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Assessment of toxic metal contamination and water source usage in mining-affected communities

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Abstract: Coal mining activities often raise concerns about heavy metal contamination in surrounding water and soil, threatening environmental quality and public health. This study investigates the concentration of six toxic metals (Cu, Cd, Mn, Zn, Pb, and Fe) in water and soil samples collected around the PT. X in Riau Province, Indonesia mining site to assess environmental impacts and inform sustainable management. Sampling was conducted across multiple locations including pits, rivers, settlements, and operational areas during the rainy season. Exploratory descriptive analysis was conducted to compare measured metal concentrations with national and international quality standards. Results show that while most heavy metal levels remain below regulatory thresholds, iron concentrations in river water approach the permissible limit, indicating potential seasonal risks. Cadmium and lead were generally undetectable, highlighting effective pollution control. Soil samples showed localised exceedances of Cu, Zn, and Mn near riverine and residential areas, indicating site-specific contamination with potential ecological and human health implication. Despite available alternatives, local communities continue to rely heavily on river water, exposing them to potential health hazards. During the study period, most metal concentrations in water did not exceed current standards, whereas local exceedances of selected elements were observed in soil, thus seasonal monitoring, community education, and improved access to safe water are essential for environmental and public health protection.

Keywords: coal mining, environmental monitoring, public health risk, soil pollution, toxic metal contamination, water quality

INTRODUCTION

Coal mining remains a vital sector that significantly contributes to national economic growth and energy production. However, these benefits come with substantial environmental trade-offs. In many developing countries, including Indonesia, coal mining activities are still associated with significant environmental degradation particularly in the form of soil and water contamination (Pambudi *et al.*, 2023a). One of the most critical environmental issues is the accumulation of toxic metals in the surrounding environment, which poses serious threats to ecological integrity and human health (Zeng *et al.*, 2022).

Ideally, mining operations should integrate environmental safeguards from planning to post-operational stages (Ma *et al.*, 2021). Best practices include routine environmental monitoring, effective waste treatment, and ecological rehabilitation (Antonkiewicz *et al.*, 2025). However, in reality, many coal mining operations, especially in remote or less regulated areas, fail to fully implement these practices (Al Naggar, Khalil and Ghorab, 2018). This discrepancy between expected and actual environmental management creates persistent risks to ecosystem (Dlamini and Xulu, 2019).

In Indonesia, one of the important coal-producing regions is Indragiri Hulu Regency in Riau Province, where several active and abandoned mining sites are located near settlements and small rivers (Pambudi *et al.*, 2023c). Local communities in villages heavily on surface water and shallow wells for daily domestic needs. Over the past few years, local residents and environmental advocacy groups have raised concerns over possible contamination of these water sources, following visible changes in water colour, unpleasant odour, and the decline of aquatic organisms (Pambudi *et al.*, 2023b).

These concerns culminated in episodes of social tension between local residents, civil society organisations, and the mining company, as communities suspected that waste discharge and runoff from coal stockpiles were polluting nearby rivers and ponds (Pambudi *et al.*, 2023c). Hydrologically, Indragiri Hulu experiences distinct wet and dry seasons that strongly influence surface runoff and water retention in former mining voids (Pambudi *et al.*, 2023a). During the wet season, leaching of toxic metals from overburden and tailing materials increases, allowing pollutants to enter nearby rivers and community ponds (Pambudi, Utomo and Handoko 2025). Conversely, in the dry season, evaporation processes and reduced water exchange may intensify the concentration of metals in stagnant water bodies (Ariani, Hanudin and Haryono, 2022). Understanding this seasonal variation is essential for assessing actual exposure risks and designing appropriate mitigation measures. This study therefore aims to assess heavy metal contamination in community water sources within mining-affected areas of Indragiri Hulu, focusing on both surface and groundwater.

MATERIALS AND METHODS

STUDY AREA

This study was conducted in Riau Province, Indonesia which includes the coal mining concession area of PT. X. The company operate under Mining Business Permits (Ind.: Izin Usaha Pertambangan – IUP) issued by the local government. The area is characterised by undulating topography with several artificial voids and sedimentation ponds that directly connect to community-used rivers. Settlements are located within a 1–3 km radius from the mine pits, and many households rely on shallow wells and nearby rivers for daily water needs. The study area location is presented in Figure 1.

