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Causas, consecuencias e impacto de los niveles de cadmio en la calidad del grano de cacao en Ecuador

Causes, consequences, and impact levels of cadmium on cocoa bean quality in Ecuador

Causas, consequências e níveis de impacto do cádmio na qualidade dos grãos de cacau no Equador

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Ciencias Técnicas y Aplicadas
Artículo de Investigación

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Resumen

Este documento de revisión integral aborda el importante problema de la contaminación por cadmio (Cd) en los granos de cacao ecuatorianos. Explora las diversas fuentes de esta contaminación, que incluyen tanto la composición natural del suelo como factores inducidos por el hombre, como las prácticas agrícolas. El artículo evalúa los efectos adversos del Cd sobre la calidad de los granos de cacao y las consiguientes implicaciones para la salud pública. También analiza el impacto más amplio en el comercio internacional del cacao, centrándose particularmente en los desafíos que enfrentan los productores ecuatorianos para cumplir con los estrictos estándares de seguridad establecidos por entidades como la Unión Europea. Al profundizar en los riesgos para la salud asociados con el Cd en los productos de cacao, la revisión destaca la urgencia de abordar esta contaminación. Evalúa diferentes técnicas de remediación de suelos, sugiriendo que las estrategias deberían adaptarse específicamente a las condiciones regionales en las áreas de cultivo de cacao. Este enfoque se destaca como crucial para reducir eficazmente los niveles de Cd en los granos de cacao. Además, el artículo subraya la importancia de comprender la distribución geográfica de la contaminación por Cd. Este conocimiento se considera esencial para la formulación de políticas eficaces y para implementar intervenciones específicas para abordar el problema. La revisión aboga por un enfoque colaborativo, que combine la investigación científica con el desarrollo de políticas. Esta sinergia se presenta como clave para desarrollar prácticas de gestión sostenible. En conclusión, el documento llama a realizar esfuerzos concertados para garantizar la seguridad, la calidad y la competitividad global del cacao ecuatoriano. Integra el análisis bibliométrico como herramienta metodológica para enriquecer la comprensión del alcance y profundidad del problema de la contaminación por Cd en la industria del cacao en Ecuador.

Palabras clave: Contaminación por Cadmio; Calidad del grano de cacao; Remediación del suelo; Agricultura Ecuatoriana; Normas de Seguridad Alimentaria.

Abstract

This comprehensive review paper addresses the significant issue of cadmium (Cd) contamination in Ecuadorian cocoa beans. It explores the various sources of this contamination, which include both natural soil composition and human-induced factors like agricultural practices. The paper assesses the adverse effects of Cd on the quality of cocoa beans and the subsequent implications

for public health. It also discusses the broader impact on international cocoa trade, particularly focusing on the challenges faced by Ecuadorian producers in adhering to the strict safety standards set by entities such as the European Union. In delving into the health risks associated with Cd in cocoa products, the review highlights the urgency of addressing this contamination. It evaluates different soil remediation techniques, suggesting that strategies should be specifically tailored to regional conditions in cocoa farming areas. This approach is emphasized as crucial for effectively reducing Cd levels in cocoa beans. Moreover, the paper underscores the importance of understanding the geographical distribution of Cd contamination. This knowledge is deemed essential for effective policy-making and for implementing targeted interventions to tackle the issue. The review advocates for a collaborative approach, combining scientific research with policy development. This synergy is presented as key to developing sustainable management practices. In conclusion, the paper calls for concerted efforts to ensure the safety, quality, and global competitiveness of Ecuadorian cocoa. It integrates bibliometric analysis as a methodological tool to enrich the understanding of the scope and depth of the Cd contamination issue in Ecuador's cocoa industry.

Keywords: Cadmium Contamination; Cocoa Bean Quality; Soil Remediation; Ecuadorian Agriculture; Food Safety Regulations.

Resumo

Este artigo de revisão abrangente aborda a questão significativa da contaminação por cádmio (Cd) nos grãos de cacau equatorianos. Explora as várias fontes desta contaminação, que incluem tanto a composição natural do solo como factores induzidos pelo homem, como práticas agrícolas. O artigo avalia os efeitos adversos do Cd na qualidade dos grãos do cacau e as implicações subsequentes para a saúde pública. Também discute o impacto mais amplo no comércio internacional de cacau, concentrando-se particularmente nos desafios enfrentados pelos produtores equatorianos na adesão aos rigorosos padrões de segurança estabelecidos por entidades como a União Europeia. Ao investigar os riscos para a saúde associados ao Cd nos produtos de cacau, a revisão destaca a urgência de abordar esta contaminação. Avalia diferentes técnicas de remediação do solo, sugerindo que as estratégias devem ser especificamente adaptadas às condições regionais nas áreas de cultivo de cacau. Esta abordagem é enfatizada como crucial para reduzir eficazmente os níveis de Cd nos grãos do cacau. Além disso, o artigo ressalta a importância de compreender a

distribuição geográfica da contaminação por Cd. Este conhecimento é considerado essencial para a elaboração de políticas eficazes e para a implementação de intervenções específicas para resolver o problema. A revisão defende uma abordagem colaborativa, combinando investigação científica com desenvolvimento de políticas. Esta sinergia é apresentada como fundamental para o desenvolvimento de práticas de gestão sustentáveis. Concluindo, o documento apela a esforços concertados para garantir a segurança, a qualidade e a competitividade global do cacau equatoriano. Integra a análise bibliométrica como ferramenta metodológica para enriquecer a compreensão do alcance e profundidade da questão da contaminação por Cd na indústria do cacau do Equador.
Palavras-chave: Contaminação por Cádmio; Qualidade do Grão de Cacau; Remediação de Solo; Agricultura Equatoriana; Regulamentos de Segurança Alimentar.

