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Accumulation of Pb, Cd, and Cr in Soil and Rice Grain at Irrigated Conventional Rice Farming of Tajum Sub-Watershed, Banyumas Regency

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Abstract: Heavy metal contamination of Pb, Cd, and Cr in soil and rice grains harms the environment and human health if the content exceeds the safe threshold. This study aimed to determine the accumulation of Pb, Cd, and Cr in soil and rice grain in irrigated rice fields at the Tajum sub-watershed, Banyumas Regency. The rice fields of location sampling in the Tajum sub-watershed area were Pekuncen District (Karangkemiri Village, Pasiraman Kidul Village), Ajibarang District (Ajibarang Kulon Village), Wangon District (Cikakak Village), Jatilawang District (Tinggarjaya Village), Rawalo District (Memanti Village and Village Pesawahan), Purwojati District (Karangtalun Kidul Village). The grid system was applied for soil and rice grain sampling. The study results showed that the Pb, Cd, and Cr in the soil increased in all locations during one growing season even below threshold limit values except Cd. Mostly found that Pb, Cd, and Cr in rice grains exceed the threshold limit values. Pb in rice grain ranged from 0.78 to 26.93 mg/Kg, while Cd 0.04 to 1.83 mg/Kg, and Cr 3.43 to 7.54 mg/Kg. According to the Pollution Index, all areas of rice fields were polluted by Pb, Cd, and Cr with criteria of medium to high.

Keywords: Banyumas regency; heavy metals; pollution; rice production; Tajum sub-watershed

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1. Introduction

Rice is the main food commodity consumed by Indonesian people whose needs continue to increase as the population increases. According to Shahbandeh (2025), world rice consumption has increased significantly, which in the 2008/2009 harvest year showed world rice consumption of 437,179 million tons and in the 2024/2025 harvest year, it became 530,239 million tons. According to the Central Statistics Agency (2025), rice production in Indonesia as 2024 reached 52,66 million tons of dry-milled grain, a decrease of 1.64% from production in 2023. For the Banyumas region, the 2024 paddy field harvest area in 27 sub-districts was 69,974 ha, and lowland rice production was 238,181 tons referring to a 5,80 tons/ha productivity.

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Rice production that has been developed still uses conventional systems which are indicated to have caused environmental pollution and have become a major issue in the world because they cause a decrease in soil and food quality due to the accumulation of heavy metals. According to Hindarwati et al. (2018), efforts to increase rice production which are carried out by providing continuous input of synthetic fertilizers and pesticides, harm the environment. According to Anacleto et al. (2017), the largest source of heavy metal contamination in the agricultural sector is generated from synthetic fertilizers and pesticides. Mar et al. (2015) stated that Cd is a common pollutant mostly found in phosphate fertilizers. Application of phosphate fertilizer over one year caused an increase in Cd in the soil from 0.05 mg/kg to 0.18 mg/kg. Evidence of heavy metal pollution was revealed by Mulyadi (2013), there was an accumulation of Pb of 0.23-1.23 mg/kg in rice fields which was very intense in the application of synthetic fertilizers and pesticides in the rice fields of the Juwana Sub-watershed, Pati, Central Java.

Apart from the application of fertilizer, the spray of pesticides also allows the accumulation of heavy metals in the soil and plant parts. Manurung et al. (2018), stated that several pesticides and fungicides contain the heavy metal Cr, due to active compound of Dimetomorf, Mancozeb, and Propineb. Therefore, the conventional rice cultivation system causes the accumulation of heavy metals Pb, Cd, and Cr in the soil, which will cause the absorption of heavy metals by plants along with the absorption of water and nutrients, so that the heavy metals Pb, Cd, and Cr will accumulate in the soil, parts of plants, and rice.

Accumulation in some parts of plants, especially rice, can endanger human health. According to Mahupawar (2015), consumption of agricultural products containing heavy metal residues can cause several serious diseases such as the heavy metal Cd causing kidney and bone disorders. Based on the standards of the Ministry of State for Population and Environment of Indonesia, and Dalhousie University (1992), the maximum threshold for Pb in soil is 100 mg/kg, Cr 100 mg/kg, and Cd 0.5 mg/kg. FAO/WHO (2002) requires a maximum threshold for rice, namely Cr of 0.01 mg/kg, Pb and Cd of 0.2 mg/kg. Therefore, information regarding the content of heavy metals Cd, Pb, and Cr in soil and rice can be a basis for determining remediation actions for heavy metals in rice fields so as not to cause accumulation in rice which can be harmful to humans if consumed.