FIELD SAMPLING

This study focused on the toxic metals content of Cu, Cd, Zn, Fe, Mn, and Pb. The selection of these toxic metals in this study is crucial due to their environmental and health impacts. This study was conducted in 4 stages, namely (1) field observation, (2) water and soil sampling, (3) laboratory testing, and (4) synthesis of test results. Each stage was performed sequentially and carefully. Field observations were first carried out to assess hydrological connections between mining voids and downstream rivers. Sampling points were then determined using purposive sampling based on proximity to potential pollution sources and community water use patterns, taken only once in November. Three sampling points were established inside the mining area (pit, void, and camp) and three outside (river, water resource, and community well in settlement area). Soil samples were also collected to assess potential toxic metal depositions around the same transect. Figure 1 illustrates these points spatially across the landscape. Water samples (2 dm^3 each) were collected at approximately 30 cm below the surface using pre-cleaned polyethylene bottles. Soil samples (1 kg) were taken from 0–50 cm depth using a stainless-steel auger and kept in acid-washed polyethylene bags. The 0–50 cm depth was selected to represent the biologically active soil zone relevant to mining impacts, encompassing surface inputs, root interaction, and potential downward metal migration. Samples were composed to assess cumulative contamination rather than vertical gradients, consistent with reconnaissance-level soil monitoring practices in mining-affected agricultural landscape.

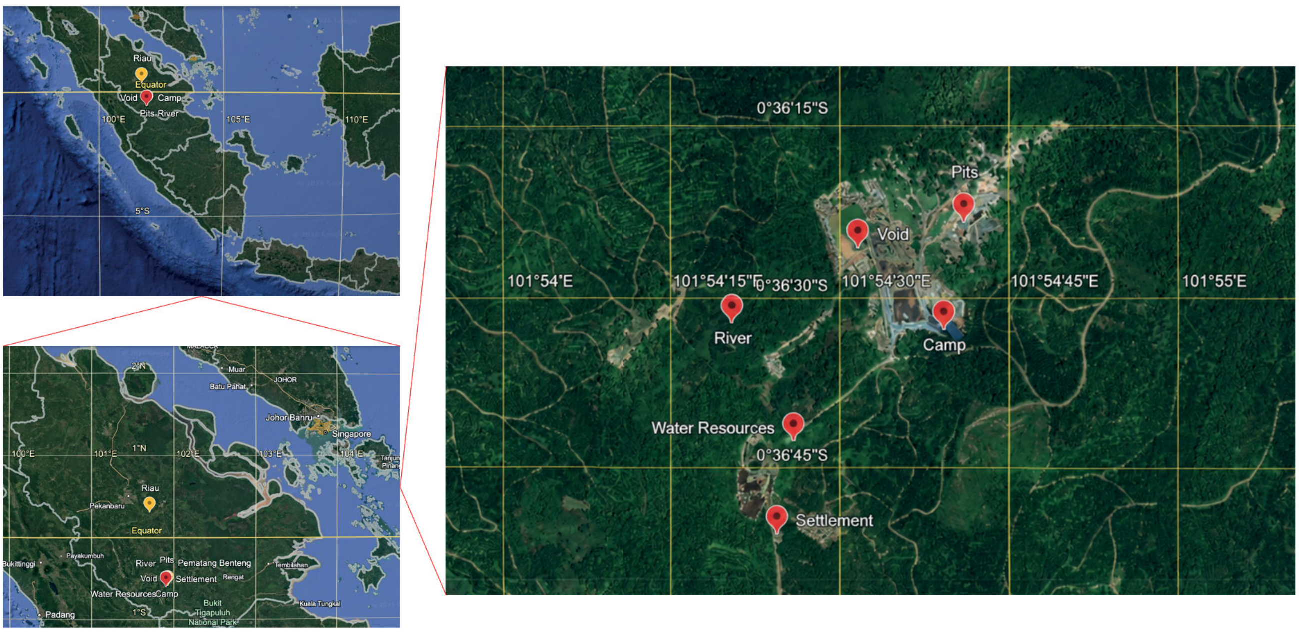

Fig. 1. Study area location and samplings; source: own elaboration based on Google maps

LABORATORY ANALYSIS

All water and soil samples were analysed at the Laboratory of Environmental Quality, Graduate School of Sustainable Development, Universitas Indonesia (ISO/IEC 17025 accredited). Heavy metal concentrations were measured using Atomic Absorption Spectrophotometry (AAS, Perkin Elmer Analyst 400) following APHA 3120B method (Baird, Eaton and Rice, 2017). Calibration curves were constructed using multi-element standard solutions (Merck). Each analysis included triplicate measurements, reagent blanks, and certified reference materials to ensure data reliability. The AAS flame method was used to test the water and soil samples, with the limit of detection (*LOD*) and limit of quantification (*LOQ*), recovery present, and reagent values. The process was conducted using two basic stages, namely calibration curve creation (A) and samples measurement (B). However, when the concentration exceeded the highest standard of calibration, the dilution process and sample measurement are repeated. Furthermore, calculations were performed to determine the final value of the concentration of a metal (C). A comprehensive explanation of each stage of the sample testing process is provided in Figure 2.

