HCR
Humans and Chemical Regimes
HCR 3(1): 19–33
ISSN 3048-393X

Institute for Advanced Science, Social and Sustainable Future
MORALITY BEFORE KNOWLEDGE

Risk contamination Cadmium (Cd) in agricultural soil to national food security: An integrative study

Dea Hastaning Tantri[1,*]
[1] *Independent Researcher, Indonesia.*
*Correspondence: deahastaning@gmail.com

Received Date: November 21, 2025 Revised Date: February 5, 2026 Accepted Date: February 26, 2026

ABSTRACT

Background: Cadmium (Cd) contamination in agricultural soils poses serious risks to ecosystem stability, crop productivity, and food security in Indonesia. Industrial discharge and long-term agrochemical use contribute to increasing Cd accumulation, particularly in intensively cultivated and industrialized regions. This study evaluates spatial variation, contamination levels, and ecological risks of Cd in agricultural soils in West Java and Central Java. **Methods:** A quantitative descriptive–comparative approach was applied using secondary data from indexed scientific publications and Statistics Indonesia (BPS) for 2022–2024. Standardized Cd concentrations (mg/kg dry weight) obtained from AAS and ICP–OES analyses were synthesized. Contamination Factor (CF) and Ecological Risk factor (Er) were calculated using the Hakanson (1980) model. Correlation analysis examined the relationship between soil Cd levels and the percentage of polluted villages. **Findings:** Bandung Regency (West Java) showed the highest Cd concentration (6.6 mg/kg) with extreme ecological risk (Er = 990), linked to textile and electroplating industries and wastewater discharge. The Brebes–Demak–Pati region (Central Java) recorded moderate to high contamination (2.2 mg/kg; Er = 330), mainly from prolonged fertilizer and pesticide use. Despite soil contamination, Cd in rice from Semarang remained below detection limits (<0.02 mg/kg). A strong positive correlation (r = 0.72) confirms spatial association between industrial density and soil Cd burden. **Conclusion:** Cd contamination presents significant ecological risks, especially in industrial-agricultural zones. Strengthened industrial waste regulation, integrated soil–water monitoring, and periodic evaluation are essential to prevent further accumulation and safeguard food security. **Novelty/Originality of this article:** This study integrates ecological risk modeling with spatial-statistical correlation using recent national data, providing an updated comparative assessment of Cd contamination dynamics across key agricultural regions in Indonesia.

KEYWORDS: Cadmium (Cd); contamination agriculture; pollution soil; risk ecology.

1. Introduction

Cadmium (Cd) is one metal the weight in general shaped soft colored bluish or white silvery. Metal This in a way occurs naturally in soil, along with minerals and water (Charkiewicz et al., 2023). High toxicity and serious bioaccumulation rates make Cd classified as carcinogens group 1 (Zulfiqar et al., 2022). This carrying CD is ranked 7th in the list of 20 most toxic metals (Jaishankar et al., 2014). The presence of CDs is frequently found together with zinc, lead, or copper Because characteristic those who are similar. The largest Cd occurs in the industry metallurgy like factories smelting zinc or in purification iron rough (Charkiewicz et al., 2023). Concentration cadmium (Cd) in the crust continent is generally about 0.1 mg/kg of soil, however the level tends higher on the layer land above the land agriculture because it accepts additional CD from deposition air, fertilizer, and

Cite This Article:
Tantri, D. H. (2026). Risk contamination Cadmium (Cd) in agricultural soil to national food security: An integrative study. *Humans and Chemical Regimes, 3* (1), 19-33. https://doi.org/10.61511/hcr.v3i1.3243

materials to improve land (Sterckeman, 2025). Improvement of Cd levels in land can be caused by various factors, such as weathering geology, activities mining and smelting, emissions industry, emissions vehicles, irrigation using waste water, as well as production processes agriculture (Ran et al., 2024). Pollution metal weight in the environment agriculture has appeared as an issue important for environment and health communities around the world. Among various types of metal heavy, Cadmium (Cd) is known because of its high mobility, level of bioavailability, as well as its toxicity, which can cause degradation of severe ecological and risk health chronic through bioaccumulation in plants and chains food (Alloway, 2013).

Cd contamination in soil agriculture especially originates from anthropogenic emission industry, fertilizer phosphates, pesticides, and irrigation using contaminated water (Liu et al., 2021). Metal particles heavy and metalloid become pollutants in land agriculture because they potentially endanger health and disturb production plants if there is high concentration in earth. Metal heavy has resistant properties to degradation. Plants that are not capable of absorbing or dissolving it make metal heavy accumulated in land in the very long term (Angon et al., 2024). Cd resistance inside land cause threat term long Because no can decompose in a way biological and tend to Keep going accumulated along time Mechanism displacement cadmium (Cd) from land to root similar with mechanism displacement cation others. Form The main Cd is absorbed by cells root is Cd^{2+}. Gradient potential valuable electrochemistry negative on the membrane plasma push entry various cations, including Cd^{2+} from land to root in a way diffusion (Sterckeman, 2025). Plants absorb metal heavy from solution land through roots, which causes accumulation of metal weight on the network plants and give rise to risk of health potential for consumers when he enters in chain supply food (Hamoud et al., 2024). The entry of Cd^{2+} into in root started from wall cell outermost. Network walls cell root form apoplast, pathway where ions diffuse going to cylinder center root (stele), place vessels transport are located. Some of the ions will bind to the apoplast because the presence of loaded sites is negative that can complicate metal. When Cd reaches the Casparian band of metal this will be blocked by lignin and suberin so that He will enter to cytoplasm passing through the transporter protein located in the membrane cells (Sterckeman, 2025). The presence of accumulated Cd in cell plants This will bother conditions physiology and morphology plants. Plants can experience slow growth, small leaves, wide leaves, and yellowing. Disruption of pigments in plants because of the chlorophyll pigment or enzyme photosynthesis disturbed result in activities photosynthesis and metabolism in plants are also disturbed (Ran et al., 2024). Cadmium will Keep going accumulated in plants so that this also reduces quality plants so that also affects the quality from products results in agriculture.

