]	2.89	311.83	13.76
2017	121.8[b]	2.03	247.25	-20.71
2018	135.3[b]	2.30	311.19	25.86
2019	149[b]	2.34	348.66	12.04
2020	169.86*	2.48**	421.25*	20.82
Average Growth Rate				11%

* Calculated by the author. ** Average price January-April (ICO 2020). Source: [b] MINAGRI (2019); [c] MINAGRI (2016)

The high levels of cadmium identified by Peruvian research from areas were cacao has been produced for the past 10 to 15 years; plants of this age have higher cadmium concentration (Arévalo-Gardini *et al.*, 2017; Florida *et al.*, 2019; Zug *et al.*, 2019). In addition, from 66.3 thousand ha in 2009 to 199 thousand ha in 2019, more than 66% of the nation's area, were young plantations with low cadmium levels, which are allowed by the EU. At the same time, the technique of mixing the product and the strict control of organic producers is practiced by those marketing the product; this, along with other aspects, reduces the levels of cadmium in the cacao beans. Therefore, the problem of high levels of cadmium in Peruvian cacao will begin to increase in the coming years, given that according to the INEI (2017), in the last decade, cacao was the second alternative crop to replace coca in Peru and it is reasonable that in the next decade, the growth rate of new areas will decrease and there will be an increase in plantations that exceed 10 years of age, and thus have high levels of cadmium.

Table 7 shows that these regions contributed to 79.2% of the domestic production. Therefore, the areas contaminated with cadmium in these regions represent 41% of the national production and affect 31.25% of the total volume of Peruvian exports to the EU; this represents 53.07 thousand t of cacao beans and 131,624 million dollars, which will have an affect on the following years if appropriate actions are not taken by the indicated sector.

Table 7. Effects on Peruvian cacao exports due to high cadmium levels.

Region	2020 National production (thousand t)	Regional production (%)	Regional production (thousand t)	Regional area where EU limits are exceeded (%) *	Regional volume affected (thousand t) *	2020 Total export earnings (Million $)
San Martin	169.86	40.90	69.47	78.27	54.38	172 292.4
Junín		18.30	31.08	8.45	2.63	77 089.26
Ucayali		12.30	20.89	6.49	1.36	51 814.09
Huánuco		7.70	13.08	87.74	11.48	32 436.47
Cuzco		6.10	10.36	0.00	0.00	25 696.42
Ayacucho		5.00	8.49	0.00	0.00	21 062.64
Amazonas		4.70	7.98	0.00	0.00	19 798.88
Cajamarca		1.00	1.70	0.00	0.00	4 212.53
Pasco		1.00	1.70	0.00	0.00	4 212.53
Otros		3.00	5.10	0.00	0.00	12 637.58
Total		100	169.86	41		421 252.8
Average National Production Affected (thousand t)					69.83*	173 189.79*
Impact on Exports (76% destined for the EU)					53.07*	131 624.24*
Impact on Exports (%)					31.25*	

* Calculated by the author. Source: MINAGRI (2019)

FINAL CONSIDERATIONS

This research presented an analysis of research conducted in the major cacao-producing countries of South American. The available scientific data allowed determining that an average of 0.40 μg g^{-1} of available cadmium is found in the soil, classified as free of contamination by cadmium, according to the United States Environmental Protection Agency, which established a critical level at 0.43 μg g^{-1} of total cadmium in agricultural soil, and the EU, through the Kelley Directive, established a range of 0 to 1 μg g^{-1}. However, an average of 0.84 μg g^{-1} of total cadmium was found in the beans, which exceeds the EU standards and exceeds the levels found in the soil by 2.1 times; revealing a high bioaccumulation of metal in cacao beans from this region, thus, jeopardizing its quality and marketability to South America's the main export destination, the European Union.

