

EVALUATION OF SOIL MICRONUTRIENT (Fe, Mn, Cu, AND Zn) AND TOXIC HEAVY METALS (Pb AND Cd) IN AGRICULTURAL LANDS OF BREBES REGENCY, CENTRAL JAVA

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ABSTRACT

Intensive agricultural practices accompanied by continuous application of fertilizers and pesticides may alter soil nutrient balance and affect soil quality. This study aimed to evaluate the availability of essential micronutrients (Fe, Mn, Cu, and Zn), Pb and Cd content in agricultural soils of Brebes Regency, Central Java. Soil samples were collected from 39 locations representing contrasting agroecological conditions in the northern and southern regions. Soil chemical properties were analyzed, while micronutrients, Pb, and Cd availability were determined using diethylenetriaminepentaacetic acid (DTPA) extraction, and total Pb and Cd was measured by wet digestion using HNO₃-HClO₄. The results showed that essential micronutrients availability (Fe ranging from 63.7-152 ppm, Cu 6.62-10.6 ppm, Zn 2.12-3.39 ppm, and Mn 62.1-86.2 ppm) were generally in the sufficient category. The availability of Fe, Cu, and Zn in the northern region was significantly lower than in the southern region, while Mn did not differ significantly. Total Pb and Cd concentrations (ranged from 6.10-6.55 ppm and 0.21-0.44 ppm, respectively) in both regions were within normal threshold limits. However, Pb and Cd bioavailability was higher in the northern region (reaching 10.9% and 35.5%, respectively) compared to 5.07% and 30.5% in the southern region, with Cd showing greater bioavailability than Pb. These findings indicate that intensive land management affects micronutrient distribution and heavy metal behavior in soils. The results provide important information for soil quality evaluation and balanced nutrient management to support sustainable agricultural practices in Brebes Regency.

Key words: Brebes, intensive agricultural practice, nutrient management, soil quality

INTRODUCTION

Indonesia's food demand continues to increase in line with population growth and socio-economic development, thereby intensifying pressure on agricultural land to maintain and improve crop productivity (Arifin *et al.*, 2019; Chaireni *et al.*, 2020; Salasa, 2021). In response to this demand, intensive agricultural practices have been widely adopted, particularly through the continuous application of inorganic fertilizers and pesticides. Although these practices enhance short-term yields, long-term agricultural intensification through excessive fertilizer and pesticide use can degrade soil health, alter soil chemical balance, and leave persistent residues, thereby necessitating careful evaluation and sustainable management to support long-term agricultural sustainability (Al-Busaidi *et al.*, 2022; Sahara *et al.*, 2025). Brebes Regency is one of the major agricultural production centers in Indonesia, especially for shallots and other food crops. To achieve high yields, farmers in this region commonly apply large amounts of nitrogen (N), phosphorus (P), and potassium (K) fertilizers, often exceeding recommended rates, combined with frequent pesticide applications (Basuki, 2009; Susilawati *et al.*, 2019). According to BPS (2019), shallots dominate agricultural production in Brebes Regency, followed by rice, maize, chili, cassava, and other food crops. This intensive cropping system has been maintained for long periods under contrasting regional conditions, where the northern part of Brebes Regency is characterized by lowland areas, while the southern part consists of highland regions. Most intensive farming systems are practiced in the northern of Brebes Regency.

Continuous and excessive application of N, P, and K fertilizers can significantly alter soil chemical properties

and nutrient interactions. High rates of P fertilization are known to reduce the availability of essential micronutrients such as Zn, Fe, Mn, and Cu through precipitation reactions, competitive adsorption, and the formation of insoluble complexes in the soil (Ali *et al.*, 2014; Mondal dan Hazra, 2018). Similarly, excessive N fertilization may affect soil pH and organic matter dynamics, indirectly influencing micronutrient solubility and uptake by plants (Liu *et al.*, 2023; Zhang *et al.*, 2024). As a result, soils under long-term intensive fertilization may exhibit sufficient or even excessive macronutrient status while simultaneously experiencing micronutrient deficiency, particularly Zn (Puniya *et al.*, 2019).

In addition to its effect on micronutrient availability, prolonged and intensive use of inorganic fertilizers and agrochemicals may contribute to the accumulation of potentially toxic heavy metals in agricultural soils. Phosphate fertilizers, in particular, are known to contain trace amounts of heavy metals such as Cd and Pb, which can gradually accumulate in soil with repeated application. Pesticide use in shallot farming in Brebes Regency is widely reported to be intensive, including frequent spraying with short intervals and the common practice of mixing multiple insecticides in a single application, a pattern often associated with efforts to maintain efficacy under high pest pressure and resistance issues (Basuki, 2009; Adiyoga *et al.*, 2022). Under certain soil conditions, including low organic matter content and specific pH ranges, these metals may become more bioavailable and pose risks to crop quality, environmental health, and food safety. The impact of intensive fertilization on soil micronutrients and heavy metals may be further modified by regional soil characteristics and land management practices. Differences in parent material, soil

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pH, cation exchange capacity (CEC), topography, soil texture, and organic matter content between northern and southern regions of Brebes Regency are expected to influence nutrient retention, metal mobility, and bioavailability. Soils in the northern region generally develop from alluvial deposits with fine to medium textures and relatively low organic matter due to intensive land management. In contrast, the southern region, dominated by volcanic parent material, has a more varied texture and higher organic matter. Therefore, a comprehensive assessment of essential micronutrient availability and toxic heavy metal content is necessary to understand soil quality conditions under intensive agricultural management.

This study aimed to evaluate the essential micronutrients availability (Fe, Mn, Cu, and Zn) and the content of toxic heavy metals (Pb and Cd) in soils of the northern and southern regions of Brebes Regency. The results are expected to provide scientific evidence for soil quality evaluation and to support balanced fertilization strategies as part of sustainable agricultural management in intensively cultivated areas.