2. Materials and Methods

2.1. Soil and rice grains sampling site

The research was carried out in April to December 2021, and located in irrigated rice fields in the Tajum sub-watershed area which includes Pekuncen District (Karangkemiri and Pasiraman Kidul Villages), Ajibarang District (Ajibarang Kulon Village), Wangon District (Cikakak Village), Jatilawang District (Tinggarjaya Village), Rawalo District (Menganti and Pesawahan Villages), Purwojati District (Karangtalun Kidul Village) (Table 1 and Figure 1).

Table 1. Sampling site of the study at irrigated rice of Tajum Sub-Watershed

Sampling Number	District	Village	Coordinate location	
			X	Y
1	Pekuncen	Karangkemiri	109°4′29″ E	7°20′33″ S
2	Pekuncen	Pasiraman Kidul	109°4′23″ E	7°21′50″ S
3	Ajibarang	Ajibarang Kulon	109°4′12″ E	7°24′49″ S
4	Wangon	Cikakak	109°4′31″ E	7°28′57″ S
5	Jatilawang	Tinggarjaya	109°4′8″ E	7°31′52″ S
6	Rawalo	Menganti	109°4′6″ E	7°33′30″ S
7	Rawalo	Pesawahan	109°4′49″ E	7°31′17″ S
8	Purwojati	Karangtalun Kidul	109°5′47″ E	7°29′38″ S

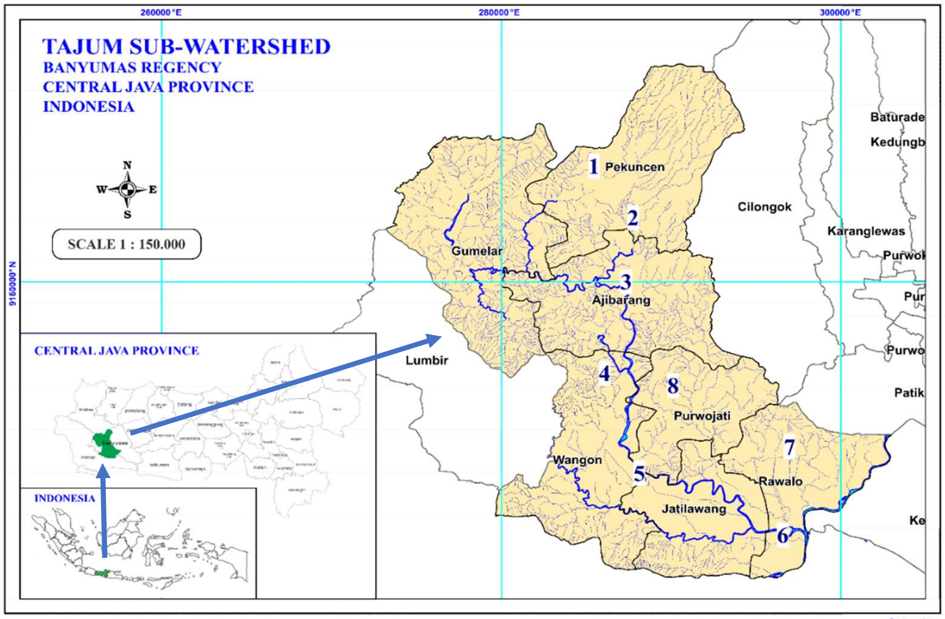

Figure 1. Sampling site of the study at irrigated rice of Tajum Sub-Watershed, Banyumas District.

2.2. Sampling method

The research was carried out using a grid system. Soil samples were taken using a soil auger at a depth of 20 to 30 cm, which is the effective root depth of rice plants. Soil samples are taken in a particular research area using a grid system, namely one sampling point consisting of 5 samples (individuals) with about 50 m for each sub-sample in the field. Five samples were collected and composite in each sampling point as one soil sample from a given area.

Sampling in the field was also based on several considerations concerning the type of irrigated rice fields and had almost the same planting time (Figure 1). Determination of sample points in the field was carried out using Essential GPS to determine the appropriate coordinates so that coordinate points were obtained based on a preliminary survey for suitability of the land (Table 1 and Figure 1). Soil and rice grain samples were taken at the prior harvest time of rice.

2.3. Heavy metal analysis

Assessment of heavy metals content in soil and rice grains. Both samples were taken at each site sampling (Table 1 and Figure 1). Measurement of heavy metals content was done after the preparation of soil by air dried, crushed, and sieved in 2 mm size. Preparation for rice grains was needed for about one hundred grains. The process of sample preparation was conducted using acid digestion method in accordance with the procedures outlined in Technical Instruction for chemical analysis of soil, plants, water and fertilizer from Indonesian ministry of Agriculture.