DATA ANALYSIS

After conducting the tests, the results were compared with water and soil quality standards, as stipulated by applicable regulations. Descriptive explorative analyses were performed to compare toxic metal concentrations with applicable Indonesian standards, namely: (1) Government Regulation Number 22/2021 for Environmental Management and Protection (Peraturan, 2021) (2) Regulation of the Minister of Health of the Republic of Indonesia Number 32 of 2017 concerning environmental health quality standards and water health requirements for sanitation hygiene purposes, swimming pools, solus per aqua and public baths (Peraturan, 2017), (3) Minister of Environment Decree Number 113/2003 for coal mining wastewater (Keputusan, 2003). Soil tests results were compared to reference values by Pickering (1980). Monthly rainfall data from 2017–2021 (Fig. 3) were analysed descriptively to assess seasonal patterns and their potential influence on toxic metal transport, dilution, and accumulation in environmental media. Qualitative data from community interviews were integrated to triangulate biophysical results, highlighting local perceptions of pollution and adaptive water-use behaviour.

To complement the physicochemical analysis, a socio-environmental survey was conducted in affected villages. Using purposive sampling, 59 households were interviewed through semi-structured questionnaires. The survey aimed to document community perceptions of water quality, changes in aquatic life, health complaints, and reliance on alternative water sources. Data were analysed qualitatively through thematic coding to identify patterns linking community experiences with environmental measurement results. This participatory approach aligns with the socio-environmental orientation of the study, enabling contextual interpretation of contamination risks and community resilience strategies.

RESULTS AND DISCUSSION

TOXIC METAL CONTENTS IN WATER

Coal mining operations inherently modify the surrounding natural ecosystems through land disturbance, overburden, and the use of heavy machinery. These activities, directly or indirectly, influence water quality through surface runoff, sediment transport, and potential leaching of toxic metals. As reported by Krogulec *et al.* (2025), coal extraction involves mechanical, chemical, and physical processes that can alter the chemical composition of surrounding environments. Moyo *et al.* (2024), emphasise that such activities can leave significant footprints on soil, water, and biota. In this context, a comprehensive analysis of water quality around mining areas becomes critical to under-