MATERIALS AND METHODS

Study Area

The study was conducted in shallot-growing areas of Brebes Regency, Central Java, Indonesia. Soil sampling was carried out at 39 locations distributed across 36 villages in 17 sub-districts, representing contrasting agroecological conditions between the northern and southern regions of Brebes Regency. Soil samples were taken on agricultural land with shallot, corn, mung beans, rice, and cassava commodities intercropped with bananas, as well as forest land with teak and pine commodities by purposive random sampling by considering land with potential for shallot cultivation, while outside agricultural land as a comparison. The sampling sites were located at altitudes ranging from 4 to 1000 meters above sea level and at slopes of 0 to 39%. A total of 32 sampling points were located in the northern region and 7 sampling points were located in the southern region (Figure 1). The northern region, which represents the main intensive agricultural zone, required a higher sampling density to capture spatial variability in soil properties. In contrast, the southern region has more limited and heterogeneous agricultural land, resulting in fewer sampling points. Thus, the sampling design prioritized representativeness of soil variability. Inceptisols were the dominant soil type in both the northern and southern regions of the study area, although in the southern region there is an area with Andisols.

Soil Sampling and Analysis

Soil samples were collected using a composite sampling method, in which each composite sample consisted of 5-10 subsamples taken randomly within each

sampling plot. Soil samples were taken at a depth of 0-20 cm. In total, 39 sampling points were established. Soil samples collected from the field were air-dried to a constant moisture condition, then ground using a mortar and pestle, and sieved to obtain particle fractions passing through 2 mm and 0.5 mm sieves. The prepared soil samples were subsequently analyzed to determine the available concentrations of micronutrients (Fe, Mn, Cu, and Zn), the available and total concentrations of toxic heavy metals (Pb and Cd), as well as selected soil chemical properties. Detailed analytical methods are presented in Table 1. Determination of exchangeable bases, toxic heavy metal and micronutrient concentrations was performed using an Atomic Absorption Spectrophotometer (AAS).

Measurements of micronutrients, Pb, Cd, and selected soil chemical properties were conducted at the Soil Chemistry and Fertility Laboratory, Department of Soil Science and Land Resources, Faculty of Agriculture, IPB University. The criteria for assessing soil chemical properties and micronutrients are based on the criteria of the Eviati *et al.* (2023). The total toxic heavy metal concentrations measured in study area were subsequently compared with established critical threshold values for heavy metals in soils refers to Alloway (1995). Bioavailability of heavy metals was calculated by dividing the concentration of extracted metals by total metals and multiplying by 100% (Mahendra *et al.*, 2018).

Table 1. Soil Chemical Analysis Methods

No.	Parameters	Methods
1	pH	H ₂ O 1:5
2	Organic Carbon	Walkley and Black
3	CEC	NH ₄ OAc 1 N pH 7.0 Extraction
4	Exchangeable Bases (Ca, Mg, K, and Na)	NH ₄ OAc 1 N pH 7.0 Extraction
5	Available Micronutrients (Fe, Mn, Cu, and Zn)	DTPA Extraction (<i>Diethylenetriaminepentaacetic Acid</i>)
6	Available Pb and Cd	
7	Total Pb dan Cd	Wet digestion using HNO ₃ -HClO ₄

Data Analysis

Data analysis was carried out with the help of microsoft office software, namely microsoft excel and microsoft word. Pearson correlation tests were conducted on the SAS On Demand Academic Studio website to see the relationship between soil chemical properties and the availability of essential micronutrients and toxic heavy metals. To compare the availability of micronutrients, Pb, and Cd between the northern and southern regions, an independent t-test was used at a 5% significance level. For parameters with a *p-value* > 0.05, H₀ is accepted (the parameter values in the two regions are not significantly different), while for *p-value* < 0.05, H₁ is accepted (the parameter values in the two regions are significantly different). Independent t-test was conducted on the R studio.