Exposure to Cd through track consumption, absorption skin, and inhalation in developing countries was assessed higher. Condition This causes Adverse health impacts. The entry of Cd through contaminated food and water is source exposure main. Contaminated soil, water and feed metal are heavy because metals it also accumulates in plants food good to consume directly by humans or livestock (Hamoud et al., 2024). Exposure to Cd at low levels even though, can cause serious damage to human organs. High consumption or intensity can cause symptoms like painful stomach, sensation burning, nausea, vomiting, increased saliva production, cramps muscle, dizziness, shock, loss consciousness, or even seizures in 15–30 minutes after exposure (Charkiewicz et al., 2023). Simple can analogized although Cd content in plant or vegetable low, if level consumption high and deep term long time because is consumption main man so exposure This will endanger the health of the body (Hamoud et al., 2024). Examples that can be taken are height consumption rice. Indonesia is a country with a fairly high level of rice consumption. high. Research that has been conducted in Banyumas, Central Java, revealed that rice in the area has its own Cd content. Mentioned Cd in rice reached 0.10–2.16 ppm, and 9 of 37 locations (24.32%) exceeded the safety limit. food (0.4 ppm). that Cd levels in Banyumas rice fields reached 0.11–3.01 ppm, and 56.75% of the location exceeded the maximum limit (Ahadiyat et al., 2023).

In Indonesia, rapid industrialization and intensive agriculture has contributed to the accumulation of Cd gradually on the ground. Research previously shows that the area that combines activity industry and agriculture, especially in West Java, is more prone to increase in Cd due to industry textiles and metals (Anggraeni et al., 2024). In contrast, Central Java is dominated by landscape agriculture and its own potential accumulation of Cd especially from residue fertilizers and pesticides (Zu'amah et al., 2022). Although thus, the analysis of a comprehensive spatial that integrates laboratory data scientific and statistical environment is still very limited. Understanding pattern CD distribution is very important Not only for evaluating quality environment, but also for ensuring security, food and management sustainable land use. The Indonesian National Standard (SNI 7387:2009) limits Cd levels in soil agriculture up to ≤ 3 mg/kg and in grain rice up to ≤ 0.2 mg/kg. Exceeding this limit can lower fertility land and pollute material food mainly like rice, which is a component mainly in pattern Eat part big Indonesian society (Wahyuningsih et al., 2023).

With background behind said , research This done For analyze levels and distribution spatial Cd contamination in agricultural areas of Central Java and West Java, as well as evaluate risk ecological (Er) using secondary data from studies and reports national latest research this also aims For identify correlation between measured Cd concentrations and reports case pollution land from statistics national official , so that give greater understanding wide about condition Cd contamination in Indonesia. It is hoped that in the review study this will bring study more carry on regarding what actions and efforts should be taken in the future to evaluate and increasingly increase quality resilience food so that also improve the quality of health.

2. Methods

This study employs a descriptive–comparative quantitative approach to analyze the level of cadmium (Cd) contamination in agricultural areas in Indonesia. This approach is intended to provide a systematic comparison of contamination levels across different regions while maintaining objectivity through numerical data analysis. Ontologically, this research is grounded in the assumption that Cd pollution is an empirical phenomenon that can be objectively measured through observable and quantifiable indicators. Therefore, the study treats contamination levels as measurable realities that reflect environmental conditions influenced by human activities.

From an epistemological perspective, this research adopts a positivist paradigm, aiming to generate knowledge through systematic measurement, classification, and statistical analysis of secondary data. This paradigm emphasizes objectivity, replicability, and the use of standardized data sources, ensuring that the findings are both reliable and generalizable. Furthermore, the use of a quantitative framework allows for the identification of patterns, trends, and regional disparities in Cd contamination levels.

2.1 Location and period study

The study was conducted in two main regions on the island of Java: Central Java Province (particularly Brebes, Demak, and Pati Regencies) and West Java Province (Bandung Regency). The selection of these locations is based on their contrasting environmental and socio-economic characteristics, which are expected to influence the level and distribution of Cd contamination. Central Java represents an intensive agricultural region with extensive use of agrochemicals such as fertilizers and pesticides, which are known to contribute to heavy metal accumulation in soils. In contrast, West Java is characterized by dense industrial activities, including manufacturing and processing industries, which pose a significant risk of heavy metal pollution through industrial waste discharge. This comparative setting allows the study to capture different sources and pathways of Cd contamination.

The period of analysis was conducted from May to September 2024, coinciding with the dry season. This period was deliberately selected because agricultural activities and irrigation patterns tend to be more stable, reducing variability caused by rainfall and allowing for more consistent interpretation of contamination levels. Additionally, the dry season may intensify the concentration of heavy metals in soil due to reduced dilution effects.

2.2 Data and sources

All data used in this study are secondary data, obtained from one national statistical source and three peer-reviewed scientific publications indexed in reputable databases. The use of secondary data enables broader coverage of study areas while ensuring efficiency in data collection. The selected data sources were chosen based on their credibility, methodological rigor, and relevance to the research objectives. National statistical data provide macro-level insights into environmental and agricultural conditions, while scientific publications offer detailed measurements and analysis of Cd contamination at the field level.

To ensure consistency and comparability, all data were carefully reviewed, standardized, and analyzed using uniform criteria. This process includes verifying measurement units, aligning sampling methods where possible, and ensuring that the data reflect similar environmental contexts. The integration of multiple data sources strengthens the validity of the findings and supports a more comprehensive understanding of Cd contamination patterns.

Table 1. Sources and characteristics of secondary data

Source	Location	Sample type	Parameter
BPS (2024)	National (34 provinces)	Village / area data aggregated urban areas	Percentage villages that are polluted by land, water, or air
Zu'amah et al. (2022)	Brebes, Demak, Pati (Central Java)	child agriculture (land cultivation shallots)	Cd (mg/kg), I_geo
Wahyuningsih et al. (2023)	Semarang (Central Java)	Rice (Oryza sativa L.)	Cd (mg/kg)
Anggraeni et al. (2024)	Bandung (West Java)	Agricultural land and land area industry	Cd (mg/kg), Er

2.3 Variables and data processing

The main variables analyzed in this study include Cd concentration (mg/kg), sample type (soil or rice), provincial location, and ecological risk factor (Er). These variables were selected to provide a comprehensive understanding of both the distribution and potential environmental impact of Cd contamination across different regions. The inclusion of sample type allows for comparison between contamination in soil and its potential transfer to agricultural products, particularly rice as a staple food.