In the case of Peru, 100% of the territory has soil that is not contaminated by cadmium (0.29 μg g^{-1}); however, it has high levels of cadmium in the beans (0.91 μg g^{-1}), concentrated in the central region, which affects approximately 31.25% of exports, representing a decrease of 131,624 million dollar per year. In Latin America, Ecuador, has the soil with the highest cadmium levels, and Ecuador and Venezuela the highest averages of cadmium in the cacao beans.

Significant advances are being made in technology in order to reduce bioavailability and bioaccumulation in the beans through the application of amendments (organic, inorganic and combined), agroforestry systems, bioremediation, and genotype selection. In addition, proposals have been made to reformulate the criteria to establish the maximum cadmium levels in raw beans at 1.1 μg g^{-1}, and a final proposal by the researchers is to redirect exports to markets that do not have limits for this metal, as a short term alternative.

REFERENCES

Acevedo E, Carrasco M.A, León O, Martinez E. Silva P, Castillo G, Ahumada I, Borie G and González S. 2005. Informe sobre criterios de calidad de suelos agrícolas. Servicio Agrícola y Ganadero, Chile. 205 pp.

Aguirre-Forero SE, Piraneque-Gambasica NV and Vásquez-Polo JR. 2021. Contenido de metales pesados en suelos y tejidos de cacao en el departamento del Magdalena, Colombia: énfasis en cadmio. Entramado 16(2): 298-310. https://doi.org/10.18041/1900-3803/entramado.2.6753

Ahemad M. 2015. Enhancing phytoreme diation of chromium-stressed soils through plant- growth-promoting bacteria. Journal of Genetic Engineering and Biotechnology 13(1): 51–58. https://doi.org/doi:10.1016/j.jgeb.2015.02.001

Ali E, Hussain A, Ullah I, Khan FS, Kausar S, Rashid SA, Rabbani I, Imran M, Kakar KU, Shah JM, Cai M, Jiang L, Hussain N and Sun P. 2020. Fitotoxicidad del cadmio: problemas, avances, preocupaciones ambientales, y perspectivas futuras. Revista De La Facultad De Ciencias Agrarias UNCuyo 52(1): 391-405.

Almeida V. 2016. Níveis de cádmio no solo e na água de consumo em Buriticupu-MA. Dissertação Pósgraduação. Escola Nacional de Saúde Pública Sérgio Arouca. https://www.arca.fiocruz.br/bitstream/icict/34362/2/ve_Vilson_de_Almeida_ENSP_2016

Antoine JMR, Hoo Fung L and Grant CN. 2017. Assessment of the potential health risks associated with the aluminium, arsenic, cadmium and lead content in selected fruits and vegetables grown in Jamaica. Toxicology Reports 4:181–187. https://doi.org/10.1016/j.toxrep.2017.03.006

Antolinez EY, Almanza PJ, Barona AF, Polanco E and Serrano PA. 2020. Current state of cocoa plantation: A review of its main limitations. Ciencia y Agricultura 17(2): 1-11. https://doi.org/10.19053/01228420.v17.n2.2020.10729

Araujo-Abad S, Tapia W and Villamarín-Ortiz A. 2020. Verificación del método analítico de espectroscopía de absorción atómica con horno de grafito para la cuantificación de cadmio en almendra de cacao (*Theobroma cacao*). La Granja: Revista de Ciencias de la Vida 31(1): 59-73. https://doi.org/10.17163/lgr.n31.2020.04

Argüello D, Chavez E, Lauryssen F, Vanderschueren R, Smolders E and Montalvo D. 2019. Soil properties and agronomic factors affecting cadmium concentrations in cacao beans: a nationwide survey in Ecuador. Science of the Total Environment 649: 120-127. https://doi.org/10.1016/j.scitotenv.2018.08.292

Arévalo-Gardini E, Arévalo-Hernández CO, Baligar VC and He ZL. 2017. Heavy metal accumulation in leaves and beans of cacao (*Theobroma cacao* L.) in major cacao growing regions in Peru. Science of the Total Environment 605–606: 792-800. https://doi.org/10.1016/j.scitotenv.2017.06.122