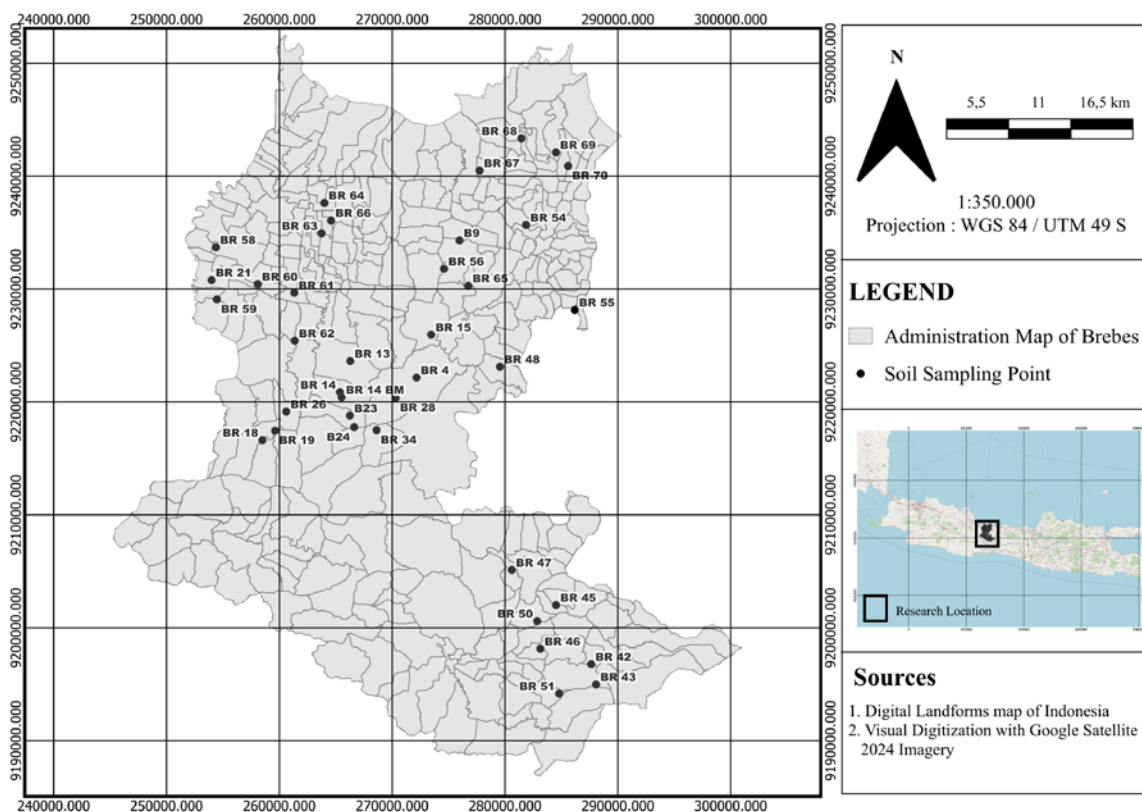


Figure 1. Map of soil sampling locations on several farms in Brebes District (Nadalia *et al.*, 2025)

RESULTS AND DISCUSSION

The Soil Chemical Properties in Study Area

Soil chemical properties differed markedly between the northern and southern regions of Brebes Regency (Table 2), reflecting contrasting agroecological conditions and long-term management intensity. Soils in the northern region were generally neutral (mean pH 6.9), whereas soils in the southern region were slightly acidic (mean pH 5.9). Soil reaction is a primary factor controlling nutrient availability and metal mobility in soils. Neutral to slightly alkaline conditions may decrease the solubility of micronutrients such as Fe, Mn, and particularly Zn due to precipitation reactions and stronger adsorption onto soil colloids. High phosphate availability under intensive fertilization can further promote the formation of less soluble Zn compounds (Alloway, 1995; Ahmed *et al.*, 2024). Conversely, slightly acidic conditions generally enhance micronutrient solubility, as demonstrated in tropical acid soils where extractable Fe, Mn, Zn, and Cu closely follow soil acidity and sorption dynamics (Supriatin dan Salam, 2024).

Organic carbon content was low in the northern region (mean 1.31%) but moderate in the southern region

(mean 2.54%). Soil organic matter plays a crucial role in nutrient retention and metal complexation through organo-metal interactions. Lower organic carbon in the northern lowlands is likely related to intensive cropping and limited residue return, whereas higher carbon levels in the southern uplands may enhance nutrient buffering capacity. Recent evidence suggests that carbon availability interacts with exchangeable base cations and nutrient dynamics under long-term intensive fertilization systems (Jiang *et al.*, 2024).

Cation exchange capacity (CEC) was very high in the northern region (44.2 cmol(+)/kg) and moderate in the southern region (22.1 cmol(+)/kg). This condition is influenced by the relatively higher proportion of 2:1 clay minerals in the northern region compared to the southern region. Exchangeable Ca, Mg, and K were substantially higher in the northern soils, indicating prolonged accumulation of base cations under intensive fertilization. While high CEC improves macronutrient retention, excessive base cation saturation may alter micronutrient balance through competitive adsorption processes (Fageria, 2016). These contrasting soil chemical characteristics provide a mechanistic framework for understanding regional differences in micronutrient distribution and behavior.

Table 2. Soil chemical properties in study area

Soil Chemical Properties	Min	Max	Mean	Criteria
North Brebes (n=32)				
pH H ₂ O 1:5	5.1	8.1	6.9	Neutral
Organic C (%)	0.5	2.7	1.31	Low
CEC (cmol(+)/kg)	17.6	56.5	44.2	Very High
Exchangeable Ca (cmol(+)/kg)	22.7	79.5	44.3	Very High
Exchangeable Mg (cmol(+)/kg)	2.06	12.9	7.19	High
Exchangeable Na (cmol(+)/kg)	0.07	4.07	0.63	Medium
Exchangeable K (cmol(+)/kg)	0.13	2.33	0.56	High
South Brebes (n=7)				
pH H ₂ O 1:5	5.3	6.2	5.9	Slightly Acid
Organic C (%)	1.80	3.18	2.54	Medium
CEC (cmol(+)/kg)	11.1	27.0	22.1	Medium
Exchangeable Ca (cmol(+)/kg)	1.94	19.1	14.1	High
Exchangeable Mg (cmol(+)/kg)	0.37	5.35	3.63	High
Exchangeable Na (cmol(+)/kg)	0.06	0.39	0.22	Low
Exchangeable K (cmol(+)/kg)	0.10	1.16	0.39	Low

Source: Nadalia *et al.* (2025)

Essential Micronutrients

The levels of Fe, Mn, Cu, and Zn available in the research locations in both the northern and southern regions are in the sufficient category. The availability of soil Fe, Mn, Cu and Zn in the northern region of Brebes Regency is relatively lower than that in the southern region. The t-test results showed that the availability of Fe, Cu, and Zn in the northern region was significantly lower than in the southern region, while Mn did not show a significant difference (Table 3). This is due to different soil management practices and land use between the two regions. The northern region of Brebes Regency, which is in the form of lowlands area, is dominated by shallot and rice agricultural land use with land management systems that experience periodic flooding. Repeated flooding-drying cycles cause fluctuations in soil redox conditions. Under flooding (anaerobic) conditions, Fe³⁺ and Mn⁴⁺ are reduced to the more soluble Fe²⁺ and Mn²⁺, whereas under dry (aerobic) conditions, these nutrients are re-oxidized and precipitated as oxides or hydroxides. In addition, available nutrients can also be absorbed by plants for plant growth. Nutrient loss from surface soil can also occur through leaching, especially if it gets a large water flow discharge such as high rainfall, heavy irrigation, or erosion so that nutrients become lower.