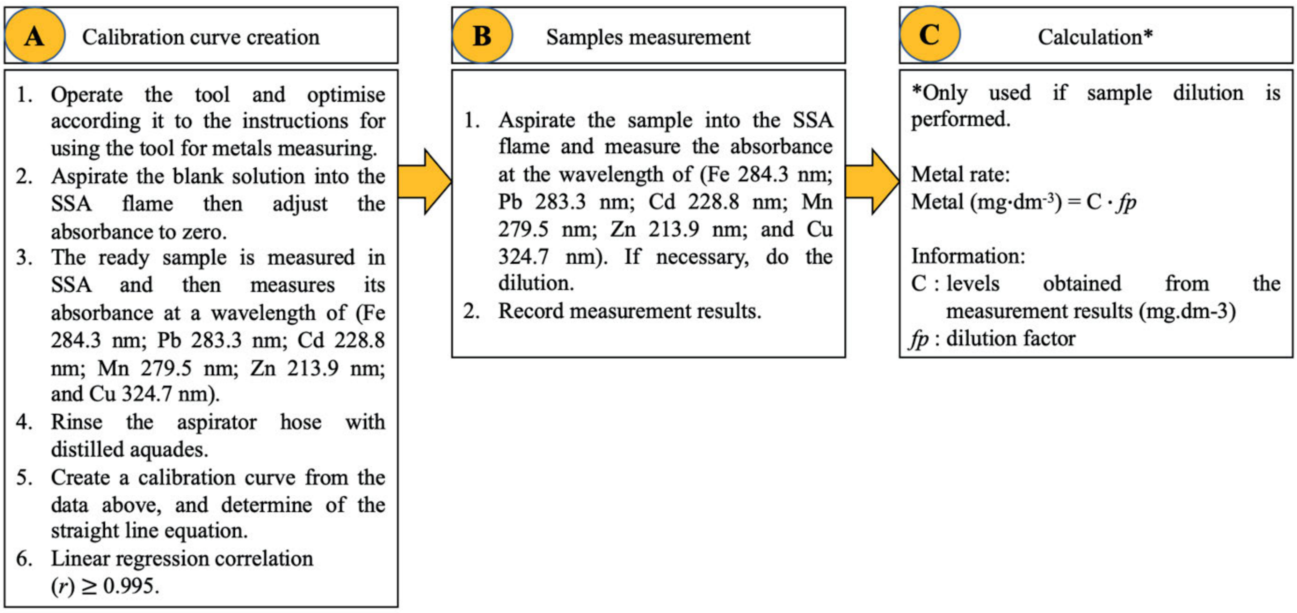

Fig. 2. The stages of the sample testing process; C = levels obtained from the measurement results (mg·dm^{-3}), fp = dilution factor; source: own elaboration

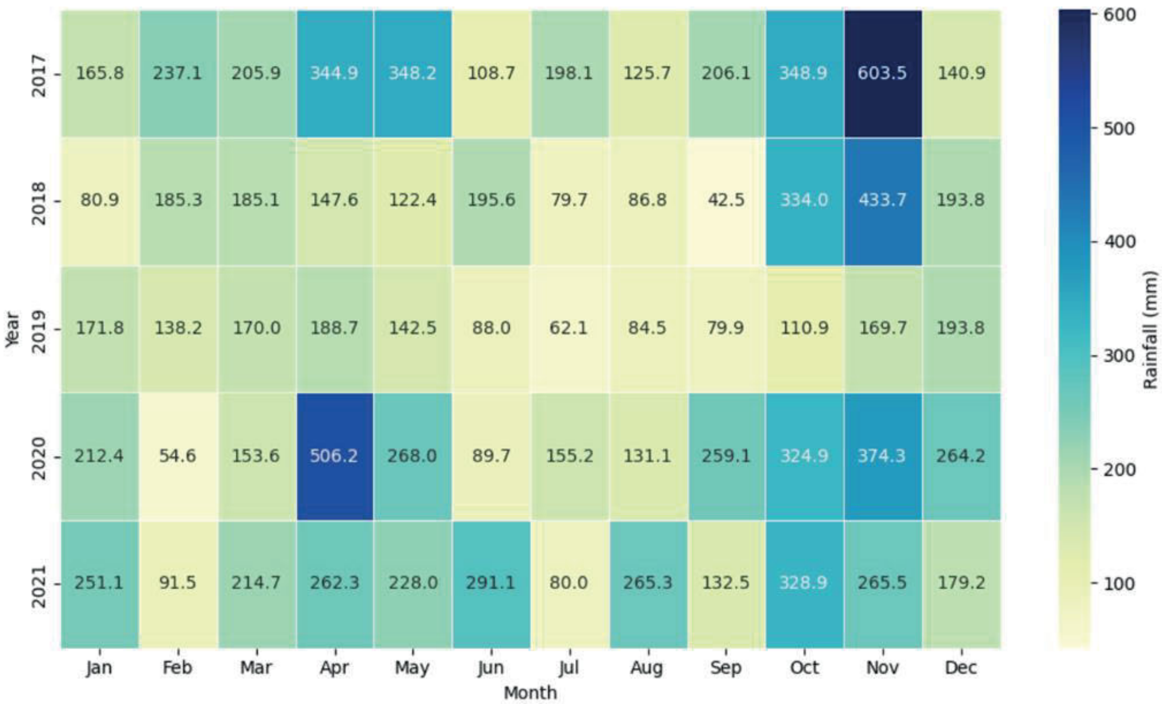

Fig. 3. Monthly rainfall heatmap (mm) 2017–2021; source: BPS (2022)

standing environment impacts and safeguarding public health. The concentration of six toxic metals (Cu, Cd, Fe, Zn, Mn, and Pb) across six sampling points around PT. X: pits, voids, camp, water sources, rivers, and settlement is presented in Table 1. The data indicate that while most measured parameters are below regulatory threshold, certain findings warrant closer examination.