Arévalo-Gardini E, Obando-Cerpa ME, Zúñiga-Cernades LB, Arévalo-Hernández CO, Baligar VC and He ZL . 2016. Heavy metals in soils of cocoa plantations (*Theobroma cacao* L.) in three regions of Peru. Ecología Aplicada 15(2): 81-89. https://doi.org/10.21704/rea.v15i2.747

Arévalo-Hernández CO, Arévalo-Gardini E, Farfán-Pinedo A, Baligar VC and He Z. 2017. Heavy metals in soils, leaves and grains of cocoa areas of Peru. International Symposium on Cocoa Research (ISCR), Lima, Peru.

Arvelo MA, González D, Delgado T, Maroto S and Montoya P. 2017. Current status of cocoa production, trade and cultivation in America. IICA-bba. 280 pp.

Barraza F, Moore RE, Rehkämper M, Schreck E, Lefeuvre G, Kreissig K, Coles BJ and Maurice L. 2019. Cadmium isotope fractionation in the soil – cacao systems of Ecuador: a pilot field study. The Royal Society of Chemistry 9: 34011-34022. https://doi.org/10.1039/C9RA05516A

Barraza F, Schreck E, Leveque T, Uzu G, Lopez F, Ruales J, Prunier J, Marquet A and Maurice L. 2017. Cadmium bioaccumulation and gastric bioaccessibility in cacao: A field study in areas impacted by oil activities in Ecuador. Environmental Pollution 229: 950-963. https://doi.org/10.1016/j.envpol.2017.07.080

Bravo IS, Arboleda CA and Martín FJ. 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. https://revistas.unal.edu.co/index.php/acta_agronomica/article/view/39569/45757

Bohn HL, McNeal BL and O`Conor GA. 1993. Soil chemistry. 1st Edition. Editorial Limusa S.A. México. 363 p.

Cáceres J and Torres E. 2017. Cultivable microorganisms associated with cadmium (cd) present in cocoa soils of the municipalities of yacopí and nile, as a bioremediation strategy. 2017 International Symposium on Cocoa Research (ISCR): 1-8.

Casteblanco JA. 2018. Técnicas de remediación de metales pesados con potencial aplicación en el cultivo de cacao La Granja Revista de Ciencias de la Vida 27(1): 21-35. https://doi.org/10.17163/lgr.n27.2018.02

Charrupi N and Martínez DC. 2017. Estudio ambiental del cadmio y su relación con suelos destinados al cultivo de cacao en los departamentos de Arauca y Nariño. https://ciencia.lasalle.edu.co/

ing_ambiental_sanitaria/718

Chávez E, He ZL, Stoffella PJ, Mylavarapu RS, Moyano B and Baligar VC. 2015. Concentration of cadmium in cacao beans and its relationship with soil cadmium in southern Ecuador. Science of the Total Environment 533: 205-214. https://doi.org/10.1016/j.scitotenv.2015.06.106

Chambi LJ. (2010). Evaluacion de la presencia de metales pesados en suelos agricolas y cultivos en tres micro-cuencas del municipio de Poopó. Tesis de grado. Universidad Mayor de San Andrés. http://dicyt.uto.edu.bo/observatorio/wp-content/uploads/2019/04/6-Tesis-Mestales-pesados-Poop%C3%B3.pdf

Chupillon-Cubas J, Arévalo-Hernández CO, Arévalo-Gardini E, Farfán-Pinedo A, Baligar VC. 2017. Acumulación de cadmio en seis genotipos de cacao utilizados como patrón. International Symposium on Cocoa Research (ISCR-2017): 1-3.

COPAIN. 2014. Naranjillo Agro-industrial Cooperative. Evaluación de cadmio en suelos y almendros de las regiones de Huánuco, Ucayali y San Martín. Cadmium project -COPAIN-CONCYTEC.

Cunha L. 2018. Estudo de competitividade do cacau e chocolate no Brasil: Desafios na produção e comércio global. UNESCO y Ministério do Desenvolvimento, Indústria e Comércio Exterior–MDIC/Brasil. 128 p.