2.5 g of the ground soil sample was accurately weighed and placed into a digestion vessel. After being added by 5 ml of HNO_3 at room temperature, the vessel was closed and put in microwave. The temperature was set to 200°C for 30-60 minutes. After the vessel is cooled, the extract is transferred to a 25 ml flask, diluted with H_2O, and the volume adjusted to the mark. It is shaken until homogeneous, then filtered through filter paper to obtain a clear extract. The clear extract is used for the measurement of heavy metals Pb and Cd, using the Flame AAS method for ppm concentrations (Eviati et al. 2023).

2.4. Index of pollution

Calculation of the level of heavy metal Cd, Pb, and Cr contamination of soil can be calculated using the Pollution Index (PI) (Ripin et al., 2014)

$PI = Cn/Bn$

Note:

PI : Pollution Index

Cn : end concentration of heavy metal in soils (mg/kg)

Bn : onset concentration of heavy metal in soils (mg/kg)

The PI value is classified as low (PI=1), medium ($1<PI\leq 3$), and high (PI>3). The soil samples were taken at the onset of planting time and before harvest time.

3. Results

3.1. Pb, Cd, and Cr contents in soils

Table 2 showed that the levels of Pb content in soil were still below the threshold limit values in the range of 20 – 40 mg/kg. The lowest and highest content of Pb in soils were at Pasiraman Kidul (20.48 mg/kg) and Pesawahan (39.92 mg/kg), respectively. Two locations had an accumulation lower than 30 mg/kg (Pasiraman Kidul and Karangkemiri) and the other locations had more than 30 mg/kg.

Soil Cd levels at various locations above the threshold limit values (Table 2). Content of Cd in the soil at all locations sampling more than 0.8 mg/kg as the maximum safe limit. Content of soil Cr in all locations below the threshold limit values of 100 mg/kg. Some locations such as Karangkemiri, Pasiraman Kidul, and Cikakak had the Cr accumulation less than 30 mg/kg but other locations were more than 30 mg/kg even lower than 100 mg/kg (Table 2).

Table 2. Contents of Pb, Cd, and Cr in the soil at rice fields in the Tajum Sub-watershed

Site Study	Pb (mg/kg)	Cd (mg/kg)	Cr (mg/kg)
Karangkemiri	27.37	1.94 *	27.92
Pasiraman Kidul	20.48	1.29 *	27.99
Ajibarang Kulon	34.87	2.58 *	42.61
Cikakak	31.99	2.34 *	27.37
Tinggarjaya	35.56	2.39 *	35.74
Menganti	34.40	2.67 *	61.32
Pesawahan	39.92	3.01 *	49.21
Karangtalun Kidul	37.79	2.66 *	52.00

Note: The World Health Organization (WHO) (1996) standard of threshold limit values: Pb (100 mg/kg), Cd (0.8 mg/kg), Cr (100 mg/kg); *: heavy metals concentration above threshold limit values in soils).

3.2. Pb, Cd, dan Cr contents in rice grains

The contents of Pb, Cd, and Cr in rice grains at all sampling locations showed levels above the threshold limit values. A very high Pb value in rice was in Ajibarang Kulon Village with a content of more than 20 mg/kg. Other locations' Pb content ranges from 1.00 – 5.00 mg/kg, except Pesawahan Village < 1 mg/kg.

Table 3. Contents of Pb, Cd, dan Cr in rice grains at rice fields in the Tajum Sub-watershed

Site Study	Pb (mg/kg)	Cd (mg/kg)	Cr (mg/kg)
Karangkemiri	4.26*	0.39*	4.35*
Pasiraman Kidul	4.77*	0.43*	3.92*
Ajibarang Kulon	26.93*	1.83*	7.54*
Cikakak	1.96	0.21*	4.17*
Tinggarjaya	2.61*	0.22*	4.66*
Menganti	3.12*	0.11*	3.43*
Pesawahan	0.78	0.04 *	5.58*
Karangtalun Kidul	4.33*	0.21*	5.83*

Note: The World Health Organization (WHO) (1996) standard of threshold limit values: Pb (2 mg/kg), Cd (0,02 mg/kg), Cr (1,30 mg/kg); *: heavy metals concentration above threshold limit values for food.

Cd content in rice grains was over the threshold limit value in all areas of the rice field, and Ajibarang Kulon Village showed the accumulation higher than 20 mg/kg. Other villages showed Cd accumulation in rice grains less than 5 mg/kg (Table 3). The content of Cr in rice grains showed that all locations contain very high levels in the range of 3.00 – 8.00 mg/kg and exceed the threshold limit values for rice.