Introduction

Cadmium (Cd), a highly toxic heavy metal, presents significant risks to ecosystems, affecting soils, plants, microorganisms, and human health. Its high mobility and capacity for accumulation in plant organs, particularly in cocoa beans, raise concerns for food safety globally (Bimonte et al., 2021; Di et al., 2022). In cocoa crops across Latin America, Cd levels frequently exceed international standards for processed foods, necessitating meticulous monitoring to ensure product safety. This issue is particularly pertinent in Ecuador, where cocoa production is a major agricultural sector. The absorption of Cd by plants, including cocoa, from soil is influenced by the metal's bioavailability, which in turn is affected by soil properties such as mineralogy, pH, and organic matter content. The cycling of Cd between soil and cocoa trees via leaf litter introduces another dimension of complexity in understanding its presence in cocoa beans (Abt and Robin, 2020; Gómez-Ochoa et al., 2022).

Cadmium in soil originates from both geogenic and anthropogenic sources. The concentration of geogenic Cd varies depending on rock types, with sedimentary rocks generally exhibiting higher Cd levels. Anthropogenic contributions, often from phosphate-based fertilizers, can significantly elevate soil Cd content. Identifying the source of contamination is crucial for developing effective soil treatment strategies to mitigate Cd contamination. The vertical distribution of Cd in soil profiles, with lower concentrations at increased depths, further complicates the dynamics of Cd absorption by plants. In cocoa plantations, this variability necessitates a thorough understanding of soil Cd distribution for effective management (Kubier et al., 2019).

Cadmium accumulation in cocoa beans affects product quality and safety. Studies have shown that Cd concentration in cocoa beans can be predicted using spatial regression models that consider various soil properties and cadmium levels in different plant tissues, such as leaves and leaf litter. The spatial variability of Cd in soil and plant tissues indicates the potential for site-specific strategies to manage Cd levels in cocoa production. Furthermore, the higher concentration of Cd in cocoa leaves and leaf litter compared to beans suggests significant Cd cycling within the cocoa ecosystems, underscoring the importance of understanding the entire cocoa agroecosystem in managing Cd contamination (Joya-Barrero et al., 2023; Takrama et al., 2015; Zakariyya et al., 2022).

The relationship between soil characteristics and Cd accumulation in cocoa beans is complex. Correlations have been observed between soil pH, Cd content in soil (both total and available), and Cd concentration in cocoa beans. These correlations suggest that soil pH and Cd content significantly influence Cd uptake by cocoa plants. Furthermore, the interaction of Cd with other micro-elements in the soil, such as zinc, affects its availability and uptake by plants. This highlights the importance of a comprehensive understanding of soil chemistry in managing Cd levels in cocoa crops (Marković et al., 2019).

This study aims to explore the causes, consequences, and levels of impact of cadmium contamination on cocoa bean quality in Ecuador. By examining the interaction between soil properties, Cd distribution, and cocoa plant physiology, we seek to develop a clearer understanding of the dynamics of Cd accumulation in cocoa beans. We will utilize spatial regression models to analyze the correlation between soil characteristics and Cd levels in cocoa beans. This will help us determine the extent to which soil management practices can mitigate the risk of Cd contamination in cocoa crops. The goal is to provide actionable insights for cocoa farmers and policymakers to ensure the production of high-quality, safe cocoa products in Ecuador.

Methods

This review paper synthesizes methodologies from several studies to understand the causes, consequences, and impact levels of cadmium (Cd) contamination in cocoa beans in Ecuador. The primary focus is on assessing the cadmium accumulation in cocoa beans and its relation to soil characteristics, agricultural practices, and environmental factors.

Data Collection

Literature Review: A comprehensive review of existing literature, including scientific articles, government reports, and industry guidelines, was conducted. The sources were primarily focused on studies conducted in Ecuador and other relevant cocoa-producing regions.

Study Area Selection: The review included studies from various cocoa-producing regions in Ecuador, known for their different environmental and soil characteristics. Cocoa Bean Sampling: Data from studies that involved sampling cocoa beans from different cocoa plantations across Ecuador were included. Emphasis was placed on studies that considered diverse cocoa varieties and cultivation practices.

To enhance our data collection and analysis in the study, we utilized the bibliometrix R package for comprehensive bibliometric analysis. We extracted bibliographic data from leading academic databases including Scopus, Web of Science, and PubMed. This methodological approach allowed for a systematic review of literature, focusing on scientific articles, government reports, and industry guidelines relevant to cadmium contamination in cocoa from Ecuador and other major cocoa-producing regions. Our study incorporated diverse data, including cocoa bean samples from various Ecuadorian plantations, reflecting different environmental conditions, cocoa varieties, and farming methods.