For studies that report multiple soil depths, the average concentration value was used to ensure consistency and comparability across datasets. This approach minimizes variability and allows for a more standardized interpretation of contamination levels. The background value for natural, uncontaminated soil was set at 0.2 mg/kg, following Loska & Wiechuła (2004), which serves as a reference point for assessing the degree of anthropogenic influence on Cd accumulation.

Furthermore, Cd concentration is classified into modified pollution categories based on Alloway (2013), where concentrations below 1 mg/kg are considered low, values between 1–3 mg/kg are categorized as moderate, concentrations of 3–8 mg/kg are classified as high, and levels exceeding 8 mg/kg are considered very high. This classification framework facilitates clearer interpretation of contamination severity and supports comparative analysis between regions. In addition, it provides a practical basis for linking contamination levels with potential ecological and health risks, thereby strengthening the analytical relevance of the study.

2.4. Analysis

To assess the potential environmental impact of cadmium contamination, a quantitative risk evaluation approach was applied. This approach allows for the integration of contamination levels with the toxicological characteristics of the metal, providing a more comprehensive assessment of ecological risk. Risk ecological from Cd contamination was evaluated using the Contamination Factor (CF) and Ecological Risk Factor (Er) developed by Håkanson (1980), with conditions: C_background = 0.2 mg/kg and T_r (Cd) = 30.

$$CF = \frac{C_{sample}}{C_{baground}} \quad \text{(Eq. 1)}$$

$$Er = Tr \times CF \quad \text{(Eq. 2)}$$

The risk level is interpreted as follows: an Er value of less than 40 indicates a low risk, values between 40 and 80 indicate a moderate risk, values between 80 and 160 reflect a considerable risk, values between 160 and 320 indicate a high risk, and values greater than 320 represent a very high ecological risk. This classification framework provides a standardized basis for evaluating ecological threats and enables consistent comparison of contamination severity across different regions and studies. Furthermore, it supports decision-making by identifying priority areas that require immediate environmental management and remediation efforts.

Descriptive statistical analysis was conducted to determine the average, minimum, maximum, and range values of Cd concentration in each region. Furthermore, comparative and correlational analyses were performed to evaluate the relationship between the average Cd levels per province and the percentage of polluted villages as reported by BPS (2024). The results of the analysis are presented in the form of tables illustrating spatial variation and the correlation patterns between measured Cd pollution levels and the national pollution database.

3. Results and Discussion

3.1 Variations spatial Cd contamination in agricultural land

Secondary data analysis shows existence variation sufficient spatially large in concentration Cadmium (Cd) in various regions and types samples studied. The agricultural - industrial zone in Bandung (West Java) has the highest average Cd concentration, namely 6.6 mg/kg. The Brebes–Demak–Pati region (Central Java) occupies the order next with an average of 2.2 mg/kg. Meanwhile, the Cd content in the sample rice from Semarang (Central Java) is very low, even below the detection limit (<0.02 mg/kg). This pattern shows a clear transition in level contamination, from the dominant area agriculture going to areas that have activity industry congested.

The highest Cd levels recorded in Bandung have exceeded the limits set by the Indonesian National Standard (SNI 7387:2009) for agricultural land (≤ 3 mg/kg), as well as the FAO/WHO (2007) threshold values. The calculated Contamination Factor (CF) and Ecological Risk Factor (Er) indicate that the Bandung area exhibits significantly higher levels of contamination and ecological risk compared to other regions (Håkanson, 1980). These findings suggest the presence of substantial contamination pressure in the region.

Table 2. Concentration Cadmium at the research site

Location	Sample type	Range (mg/kg)	Average (mg/kg)	Category pollution
Brebes–Demak–Pati (Central Java)	Farm	1.10–3.53	2.20	Intermediate to tall
Semarang (Central Java)	Rice (Oryza sativa L.)	<0.02	0.02	Low
Bandung (West Java)	Agricultural and industrial land	0.15–18.10	6.60	Very high

In contrast, Cd levels in Central Java remain within a moderate range and are relatively more manageable. This pattern reflects a clear transition from predominantly agricultural land use to areas characterized by dense industrial activity. These findings are consistent with previous studies, which reported that 56.75% of rice fields in Banyumas contain Cd levels exceeding the maximum permissible concentration (MPC), and 24.32% of rice samples exceed food safety standards (Ahadiyat et al., 2023).

3.2 Sources contamination: Industry vs agricultural inputs

Ecological analysis shows that the pattern of Cd contamination in West Java and Central Java originates from significantly different sources. In the Bandung area, high Cd levels are strongly correlated with industrial activities such as textile production, electroplating, metal manufacturing, and fossil fuel combustion, all of which generate waste rich in Cd, Pb, and Cr. International studies confirm that industrial and metallurgical sectors are dominant contributors to Cd emissions in various regions, followed by coal combustion and electroplating processes (Angon et al., 2024). This evidence is consistent with reports indicating that densely industrialized areas tend to have elevated Cd levels in irrigation water and sediments due to chronic exposure to untreated or partially treated wastewater (Rizwan et al., 2016). In addition, atmospheric deposition from industrial emissions may further contribute to Cd accumulation in surrounding agricultural soils, intensifying long-term environmental risks. The combination of point-source pollution and continuous emissions creates a cumulative contamination effect that is difficult to reverse without strict environmental regulation.