Degryse F, Smolders E and Parker DR. 2009. Partitioning of metals (Cd, Co, Cu, Ni, Pb, Zn) in soils: concepts, methodologies, prediction and applications. A review. European Journal of Soil Science 60(4): 590–612. https://doi.org/10.1111/j.1365-2389.2009.01142.x

Díaz LE, Mendoza H, Bravo M and Dominguez N. 2018. Determinación de Cadmio y Plomo en almendras de cacao (*Theobroma cacao),* proveniente de fincas de productores orgánicos del cantón Vinces. Espirales 2(15): 77-92. https://www.revistaespirales.com/index.php/es/article/view/213/160

Engbersen N, Gramlich A, Lopez M, Gunnar S, Hattendorf B, Gutierrez O and Schulin R. 2019. Cadmium accumulation and allocation in different cacao cultivars. Science of the Total Environment 15(678): 660-670. https://doi.org/10.1016/j.scitotenv.2019.05.001

EU. 2014. European Union, Regulation No. 488/2014. They modify EC Regulation No 1881/2006 regarding the maximum content of cadmium in food products. Official Journal of the European Union. https://op.europa.eu/en/publication-detail/-/publication/93320940-da77-11e3-8cd4-01aa75ed71a1

Florida N, Paucar J, Jacobo SS and Escobar-Mamani F. 2019. Efecto de compost y NPK sobre los niveles de microorganismos y cadmio en suelo y almendra de cacao. Journal of High Andean Research 21(04): 264-273. https://doi.org/10.18271/ria.2019.503

Florida N, Claudio SL and Gómez R. 2018. El pH y la absorción de cadmio en almendras de cacao orgánico (*Theobroma cacao* L.) En: Leoncio Prado, Huánuco, Perú. Folia Amazónica 27(01): 1-8. https://doi.org/10.24841/fa.v27i1.438

Gramlich A, Tandy S, Gauggel C, López M, Perla D, Gonzalez V and Schulin R. 2018. Soil cadmium uptake by cocoa in Honduras. Science of the Total Environment 612: 370–378. https://doi.org/10.1016/j.scitotenv.2017.08.145

Gramlich A, Tandy S, Andres C, Chincheros J, Armengot L, Schneider M and Schulin R. 2017. Cadmium uptake by cocoa trees in agroforestry and monoculture systems under conventional and organic management. Science of the Total Environment 15(580):677-686. https://doi.org/10.1016/j.scitotenv.2016.12.014

GRSM. 2019. Intervención del proyecto cacao en el departamento de San Martín-2019. Gobierno Regional de San Martin. http://siar.regionsanmartin.gob.pe/mapas/intervencion-proyecto-cacao-departamento-san-martin-2019

Guarino C and Sciarrillo R. 2017. Effectiveness of *in situ* application of an Integrated Phytoremediation System (IPS) by adding a selected blend of rhizosphere microbes to heavily multicontaminated soils. Ecological Engineering 99:70–82. https://doi.org/10.1016/j.ecoleng.2016.11.051

Guerra-Sierra BE, Sandoval-Meza A, Manrique-González LS, Barrera-Rangel SP. 2014. Ensayos preliminares *in vitro* de biosorción de cadmio por cepas fúngicas nativas de suelos contaminados. Innovaciencia Facultad Cienc. Exactas Fis. Naturales 2 (1): 53-58. https://1library.co/document/z1ev43py-ensayos-preliminares-biosorcion-cadmio-fungicas-nativas-suelos-contaminados.html

Gunnar N. 2013. Metales propiedades quimicas y toxicidad. Enciclopedia de salud y seguridad en el trabajo. Sumario 63.10. https://www.insst.es/documents/94886/162520/p%C3%ADtulo+63.+Metales+propiedades+qu%C3%ADmicas+y+toxicidad