Environmental and Agricultural Factors

Agricultural Practices: The review considered studies that examined the impact of different agricultural practices, including types of fertilizers used, irrigation practices, and crop management techniques on cadmium uptake by cocoa plants. Environmental Assessment: Environmental factors such as proximity to industrial areas, natural soil composition, and historical land use were considered in the analysis of cadmium contamination levels.

Quality and Safety Standards

Comparison with International Standards: The cadmium levels in cocoa beans were compared with international safety standards, such as those set by the European Union, to assess the potential health risks and market implications for Ecuadorian cocoa.

Limitations

Data Variability: Given the varied methodologies of the studies included, there is an inherent variability in the data that may affect the generalizability of the findings. Regional Focus: While the review focuses on Ecuador, the findings may not be directly applicable to other cocoa-producing regions due to differences in environmental conditions and agricultural practices.

Results and discussion

Bibliometric analysis

The bibliometric analysis reveals a landscape of research sources on cadmium (Cd) contamination in cocoa beans. 'The Science of the Total Environment' emerges as the most cited journal, indicating its prominence in this field with three documents. Other key journals with one document each include 'Chemosphere', 'Environmental Pollution', 'Environmental Research', and 'Food Research International', signifying a multidisciplinary interest spanning environmental science and food safety. Journals such as 'Heliyon', 'International Journal of Environmental Research', and 'RSC Advances' also contribute to the discourse, reflecting a wide-ranging academic engagement with the topic of Cd contamination and its impact on agriculture and health (Figure 1).