3.3. Pollution Index of Pb, Cd, dan Cr in rice field

The Pollution Index (PI) value for the heavy metal Pb in the Tajum Sub-watershed was in moderate pollution conditions in all locations (1<PI≤3). The highest PI of Pb was in Tinggarjaya Village (2.96). The Pollution Index (PI) Cd value in Table 4 showed that the three locations had the high category such as Tinggarjaya Village (5.31), Pesawahan Village (4.07), and Cikakak Village (3.16). The medium category was in seven research locations i.e. Menganti Village (2.57), Karangtalun Kidul Village (2.46), Ajibarang Kulon Village (1.91), Karangkemiri Village (1.45), Pasiraman Kidul Village (1.29).

Table 4. Pollution Index (PI) of Pb, Cd, dan Cr in the soil at rice fields in the Tajum Sub-watershed

Site Study	PI Pb	PI Cd	PI Cr
Karangkemiri	0.73	1.45	2.16
Pasiraman Kidul	0.97	1.29	2.11
Ajibarang Kulon	1.40	1.91	2.33
Cikakak	2.17	3.16	2.47
Tinggarjaya	2.96	5.31	6.23
Menganti	1.73	2.57	4.27
Pesawahan	2.29	4.07	5.84
Karangtalun Kidul	1.94	2.46	2.73

Note: The PI value is classified as low (PI=1), medium (1<PI≤3), and high (PI>3) (Ripin et al., 2014).

The Pollution Index (PI) Cr value showed that there were three locations in the high category i.e. Tinggarjaya Village (6.23), Pesawahan Village (5.84), and Menganti Village (4.27). The medium category showed in Karantalun Kidul Village (2.73), Cikakak Village (2.47), Kranggan Village (2.40), Ajibarang Kulon Village (2.33), Karangkemiri Village (2.16), and Pasiraman Kidul Village (2.11). Generally, the Pollution Index (PI) values for the heavy metals of Pb, Cd, and Cr at all research locations at rice fields in the Tajum sub-watershed showed moderate to high polluted conditions (Table 4).

Based on the calculation of the Pollution Index (PI), it has been found that the rice fields in the Tajum Sub-watershed, Banyumas Regency were polluted by Pb, Cd, and Cr in medium criteria viz. 75%, 62.5% and 50%, respectively.

4. Discussion

The content of Pb in soils at eight locations was still below the specified critical limit of 100 mg/kg (WHO, 1996). The highest Pb content in the soil was found in Pesawahan village at 39.92 mg/kg, while the lowest Pb content was in Tinggarjaya village at 12 mg/kg. The accumulation of Cd in soil exceeded the threshold limit values. According to The World Health Organization (WHO) (1996), the maximum threshold for Cd in soil is 0.8 mg/kg. The highest Cd content was in Pesawahan village at 3.01 mg/kg. The highest Cr content was in Menganti Village at 61.32 mg/kg. But, in the same condition as Pb, the content of Cr was still below the safe threshold of 100 mg/kg (WHO, 1996).

According to the accumulation of heavy metals (Pb, Cd, and Cr) in soil at the rice field area, varied conditions were observed. The accumulation of Pb in some countries, particularly as a major crop in rice production, indicates a low concentration under the WHO standard. But the content of Cd in soil indicates high concentration commonly in some countries, except in some places in India and Malaysia (Table 5).

Table 5. Contents of Pb, Cd, and Cr in the soil of rice producing countries

Countries	**Area**	Pb (mg/kg)	Cd (mg/kg)	Cr (mg/kg)	References
Indonesia	Banyumas Regency	32.79	2.36	40.52	This study
Bangladesh	Savar	38.07	14.98	46.93	Hasan et al., 2022
	Gazipur	42.78	11.08	40.76	
	Ashulia	34.09	18.56	34.87	
Philippines	Solana, Cagayan valley	>8.00	<10.90	<36.80	Sanchez et al., 2015
	Sta. Cruz, Central Luzon	>8.00	<10.00	1126.50	
	Sta. Rosa City, Laguna	16.20	<10.00	<36.80	
China	Hunan Province	51.40	1.40	27.20	Zeng et al., 2015
India	East Coast	5.30-19.80	0.02-0.60	1.3-7.80	Satpathi et al., 2014
Malaysia	Papar district, sabah	8.03	0.32	4.16	Payus et al. 2015
	Kubang Pasu, Kedah	3.72	0.20	2.30	Looi et al. 2014

Note: The World Health Organization (WHO) (1996) standard threshold limit values: Pb (100 mg/kg), Cd (0.8 mg/kg), Cr (100 mg/kg); *: heavy metals concentration above threshold limit values in soils).

In some places in Bangladesh, the accumulation of Cd is very high, resulted more than five-fold compared to other places in many countries. The heavy metal of Cr resulted below the concentration based on WHO standard, generally (Table 5). This condition showed the information that in many countries rice field soil area have the potential to accumulate heavy metals of Pb, Cd, and Cr, even in varying concentrations.