On the other hand, in the Brebes–Pati area, the source of contamination is more diffuse and primarily originates from the long-term accumulation of agricultural inputs. Phosphate fertilizers are known to contain Cd as an impurity, with certain formulations such as SP-36 containing approximately 8–20 ppm Cd. Continuous application of phosphate fertilizers contributes to the gradual buildup of Cd in the root zone. Intensive agricultural studies have shown that phosphate fertilizers and inorganic pesticides are among the main sources of Cd in rice paddy ecosystems in Asia (Nawab et al., 2018). This is in line with findings indicating that conventional high-input rice fields tend to have higher soil Cd content compared to low-input or organic farming systems. Furthermore, irrigation practices and soil properties, such as pH and organic matter content, can influence the mobility and bioavailability of Cd, thereby affecting its uptake by crops. Over time, this diffuse accumulation may pose significant risks to food safety and human health, particularly in staple crops such as rice.

The differences in contamination patterns imply the need for area-based mitigation strategies (Ahadiyat et al., 2023). In industrial areas such as Bandung, priority should be given to improving wastewater treatment systems, strengthening emission controls, and enhancing effluent quality monitoring. Additionally, stricter enforcement of environmental regulations and the adoption of cleaner production technologies are essential to reduce future contamination. Meanwhile, in intensive agricultural areas such as Brebes–Pati, mitigation strategies can focus on regulating fertilizer quality, monitoring Cd content in phosphate-based products, and promoting alternative practices such as the use of organic amendments and the selection of low Cd-accumulating rice varieties. Farmer awareness and sustainable agricultural practices also play a crucial role in minimizing long-term contamination risks. This source-based approach enables more precise and effective Cd risk management, ensuring that mitigation efforts are tailored to the dominant sources of pollution in each region.

3.3 Risks ecological based on Hakanson model

The Ecological Risk Factor (Er) value shows level different risks between regions. Bandung reached Er ≈ 990, which is included in the category of very *high ecological risk,* indicating threat Serious on soil biota and function ecosystem. Central Java has Er value ≈ 330, remains categorized as risk tall However Still within the limits that can be controlled. Profile risk strengthens results BPS mapping (2024), where 5.2% of villages in West Java and 2.8% in Central Java reported pollution. Pearson correlation (r=0.72) between Cd concentration results laboratory and proportions village polluted support validity BPS statistics as indicator beginning detection contamination.

Table 3. Contamination Factor (CF) and Ecological Risk Factor (Er) of Cd

Location	Average Cd (mg/kg)	CF = Cs/ Cb	Er = 30×CF	Category risk ecology
Brebes–Demak–Pati (Central Java)	2.20	11.0	330	Tall
Semarang (Central Java)	0.02	0.10	3	Low
Bandung (West Java)	6.60	33.0	990	Very high

The very high Ecological Risk (Er) value of 990 in Bandung indicates an extremely high ecological risk, posing serious threats to soil biota and leading to a decline in the quality of the surrounding environment. Meanwhile, the Er value of 330 in Central Java remains significant, although lower compared to Bandung, and still reflects considerable ecological pressure. The Cd content in rice from Semarang is still within safe limits, indicating that the transfer and accumulation of Cd into edible plant tissues remain relatively low at present. However, continuous exposure and long-term accumulation may increase the risk of Cd entering the food chain in the future if no preventive measures are taken. This condition highlights the importance of early monitoring before contamination reaches critical levels in agricultural products.

When these data are correlated with pollution data from BPS (2024), approximately 3.5% of villages in Indonesia are reported to experience land pollution, with the highest proportions found in West Java (5.2%) and Central Java (2.8%). Statistical analysis produced a Pearson correlation coefficient of r = 0.72, indicating a strong positive relationship between laboratory-measured Cd concentrations and the percentage of polluted villages. These findings reinforce that BPS data can serve as a reliable preliminary indicator for detecting heavy metal contamination in agricultural areas.

Furthermore, this relationship suggests that integrating national statistical data with field-based measurements can improve the accuracy of environmental assessments. It also provides a practical basis for policymakers to prioritize monitoring and mitigation efforts in high-risk regions. Such an integrated approach is essential for developing effective strategies to manage heavy metal contamination and to safeguard both environmental and public health.

3.4 Bioaccumulation in rice and health implications

Although soil Cd in some areas is quite high, high Cd in rice does not always increase comparable, appropriate principal Cd bioavailability is influenced by fraction clay, material organic, pH, and redox (Alloway, 2013). This explains why Semarang rice has very low Cd even though it is located in a nearby area with central urban activities. Other studies have found that 24.32% of rice in Banyumas contains Cd exceeding the FAO/WHO limit (0.2 – 0.4

mg/kg), confirming that accumulation in network plants is still at risk (Ahadiyat et al., 2023). It was recorded that chronic Cd exposure through food can trigger nephrotoxicity, damage liver, disorders enzyme thiol, pressure oxidative, up to cancer (Angon et al., 2024).

Apart from being influenced by condition land, variety Cd bioaccumulation in rice is also determined by the mechanism physiology of rice in translocating metal from root to grain. Recent studies show that the true Cd fraction can absorb the body (relative bioavailability/Cd-RBA) can reach 42–76%, depending on the mineral content, acid physic and character rice varieties (Yang et al., 2023). However, although total Cd content in rice is at the level of low value, high bioavailability still can increase risk exposure to toxicity. This is confirmed that evaluation risk must consider not only total Cd content, but also properties of its bioaccessibility.

Study toxicology food disclose that rice from “high-accumulator” varieties can trigger stress oxidative and injury mobile, whereas “low-accumulator” varieties show level greater bioaccessibility low and not cause significant inflammation response (Zhao et al., 2021). Approach agronomist like election varieties low Cd accumulation is an important mitigation strategy, especially in areas that have land with contamination moderate until tall.

From the side health society, Cd is known as highly bioaccumulative metal with *biological half-life* reach 10–30 years in kidneys, so that exposure chronic through consumption rice can trigger nephrotoxicity, tubular damage, stress oxidative, disorders heart, until improvement risk carcinogenic (Satarug et al., 2024). This is in line with findings in the field, such as research in Banyumas which shows that 24.32% of the sample rice has exceeded the FAO/WHO limits (Ahadiyat et al., 2023). Therefore, integration monitoring soil, testing bioavailability rice, and election rice varieties become important for lower potential long-term Cd exposure length on consumers.