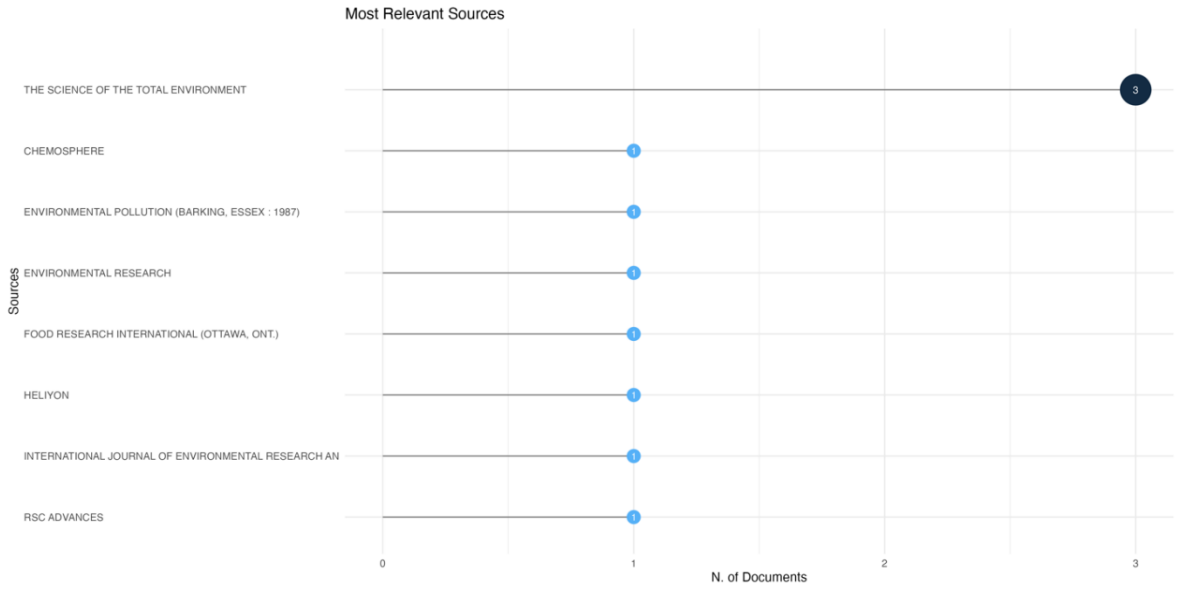

Figure 1. *Bibliometric analysis results for most relevant sources.*

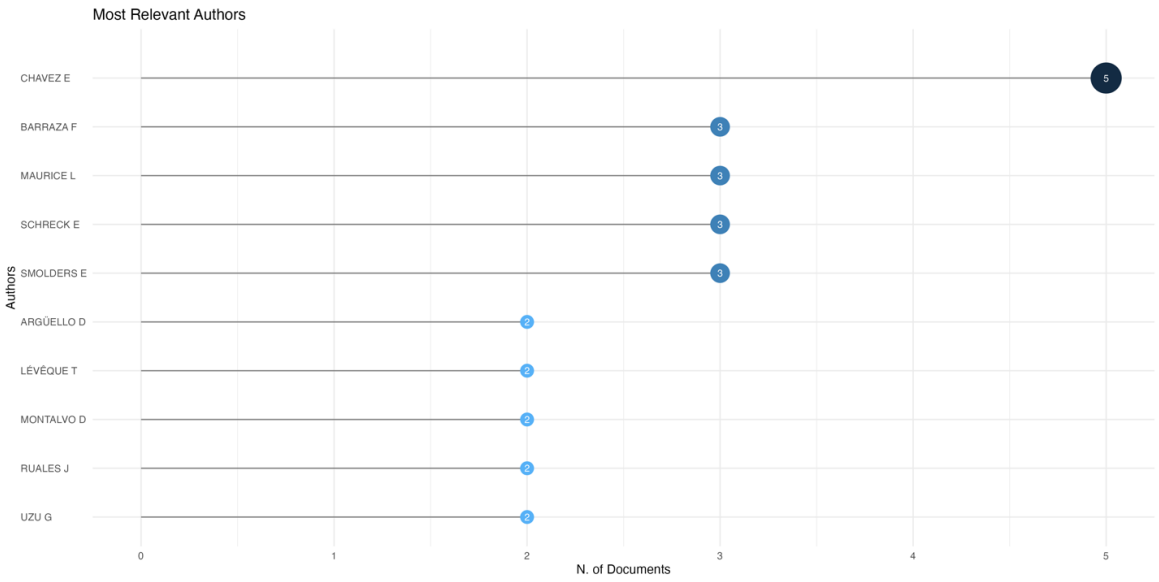

Figure 2. *Most relevant authors.*

The bibliometric analysis identifies key contributors in the field of cadmium (Cd) contamination research. E. Chavez stands out with the highest number of documents, contributing to five papers, indicating a significant role in advancing the understanding of Cd contamination in cocoa beans. Close collaborators or those with focused research interests, such as F. Barraza, L. Maurice, E. Schreck, and E. Smolders, each have three publications to their names. This pattern suggests a concentrated research effort within a network of scholars dedicated to this critical area of study. Their collective work forms the cornerstone of current knowledge on Cd contamination, its impact on cocoa quality, and remediation strategies (Figure 2).

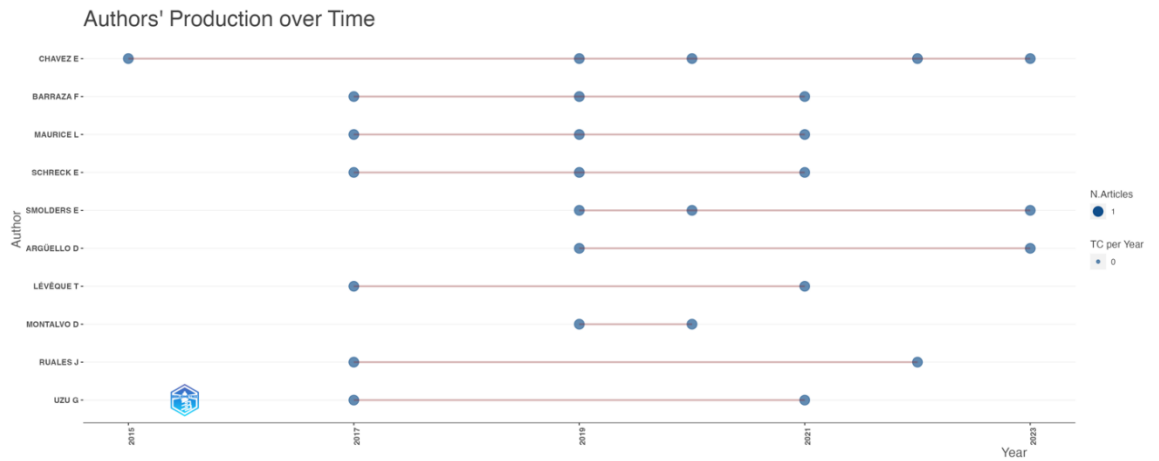

Figure 3. *Authors contribution over time.*

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The bibliometric data on authors' publication history illustrates a timeline of research output spanning several years. E. Chavez, as the most prolific author, shows a consistent publication record, indicating sustained contributions to the field of Cd contamination research. Other key researchers like F. Barraza, L. Maurice, E. Schreck, and E. Smolders also exhibit a steady stream of publications, reflecting ongoing engagement with the subject. The timeline suggests a growing body of work in this research area, with peaks indicating collaborative efforts and key periods of study (Figure 3).