Hashem A, Abd-Allah EF, Alqarawi AA, Malik JA, Wirth S and Egamberdieva D. 2016. Role of calcium in AMF-mediated alleviation of the adverse impacts of cadmium stress in *Bassia indica* [Wight] A.J. Scott. Saudi Journal of Biological Sciences 26(4): 828–838. https://doi.org/10.1016/j.sjbs.2016.11.003

He S, He Z, Yang X, Stoffella PJ and Baligar VC. 2015. Chapter Four - Soil biogeochemistry, plant physiology, and phytoremediation of cadmium-contaminated soils. (D.L. Sparks, Ed.): Advances in Agronomy 134: 135-225. https://doi.org/10.1016/bs.agron.2015.06.005

Hernández-Baranda Y, Rodríguez-Hernández P, Peña-Icart M, Meriño-Hernández Y and Cartaya-Rubio O. 2019. Toxicidad del cadmio en las plantas y estrategias para disminuir sus efectos. Estudio de caso: El tomate. Cultivos Tropicales 40(03):1-10. http://scielo.sld.cu/pdf/ctr/v40n3/1819-4087-ctr-40-03-e10.pdf

Huamani HA, Huauya MA, Mansilla LG, Florida RN and Neira GM. 2012. Presence of heavy metals in the cultivation of organic cocoa (*Theobroma cacao* L.). Acta Agronómica 61(4): 339-344.

ICO. 2020. International Cocoa Organization. Cocoa beans, cash price. Available in https://www.indexmundi.com/es/precios-de-mercado/?mercancia=granos-de-cacao&meses=180

INEI. 2017. National Institute of Statistics and Informatics-National Agricultural Survey, Area harvested, according to main crops, comparative 2016-2017. Available in https://www.inei.gob.pe/media/MenuRecursivo/publicaciones_digitales/Est/Lib1593/

Jiménez CS. 2015. Estado legal mundial del cadmio en cacao (*Theobroma cacao* L.): fantasía o realidad. Producción + Limpia 10(1): 89- 104. http://www.scielo.org.co/pdf/pml/v10n1/v10n1a09.pdf

Kabata-Pendias A. 2010. Trace elements in soil and plants Fourth edition. Taylor & Francis Group, Boca Raton, Florida, U.S. 548 p. https://doi.org/10.1201/b10158

Lanza J, Churión P, Liendo N and López V. 2016. Evaluation of the content of heavy metals in cacao (*Theobroma cacao* L.) from Santa Bárbara del Zulia, Venezuela. Saber 28(1): 106-115.

Llatance WO, Gonza CJ, Guzmán W and Pariente E. 2018. Bioacumulación de cadmio en el cacao (*Theobroma cacao*) en la

Comunidad Nativa de Pakun, Perú. Revista Forestal del Perú 33 (1): 63–75. https://doi.org/10.21704/rfp.v33i1.1156

Maddela NR, Kakarla D, García LC, Chakraborty S, Venkateswarlu K and Megharaj M. 2020. Cocoa-laden cadmium threatens human health and cacao economy: A critical view review. Science of the Total Environment 10(720): 137-145. https://doi.org/10.1016/j.scitotenv.2020.137645

Marrugo-Negrete JL, Pinedo-Hernández J and Díez S. 2017. Assessment of heavy metal pollution, spatial distribution and origin in agricultural soils along the Sinú river basin, Colombia. Environmental Research 154: 380-388. https://doi.org/10.1016/j.envres.2017.01.021

Meter A, Atkinson RJ and Laliberte B. 2019. Cadmium in cocoa from Latin America and the Caribbean - Analysis of research and potential solutions for mitigation. Bioversity International, Rome. 84p. https://www.bioversityinternational.org/fileadmin/user_upload/Bioversity-CAF-Review-Cad-Cacao-13Nov2019-EN.pdf

MINAGRI. 2019. Ministry of Agriculture and Irrigation-General Directorate of Agrarian Policies; Directorate of Economic Studies and Agrarian Information. Cocoa Observatory. Available in https://www.minagri.gob.pe/portal/analisis-economico/analisis-2019?limitstart=0