3.5 Mechanism entry of Cadmium (Cd) from industrial/ mining activities to environment agriculture

Analysis results show that the Cd transfer from source industry / mining to land agriculture happens through a number of tracks integrated — atmospheric, hydrological, and solid material — that interact with each other depending on topography, management land, and characteristics of tailings or waste industry. The general scheme also described by Sterckeman (2025) includes stages following: emissions /leaching from sources, transport (air /water/ particles), deposition and accumulation in terrestrial media, changes speciation chemicals in the root zone, as well as absorption plant through root root or foliar (Sterckeman, 2025).

First, the path atmospheric — dust from activity mineral processing, dry tailings chunks, and emissions factories can transport faction particulates containing Cd to area agriculture surrounding; particles This then experiences deposition to surface land or plants. Atmospheric deposition is greatly influenced by the speed of wind, size particles, and distance from source (Hou et al., 2020). Deposition atmospheric often produces contamination “hotspots” on the surface soil and leaves, which later can wash to soil by rain or enter directly through the stomata under certain conditions. Second, the path hydrological and run-off are mechanisms mainly in areas that receive runoff from mine or industrial zones — including flow surface, tailings runoff, and mill effluent discharge to channel Irrigation. Case studies in mining areas show that irrigation and runoff water can donate proportionally big insert CD into land agriculture (sometimes >50–75% of total input), because Cd is dissolved in phase dissolved or transported as particulates suspended (Fan et al., 2022; SSRN case study). In the landscape plains low with network irrigation surface, flow This deposits Cd on the layer smooth (clay) which has capacity adsorption tall so that it creates accumulation term long. Third, mud /tailings and erosion physique present a solid material rich in Cd which, when not managed, can erode to rivers, canals, and rice fields. Failure tailings embankment or workmanship re-use the disposal area increase risk release of big material metal weight (Cacciuttolo et al., 2023). Tailing’s material can also cause local pH changes (e.g., acid mine drainage) that increase Cd solubility and enlarge its bioavailability.

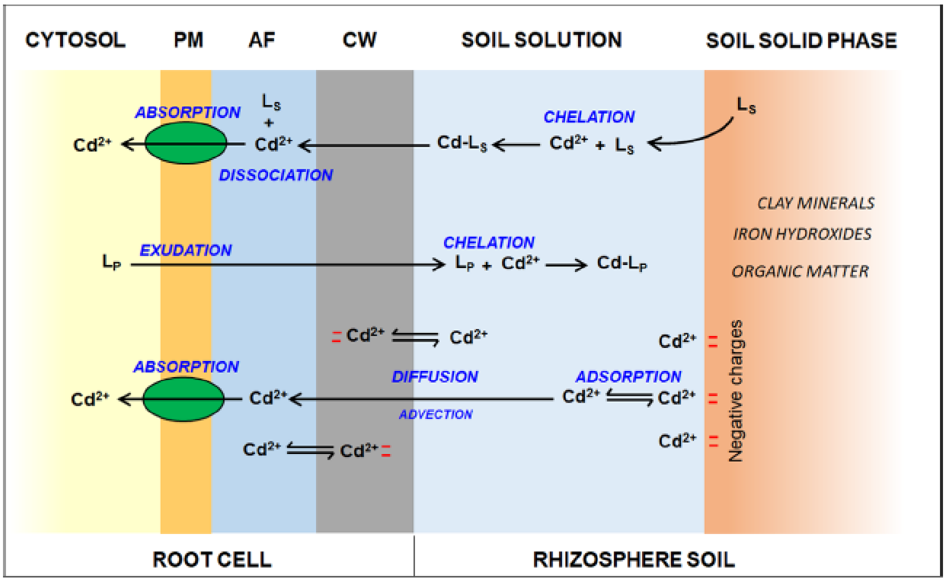

Fig. 1. Schematic representation of the main reactions and processes controlling cadmium (Cd) absorption at the root–soil interface. PM = plasma membrane (containing transport proteins, shown in green); AF = apoplastic fluid; CW = cell wall; LS = soil-derived organic ligands; LP = root exudate-derived organic ligands (Sterckeman, 2025).

After entering land, speciation Cd chemistry — what is it? bound to organics, adsorbed on Fe/Mn oxides, or is at as dissolved ion Cd^{2+} — determines mobility and availability for plants. Sterckeman (2025) emphasizes that transition between faction bound and dissolved are greatly influenced by pH, redox, and organic ligands exudate root; condition acid and redox changes (e.g., in the pattern flooding – drying of rice fields) increases available Cd fraction for absorbed roots. At the root level in plants, Cd utilizes nutrient transporters (e.g., Zn/Fe transporters) to enter cell root, then part stored in vacuoles root temporary part Again translocated to part on plants, including grain, depending genotype plants and conditions soil (Sterckeman, 2025; Hou et al., 2020).

Implications practical findings This emphasize the need mitigation layered: control emission particles and runoff at the site industry / mining, engineering tailings management, improvement practice irrigation for prevent dissolved input, as well as action management land at the level footprint (pH amendment, addition material organic or biochar) for lower availability of CD. Interventions that target stages crucial in chain source-pathway-recipient will be more effective compared to a single strategy, as suggested by review Cd input-output study (Fan et al., 2022) and study tailings impacts (Cacciuttolo et al., 2023).

3.6 Distribution pattern spatial and environmental dynamics

In a way spatially, Cd pollution tends to clustered in lowland areas low with overlapping overlap activity industry and agriculture, especially in the Bandung area south (Majalaya , Ciparay , and Pangalengan) —the area known own industry waste textiles and metals Cd- rich waste channel irrigation . On the other hand, the Central Java region north (Brebes–Pati) shows level contamination moderate, especially caused by accumulation of fertilizer phosphates and pesticides inorganic containing Cd as contaminants traces. Findings this in line with (Anggraeni et al., 2024), which states that waste industry textiles contribute big to increase in Cd in the land agriculture around.

Although Cd levels in rice from Semarang still are under threshold safe (<0.02 mg/kg), accumulation sustainable in land still causes risk term long through displacement metal to chain food. Statement This in accordance with findings, that Cd tends to accumulate in the system roots plants and can move to rice grains especially in acidic soil conditions (Wahyuningsih et al., 2023). Therefore, step prevention must focus on soil pH regulation, use fertilizer low Cd, as well as monitoring irrigation water quality.

