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Rofner, Nelino Florida

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

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

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Nelino Florida Rofner^{1*}

ABSTRACT

Keywords:

Bioaccumulation
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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

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 in alation 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 $\mu\text{g g}^{-1}$ 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 $\mu\text{g g}^{-1}$ 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 $\mu\text{g g}^{-1}$ (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 $\mu\text{g g}^{-1}$ 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 $\mu\text{g g}^{-1}$ (Bohn *et al.*, 1993); although more specific studies have found it to be between 0.07 and 1.1 $\mu\text{g g}^{-1}$, with a natural base level of 0.5 $\mu\text{g g}^{-1}$ (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 varying 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 magnesium 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 $0.42 \mu\text{g g}^{-1}$, being categorized as having soil that is not contaminated by cadmium, according to the USEPA ($0.43 \mu\text{g g}^{-1}$), 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 ($\mu\text{g g}^{-1}$)
Araujo-Abad <i>et al.</i> (2020)	Ecuador	--	0.304
Argüello <i>et al.</i> (2019)	Ecuador	560	0.44
Barraza <i>et al.</i> (2019)	Ecuador	145	0.20
Barraza <i>et al.</i> (2017)	Ecuador	113	0.44
Chávez <i>et al.</i> (2015)	Ecuador	76	0.85
Mite <i>et al.</i> (2010)	Ecuador	568	0.49
Chambi (2010)	Bolivia	18	0.39
Gramlich <i>et al.</i> (2017)	Bolivia	--	0.20
Aguirre-Forero <i>et al.</i> (2021)	Colombia	--	0.02
Silva (2019)	Colombia	--	0.096
Charrupi and Martínez (2017)	Colombia	--	1.15
Marrugo-Negrete <i>et al.</i> (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 it 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 cacao 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 ($\mu\text{g g}^{-1}$)	UTM Coordinates		
	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		
North		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	
	San Martin		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				
Junín		Satipo	4	0.10	539354E-8755739N		
		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		
		Huánuco	J. Crespo y Castillo	3	0.82	388995E-8976876N	
				3	0.41	383134E-8994796N	
				3	0.16	389956E-8988252N	
				5	0.26	374175E-9014524N	
		Center		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 territory 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%, $0.1 \mu\text{g g}^{-1}$; for chocolate with cacao solids of less than 50% and milk chocolates with cacao solids greater than or equal to 30%, $0.3 \mu\text{g g}^{-1}$; for chocolates with cacao solids greater than or equal to 50%, $0.8 \mu\text{g g}^{-1}$; and for cocoa powder, $0.6 \mu\text{g g}^{-1}$ (EU, 2014).