Table 3. Essential micronutrient status in northern and southern Brebes Regency

Essential micronutrient	Brebes Regency		p-value
	North	South	
Available Fe (ppm)	63.7 ± 33.9	152 ± 34.4	0.000
Available Cu (ppm)	6.62 ± 2.76	10.6 ± 2.00	0.001
Available Zn (ppm)	2.12 ± 1.05	3.39 ± 1.16	0.027
Available Mn (ppm)	62.1 ± 64.2	86.2 ± 88.8	0.516

The values expressed are mean ± SD. p-value < 0.05 significant value

The southern region is dominated by highland or mountainous areas with pine forest land use and agricultural land use of shallots, rice, cassava intercropped with bananas, and corn. Differences in the availability of micronutrients Fe, Mn, Cu, and Zn are caused by soil properties, topography, climatic factors, and vegetation (Zhu *et al.*, 2021). In general, higher elevations tend to be associated with greater soil organic carbon and modified nutrient dynamics due to cooler temperatures, reduced

decomposition rates, and changes in vegetation and microclimate (Sun *et al.*, 2025).

Zn showed the clearest regional contrast, with consistently lower mean values in the northern region. Zn availability is strongly controlled by soil pH and sorption precipitation processes; as soil pH approaches neutral to alkaline conditions, Zn becomes less soluble due to stronger adsorption onto soil surfaces and the formation of less available. Recent syntheses confirm the dominant role of soil physicochemical properties, particularly pH and reactive surfaces in regulating Zn retention and release (Yu *et al.*, 2023). Moreover, long-term intensive systems characterized by high phosphorus inputs may intensify P-Zn antagonism through the formation of less soluble Zn-phosphate compounds and reduced plant uptake efficiency (Nadeem *et al.*, 2024). These mechanism explain why Zn concentrations were relatively lower in the northern soils despite adequate macronutrient status. In contrast, higher extractable Fe in the southern region is consistent with slightly acidic conditions and greater organic matter, which promote micronutrient solubility and complexation rather than precipitation.

Mn exhibited the widest variability, reflecting its strong dependence on both pH and redox dynamics. This is indicated by the high standard deviation of Mn, likely driven by redox dynamics and differences in environmental conditions among locations. Periodic saturation and drainage cycles can shift Mn between oxidized and reduced forms, substantially altering its soluble fraction (Wang *et al.*, 2022; Khoshru *et al.*, 2023). Cu availability, meanwhile, appears closely linked to organic matter content, as Cu forms stable complexes with organic functional groups that regulate its mobility and extractability (Eduah *et al.*, 2024). Although all micronutrients were classified as sufficient, the consistent lower Zn and generally lower micronutrient means in the northern region suggests a potential risk of nutrient imbalance under continued macronutrient dominated fertilization. Therefore, periodic monitoring of plant available Zn and implementation of balanced fertilization strategies are essential to sustain long-term productivity in intensive shallot systems.

Toxic Heavy Metals

The levels of total-Pb and Cd, and available Pb and Cd in the study areas in both the northern and southern

regions are in the normal category. Soil total-Pb, total-Cd, and available Cd levels in the northern region of Brebes Regency are relatively lower than those in the southern region. The t-test results indicated that available Pb was significantly higher in the northern soils, whereas total-Cd was significantly lower compared to the southern soils (Table 4). Lead is typically retained in relatively stable fractions through strong sorption to clay minerals, Fe-Mn oxides, and organic matter, particularly under neutral to slightly alkaline conditions. However, high base saturation and competitive cation interactions may influence Pb exchange equilibria and redistribute Pb into weakly adsorbed fractions. Bradl (2004) emphasized that even in soils with low total Pb concentrations, changes in pH, ionic strength, and cation competition can modify Pb lability without substantially altering total content. Therefore, the higher extractable Pb in the northern region may reflect shifts in surface binding equilibria rather than external contamination sources.

Table 4. Toxic heavy metal status of soil in the northern and southern regions of Brebes Regency

Toxic heavy metal	Brebes Regency		p-value
	North	South	
Total-Pb (ppm)	6.10 ± 1.16	6.55 ± 1.72	0.524
Available Pb (ppm)	0.67 ± 0.68	0.13 ± 0.16	0.000
Total-Cd (ppm)	0.21 ± 0.17	0.44 ± 0.20	0.020
Available Cd (ppm)	0.07 ± 0.05	0.10 ± 0.05	0.130

The values expressed are mean ± SD. p-value < 0.05 significant value

The threshold value of Pb normal soil is 2-300 mg/kg, critical is 100-400 mg/kg (Alloway, 1995). Based on this, the results of the analysis of total-Pb and available Pb content in all soils in the northern and southern regions of Brebes Regency are below the maximum allowable threshold or normal criteria so there is a tendency not to cause pollution. Soils in the northern region have higher available Pb values compared to soils in the southern region. This is due to the most influential factor on the presence of toxic heavy metals in the soil, namely differences in intensive land management such as the excessive application of inorganic synthetic fertilizers that allows heavy metal Pb to settle and accumulate in the soil. Long-term intensive fertilization has been identified as one of the key drivers of heavy metal accumulation, including Pb, in agricultural soils under high input production systems (Liu *et al.*, 2023). It is feared that toxic heavy metals in fertilizers will accumulate in the soil and be transported by crops

through the harvest and enter the human food chain. In addition, excessive use of synthetic pesticides also affects the concentration of Pb in the soil.

According to Alloway (1995), the maximum threshold value of Cd set is 3-8 ppm. Based on this, the results of the analysis of total-Cd and available Cd content in all soils in the northern and southern regions of Brebes Regency are below the maximum allowable threshold or normal criteria so that they do not indicate heavy metal pollution. Cd inputs in agricultural soils are often associated with long-term application of phosphate fertilizers (Herrero dan Martin, 1993). Cd behavior in soils is strongly influenced by its relatively weak sorption affinity compared to Pb, resulting in higher mobility and bioavailability across a wide range of soil pH conditions (Nungula *et al.*, 2024). The low Cd heavy metal content in this study may also be related to moderate to high CEC, which can contribute to Cd retention. However, due to its weaker sorption affinity, Cd remains more mobile than Pb, and its environmental risk should be evaluated not only based on total concentration but also on its bioavailable fraction.