Analysis more spatially wide shows that Cd distribution is not only influenced by proximity to source pollutants, but also by the dynamics's hydrology and texture. In the area plains low with irrigation surface, Cd tends to be transported through water flow and deposited on the ground textured clay that has capacity adsorption high (Xu et al., 2023). This causes persistent Cd "hotspot" patterns in the long term, even when source polluters are already reduced. On the other hand, the area with land sandy or structured off — even though rarer in the Javanese rice field landscape— shows greater Cd mobility so that potential enters to system roots faster.

Apart from the physical factors, management land like pattern flooding – drying participates influence Cd mobility. In the system *alternate wetting and drying* (AWD), change redox repetitive can dissolve back Cd from fraction Fe/Mn oxide, increasing available Cd fraction for plants (Zhang et al., 2021). Instead, the land is submerged in a consistent way and tends to maintain Cd in form not enough dissolved. Understanding the connection between dynamics redox and bioavailability of Cd is important for determining conservation strategies for land-based condition sites (site-*specific management).*

Repair conditions land through additional material organic, biochar, or mineral absorbent proven effective lower Cd mobility up to 20–70% in various studies in the field (Han et al., 2024). Amend the increased pH, enrich capacity swap cations, as well as bind Cd to more fractions stable. Intervention based land like this is important especially for areas that have shown chronic Cd accumulation consequence combination activity industry and agricultural inputs. Thus, the approach remediation must consider variability in spatial and dynamic environment so that it can cut off track Cd displacement from land to plant.

3.7 Implications study

Research results have these own implications for the environment, health society, system agriculture, and national policy. Concentration of high levels of cadmium (Cd) in certain areas like Bandung, especially with mark *Ecological Risk* (Er) is extreme, indicating that land agriculture currently is in degraded condition. Cd is known to hinder activity of microorganisms, lowering activity enzymes, as well as disrupt ecological processes like decomposition and mineralization nutrients (Zhang et al., 2022). Imbalance of ecosystem land These implications straight to the bottom fertility term length and capability land in maintaining productivity agriculture. In addition, the findings warn that area agriculture intensive can experience damage permanent If no quick action remediation, in particular because Cd is metal non-degradable weight that can endure in land during a number of decades (Alloway, 2013). In plant food, Cd causes stress physiological, inhibiting photosynthesis, reducing biomass, as well as absorption of essential nutrients such as Fe, Mg, and Zn (Khan et al., 2021). This not only reduces harvest, but also reduces quality results in agriculture. When Cd contamination reaches a point certain plants can experience accumulation of metal that finally enters chain food.

Implication's health becomes very significant remembering that Cd is a poisoned kidney, disruptor metabolism bones, and triggers stress oxidative chronic (Humphries et al., 2022). Although a number of sample rice like from Semarang shows very low Cd levels, conditions contaminated land still become threat Because changes in soil pH, use irrigation contaminated, or application fertilizer phosphate can increase Cd bioavailability and triggers displacement metal to network food (Wahyuningsih et al., 2023). This exacerbated by the fact that rice and vegetables certain own capacity high accumulation of Cd, so that population living in agricultural areas polluted own risk more exposure big. From the angle view policy, results study This demand exists to repair regulations about disposal waste industry, supervision quality fertilizer phosphate, and control potential agrochemicals and add Cd load on land agriculture. Implementation of phytoremediation using plant hyperaccumulators, such as *Brassica juncea* and vetiver, are one of the practical implications that can quickly be done because of proven effective lower Cd concentration in soil (Sari & Wicaksono, 2023). In addition, the findings of strong correlation between soil Cd levels and statistical data village pollution show the need for system warning early data- based, which can become guidelines for governments in prioritizing risk areas tall for intervention. Thus, research These own implications wide to management land, security food, health public, and environmental monitoring systems nationally.

3.8 Significance study

This has its own significance, high scientific and strategic, both in context of global literature as well as policy nationally. In general, scientific, research This give contribution means in understanding about pattern Cd pollution in developing countries with system agriculture and industry are interconnected overlapping overlap. Research results This strengthen theory about track double contamination (dual contamination pathways) — namely that Cd in land can originate from activity industry and agrochemical inputs like fertilizer phosphates and pesticides (Huang et al., 2021). In addition, the results study shows that total Cd concentration in soil No always reflect size accumulation in plant food, so that emphasize draft that Cd bioavailability is determined by the characteristics land such as pH, content material organic, and capacity swap cation (CEC) (Rizwan et al., 2016). This enriched literature about metal transfer mechanism heavy from land to plants, as well as expand reference about variability spatial Cd pollution in land agriculture.

From the side methodological, research shows the importance of approach integrative based on secondary data in map risk metal heavy. This is significant because it gives alternative economical cost and efficiency for a country like Indonesia which has a very large agricultural area and limited resources source Power study field. With combining laboratory data, national statistics, and references to scientific research, this proves that pattern Cd pollution can be identified in a way accurate without taking expensive intensive care (Kurniawan et al., 2020). In general, strategic research gives a strong base for development system monitoring nationally for metal weight, and can be made into references in compilation policy-based evidence (evidence-*based policy)* related security food, health society and governance waste industry. Significance research also lies in its contribution to global issues regarding food security — especially in context change climate that improves risk mobilization metal heavy in land. With Thus, research not only give benefit academic, but also valuable important for formulation policy environment and food term length at level national and international.

4. Conclusion

This study confirms the existence of a clear connection between level contamination Cadmium (Cd) in land and statistics pollution national figures reported by BPS on Java Island. show that the Bandung area is experiencing level contamination and risks the most serious ecological, reflecting pressure high environment consequence activity intensive industry and urbanization. On the other hand, Semarang shows relative safe conditions, indicating management of a better environment, good or exposure source of more low pollutants. Correlations strongly positive between Cd concentration in the field and indicators recorded pollution in a way official strengthening importance integration between scientific data and systems monitoring government approach integrated This not only increase accuracy evaluation risk, but also strengthen base for taking policy-based evidence. In the future, research needs to expand in a way that covers more many agricultural and urban areas in Indonesia, at the same time include analysis of heavy metals such as Pb, Hg, and As. Multi- metal approach will give greater understanding comprehensively about dynamics pollution and potential the impact to the health ecosystem and humans. Thus, the results studies can contribute directly to strengthening governance risk environments as well as development of more mitigation strategies effective and sustainable.