Copper (Cu), zinc (Zn), and iron (Fe) were consistently detected across sites, with Fe reaching 0.796 mg·dm^{-3} in river samples close to the 1.0 mg·dm^{-3} regulatory limit (Peraturan, 2021). This suggests potential exceedance during drier periods, given Fe's tendency to accumulate and affect water quality. In contrast, cadmium (Cd), manganese (Mn), and lead (Pb) were largely below detection limits, though their absence does not guarantee safety, as even trace exposure can pose significant developmental and neurological risks, as noted by Zhou *et al.* (2022). Samples from camp and settlement areas also met sanitation standards, yet shallow groundwater depths (4–12 m) increase vulnerability to contamination during heavy rainfall or flooding.

The community water source used for cooking during the dry season similarly fell within permissible limits, though its Fe concentration (0.795 mg·dm^{-3}) warrants attention for potential seasonal increases. This concern aligns with Sahoo *et al.* (2023), who emphasised Fe's influence on electrochemical soil conditions and broader geophysical processes. Importantly, all samples were collected during the rainy season, when dilution lowers contaminant levels; thus, actual concentrations may be higher in drier months. As highlighted by Jabłońska-Czapla, Szopa and Rosik-Dulewska (2014) time-series monitoring is essential to capture seasonal fluctuations in heavy metal pollution around mining areas.

TOXIC METALS CONTENT IN SOIL

In line with environmental assessment guidelines issued by the Directorate of Mineral and Coal (Ministry of Energy and Mineral Resources), comprehensive monitoring of mining impacts must include both water and soil parameters to capture the full

Table 1. Toxic metals concentration in water sample around PT. X

Toxic metal	Concentration (mg·dm^{-3}) in						*SD*	Quality standards and threshold
	pit	void	camp	water source	river	settlement		
Cu	0.468	0.802	0.410	0.392	0.584	1.000	0.244	NA
Cd	0.004	0.004	0.004	0.004	0.004	0.004	0.000	0.005 (Peraturan, 2017)
Fe	0.134	0.728	0.120	0.202	0.795	0.162	0.315	0.3 (Peraturan, 2021), 1.0 (Peraturan, 2017)
Mn	ND	ND	0.348	ND	ND	ND	–	0.1 (Peraturan, 2021), 0.5 (Peraturan, 2017)
Pb	0.085	0.085	0.085	0.085	0.085	0.085	0.000	0.03 (Peraturan, 2021), 0.05 (Peraturan, 2017)
Zn	0.080	0.090	0.102	0.080	0.086	0.078	0.009	NA

Explanations: *SD* = standard deviation, ND = not detected, NA = not applicable.
Source: own study.

spectrum of environmental conditions. The concentrations of selected toxic metals (Cu, Cd, Zn, Fe, Mn, and Pb) in soil samples collected from five locations surrounding PT. X's mining site: pits, voids, camp area, riverbanks, and settlement are illustrated in Table 2.

Pickering's quality standard (Pickering, 1980) is exceeded for Cu levels, while Cd remains entirely below it (Tab. 2). Concentrations of Zn surpass the threshold in voids and camp areas but stay below it in pits, rivers, and settlements. Also Mn and Pb are above the standard in voids, camp, and rivers, yet lower in pits and settlements; Fe has no prescribed limit. These findings indicate soil contamination by Cu, Zn, Mn, and Pb within the PT. X area, and by Cu and Mn in surrounding zones, although Zn, Pb, and Cd have not impacted areas beyond the mine. Consistent with Raj and Das (2023), who highlight toxic metals as indicators of environmental quality due to their accumulation in soil and water, the exceedances of Cu and Mn suggest localised environmental risks requiring further scrutiny.

Verification using standards from Environment Protection Authority of Australia (EPA Tas, 2018), National standard of the People's Republic of China (GB 15618-2018); United States Environmental Protection Agency (USEPA, 2017) shows that Pb, Cd, and Fe remain within safe limits, reinforcing that soils at PT. X and adjacent areas are generally stable and not experiencing harmful contamination. These results support the view that PT. X conducts mining responsibly, contradicting findings by Pambudi, Utomo and Handoko (2025), who reported negative impacts of coal mining on soil fertility and water quality. The conditions observed here, chemical and physical parameters within normal limits provide empirical evidence that coal mining does not inevitably cause environmental degradation and can align with sound environmental management when properly implemented.