Correlation of Soil Chemical Properties with Micronutrient Availability and Toxic Heavy Metal

The correlation analysis (Table 5) indicates that soil pH plays an important role in controlling micronutrient availability. Available Fe showed a highly significant negative correlation with pH, while available Cu and available Mn exhibited significant negative correlations. These results suggest that increasing soil pH reduces the availability of Fe, Cu, and Mn. The negative relationship implies that under higher pH conditions, micronutrients tend to precipitate or become strongly adsorbed, forming less soluble hydroxide or oxide.

Soil organic carbon showed a contrasting pattern. Available Fe and available Cu were very significantly positively correlated with organic C, while available Zn showed a significant positive correlation. Similar results were also shown by Nisab *et al.* (2020), who stated that the relationship between micronutrients extracted with DTPA showed a positive correlation with organic C. The positive association suggests the formation of soluble organo-mineral complexes (chelates), which increase micronutrient mobility and extractability. A strong positive correlation with Cu and Zn is determined by the decomposition of organic matter.

Table 5. Correlation of soil chemical properties with micronutrient availability (Fe, Mn, Cu, and Zn)

Correlation	pH H ₂ O	Organic C	CEC	Exc Ca	Exc Mg	Exc Na	Exc K
Available Fe	-0.62 **	0.68 **	-0.52 **	-0.74 **	-0.12	0.07	-0.12
Available Cu	-0.36 *	0.54 **	-0.42 **	-0.56 **	0.06	0.16	-0.06
Available Zn	-0.29	0.37 *	-0.43 **	-0.47 **	-0.01	0.44 **	0.23
Available Mn	-0.37 *	0.06	-0.06	-0.26	0.10	-0.19	-0.26
Total-Pb	0.10	-0.06	-0.12	0.03	-0.32 *	-0.02	0.15
Available Pb	-0.04	-0.24	0.39 *	0.16	0.22	-0.31	-0.13
Total-Cd	-0.10	0.23	-0.35 *	-0.27	-0.42 **	-0.25	0.04
Available Cd	-0.03	0.18	-0.16	-0.11	-0.40 *	-0.31	0.07

Notes: Pearson Correlation Test * (Significant P<0.05); ** (Highly Significant P<0.01); pH H₂O 1:5; Exc Ca = Exchangeable Ca; Exc Mg = Exchangeable Mg; Exc Na = Exchangeable Na; Exc K = Exchangeable K

CEC showed a significant negative correlation with several micronutrients, including Fe, Cu, and Zn. This relationship suggests that soils with higher CEC, which are typically associated with greater clay content and reactive surfaces, tend to retain micronutrients more strongly through adsorption and complexation processes, thereby reducing their extractable fraction. However, the effect of CEC on micronutrient availability depends on soil conditions, particularly pH and base saturation. Under neutral to alkaline conditions with high Ca levels, as observed in the northern soils, competitive interactions and precipitation processes may further reduce the availability of micronutrients. A similar pattern was observed with exchangeable Ca, which exhibited highly significant negative correlations with Fe, Cu, and Zn. These results indicate that increasing Ca saturation may enhance competitive adsorption or precipitation processes, thereby decreasing micronutrient availability. Available Zn also showed a significant positive correlation with exchangeable Na, suggesting that ionic interactions may influence Zn mobility under certain soil conditions.

Regarding heavy metals, total-Cd exhibited a highly significant negative correlation with exchangeable Mg, and available Cd showed a significant negative correlation with exchangeable Mg. These findings indicate that higher Mg concentrations are associated with lower total and available Cd levels in soil. Research by Matos *et al.* (2001) mentioned that, soil characteristics that are significantly correlated on retention and mobility with Cd are base saturation and exchangeable Mg. This relationship suggests that Mg may influence Cd retention through competitive adsorption mechanisms or by enhancing Cd stabilization in less labile forms. Overall, the correlation analysis highlights that soil pH, organic C, CEC, and exchangeable base cations collectively regulate micronutrient availability and Cd behavior in the studied soils. The dominant controls appear to be pH and Ca

saturation for micronutrients, and Mg content for Cd dynamics.

Bioavailability of Toxic Heavy Metals

Bioavailability of Pb and Cd can be expressed by the percentage of DTPA-extracted metals. The percentage of Pb and Cd bioavailability extracted by DTPA at the study site based on the grouping of locations in the northern and southern regions of Brebes Regency is presented in Figure 2. Pb bioavailability in the northern region of Brebes Regency is around 10.9% and the southern region of Brebes Regency is around 5.07%. Soils in the northern region have higher Pb bioavailability values compared to the southern region. Cd bioavailability in the northern area of Brebes Regency is around 35.5% and the southern area of Brebes Regency is around 30.5%. Soils in the northern region have higher Cd bioavailability values compared to the southern region.

The high bioavailability of toxic heavy metals is caused by agrochemical activities including fertilization and excessive use of pesticides. This causes the accumulation of toxic heavy metal residues in the soil which causes agricultural soil to become saturated, thus reducing the level of productivity of the crops planted (Karyadi, 2008). Variations in bioavailability levels on each land in the northern and southern regions of Brebes Regency can be caused by metal binding and solubility in acidic soils. Metals with a high enough percentage will be absorbed into plants that grow on that land compared to other lands with different absorption capacity of each plant (Mahendra *et al.*, 2018). Extracted metals are bioavailable metals while unextracted metals can be non-bioavailable. Metals are potentially bioavailable when metals bind to Fe or Mn oxides and non-bioavailable metals when metals bind to silicates (Siaka *et al.*, 2021). The higher the percentage of extracted metals, the greater the potential for metals to be absorbed by plants (Reeder *et al.*, 2006).