Following the WHO standard for the accumulation of heavy metals in rice grains, in some countries, it is high. The accumulation of Pb, Cd, and Cr in rice grains at Southeast Asia above the WHO standard, especially in the Philippines, tend to be very high. Heavy metal of Cr content in rice grains is slightly low in some area of China, India, and Malaysia. The data showed that the variance of heavy metal content in rice grains differs among countries. But, generally, accumulation of Pb, Cd, and Cr in rice grains from the major crop of rice countries is above the standard threshold limit by the WHO (Table 6).

Table 6. Contents of Pb, Cd, dan Cr in rice grains at rice fields in Several rice producing countries

Countries	Area	Pb (mg/kg)	Cd (mg/kg)	Cr (mg/kg)	References
Indonesia	Banyumas Regency	6.090	0.430	4.930	This study
Bangladesh	Savar	1.21	1.43	19.78	Hasan et al., 2022
	Gazipur	nd	0.98	11.54	
	Ashulia	1.32	1.61	23.67	
Philippines	Solana, Cagayan valley	<8.0	<10.0	<36.8	Magahud et al., 2015
	Sta. Cruz, Central Luzon	<8.0	<10.0	<36.8	
	Sta. Rosa City, Laguna	<8.0	<10.0	<36.8	
China	Hunan Province	0.023	0.312	0.106	Zeng et al., 2015
India	East Coast	0.01-1	0.02-0.05	0.1-0.6	Satpathi et al., 2014
Malaysia	Papar district, sabah	2.06	0.13	4.12	Payus et al. 2015
	Kubang Pasu, Kedah	0.21	0.01	0.04	Looi et al. 2014

Note: The World Health Organization (WHO) (1996) standard threshold limit values: Pb (2 mg/kg), Cd (0,02 mg/kg), Cr (1,30 mg/kg); *: heavy metals concentration above threshold limit values for food.

Since the implementation of synthetic fertilizers is still massive by conventional farming systems, it causes adverse effects on agroecosystems, especially in rice farming. Phosphate is one of the plant nutrition sources that has indicated an increase in heavy metals accumulation such as Cd in soils. According to Sharma et al. (2005), the use of phosphate fertilizer in the long term will cause the accumulation of heavy metals in the soil, so the Cd content will continue to increase and exceed the safe threshold which has an impact on land degradation and the accumulation of Cd in plants which will be dangerous if consumed by humans. Liu et al. (2015), an increase in heavy metal pollution such as Pb and Cd comes from providing synthetic chemical inputs such as the use of several types of pesticides and synthetic chemical fertilizers. Another statement mentioned that one source of Cd contamination in agriculture is the application of phosphate fertilizer (Salmanzadeh et al., 2016). Thus, Bigalke et al (2017) also noted that phosphate fertilizer application could increase the Cd content on agricultural land because the raw material for making phosphate fertilizer comes from phosphate rock which naturally contains Cd.

Another source of heavy metals in agricultural soils comes from irrigation water. This area of study was inside the Serayu River watershed. As reported by Sukarjo et al. (2023), the water in the Serayu River is moderately polluted by heavy metals. However, Cd was only detected in one location, indicating that the Serayu River irrigation system is considered Cd-free. Based on these findings, it can be concluded that the high levels of Cd in the soil of the studied area originated from the use of synthetic fertilizers in rice cultivation.

Phosphate fertilizers are frequently identified as the primary source of soil contamination of Cd in agricultural areas and widespread sources of certain heavy metals in paddy soils. The consensus in many recent studies, particularly concerning the highly toxic metal Cadmium (Cd), points to agricultural inputs as a primary and often dominant source of accumulation in paddy soils over atmospheric deposition (Wang et al., 2025).

Generally, the accumulation of Pb, Cd, and Cr in rice grains at all locations exceeded the safe limit by WHO. Irrigated rice fields have a high chance of heavy metal accumulation due to the influence of stagnant water in rice fields which causes increased accumulation of heavy metals by plants. Heavy metals will be transported along with the absorption of water and nutrients from the soil. Williams et al. (2006) noted that rice cultivated with water, in this case, the irrigated rice fields, is more susceptible to heavy metal contamination and high concentrations in the rice grains. According to Amelia et al. (2015), heavy metals in the soil will be absorbed by plant roots together with water and will be distributed to other parts of the plant, where heavy metals that manage to penetrate the root endodermis, the metal will be carried by the transpiration flow to some parts of the plant through xylem tissue leads to other plant parts such as leaves, stems and grain. Moreover, Mahmud et al. (2021) revealed that rice grown in rice fields with an irrigation system has a high accumulation of heavy metals in the rice grains.