EFFECT OF RAINFALL ON TOXIC METALS CONCENTRATION IN THE MINING AREA

The presence of toxic metals in water is closely linked to mining-related contamination and rainfall, where higher rainfall increases surface flow and water volume, causing natural dilution that reduces pollutant concentrations, a mechanism also described by Wu *et al.* (2025), who noted that added water volume lowers contaminant levels. However, not all pollutants dilute easily, as shown by Zhang *et al.* (2022) with dichloro diphenyl trichloroethane (DDT), which remains poorly soluble even with increased solvent volume. In this study, the six tested toxic metals showed high solubility and remained below quality standards, aligning with Li T. *et al.* (2025), who found lower metal concentrations at deeper, higher-volume river layers due to stronger currents enhancing dilution.

Vegetation surrounding water bodies contributes to the reduction of heavy metal concentrations, as supported by findings that mangroves possess the ability to absorb metals such as Cu and Zn through measurable transfer factors (Takarina, 2020). Although toxic metals vary in molecular weight and are generally insoluble in water due to their ionic bonds, hydrological processes particularly rainfall can disperse accumulated metals by diluting sediments and transporting dissolved fractions through water flow. These mechanisms align with observations from Gupta *et al.* (2024), who demonstrated that the distribution of metals such as As, Cu, Cd, Pb, Ni, and Zn in aquatic ecosystems is highly dependent on water volume and current dynamics.

At the study site, sampling conducted in early November 2024 following the peak monthly rainfall of 328.9 mm revealed heavy metal concentrations in soil and water that remained within normal limits, with several parameters falling below detection limits. These results contrast sharply with findings from coal mining areas in China and Vietnam, where Cd levels reached 0.75–1.29 mg·dm^{-3} (Zeng *et al.*, 2022) and 0.23 mg·dm^{-3} (Marquez *et al.*, 2018), respectively. In comparison, Cd concentrations at the PT. X location were not detected, suggesting favourable environmental conditions. Nonetheless, the influence of high rainfall on dilution cannot be ruled out, indicating the need for supplementary sampling during the dry season to ensure more robust comparative assessments.

THE RISK TOXIC METALS TO PUBLIC HEALTH

Understanding the public health risks of toxic metal exposure requires consideration of community water-use behaviour within its socio-demographic context. The surveyed households are predominantly long-term residents engaged in agriculture, with moderate education and income levels that may constrain access to alternative and safer water infrastructure (Tab. 3). These characteristics shape patterns of reliance on surface water and groundwater sources, thereby influencing the magnitude and persistence of exposure to mining-related metal contamination.

Table 2. Toxic metals concentration in soil sample around PT. X

Toxic metal	Concentration (mg·kg^{-1}) in					*SD*	Normal value[1)]
	pit	void	camp	river	settlement		
Cu	8.65	20.67	26.24	9.63	8.43	8.222	2–100
Cd	ND	ND	ND	ND	ND	–	0.1–7
Fe	2,731.96	12,432.72	10,852.41	9,606.15	6,324.62	3,878.31	NA
Mn	47.35	182.65	191.03	296.73	23.14	112.797	100–4000
Pb	1.55	6.11	0	ND	ND	3.177	2–200
Zn	7.1	68.32	59.35	4.38	8.82	31.458	10–300

1) Acc. to: Pickering (1980).
Explanations: ND = not detected, NA = not applicable.
Source: own study.

Table 3. The surveyed households socio-demographic characteristics

Variable	Category	Household (*n*)	Percentage (%)
Occupation	civil servant	3	5.1
	farmer	41	69.5
	mining worker	7	11.9
	trader	2	3.4
	daily labourer	6	10.2
Length of residents	<1 year	0	0
	1–5 years	0	0
	5–10 years	0	0
	10–15 years	11	18.6
	>15 years	48	81.4
Education level	primary school	8	13.6
	junior high school	11	18.6
	senior high school	36	61
	diploma/bachelor's degree	4	6.8
	postgraduate degree	0	0
Monthly income (IDR)	<1 mln	5	8.5
	1–2 mln	11	18.6
	2–3 mln	31	52.5
	3–4 mln	9	15.3
	>4 mln	3	5.1

Explanations: *n* = number, IDR1 = USD0.000058.

The surveyed households are predominantly agrarian, with nearly 70% engaged in farming, indicating strong dependence on land and water resources, a recognised vulnerability factor in mining-affected rural areas (Li S. *et al.*, 2025). Most residents are long-term inhabitants, with over 76% residing in the area for more than ten years, implying sustained exposure to local environmental conditions and cumulative contamination risks, particularly through surface water use (Pambudi, 2025). Educational attainment and income levels are generally moderate, which may constrain access to information and financial capacity for safer water infrastructure, reinforcing continued reliance on potentially contaminated water sources as observed in comparable mining regions (Nurlaela *et al.*, 2020). Collectively, these characteristics align with exposure-based definitions of mining-affected communities, where vulnerability is shaped by both environmental proximity and socio-demographic factors influencing adaptive capacity and risk perception (Pambudi, Utomo and Handoko, 2025). Within this context, household water-use decisions are largely shaped by practical constraints and the availability of naturally accessible water sources.