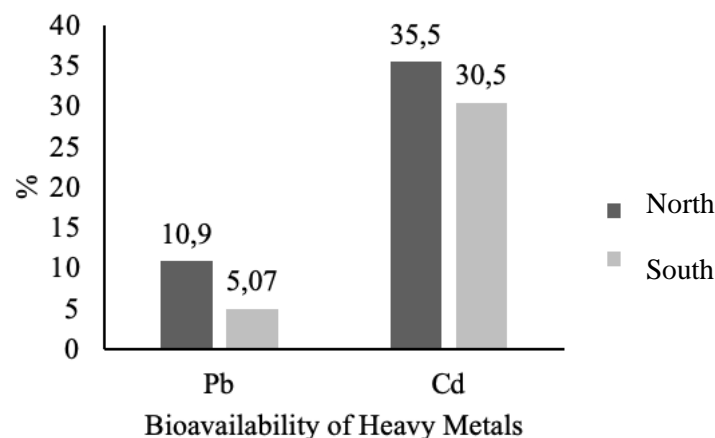


Figure 2. Bioavailability of toxic heavy metals (Pb and Cd) in soil by clustering locations in the northern and southern regions of Brebes Regency

Based on the analysis, the bioavailability of Cd metal is higher than Pb metal. Cd's higher bioavailability has important agronomic and food safety implications; Cd is more readily uptake by crops than Pb and tends to accumulate in edible tissues even at relatively low soil concentrations, posing significant risk to human health in vegetable production systems (Alhaj Hamoud *et al.*, 2024; Chen *et al.*, 2024; Yu *et al.*, 2024). Although current values remain within normal concentration ranges, the relatively high percentage of bioavailable Cd suggests that these soils are chemically dynamic and responsive to management practices. Therefore, assessment of heavy metal risk in intensive agricultural systems should prioritize bioavailable fractions rather than total concentrations alone.

The findings of this study highlight the need to shift from input-oriented fertilization toward chemically informed soil management in the intensive shallot production systems of Brebes Regency. Although total concentrations of micronutrients and heavy metals remain within acceptable limits, the interaction between neutral pH, high base saturation, and repeated NPK fertilization may progressively suppress Zn availability and increase Cd lability. Therefore, sustainable nutrient management should incorporate balanced fertilization strategies that include periodic micronutrient assessment particularly Zn alongside routine monitoring of bioavailable Cd fractions rather than relying solely on total metal concentrations. Optimizing phosphorus application rates, promoting organic matter inputs, and integrating soil testing based fertilization recommendations could help stabilize micronutrient dynamics and minimize potential trace metal risks. Implementing such science-based soil management practices is essential to maintain long-term productivity, soil health, and food safety in this nationally strategic shallot-producing region.

CONCLUSION

The availability of Fe, Cu, and Zn in the northern region was significantly lower than in the southern region, while Mn did not differ significantly. These differences were significantly influenced by soil pH, organic carbon, CEC, and exchangeable bases. Total Pb, Cd, and available Cd were generally lower in the northern soils; however, available Pb was significantly higher, whereas total-Cd was significantly lower compared to the southern soils. In contrast, the bioavailability of both Pb and Cd was higher in the northern region, with Cd showing greater bioavailability than Pb. The results provide important information for soil quality evaluation and balanced nutrient management to support sustainable agricultural practices in Brebes Regency.

DAFTAR PUSTAKA

- Adiyoga, W., N. Khaririyatun, and R. Murtiningsih. 2022. Criteria of pesticide selection in shallot pest disease control in Brebes Regency, Central Java. *E3S Web of Conferences*, 361:03005. doi:10.1051/e3sconf/202236103005.
- Ahmed, N., L. Deng, M-N, Narejo, I. Baloch, L. Deng, S. Chachar, Y. Li, J. Li, B. Bozdar, Z. Chachar, F. Hayat, M. Chachar, L. Gong, and P. Tu. 2024. Bridging agro-science and human nutrition: zinc nanoparticles and biochar as catalysts for enhanced crop productivity and biofortification. *Front. Plant Sci.*, 15. doi:10.3389/fpls.2024.1435086. [diunduh 2026 Feb 16]. Tersedia pada: <https://www.frontiersin.org/journals/plant-science/articles/10.3389/fpls.2024.1435086/full>.
- Al-Busaidi, W., R. Janke, D. Menezes-Blackburn, M. Mumatz Khan. 2022. Impact of long-term agricultural farming on soil and water chemical properties: A case study from Al-Batinah regions (Oman). *Journal of the Saudi Society of Agricultural Sciences*, 21(6):397–403. doi:10.1016/j.jssas.2021.11.002.
- Alhaj Hamoud, Y., H. Shaghaleh, M. Zia-ur-Rehman, M. Rizwan, M. Umair, M. Usman, M.A. Ayub, U. Riaz, G.S.H. Alnusairi, and S.M.S. Alghanem. 2024. Cadmium and lead accumulation in important food crops due to wastewater irrigation: Pollution index and health risks assessment. *Heliyon*, 10(3):e24712. doi:10.1016/j.heliyon.2024.e24712.
- Ali, F., A. Sadiq, I. Ali, M. Amin, and M. Amir. 2014. Effect of applied phosphorus on the availability of micronutrients in alkaline-calcareous soil. *Journal of Environment and Earth Science*, 4(15): 143–147.
- Alloway, B.J. 1995. *Heavy Metals in Soils*. Dordrecht: Springer Netherlands. [diunduh 2026 Feb 16]. Tersedia pada: <http://link.springer.com/10.1007/978-94-011-1344-1>.
- Arifin, B., N.A. Achsani, D. Martianto, L.K. Sari, and A.H. Firdaus. 2019. The future of Indonesian food consumption. *Jurnal Ekonomi Indonesia*, 8(1):71–102.
- Basuki, R.S. 2009. Farmers' knowledge and effectiveness of insecticide. *J. Hort.*, 19(4):459–474.
- [BPS] Badan Pusat Statistik. 2019. *Realisasi Produksi Ketersediaan Kebutuhan 14 Komoditas di Kabupaten Brebes Tahun 2019* [diakses 03/05/2024] URL:<https://brebeskab.bps.go.id/statictable/2021/06/24/1910/banyaknya-realisisi-produksi-ketersediaan-kebutuhan-14-komoditas-di-kabupaten-brebes-tahun-2019.html>
- Bradl, H.B. 2004. Adsorption of heavy metal ions on soils and soils constituents. *Journal of Colloid and Interface Science*, 277(1):1–18. doi:10.1016/j.jcis.2004.04.005.
- Chaireni, R., D. Agustanto, R.A. Wahyu, dan P. Nainggolan. 2020. Ketahanan pangan berkelanjutan. *Jurnal Kependudukan dan Pembangunan Lingkungan*, 1(2):70–79.
- Chen, X., Y. Ren, C. Li, Y. Shang, R. Ji, D. Yao, and Y. He. 2024. Study on factors influencing the migration of heavy metals from soil to vegetables in a heavy