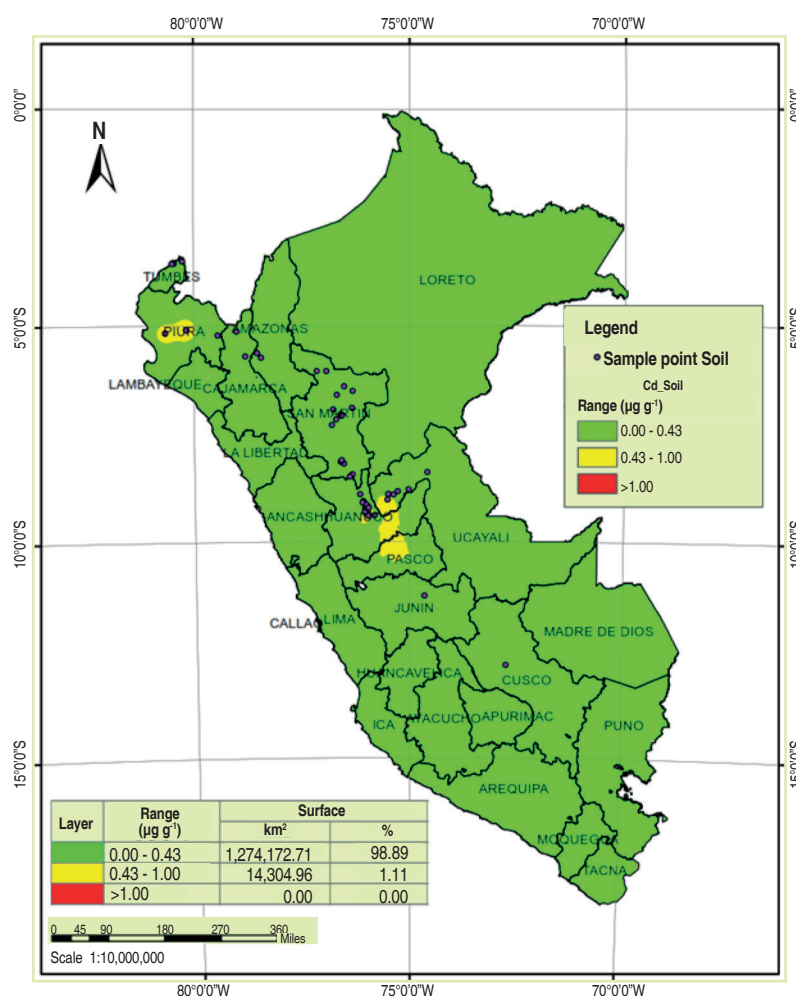


Figure 1. Geo-distribution of available cadmium in the soil of the Peruvian territory

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 $0.8 \mu\text{g g}^{-1}$ 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 ($\mu\text{g g}^{-1}$)
Argüello <i>et al.</i> (2019)	Ecuador	560	0.9
Barraza <i>et al.</i> (2019)	Ecuador	145	0.4
Barraza <i>et al.</i> (2017)	Ecuador	113	1.12
Chávez <i>et al.</i> (2015)	Ecuador	76	0.94
Mite <i>et al.</i> (2010)	Ecuador	803	0.84
Romero-Estévez <i>et al.</i> (2019)	Ecuador	--	0.75
Lanza <i>et al.</i> (2016)	Venezuela	NE	1.62
Oliveira <i>et al.</i> (2019)	Brasil	61	0.129
Aguirre-Forero <i>et al.</i> (2021)	Colombia	NE	0.66
Niño (2015)	Colombia	NE	1.62
Gramlich <i>et al.</i> (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 $0.29 \pm 0.18 \mu\text{g g}^{-1}$ and in the beans it is $0.91 \pm 0.48 \mu\text{g g}^{-1}$, 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 $1.52 \mu\text{g g}^{-1}$.

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

Zone	Region	Province	References	Cd levels ($\mu\text{g g}^{-1}$)	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
			Rupa Rupa	2	1.42	533950E- 8966760N
		Huánuco	Bella	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 bioaccumulation 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 genotypes, 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 $1.1 \mu\text{g g}^{-1}$.