The heavy metal content in rice and leaves is influenced by each physiological activity of the plant. Arao et al. (2003) and Takahashi et al. (2021) mentioned that rice can absorb heavy metals and as a phytoremediator of heavy metals. The activity of plants in absorbing heavy metals in the soil is closely related to the activity of cells in sequestering heavy metals in vacuoles. Moreover, Takahashi et al (2021) revealed that rice can release Cd in the vacuole and was found unable to carry out this ability, so this influences the high and low concentrations of the heavy metal Cd in each part of the rice plant. Rice plants that cannot sequester Cd into the vacuole, Cd will be loaded into the xylem and will accumulate in other plant parts.

The accumulation of heavy metals in rice grains, as part of the total heavy metal uptake by the plant, contributes to the decline of heavy metal content in the soil. When the rice is harvested and the biomass is removed from the field, the heavy metals are effectively taken out of the soil system (Liu et al., 2007). The decrease in heavy metal content in the soil is a direct consequence of the rice plant's physiological process of uptake, where it absorbs the metals as part of its normal nutrient acquisition. The subsequent accumulation in the grain is a sequential process of transport and re-mobilization within the plant (Wang et al., 2022).

The pollution index value is used to assess the level of heavy metal contamination (Wei et al., 2009). The Pollution Index (PI) for the Pb, Cd, and Cr in the Tajum Sub-watershed was in moderate pollution conditions in all locations in the range of $1<PI\leq3$. The highest PI of Pb, Cd, and Cr was in Tinggarjaya Village viz. 2.96, 5.31, and 6.23, respectively.

Heavy metal contamination in soils is measured as a Pollution index. Generally, the farming system still uses conventional methods with the application of synthetic fertilizer to fulfill the nutritional requirements of plants. The study reported that fertilizers contain the amount of heavy metal elements that can be retained in soil and absorbed by plants (Roudposhti et al., 2016). The source of heavy metals contamination in paddy fields generally comes from agricultural activities, even fertilization does not always accumulate cadmium and lead in the soil (Sukarjo et al., 2018).

Other studies in different places in Indonesia showed that the paddy fields in Banyumas Regency and Jombang Regency were safe for agricultural cultivation activities against heavy metal accumulation. Both studies reported that only a small portion of the sample contains Pb and Cr above their critical limit (Sukarjo et al., 2019; 2021). However, in China Hemedan City, the application of fertilizers has led to higher contents of Cd in the soil. It has been reported that the Cd concentration in the soil is governed by anthropogenic activities such as the use of phosphate fertilizers (Liu et al., 2015; Hu et al., 2018).

The pollution index in this area of study ranged from 1-3 at a medium level. It is indicated that the safe level of heavy metal accumulation could be different from other places. The variations of heavy metals in soils were influenced by i.e. anthropogenic activities, geological conditions, dosage and composition of fertilizers, and soil quality (Roudposhti et al., 2016). Vary conditions of heavy metals accumulation in soils especially in rice fields is a fact that the information of pollution level according to the elements is specifically in a given area. A specific study to figure out the heavy metals condition in agricultural land must be done, and it could not be generally informed.

5. Conclusions

Condition of rice fields in the Tajum Sub-watershed, Banyumas Regency according to the contents of Pb, Cd, and Cr in the soil was still within safe limits but in rice grains on average exceeded the safe threshold, and Pollution Index in all areas of study were a medium level, generally.