Acknowledgement

The authors convey sincere appreciation to the Ministry of Environment and Forestry of the Republic of Indonesia for provision of a quality data environment that can be accessible in an open way, which becomes important for study. Appreciation is also given to the Central Statistics Agency (BPS) for provision indicator data set comprehensive environments, which allows strong comparison between results measurement field and notes monitoring nationally. Commitment to a sustainable second institution to data transparency is a very supportive activity to study scientific and strengthening governance environment-based evidence in Indonesia. The authors also acknowledge contributions valuable to the officer's field and local data managers, whose assistance technically help ensure accuracy and reliability of the analysis presented in studies.

Author Contribution

The author contributed substantially to this study. The author was responsible for the conceptualization and study design, data collection and curation using secondary data sources, as well as data analysis and interpretation. The manuscript was drafted, reviewed, and revised by the author, who also approved the final version of the manuscript.

Funding

This research received no external funding.

Ethical Review Board Statement

Not available. This study did not involve human participants or animal subjects, as it was based entirely on secondary data.

Informed Consent Statement

Not available.

Data Availability Statement

The data used in this study are derived from publicly available sources, including published scientific articles and datasets provided by the Central Statistics Agency (BPS). Additional data supporting the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflict of interest.

References

Ahadiyat, Y. R., Fauzi, A., Herliana, O., & Hadi, S. N. (2023). Mapping heavy metals accumulation in conventional rice farming systems in Banyumas Regency, Central Java, Indonesia. *Journal of Degraded and Mining Lands Management, 10*(4), 4583–4592. https://doi.org/10.15243/jdmlm.2023.104.4583

Alloway, B. J. (2013). *Heavy metals in soils: Trace metals and metalloids in soils and their bioavailability* (3rd ed.). Springer. https://doi.org/10.1007/978-94-007-4470-7

Anggraeni, D., Oginawati, K., Fahimah, N., Salami, I. R. S., Absari, H. R., Mukhaiyar, U., Pasaribu, U. S., Sari, K. N., & Adiyani, L. (2024). Analysis of heavy metals (Pb and Cd) in soil layers of Indonesia: Spatial distribution, potential source, and groundwater effect. *Case Studies in Chemical and Environmental Engineering, 9*, 100652. https://doi.org/10.1016/j.cscee.2024.100652

Angon, P. B., Islam, M. S., KC, S., Das, A., Anjum, N., Poudel, A., & Suchi, S. A. (2024). Sources, effects and present perspectives of heavy metals contamination in soil, plants, and the human food chain. *Heliyon, 10*, e28357. https://doi.org/10.1016/j.heliyon.2024.e28357

Badan Pusat Statistik. (2024). *National environmental statistics: Polluted villages report*. BPS.

Cacciuttolo, C., Cano, D., & Custodio, M. (2023). Socio-environmental risks linked with mine tailings chemical composition: Promoting responsible and safe mine tailings management considering copper and gold mining experiences from Chile and Peru. *Toxics, 11*(5), 462. https://doi.org/10.3390/toxics11050462

Charkiewicz, A. E., Omeljaniuk, W. J., Nowak, K., Garley, M., & Nikliński, J. (2023). Cadmium toxicity and health effects: A brief summary. *Molecules, 28*, 6620. https://doi.org/10.3390/molecules28186620

Fan, T., Long, T., Lu, Y., & Yang, L. (2022). Meta-analysis of Cd input-output fluxes in agricultural soil. *Chemosphere, 303*, 134974. https://doi.org/10.1016/j.chemosphere.2022.134974

Håkanson, L. (1980). An ecological risk index for aquatic pollution control: A sedimentological approach. *Water Research, 14*(8), 975–1001. https://doi.org/10.1016/0043-1354(80)90143-8

Hamoud, Y., Shaghaleh, H., Zia-ur-Rehman, M., Rizwan, M., Umair, M., Usman, M., Ayub, M. A., Riaz, U., Alnusairi, G. S. H., & Alghanem, S. M. S. (2024). Cadmium and lead accumulation in food crops due to wastewater irrigation: Pollution index and health risk assessment. *Heliyon, 10*, e24712. https://doi.org/10.1016/j.heliyon.2024.e24712

Han, J., Wu, D., Yang, J., Shi, Y., Abid, G., Wang, L., & Li, Z. (2024). A biochar-based amendment improved cadmium (Cd) immobilization, reduced its bioaccumulation, and increased rice yield. *Frontiers in Environmental Science, 12*. https://doi.org/10.3389/fenvs.2024.1487190

Hou, D., O'Connor, D., Nathanail, P., Tian, L., & Ma, Y. (2020). Integrated GIS and multivariate statistical analysis for regional-scale assessment of heavy metal soil contamination: A critical review. *Nature Reviews Earth & Environment*. https://doi.org/10.1016/j.envpol.2017.07.021

Huang, X., Wang, L., Li, Y., & Wang, Y. (2021). Spatial variation and influencing factors of potential ecological risk in farmland soils. *Frontiers in Environmental Science, 9*, 621789. https://doi.org/10.3389/fenvs.2021.621789

Jaishankar, M., Tseten, T., Anbalagan, N., Mathew, B. B., & Beeregowda, K. N. (2014). Toxicity, mechanism and health effects of some heavy metals. *Interdisciplinary Toxicology, 7*(2), 60–72. https://doi.org/10.2478/intox-2014-0009

Li, Z., Ma, Z., van der Kuijp, T. J., Yuan, Z., & Huang, L. (2014). A review of soil heavy metal pollution from mines in China. *PLOS ONE, 9*(9), e107243. https://doi.org/10.1371/journal.pone.0107243