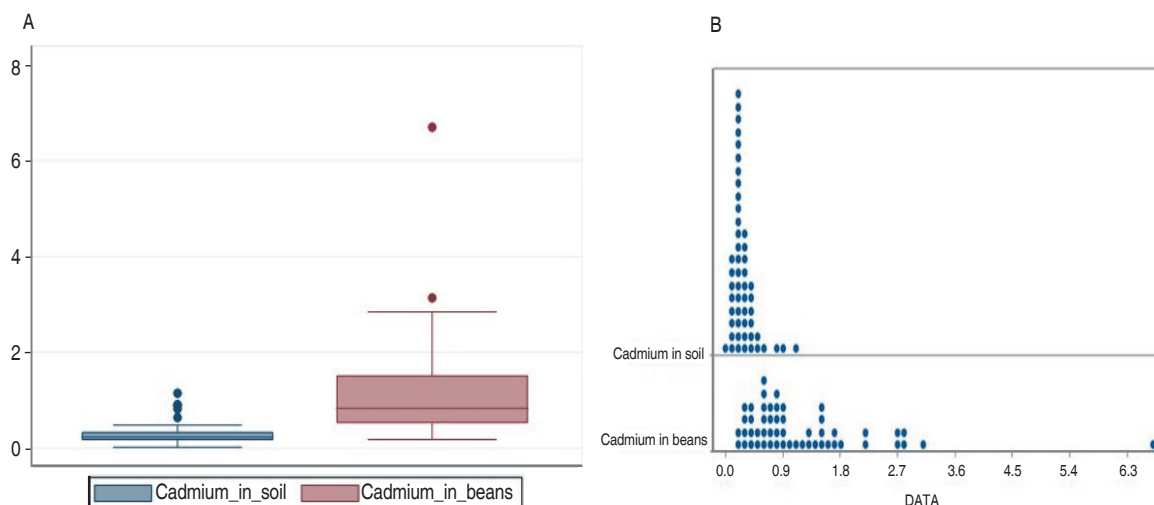


Figure 2. The dispersion of the available cadmium levels in the soil and the total cadmium in the cacao beans of the Peruvian territory. Diagram (A) and interquartile range (B).

Therefore, in the case of Peru, an uncontaminated soil should have a maximum of $0.36 \mu\text{g g}^{-1}$; far below the limits set by the current USEPA standards ($<0.43 \mu\text{g g}^{-1}$), EU ($<1 \mu\text{g g}^{-1}$) and by the Peruvian Ministry of Environment ($<1.4 \mu\text{g g}^{-1}$) (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 Martín, 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 Martín, 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 Martín 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

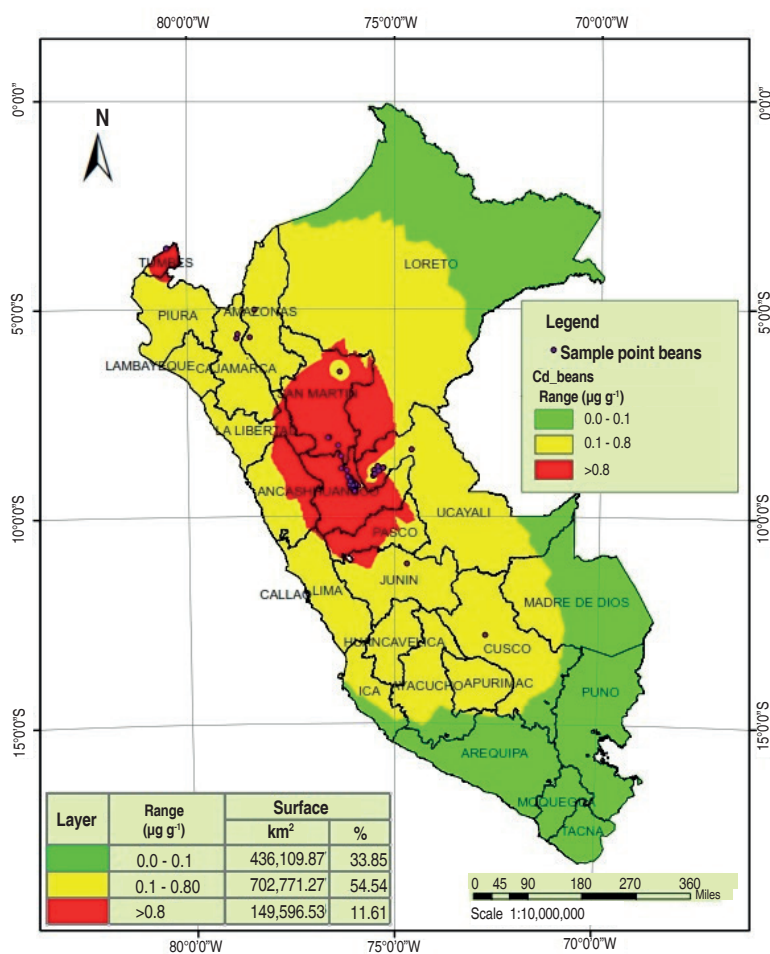


Figure 3. Geo-distribution of the cadmium in beans of the Peruvian territory.