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6. References

1. Amelia RA, Rachmadiarti F, Yuliani (2015): Analysis of lead level and the growth of rice plants in rice fields in Betas Village, Kapulungan, Gempol-Pasuruan. LenteraBio, 4, 187–191. (in Indonesian)
2. Anacleto LR, Roberto MM, Marin-Morales MA (2017): Toxicological effects of the waste of the sugarcane industry, used as agricultural fertilizer, on the test system *Allium cepa*. Chemosphere, 173, 31–42. https://dx.doi.org/10.1016/j.chemosphere.2017.01.033.
3. Arao T, Ae N (2003): Genotypic variations in cadmium levels of rice grain. Soil Science and Plant Nutrition, 49, 473–479. 93. https://dx.doi.org/10.1080/00380768.2003.10410035.
4. Bigalke M, Ulrich A, Rehmus A, Keller A (2017): Accumulation of cadmium and uranium in arable soils in Switzerland. Environmental Pollution, 221, 85-93. http://dx.doi.org/10.1016/j.envpol.2016.11.035.
5. Central Statistics Agency (2025): Rice Production in Indonesia 2024. BPS-Statistics Indonesia https://www.bps.go.id/en/pressrelease/2025/02/03/2414/-in-2024--paddy-harvested-area-was-approximately-10-05-million-hectareswith-53-14-million-tons-of-dry-unhusked-paddy--gkg--production-.html (in Indonesian)
6. Eviati S, Herawati L, Anggria L, Usman H, Tantika E, Prihatini R, Wuningrum P (2023): Technical guidelines for chemical analysis of soil, plants, water and fertilizers (3rd Edition). Ministry of Agriculture of the Republic of Indonesia. Bogor. (In Indonesian).
7. FAO/WHO (2002): Limit test for heavy metals in food additive specifications explanatory note. Joint FAO/WHO Expert Committee on Food Additives (JECFA).
8. Hasan GMAA, Das AK, Miah MAS (2022): Accumulation of heavy metals in rice (*Oryza sativa.* L) grains cultivated in three major industrial areas of Bangladesh. Journal of Environmental and Public Health, Article ID 1836597, 8p. http://dx.doi.org/10.1155/2022/1836597.
9. Hindarwati Y, Retnaningsih, Sudarno T (2018): Heavy metal content in terraced rice fields at Sruwen Tengaran Semarang, Indonesia. E3S Web of Conferences 31:1-6. http://dx.doi.org/10.1051/e3sconf/20183103009.
10. Hu B, Zhao R, Chen S, Zhou Y, Jin B, Li Y, Shi Z (2018): Heavy metal pollution delineation based on uncertainty in a coastal industrial city in the Yangtze River Delta, China. International Journal of Environmental Research and Public Health, 15, 1-13. http://dx.doi.org/10.3390/ijerph15040710.

11. Liu WX, Shen LF, Liu JW, Wang YW, Li SR (2007): Uptake of toxic heavy metals by rice (*Oryza sativa L.*) cultivated in the agricultural soil near Zhengzhou City, People's Republic of China. Bulletin of Environmental Contamination and Toxicology, 79, 209–213. http://dx.doi.org/10.1007/s00128-007-9164-0.
12. Liu MX, Yang YY, Yun XY, Zhang MM, Wang, J (2015): Concentrations, distribution, sources, and ecological risk assessment of heavy metals in agricultural topsoil of the Three Gorges Dam region China. Environmental Monitoring and Assessment, 187, 4360. http://dx.doi.org/10.1007/s10661-015-4360-6.
13. Looi LY, Aris AZ, Lim WY, Haris H (2014): Bioconcentration and translocation efficiency of metals in paddy (*Oryza sativa*): A case study from Alor Setar, Kedah, Malaysia. Sains Malaysiana, 43, 521–528.
14. Magahud JC, Badayos RB, Sanchez PB, Cruz, PCS (2015): Levels and potential sources of heavy metals in major irrigated rice areas of the Philippines. IAMURE International Journal of Ecology and Conservation, 15, 28-59. http://dx.doi.org/10.13140/RG.2.1.4735.8163.
15. Mahmud U, Salam MTB, Khan AS, Rahman MM (2021): Ecological risk of heavy metal in agricultural soil and transfer to rice grains. Discover Materials, 10, 1-13. doi: https://dx.doi.org/10.1007/s43939-021-00010-2.
16. Mahupawar M (2015): Social issues and environmental problems: effects of heavy metals on human health International. International Journal of Research, 2, 1- 7. https://dx.doi.org/10.29121/granthaalayah.v3.i9SE.2015.3282
17. Manurung M, Setyo Y, Suandewi R (2018): Accumulation of heavy metal chromium (Cr) in potato plants (*Solanum tuberosum l.*) due to application of pesticides, organic fertilizers and their combinations. Journal Kimia, 12, 165-172. https://dx.doi.org/10.24843/JCHEM.2018.v12.i02. (in Indonesian)
18. Mar SS, Okazaki M, Motobayasi T (2015): The influence of phosphate fertilizer application levels and cultivars on cadmium uptake by Komatsuna (*Brassica rapa L. var. perviridis*). Soil Science and Plant Nutrition, 58, 492—502. https://dx.doi.org/10.1080/00380768.2012.704394.
19. Ministry of State for Population and Environment of Indonesia, and Dalhousie University (1992): Environmental management in Indonesia. Report of soil quality standards for Indonesia.
20. Mulyadi (2013): Heavy metal Pb in rice field soil and grains in the Juwana sub-watershed, Central Java. Agrologia, 2, 95-101. https://dx.doi.org/10.30598/a.v2i2.263. (in Indonesian)
21. Payus C, Abu-Talip AF, Tan WH (2015): Heavy metals accumulation in paddy cultivation area of Kompipinan, Papar District, Sabah. Journal of Sustainability Science and Management, 10, 76–86.
22. Rahman M, Reichman S, Lim R, Naidu R (2014): Heavy metals in Australian grown and imported rice and vegetables on sale in Australia: Health hazard. Ecotoxicology and Environmental Safety, 100, 53-60. https://dx.doi.org/10.1016/j.ecoenv.2013.11.024. Epub 2013 Dec 20.
23. Ripin SNM, Hasan S, Kamal MI, Shahrizan N, Hashim M (2014): Analysis and pollution assessment of heavy metal in soil. The Malaysian Journal of Analytical Sciences, 18, 155-161.
24. Roudposhti GM, Karbassi A, Baghvand A (2016): A pollution index for agricultural soils, Archives of Agronomy and Soil Science, 62, 1411-1424. https://dx.doi.org/10.1080/03650340.2016.1154542.
25. Salmanzadeh M, Balks MR, Hartland A, Schipper LA (2016): Cadmium accumulation in three contrasting New Zealand soils with the same phosphate fertilizer history. Geoderma Regional, 7, 271–278. https://dx.doi.org/10.1016/j.geodrs.2016.05.001.
26. Shahbandeh M (2025): Total global rice consumption 2008/09-2024/25. statista.com.
27. Sharma RK, Agrawal M (2005): Biological effects of heavy metals: an overview. Journal of Environmental Biology, 26, 301–313. PMID: 16334259.
28. Sukarjo, Hidayah A, Zulaehah I (2018): Effect of fertilizers on the accumulation and translocation of cadmium and lead in soil and plants: Proceedings of the National Seminar on Biology and Science and Technology Education. Universitas Muhammadiyah Surakarta pp. 205-211. (in Indonesian).
29. Sukarjo, Zulaehah I, Harsanti ES, Ardiwinata AN (2021): Spatial assessment of potential ecological risks of heavy metals in paddy field soil layers Serayu hilir watershed, Central Java. Jurnal Tanah dan Iklim, 45, 69-77. http://dx.doi.org/10.21082/jti.v45n1.2021.69-77 (in Indonesian)
30. Sukarjo S, Purbalisa W, Handayani CO, Harsanti ES (2019): Assessment of heavy metal contamination risk in paddy fields and rice plants at Brantas Watershed, District of Jombang. Jurnal Tanah dan Sumberdaya Lahan, 6, 1033-1042. http://dx.doi.org/10.21776/ub.jtsl.2019.006.1.2. (in Indonesian)
31. Sukarjo S, Handayani CO, Rahayu HSP, Hidayat S (2023): Assessment of contamination level and source apportionment of heavy metals in serayu river water, Indonesia. International Journal of Conservation Science, 14, 1641-1658. http://dx.doi.org/10.36868/IJCS.2023.04.26.