- industry city. *Sustainability*, 16(24):11084. doi:10.3390/su162411084. [diunduh 2026 Feb 16]. Tersedia pada: <https://www.mdpi.com/2071-1050/16/24/11084>.
- Eduah, J.O., A. Arthur, J.A. Dogbatse, I. Amoako-Attah, and E.A. Afful. 2024. Ecological effects of soil physicochemical properties and copper speciation on the microbial properties associated with land use management in cacao production. *Environmental Technology & Innovation*, 33:103538. doi:10.1016/j.eti.2024.103538.
- Eviati, Sulaeman, L. Herawati, L. Anggria, Usman, H.E. Tantika, R. Prihatini, dan P. Wuningrum. 2023. *Analisis Kimia Tanah, Tanaman, Air, dan Pupuk*. Ed ke-3. Balai Besar Pengujian Standar Instrmen Sumberdaya Lahan Pertanian. Badan Standardisasi Instrumen Pertanian: Kementerian Pertanian Republik Indonesia.
- Fageria, N.K. 2016. *The Use of Nutrients in Crop Plants*. Boca Raton: CRC Press.
- Herrero, T.C. and L.F.L. Martin. 1993. Evaluation of cadmium levels in fertilized soils. *Bull Environ Contam Toxicol*, 50(1):61–68. doi:10.1007/BF00196542.
- Jiang, L., H. Cheng, Y. Peng, T. Sun, Y. Gao, R. Wang, Y. Ma, J. Yang, Q. Yu, H. Zhang, X. Han, and Q. Ning. 2024. Relative role of soil nutrients vs. carbon availability on soil carbon mineralization in grassland receiving long-term N addition. *Soil and Tillage Research*, 235:105864. doi:10.1016/j.still.2023.105864.
- Karyadi. 2008. Dampak penggunaan pupuk dan pestisida yang berlebihan terhadap kandungan residu tanah pertanian bawang merah di Kecamatan Gemuh Kabupaten Kendal. *AGROMEDIA: Berkala Ilmiah Ilmu-ilmu Pertanian*. 26(1):10-19. doi:<https://doi.org/10.47728/ag.v26i1.8>. [diunduh 2026 Feb 16]. Tersedia pada: <https://jurnalkampus.stipfarming.ac.id/index.php/am/article/view/8>.
- Khoshru, B., D. Mitra, A.F. Nosratabad, A. Reyhanitabar, L. Mandal, B. Farda, R. Djebaili, M. Pellegrini, B.E. Guerra-Sierra, A. Senapati, P. Panneerselvam, P.K.D. Mohapatra. 2023. Enhancing manganese availability for plants through microbial potential: a sustainable approach for improving soil health and food security. *Bacteria*, 2(3):129–141. doi:10.3390/bacteria2030010.
- Liu, Y., M. Zhang, Y. Li, Y. Zhang, X. Huang, Y. Yang, H. Zhu, H. Xiong, and T. Jiang. 2023. Influence of nitrogen fertilizer application on soil acidification characteristics of tea plantations in karst areas of Southwest China. *Agriculture*, 13(4):849. doi:10.3390/agriculture13040849.
- Liu, Z., Y. Bai, J. Gao, and J. Li. 2023. Driving factors on accumulation of cadmium, lead, copper, zinc in agricultural soil and products of the North China Plain. *Sci Rep.*, 13(1):7429. doi:10.1038/s41598-023-34688-6.
- Mahendra, R., I.M. Siaka, dan I.E. Suprihatin. 2018. Bioavailabilitas logam berat Pb dan Cd dalam tanah perkebunan budidaya kubis di daerah Kintamani Bangli. *Ecotrophic*, 12(1):42–49.
- Matos, A.T.D., M.P.F. Fontes, L.M.D. Costa, and M.A. Martinez. 2001. Mobility of heavy metals as related to soil chemical and mineralogical characteristics of Brazilian soils. *Environmental Pollution*, 111(3):429-435.
- Mondal, S. and G.C. Hazra. 2018. Phosphorus build up in soil affecting zinc availability to plants in rice based cropping system. *ORYZA-An International Journal on Rice*, 55(1):152–164. doi:10.5958/2249-5266.2018.00018.8.
- Nadalia, D., A. Hartono, and S.H. Nugraha. 2025. Evaluation of soil fertility in some farmlands in the north and south of Brebes District, Central Java, Indonesia. *IOP Conference Series : Earth and Environmental Science*, 1463:012010. doi:10.1088/1755-1315/1463/1/012010.
- Nadeem, F., S. Abbas, F. Waseem, N. Ali, R. Mahmood, S. Bibi, L. Deng, R. Wang, Y. Zhong, and X. Li. 2024. Phosphorus (P) and Zinc (Zn) nutrition constraints: A perspective of linking soil application with plant regulations. *Environmental and Experimental Botany*, 226:105875. doi:10.1016/j.envexpbot.2024.105875.
- Nisab, C.P.M., M. Sahu, and G.K. Ghosh. 2020. Distribution of DTPA A-extractable micronutrient cations (Zn, Fe, Mn, and Cu) and its relationship with physico-chemical properties in soils of Birbhum district, West Bengal. *International Journal of Chemical Studies*, 8(3):253-257.
- Nungula, E.Z., M.A. Raza, J. Nasar, S. Maitra, M.F. Seleiman, S. Ranjan, S.R. Padhan, S. Sow, D.J. Gaikwad, and H.H. Gitari. 2024. Cadmium in Soil and Plants: A Review. *Di dalam*: Jha, A.K. and N. Kumar, editor. *Cadmium Toxicity in Water: Challenges and Solutions*. [internet] Cham. Cham: Springer Nature Switzerland. hlm. 21–43. [diunduh 2026 Feb 16]. Tersedia pada: https://doi.org/10.1007/978-3-031-54005-9_2.
- Puniya, R., P.C. Pandey, P.S. Bisht, D.K. Singh, and A.P. Singh. 2019. Effect of long-term nutrient management practices on soil micronutrient concentrations and uptake under a rice–wheat cropping system. *The Journal of Agricultural Science*. 157(3):226–234. doi:10.1017/S0021859619000509.
- Reeder, R.J., M.A.A. Schoonen, and A. Lanzirrotti. 2006. Metal speciation and its role in bioaccessibility and bioavailability. *Reviews in Mineralogy and Geochemistry*. 64(1):59-113. doi:10.2138/rmg.2006.64.3. [diunduh 2026 Feb 16]. Tersedia pada: <https://www.researchgate.net/publication/235936>