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 (Castebianco, 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.

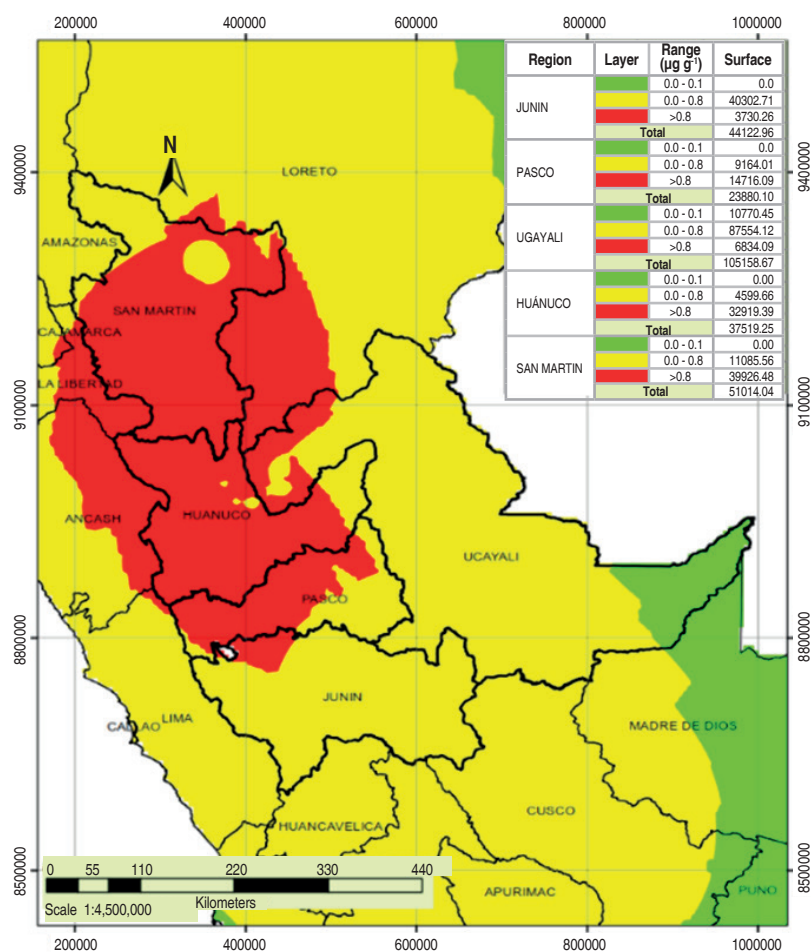


Figure 4. Regional area which exceeds the EU's tolerable limits.

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. Revoredó

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 $\mu\text{g g}^{-1}$ 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 $0.89 \pm 0.64 \mu\text{g g}^{-1}$ for the CCN51 genotype and other Ecuadorian national varieties. In the San Martín, 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 $\mu\text{g g}^{-1}$). 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 $\mu\text{g g}^{-1}$. 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, phytolatilization, 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 Sciarillo (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 ninth 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 where 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 effect 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 Martín		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	169.86	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 America. The available scientific data allowed determining that an average of $0.40 \mu\text{g g}^{-1}$ 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 $0.43 \mu\text{g g}^{-1}$ of total

cadmium in agricultural soil, and the EU, through the Kelley Directive, established a range of 0 to $1 \mu\text{g g}^{-1}$. However, an average of $0.84 \mu\text{g g}^{-1}$ 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 ($0.29 \mu\text{g g}^{-1}$); however, it has high levels of cadmium in the beans ($0.91 \mu\text{g g}^{-1}$), 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 $1.1 \mu\text{g g}^{-1}$, 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.

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