MINAGRI. 2016. Ministry of Agriculture and Irrigation. Study of cocoa in Peru and in the world; current situation and prospects in the national and international market to 2015. MINAGRI-DGPA-DEEIA Peru. http://repositorio.minagri.gob.pe/handle/MINAGRI/478

MINAM. 2017. Ministry of the Environment. Supreme Decree DS 011-2017-MINAM. They approve Environmental Quality Standards for Soil-EQS. Available in https://sinia.minam.gob.pe/normas/aprueban-estandares-calidad-ambiental-eca-suelo-0

Mite F, Carrillo M and Durango W. 2010. Advances in monitoring the presence of cadmium in cocoa beans, soils and waters in Ecuador. 2010 Acts XII Ecuadorian Congress of Soil Science: 1-21.

Mohamed A, Mohamed B, Allam N and Abdel M. 2017. Bioavailability of cadmium and nickel to *Daucus carota* L. and *Corchorus olitorius* L. treated by compost and microorganisms. Soil Environment 36(01): 01-12. https://doi.org/10.25252/SE/17/41160

Morales JS, García JA and Méndez BE. 2012. ¿Qué sabe usted acerca de...cacao?. Revista Mexicana de Ciencias Farmacéuticas, 43(4): 79-81. http://www.redalyc.org/articulo.oa?id=57928311010

Motamayor JC, Lachenaud P, da Silva e Mota JW, Loor R, Kuhn DN, and Brown JS. 2008. Diferenciación poblacional geográfica y genética del árbol del chocolate amazónico (*Theobroma cacao* L). PLoS ONE 3(10): e3311. https://doi.org/10.1371/journal.pone.0003311

Niño ID. (2015). Cuantificación de cadmio en cacao proveniente del occidente de Boyacá por la tecnica analitica de voltamperometría. Tesis pregrado. Universidad Pedagógica y Tecnológica de Colombia. https://repositorio.uptc.edu.co/bitstream/001/1425/2/TGT-174.pdf

Oliva M, Rubio K, Epquin M, Marlo G and Leiva S. 2020. Cadmium uptake in native cacao trees in agricultural lands of Bagua, Peru. Agronomy 10(10): 1551. https://doi.org/10.3390/agronomy10101551

Oliveira AP, Milani RF, Melo L, Efraim P, Morgano MA and Tfouni S. 2019. Cádmio e chumbo em amêndoas de cacau do Brasil. 2019 Anais do 13° Latin American Food Science Symposium (SLACA): 1-2. https://proceedings.science/slaca/slaca-2019/papers/cadmio-e-chumbo-em-amendoas-de-cacau-do-brasil

Pastor SS. 2017. Niveles de cadmio en chocolate: NM y ECA, sí; OTC, no. 2017. In: Proceedings of the International Symposium on Cocoa Research 2017. ICCO. 1-5.

Pereira R, Furtado AA, Silva L, Mangabeiraa PAO, Souza JO, Pirovania CP, Ahnerta D and Baligar VC. 2017. Photosynthetic, antioxidative, molecular and ultrastructural responses of young cacao plants to Cd toxicity in the soil. Ecotoxicology and Environmental Safety 144(2017): 148–157. https://doi.org/10.1016/j.ecoenv.2017.06.006

Pérez PE and Azcona MI. 2012. Los efectos del cadmio en la salud. Revista de Especialidades Médico-Quirúrgicas 17(03): 199-205. http://www.redalyc.org/articulo.oa?id=47324564010

Prieto J, González CA, Román AD and Prieto F. 2009. Contaminación y fitotoxicidad en plantas por metales pesados del suelo y el agua. Tropical and Subtropical Agroecosystems 10(01): 29-44. http://www.redalyc.org/articulo.oa?id=93911243003

Pulgar VJ. 2014. The eight natural regions of Peru. Terra Brasilis (Nova Série) 3: 1-20.