In the study location, the local communities still rely on river water and natural springs as their primary source for daily water needs. These communities are typically situated in proximity to forest areas. Due to the difficulty and cost associated with digging wells to a depth of more than 8 m, which requires specialised tools and substantial expenses, the residents are hesitant to construct their own wells. As a result, they opt to utilise the naturally available water resources without the need for extensive engineering efforts. The fulfilment of water resources for the local communities can be observed in Figure 4.

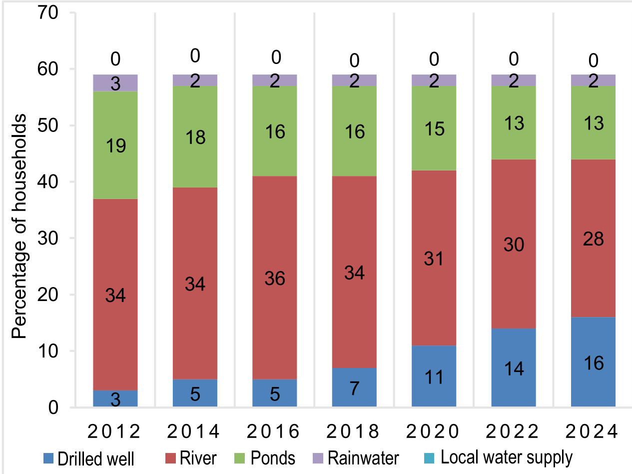

Fig. 4. Water sources usage by households around PT. X based on questionnaire; source: own study

The long-standing reliance of local communities on the Indragiri River reflects deep socio-cultural ties, with settlements historically forming along riverbanks and depending on fishing, horticulture, and river-based irrigation. This pattern parallels riparian community dynamics described by Pambudi Utomo and Handoko (2025), where rivers shape both livelihoods and cultural identity. However, data from 2012–2024 indicate a gradual shift toward groundwater sources, driven by concerns over surface water quality and increasing water demand, consistent with global rural trends (Krogulec *et al.*, 2025). Despite this transition, adoption of company-provided drilled wells remains limited, highlighting infrastructural, economic, and social barriers similar to those noted by Meftah *et al.* (2025).

Continued dependence on river water raises concern given documented contamination from mining wastewater containing toxic metals such as Cu, Zn, Mn, Fe, and Pb, all of which pose serious health risks (Doroodzani *et al.*, 2022). This situation reflects broader environmental justice issues in extractive regions, where marginalised communities often face disproportionate exposure to pollution (Sudaryatno *et al.*, 2025). Addressing these challenges requires community-centered water management that integrates equity, environmental protection, and participatory governance, as proposed by Mariyam, Putra Satria and Samsudin. (2023). Strengthening education, improving access to communal groundwater, and empowering local decision-making are essential steps toward enhancing resilience, protecting health, and balancing environmental well-being with ongoing regional development.

It is important to note that the environmental measurements presented in this study were conducted exclusively during the wet season (November), when increased rainfall can dilute contaminant concentrations in surface water and sediments. Consequently, the reported metal levels should be interpreted as representative of rainy-season conditions rather than annual maxima, as higher concentrations may occur during dry season when reduced river discharge and limited dilution can intensify contaminant accumulation. Recognising this seasonal limitation, precautionary management and mitigation measures remain essential to address potential increases in contaminant concentrations under drier hydrological conditions.

Mitigation strategies include strengthened runoff control with sedimentation systems, soil remediation through phytotechnology, and community-based safe water initiatives to reduce heavy metal mobility, improve ecosystem recovery, and enhance environmental resilience in mining-affected areas. As emphasised by Antonkiewicz *et al*. (2025), sedimentation and runoff management effectively limit the spread of contaminants in industrial landscapes. In addition, Pambudi, Utomo and Handoko (2025) highlighted the importance of community-based initiatives in providing safe water to reduce public health risks in industrially impacted areas.