- 881_Metal_Speciation_and_Its_Role_in_Bioaccessibility_and_Bioavailability.
- Sahara, D., U.K. Yaumidin, T. Suhendrata, C. Setiani, J.A. Beti, T. Dewi, A.Y. Fadwiwati, Idaryani, Atman, Yardha, E. Waas, R. Asnawi, and A. Syam. 2025. Sustainability of shallot farming system in lowland Central Java Province, Indonesia: MICMAC analysis approach. *Environmental Challenges*, 20:101212. doi:10.1016/j.envc.2025.101212.
- Salasa, A.R. 2021. Paradigma dan dimensi strategi ketahanan pangan Indonesia. *Jejaring Administrasi Publik*, 13(1):35–48. doi:10.20473/jap.v13i1.29357.
- Siaka, I.M., P.D.S. Udayani, dan W.B. Suyasa 2021. Bioavailabilitas dan kandungan Pb, Cu pada tanah dan sawi putih di Desa Baturiti. *Jurnal Kimia*, 15(1):20-28. doi:10.24843/JCHEM.2021.v15.i01.p04.
- Sun, J., H. Li, G. Jianji, Y. He, L. Xu, L. Zhang, Q. Guan, Y. Ye, Cu. Xu, and H. Wang. 2025. Influence of altitudinal zones on soil nutrient dynamics and fertility constraints in agricultural terrains of Yunnan, China. *Sci Rep.*, 15(1):43452. doi:10.1038/s41598-025-27297-y.
- Supriatin, S. and A.K. Salam. 2024. Total and extractable micronutrients in tropical acid soils of Lampung, Indonesia. *Communications in Soil Science and Plant Analysis*, 55(17):2529–2544. doi:10.1080/00103624.2024.2367250.
- Susilawati, D.M., M.S. Maarif, Widiatmaka, and I. Lubis. 2019. Evaluasi kesesuaian dan ketersediaan lahan untuk pengembangan komoditas bawang merah di Kabupaten Brebes, Provinsi Jawa Tengah. *Journal of Natural Resources and Environmental Management*, 9(2):507–526. doi:http://dx.doi.org/10.29244/jpsl.9.2.507-526.
- Wang, M., S. Chen, H. Shi, and Y. Liu. 2022. Redox dependence of manganese controls cadmium isotope fractionation in a paddy soil-rice system under unsteady pe + pH conditions. *Science of The Total Environment*, 806:150675. doi:10.1016/j.scitotenv.2021.150675.
- Yu, H., C. Li, J. Yan, Y. Ma, X. Zhou, W. Yu, H. Kan, Q. Meng, R. Xie, and P. Dong. 2023. A review on adsorption characteristics and influencing mechanism of heavy metals in farmland soil. *RSC Advances*, 13(6):3505–3519. doi:10.1039/D2RA07095B.
- Yu, Y., S. Alseekh, Z. Zhu, K. Zhou, and A.R. Fernie. 2024. Multiomics and biotechnologies for understanding and influencing cadmium accumulation and stress response in plants. *Plant Biotechnology Journal*, 22(10):2641–2659. doi:10.1111/pbi.14379.
- Zhang, L., Z. Zhao, B. Jiang, B. Baoyin, Z. Cui, H. Wang, Q. Li, and J. Cui. 2024. Effects of long-term application of nitrogen fertilizer on soil acidification and biological properties in China: A Meta-Analysis. *Microorganisms*, 12(8):1683. doi:10.3390/microorganisms12081683.
- Zhu, H., H. Ding, R. Bi, and M. Hou M. 2021. Large-extent spatial heterogeneity of soil bioavailable micronutrients and the relative roles of environmental indicators on them within maize fields. *Ecological Indicators*, 130:108071. doi:10.1016/j.ecolind.2021.108071.
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