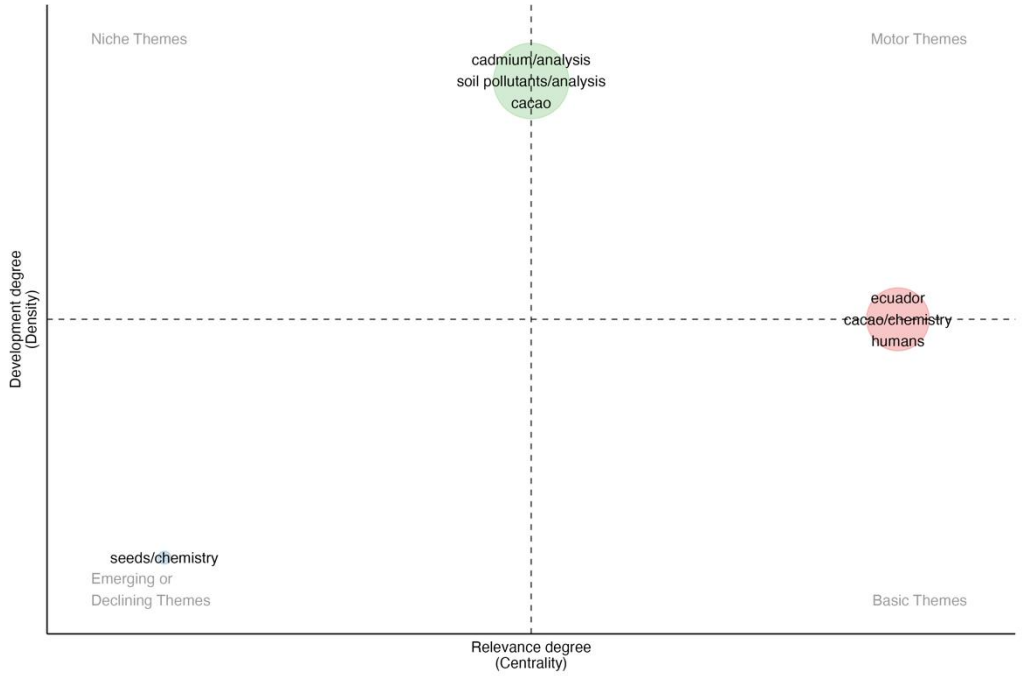

Figure 4. Motor Themes (Top Right Quadrant): Highly developed and central, indicating mature themes that are well-established in the field and receiving consistent attention in literature. Niche Themes (Top Left Quadrant): These themes are well-developed but have less centrality. They represent specialized areas that may be significant within subfields or particular contexts. Emerging or Declining Themes (Bottom Left Quadrant): Themes with lower development and centrality, which could either be new areas of interest that are not yet fully explored or older areas that are losing prominence in the field. Basic Themes (Bottom Right Quadrant): These themes are not as

developed but are central, suggesting fundamental areas of research that might be in the early stages of exploration or foundational to other, more developed areas.

The thematic map visualizes the landscape of cadmium (Cd) contamination research within the context of Ecuadorian cocoa production. "Ecuador", "cacao/chemistry", and "humans" are identified as motor themes, indicating their central role and thorough development in current literature. They serve as the backbone of research into the effects of Cd on cocoa quality and human health. In contrast, "cadmium/analysis" and "soil pollutants/analysis" are niche themes, representing in-depth but less central topics. The presence of "seeds/chemistry" in the emerging or declining quadrant suggests an area that requires further investigation or is diminishing in focus. This map underscores the strategic areas of study and guides future research efforts in addressing Cd contamination challenges (Figure 4.).

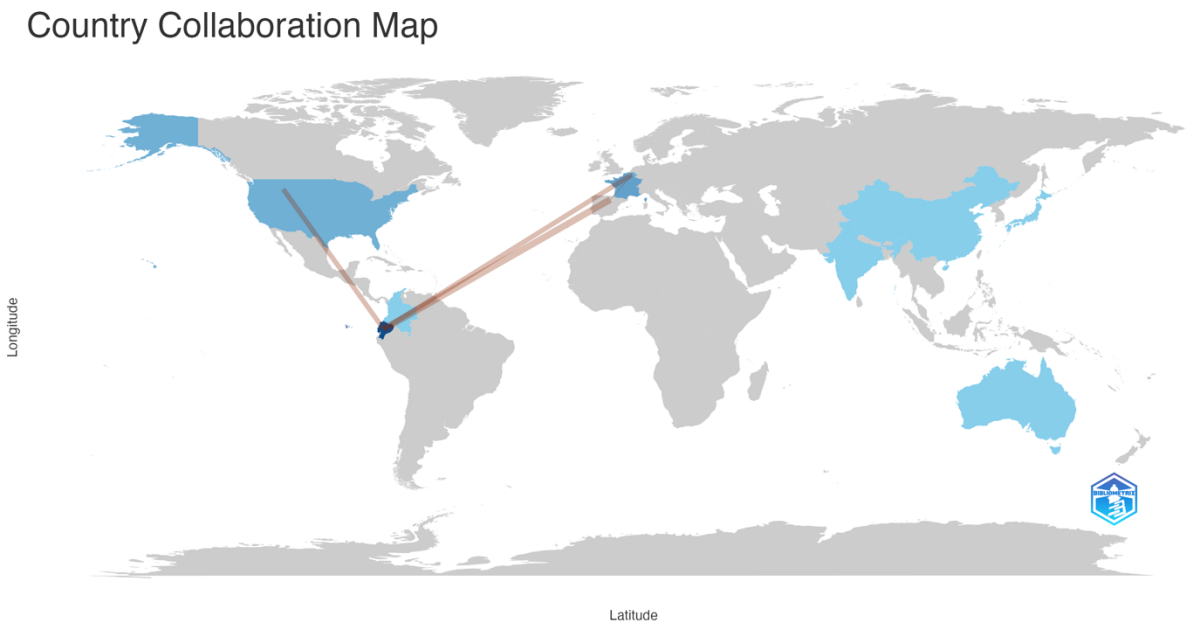

Figure 5. *Country collaboration map.*

The Country Collaboration Map illustrates the global research network on cadmium contamination in cocoa production. It visualizes international collaborations between researchers in different countries, with lines connecting nations to indicate co-authored studies. Countries in darker shades suggest a higher volume of research or greater involvement in the field. This map underscores the

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international effort to understand and address the issue of cadmium in cocoa, highlighting the cross-border cooperation essential to advancing knowledge and developing solutions (Figure 5).

Overview of Cadmium Contamination in Ecuadorian Cocoa Beans

Recent studies have revealed a concerning level of cadmium (Cd) contamination in cocoa beans from various regions in Ecuador. The contamination levels significantly exceed international safety standards, raising concerns about the implications for consumer health and the chocolate industry. This issue is particularly acute in southern Ecuador, where soil and cacao plant sampling have demonstrated a high prevalence of Cd contamination. The concentration of Cd in cacao beans often surpassed the critical level of 0.6 mg kg^{-1}, a threshold set due to the potential health risks associated with Cd consumption in cacao-based products (Chang et al., 2022; Rofner, 2021; Vázquez-deCastro et al., 2023).