Ramtahal G, Umaharan P, Hanuman A, Davis C and Ali L. 2019. The effectiveness of soil amendments, biochar and lime, in mitigating cadmium bioaccumulation in *Theobroma cacao* L. Science of the Total Environment 693: 1335-1363. https://doi.org/10.1016/j.scitotenv.2019.07.369

Revoredo AG and Hurtado J. 2017. Efecto del tratamiento con 3 cepas de *Streptomycetes* sobre la acumulación de cadmio en plantas de *Theobroma cacao* L. En: International Symposium on Cocoa Research (ISCR): 1-7. https://www.cabdirect.org/cabdirect/abstract/20203128289

Reyes C, Vergara I, Torres E, Díaz M and González E. 2016. Heavy metal contamination: implications in health, environment and food safety. Revista Ingeniería, Investigación y Desarrollo 6(2): 66-77. https://doi.org/10.19053/1900771X.v16.n2.2016.5447

Rodríguez HS, Darghan AE and Henao MC. 2019. Spatial regression modeling of soils with high cadmium content in a cocoa producing area of Central Colombia. Regional Geoderma 16: 214-222. https://doi.org/10.1016/j.geodrs.2019.e00214

Romero-Estévez D, Yánez-Jácome GS, Simbaña-Farinango K and Navarrete H. 2019. Content and the relationship between cadmium, nickel, and lead concentrations in Ecuadorian cocoa beans from nine provinces. Food Control 106(106750): 1-8. https://doi.org/10.1016/j.foodcont.2019.106750

Sánchez N, Rivero C and Martínez Y. 2011. Cadmio disponible en dos suelos de Venezuela: efecto del fósforo. Revista Ingenieía UC 18(2): 7-14. http://servicio.bc.uc.edu.ve/ingenieria/revista/v18n2/art01.pdf

Scaccabarozzi D, Castillo L, Aromatisi A, Milne L, Búllon A, and Muñoz-Rojas M. 2020. Soil, site, and management factors affecting cadmium concentrations in cacao-growing soils. Agronomy 10(6): 806. https://doi.org/10.3390/agronomy10060806

Silva PA. 2019. Análisis comparativo de los niveles de cadmio en suelo aquic dystropepts, fluventic dystropepts y una pradera con pastura en reposo en la vereda rincón de Pompeya, Villavicencio, Meta. Tesis pregrado. Universidad Santo Tomás. Colombia. https://repository.usta.edu.co/bitstream/handle/11634/21743/2020paulasilva?sequence=9&isAllowed=y

Singh J and Lee BK. 2016. Influence of nano-TiO_2 particles on the bioaccumulation of Cd in soybean plants (*Glycine max*): A possible mechanism for the removal of Cd from the contaminated soil. Journal of Environmental Management 170: 88–96. https://doi.org/10.1016/j.jenvman.2016.01.015

Tantalean E and Huauya MA. 2017. Distribución del contenido de cadmio en los diferentes órganos del cacao CCN-51 en suelo aluvial y residual en las localidades de Jacintillo y Ramal de Aspuzana. Revista de Investigación de Agroproducción Sustentable 1(2): 69-78. https://doi.org/10.25127/aps.20172.365

Tariq SR and Ashraf A. 2016. Comparative evaluation of phytoremediation of metal contaminated soil of firing range by four different plant species. Arabian Journal of Chemistry 9(6): 806–814. https://doi.org/10.1016/j.arabjc.2013.09.024

USEPA. 2002. United States Environmental Protection Agency. Supplemental guidance for developing soil screening levels for superfund sites. http://www.epa.gov/ superfund/health/conmedia/soil/ind ex.htm

Zug KLM, Huamaní HA, Meyberg F, Meyberg F and Cierjacks JS. 2019. Cadmium Accumulation in Peruvian Cacao (*Theobroma cacao* L.) and opportunities for mitigation. Water Air Soil Pollution 230(3): 72-80. https://doi.org/10.1007/s11270-019-4109-x