32. Takahashi R, Ito M, Kawamoto, T (2021): The road to practical application of cadmium phytoremediation using rice, Plants, 10, 1926. https://dx.doi.org/10.3390/plants10091926.
33. Wang W, Lu B, Li C, Wang Y (2022): Differences in the response mechanism of cadmium uptake, transfer, and accumulation of different rice varieties after foliar silicon spraying under cadmium-stressed soil. Frontiers in Plant Science, 13, 1064359. https://dx.doi.org/10.3389/fpls.2022.1064359.
34. Wang J, Wu B, Zhou L, Liu K, You A, Zha W (2025): Cadmium contamination in Asian rice (*Oryza sativa L.*): Mechanistic insights from soil sources to grain accumulation and mitigation strategies. Plants, 14, 2844. https://dx.doi.org/10.3390/plants14182844.
35. Wei C, Wang C, Yang L (2009): Characterizing spatial distribution and sources of heavy metals in the soils from mining smelting activities in Shuikoushan, Hunan Province, China. Journal of Environmental Sciences, 21, 1230-1236. https://dx.doi.org/10.1016/s1001-0742(08)62409-2.
36. World Health Organization (WHO) (1996): Permissible limits of heavy metals in soil and plants. Geneva, Switzerland.
37. Williams PN, Islam MR, Adomako EE, Raab A, Hossain SA, Zhu YG, Fieldman J, Meharg AA (2006): Increase in rice grain arsenic for regions of Bangladesh irrigating paddies with elevated arsenic in groundwaters. Environmental Science and Technology, 40, 4903–4908. https://dx.doi.org/10.1021/es060222i.
38. Zeng F, Wei W, Li M, Huang R, Yang F, Duan Y (2015): heavy metal contamination in rice-producing soils of Hunan Province, China and potential health risks. International Journal of Environmental Research and Public Health, 12, 15584–15593. https://dx.doi.org/10.3390/ijerph121215005.