Soil Characteristics and Cadmium Uptake

In the context of cadmium (Cd) contamination in Ecuadorian cocoa farms, soil characteristics play a pivotal role in Cd uptake by cacao plants. Studies have demonstrated a strong correlation between the levels of Cd in the soil and their accumulation in cacao beans. Specifically, both total recoverable and M3-extractable Cd prominently decrease with soil depth. This trend indicates that surface-level contamination, potentially due to anthropogenic activities such as the use of Cd-rich fertilizers or industrial pollution, significantly contributes to the Cd content in cacao beans. These findings emphasize the critical need for strategies to mitigate surface soil contamination. Addressing this issue is not just about reducing Cd uptake in cocoa plants; it's about safeguarding the entire ecosystem and the health of consumers. Furthermore, the distinct decrease of Cd with soil depth suggests that remediation efforts should be concentrated at the surface level, where the risk of Cd entering the food chain is highest. This aspect of Cd behavior in soil-crop systems is crucial for devising effective soil management practices and agricultural interventions aimed at controlling and minimizing Cd contamination in cocoa production. Effective management of soil health, therefore, becomes imperative to ensure the safety and quality of cocoa beans, which form the backbone of a significant agricultural industry in Ecuador (Argüello et al., 2019; Kubier et al., 2019; Stoltzfus, 2008).

Impact of Environmental and Agricultural Factors

Environmental conditions and agricultural practices play a crucial role in the variability of cadmium (Cd) contamination across different cocoa-producing regions in Ecuador. The diverse soil types, ranging from volcanic to sedimentary, significantly influence Cd bioavailability in soils, with certain soil compositions, especially those rich in organic matter, enhancing Cd uptake by cocoa plants (García et al., 2021). The soil pH is a key factor, as acidic conditions can increase Cd solubility and availability to plants. Furthermore, agricultural practices, particularly the use of phosphate-based fertilizers, have been identified as significant contributors to elevated Cd levels in soil.

These fertilizers often contain Cd as an impurity, which can accumulate in the soil over time and subsequently be absorbed by cocoa plants. This complex interplay of environmental and agricultural factors necessitates the development of region-specific strategies to manage Cd contamination effectively. Such strategies should focus on soil amendment techniques to reduce Cd availability, careful selection, and use of fertilizers, and possibly the cultivation of cocoa varieties that are less prone to Cd accumulation. The variation in Cd contamination levels across regions highlights the need for a targeted approach, considering the unique environmental and agricultural conditions of each cocoa-producing area. This approach is vital to ensure both the safety of cocoa products and the sustainability of the cocoa industry in Ecuador (Barraza et al., 2021; Rodríguez Albarrcín et al., 2019). Further analysis showed a strong statistical correlation between the Cd content in soil and that in cocoa beans. This relationship was particularly evident in surface soils at 0-5 cm depth, where higher levels of Cd contamination directly corresponded to increased Cd levels in cocoa beans. This finding is critical for understanding the mechanisms of Cd uptake by cocoa plants and emphasizes the importance of soil health in managing Cd levels in cocoa production.

Variations in Cadmium Levels Among Different Cocoa Varieties

Variability in cadmium (Cd) concentration across different cocoa varieties in Ecuador highlights the complex interplay of genetics and environment in determining metal uptake in plants. Research focusing on popular Ecuadorian varieties like Nacional and CCN-51 has revealed notable differences in Cd accumulation. Nacional, a traditional variety known for its fine flavor, often

shows lower Cd levels compared to CCN-51, a hybrid known for its high yield and disease resistance. This disparity might be attributed to genetic factors affecting the plants' capacity to absorb and translocate metals. For instance, certain genotypes within these varieties could possess inherent mechanisms to limit Cd uptake or translocation to the beans, which are the commercially relevant part of the plant (Argüello et al., 2019; Barraza et al., 2021; Rofner, 2021).

Further, the interaction between these genetic factors and environmental conditions, such as soil type and prior land use, plays a crucial role in determining the extent of Cd accumulation. For example, soils previously used for crops like maize or subjected to certain agricultural practices might exhibit different Cd dynamics, influencing the uptake by different cocoa varieties. This varietal difference in Cd accumulation is critical for developing targeted strategies in cocoa cultivation. By identifying and promoting the cultivation of low-Cd accumulating varieties and understanding their interaction with specific environmental conditions, it is possible to mitigate the risks associated with Cd contamination in cocoa beans. This approach is not only crucial for consumer health but also for maintaining the market value and reputation of Ecuadorian cocoa in the international market (Rosales-Huamani et al., 2020).

Nationwide Survey and Implications for Cocoa Bean Safety

A comprehensive nationwide survey in Ecuador has shed light on the alarming extent of cadmium (Cd) contamination in cocoa beans. This extensive study, encompassing a wide range of cocoa-producing regions, has revealed that Cd levels in many areas surpass the stringent international safety standards. This is particularly true in zones renowned for producing fine-flavor cocoa, a key export and source of pride for Ecuador. The elevated Cd levels found in these regions pose a significant challenge to maintaining the high-quality reputation of Ecuadorian cocoa (Iacumin et al., 2022).