Li, H., Luo, N., & Li, Y. (2020). Bioavailability and mobility of cadmium in agricultural soils: A critical review. *Frontiers in Environmental Science, 8*, 106.

https://doi.org/10.3389/fenvs.2020.00106

Liu, X., Song, Q., Tang, Y., Li, W., Xu, J., Wu, J., Wang, F., & Brookes, P. C. (2021). Human health risk assessment of heavy metals in soil–vegetable system. *Environmental Pollution, 277*, 116795. https://doi.org/10.1016/j.envpol.2021.116795

Loska, K., & Wiechuła, D. (2004). Application of principal component analysis for the estimation of sources of heavy metal contamination in surface soils from Upper Silesia (Poland). *Environmental Geology, 47*(6), 724–733. https://doi.org/10.1007/s00254-004-1181-1

Ma, J., Chen, Y., Wang, Y., & Li, X. (2021). Heavy metals alter soil microbial communities. *BMC Microbiology, 21*, 147. https://doi.org/10.1186/s12866-021-02167-4

Nawab, J., Khan, S., Xiaoping, W., Khan, A., Muhammad, S., & Huang, Q. (2018). The role of phosphatic fertilizers in cadmium accumulation in soils and crops. *Environmental Pollution, 241*, 293–300. https://doi.org/10.1016/j.envpol.2018.05.086

National Standardization Agency of Indonesia (BSN). (2009). *Indonesian National Standard (SNI 7387:2009): Maximum limits of heavy metal contamination in food*. BSN.

Ran, T., Cao, G., Xiao, L., Li, Y., Xia, R., Zhao, X., Qin, Y., Wu, P., & Tian, S. (2024). Effects of cadmium stress on plant growth. *BMC Plant Biology, 24*, 850. https://doi.org/10.1186/s12870-024-05551-1

Rizwan, M., Ali, S., Abbas, T., Zia-ur-Rehman, M., Hannan, F., Keller, C., & Ok, Y. S. (2016). Cadmium minimization in wheat. *Environmental Science and Pollution Research, 23*(18), 17839–17852. https://doi.org/10.1007/s11356-016-6959-1

Satarug, S., Vesey, D. A., & Gobe, G. C. (2024). Human health effects of cadmium: Toxicokinetics, biomarkers, and chronic disease risks. *Toxicology Letters, 392*, 1–15. https://doi.org/10.1016/j.toxlet.2023.11.004

Sun, K., Chen, J., Yang, Y., & Li, H. (2021). Integrating remote sensing and secondary data for soil contamination assessment. *Environmental Science and Pollution Research, 28*, 30392–30405. https://doi.org/10.1007/s11356-021-12492-0

SSRN. (n.d.). Cadmium accumulation in farmlands through deposition or irrigation downstream of mining areas (Working paper). SSRN. https://papers.ssrn.com/sol3/Delivery.cfm/

Sterckeman, T. (2025). Soil to plant transfer of cadmium. *OCL, 32*, 14. https://doi.org/10.1051/ocl/2025015

Wahyuningsih, N. E., Setiawan, H., Nabiha, P. I., & Kartasurya, M. (2023). Heavy metals contamination of local and imported rice in Semarang, Central Java, Indonesia. *Journal of Ecological Engineering, 24*(7), 49–60. https://doi.org/10.12911/22998993/163308

Wang, F., Wang, J., Song, N., & Li, Y. (2019). Distribution and ecological risk assessment of heavy metals in farmland soils. *International Journal of Environmental Research and Public Health, 16*(22), 4658. https://doi.org/10.3390/ijerph16224658

Wang, L., Liang, T., & Zhang, H. (2022). Cadmium bioavailability in soils. *Journal of Hazardous Materials, 425*, 127540. https://doi.org/10.1016/j.jhazmat.2021.127540

Wieczorek, J., et al. (2018). Assessment of the pollution and ecological risk of lead and cadmium in soils. *Environmental Geochemistry and Health, 40*, 2325–2342. https://link.springer.com/article/10.1007/s10653-018-0100-5

Xu, X., Liu, X., Zhang, Q., Wang, Y., & Chen, W. (2023). Distribution of cadmium and lead in soil–rice systems and their environmental driving factors at the island scale. *Science of the Total Environment, 878*, 164512. https://doi.org/10.1016/j.scitotenv.2023.164512

Yang, L., Zhang, X., Zhao, D., Wang, P., & Zhao, F. (2023). Bioavailability of cadmium in rice. *Foods, 12*(5), 984. https://doi.org/10.3390/foods12050984

Zhang, Y., Wang, J., Chen, W., Li, Q., & Jiang, X. (2021). Soil pH and redox-driven cadmium bioavailability in paddy fields: Implications for rice accumulation. *Journal of Hazardous Materials, 403*, 123456. https://doi.org/10.1016/j.jhazmat.2020.123456

Zhao, Q., Liu, Y., Sun, Z., & Chen, H. (2021). Bioaccessibility and toxicological response of cadmium from rice with different accumulation capacities. *Food and Chemical Toxicology, 156*, 112523. https://doi.org/10.1016/j.fct.2021.112523

Zu'amah, N., Suryadi, E., Prasetyo, B. H., & Kurniawan, A. (2022). Cadmium contamination in Indonesian paddy soils. *Journal of Agricultural Chemistry and Environment, 11*(4), 412–425. https://doi.org/10.4236/jacen.2022.114029

Zulfiqar, U., Jiang, W., Wang, X., Hussain, S., Ahmad, M., Maqsood, M. F., Ali, S., Ishfaq, M., Kaleem, M., Naveed, M., & Mustafa, A. (2022). Cadmium phytotoxicity, tolerance, and advanced remediation approaches in agricultural soils: A comprehensive review. *Frontiers in Plant Science, 13*, 773815. https://doi.org/10.3389/fpls.2022.773815

Biographies of Author

Dea Hastaning Tantri, Independent Researcher, Indonesia

- Email: deahastaning@gmail.com
- ORCID: 0009-0003-2783-2667
- Web of Science ResearcherID: N/A
- Scopus Author ID: N/A
- Homepage: N/A