The findings from the nationwide survey have profound implications for consumer health and the cocoa industry. High Cd levels in cocoa beans can lead to health risks if consumed in large quantities, raising concerns among health-conscious consumers and regulatory bodies. This situation is particularly pressing given the increasing global awareness and stringent regulations regarding food safety. The presence of high Cd levels in Ecuadorian cocoa beans could lead to reduced consumer confidence and potential barriers in international markets, especially in countries with strict food safety standards (Ramos et al., 2022)

The issue of Cd contamination in cocoa beans extends beyond health concerns to impact international trade dynamics. Countries like those in the European Union have set strict limits for Cd levels in imported cocoa products. The results of the survey indicate that many Ecuadorian cocoa beans exceed these limits, potentially leading to restrictions or bans in these lucrative markets. This poses a significant challenge for Ecuador's cocoa industry, which relies heavily on exports, especially to premium markets. Addressing these Cd contamination issues is thus critical for maintaining and expanding market access (Ramos et al., 2022; Ramtahal et al., 2015; Stoltzfus, 2008)

The nationwide survey's findings underscore the urgent need for effective strategies to mitigate Cd levels in cocoa production. This includes revising agricultural practices, exploring soil remediation techniques, and possibly developing or identifying cocoa varieties with lower tendencies for Cd accumulation. Collaborative efforts among government agencies, research institutions, and the cocoa industry are essential to develop and implement these strategies. Such measures are crucial to ensure the long-term viability and sustainability of the Ecuadorian cocoa industry in the global market (Ramtahal et al., 2015).

The Role of Anthropogenic Activities in Cadmium Pollution

The study by (Yuan et al., 2019) in southeast China presents a critical examination of the role of anthropogenic activities in cadmium pollution, particularly in the context of industrial production. It was found that in 2015, approximately 43.5 kg of cadmium were emitted into the environment in a cadmium-polluted town, with the vast majority entering the water system. This study is significant because it highlights how industrial activities, especially those related to pigment production, contribute to most cadmium emissions. The research also underscores the importance of understanding the pathways through which cadmium enters different environmental media, as it was discovered that waterways play a crucial role in transporting cadmium, leading to soil contamination. These findings have direct relevance to the situation in Ecuador, as they suggest that similar industrial and agricultural practices could be contributing to the elevated levels of cadmium in cocoa bean-producing regions.

Maddela et al. (2020) research further expands on the impact of cadmium in cocoa-based products, emphasizing the global concern for food safety and human health. The study reveals how increased bioavailability of cadmium in cacao-based horticulture poses significant risks, compounded by

factors like poverty, traditional farming practices, and a lack of awareness about cadmium's effects. This research points out the long-term health complications associated with even trace levels of cadmium, highlighting its potential to cause serious issues, particularly in children who are major consumers of chocolate products. Raju's work advocates for the development of cacao clones that have a reduced capacity to absorb cadmium and emphasizes the need for more focused research to mitigate the transfer of cadmium through the food chain. This aspect is particularly crucial for protecting the future of the chocolate industry and promoting safer cacao farming practices.

Cadmium Bioaccumulation and Its Impact on Cocoa Quality

The bioaccumulation of cadmium (Cd) in cocoa beans not only poses significant health concerns but also detrimentally impacts the quality of cocoa. Studies indicate that the presence of Cd can alter the flavor profile and physical characteristics of cocoa beans, potentially reducing their value in the global market. This is particularly crucial considering the new European Union (EU) regulations on cadmium in cacao-derived products, as discussed in (Vanderschueren et al., 2021) 2022 study. The research emphasizes that cadmium concentrations in cacao beans are typically higher than in the soil they grow in, with concentrations in Latin American beans often exceeding EU export thresholds. This regional enrichment is linked to higher soil Cd concentrations, predominantly from geogenic sources. A meta-analysis in the study suggests that soil Cd, pH, and organic carbon are key factors influencing cacao bean Cd concentrations. While postharvest practices like fermentation can slightly reduce Cd levels, long-term strategies such as breeding low Cd cultivars and applying soil treatments like lime or biochar could be more effective.

Reyes-Pérez et al. (2023) study further explores the interaction between soil Cd and cocoa plants, focusing on how the exogenous application of macronutrients affects Cd absorption and accumulation. In trials with cocoa clones CCN-51 and EET-103, increased macronutrient levels raised Cd extraction, with the highest values observed under N-P-K-S-Mg-Ca application. However, this fertilization did not reduce Cd absorption in cocoa seedlings, indicating that while macronutrients affect Cd dynamics, they don't necessarily mitigate its accumulation. These findings are essential for understanding the complex interplay between soil composition, agricultural practices, and Cd bioaccumulation in cocoa plants, underlining the need for comprehensive strategies to manage Cd levels and preserve the quality and marketability of Ecuadorian cocoa.

Efficacy of Soil Remediation Techniques

The efficacy of soil remediation techniques in Ecuadorian cocoa farms presents a complex landscape, with varying success rates largely dependent on local soil conditions and contamination levels. Research indicates that phytoremediation, utilizing certain plant species, has potential in lowering Cd levels in contaminated soils, yet its effectiveness is not uniform across all regions. This variability underlines the necessity for tailored remediation strategies, adapted to the unique characteristics of each cocoa-producing area. For instance, the application of soil amendments like biochar and lime has shown potential in some cases, particularly in altering soil pH and binding cadmium, thereby reducing its phytoavailability. Additionally, exploring genetic approaches, such as cultivating cocoa varieties with lower cadmium uptake, could offer long-term solutions. However, these approaches must be carefully evaluated for their practicality, cost-effectiveness, and potential impact on cocoa quality and yield. This highlights the need for ongoing research and development of holistic, site-specific remediation strategies that consider both the ecological and economic aspects of cocoa production.

Impact of Cadmium on Market Access and Trade

Global Market Restrictions and Cd Accumulation in Cacao poses that the accumulation of Cd in cacao beans and subsequent restrictions on safe levels of chocolate consumption have raised international concerns. This situation is particularly challenging for Ecuador, where certain cacao varieties have shown high Cd levels. These concerns are not just limited to Cd but extend to other trace elements that might be present in cacao beans. The study by (Barraza et al., 2021) examines the concentrations of various trace elements in cacao varieties from Ecuador, highlighting that some of these elements exceed local limits. This adds another layer of complexity to Ecuador's challenge in maintaining market access, particularly in regions like the European Union, where safety standards for consumables are highly stringent.

The study's findings on the presence of trace elements in different parts of the cacao plant, including leaves, pod husks, and beans, are crucial. Although the levels of toxic elements like arsenic and lead were not alarmingly high, the presence of elements like barium and molybdenum in higher concentrations than usual indicates potential mixed natural and anthropogenic origins. These

findings are essential for understanding the full spectrum of potential contaminants in Ecuadorian cocoa products and their implications for global trade, especially considering that some trace elements remained in cocoa liquor, albeit in lower concentrations (Vanderschueren et al., 2021, 2019). The research highlights varietal differences in how cacao plants absorb trace elements, including Cd. For instance, a positive correlation was found between Cd and zinc in the CCN-51 variety and Cd and nickel in the Nacional variety. These varietal differences underscore the need for further research to understand the internal mechanisms of cacao plants in relation to trace element absorption. This knowledge is vital for developing strategies to mitigate these elements' presence in cacao beans and ensuring that Ecuadorian cocoa products can meet international safety standards, thereby maintaining access to key global markets.

Geographic Distribution of Cadmium Contamination

The geographic distribution of cadmium (Cd) contamination in Ecuador shows clear patterns, with different regions exhibiting varying Cd levels in soil. Studies have revealed that these variations often align with climatic characteristics. For example, most soil samples from Peruvian cacao plantations, similar to Ecuadorian regions, showed Cd levels below the standard threshold for non-polluted soils. This comparison is crucial in understanding the geographic specificity of Cd contamination, which necessitates regionally adapted strategies in cocoa farming.

The relationship between Cd levels and soil properties like pH, as well as the impact of farming practices, underscores the complexity of managing Cd contamination. It's been observed that higher Cd concentrations are more common in alkaline soils and that the application of certain fertilizers doesn't significantly alter Cd levels. This indicates that the geographic and geological nature of the soil, rather than just agricultural practices, plays a crucial role in determining Cd levels. Hence, understanding these soil characteristics is vital for developing effective soil management strategies in cocoa-producing regions (Scaccabarozzi et al., 2020).

The variation in Cd levels across different regions, influenced by factors like climate, elevation, and geological substrate, highlights the need for targeted interventions in cocoa farming. This includes selecting appropriate cocoa varieties and tailoring soil management practices to local conditions. The understanding of how geological factors like sedimentary origin and erosion affect Cd levels can inform policy-making, emphasizing the need for a holistic approach that considers both natural and anthropogenic factors in managing cadmium contamination in cocoa production.

Long-term Implications for the Cocoa Industry

The long-term implications of Cd contamination in Ecuador's cocoa industry are multifaceted. Beyond immediate health concerns and market access issues, there's a growing need to address consumer perceptions and environmental sustainability. Ensuring the long-term viability of the cocoa industry in Ecuador will require a comprehensive approach, including continuous monitoring, research into low-Cd cocoa varieties, and collaboration between farmers, industry stakeholders, and policymakers. The goal is to balance economic, environmental, and health priorities to sustain Ecuador's reputation as a premium cocoa producer.

Conclusions

In conclusion, the issue of cadmium contamination in Ecuador's cocoa beans presents a multifaceted challenge with implications for public health, agricultural practices, and international trade. This research underscores the urgent need for targeted strategies to manage cadmium levels in cocoa production, emphasizing the importance of understanding regional soil characteristics, adopting appropriate agricultural practices, and complying with international safety standards. The future of Ecuador's cocoa industry hinges on successfully addressing these challenges, ensuring the safety and quality of its cocoa beans in the global market.

Furthermore, the study highlights the critical role of ongoing research and policy-making in addressing cadmium contamination. As Ecuador navigates the complexities of cadmium management, collaborative efforts between scientists, farmers, and policymakers are essential. These efforts should focus on developing sustainable agricultural practices, exploring innovative remediation techniques, and fostering a deeper understanding of the geographic distribution of cadmium. Such holistic approaches are vital for maintaining the integrity and competitiveness of Ecuador's cocoa industry in the international arena.

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