CONCLUSIONS

Heavy metal concentrations (Cu, Cd, Mn, Zn, Pb, Fe) in water and soil around the PT. X mining site generally remained within regulatory thresholds during the sampling period, although Pb in water exceeded the applicable limit at specific locations, indicating the need for targeted mitigation alongside existing environmental management measures despite ongoing coal extraction. Iron (Fe) concentrations in water remained within regulatory standards, while for soil no specific threshold reference was available under the applied guidline, thus interpretation should be treated cautiously. Very low cadmium (Cd) levels, compared with other mining regions, reflect strong pollution control. Community dependence on river water highlights socio-economic barriers to accessing safer groundwater. Overall, the study indicates that while most measured parameters were within regulatory limits during the sampling period, localised contamination persists. Continued seasonal monitoring, increased public awareness, and expanded safe water infrastructure are essential to protect community health and strengthen socio-environmental resilience.

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CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

REFERENCES

Al Naggar, Y., Khalil, M.S. and Ghorab, M.A. (2018) "Environmental pollution by heavy metals in the aquatic ecosystems of Egypt," *Open Access Journal of Toxicology*, 3(1), 555603. Available at: https://doi.org/10.19080/oajt.2018.03.555603.

Antonkiewicz, J. *et al*. (2025) "Sustainable management of bottom ash and municipal sewage sludge as a source of micronutrients for biomass production," *Sustainability*, 17(16), 7493. Available at: https://doi.org/10.3390/su17167493.

Ariani, M., Hanudin, E. and Haryono, E. (2022) "The effect of contrasting soil textures on the efficiency of alternate wetting-drying to reduce water use and global warming potential," *Agricultural Water Management*, 274, 107970. Available at: https://doi.org/10.1016/j.agwat.2022.107970.

Baird, R.B., Eaton, A.D. and E.W. Rice (eds.) (2017) *Standard methods for the examination of water and wastewater*. 23rd edn. Washington, DC: American Public Health Association.

BPS (2022) *Kabupaten Indragiri Hulu Dalam Angka [Indragiri Hulu Regency in Ststaistics]*. Indragiri Hulu, Riau: BPS Kabupaten Indragiri Hulu. Available at: https://inhukab.bps.go.id/id/publication/2022/02/25/71edfe8e3d92a0e61b538dd6/kabupaten-indragiri-hulu-dalam-angka-2022.html (Accessed: November 10, 2025).

Dlamini, L.Z.D. and Xulu, S. (2019) "Monitoring mining disturbance and restoration over RBM site in South Africa using LandTrendr algorithm and landsat data," *Sustainability*, 11(24), 6916. Available at: https://doi.org/10.3390/SU11246916.

Doroodzani, A.K. *et al*. (2022) "Maternal and fetal exposure to metal (loid)s, maternal nutrition status, and impact on prenatal growth in an energy rich zone and an urban area along the Persian Gulf," *Environmental Pollution*, 309, 119779. Available at: https://doi.org/10.1016/j.envpol.2022.119779.

EPA Tas (2018) "Classification and management of contaminated soil for disposal," *Information Bulletin*, 105. Environment Protection Authority Tasmania. Available at: https://epa.tas.gov.au/Documents/Information%20Bulletin%20105%20-%20Classification%20of%20Contaminated%20Soils%20(IB105)%20V3_2018.pdf (Accessed: October 10, 2025).

GB 15618-2018. *Soil environmental quality – Risk control standard for soil contamination of agricultural land. National standard of the People's Republic of China*. Available at: https://www.chinesestandard.net/PDF.aspx/GB15618-2018 (Accessed: October 10, 2025).

Gupta, M. *et al*. (2024) "Lead toxicity in plants: mechanistic insights into toxicity, physiological responses of plants and mitigation strategies," *Plant Signaling and Behavior*, 19(1), 2365576. Available at: https://doi.org/10.1080/15592324.2024.2365576.

Jabłońska-Czapla, M., Szopa, S. and Rosik-Dulewska, C. (2014) "Impact of mining dump on the accumulation and mobility of metals in the Bytomka River sediments," *Archives of Environmental Protection*, 40(2), pp. 3–19. Available at: https://doi.org/10.2478/aep-2014-0013.

Keputusan (2003) *Keputusan Menteri Negara Lingkungan Hidup Nomor 113 Tahun 2003 tentang baku mutu air limbah bagi usaha dan atau kegiatan pertambangan batu bara [Ministry of Environment Regulation of the wastewater quality standards for coal mining businesses and/or activities]*. Available at: https://komara.weebly.com/uploads/6/5/3/7/6537907/f_kepmen_lh_113_2003_baku_mutu_air_limbah_pertambangan_batu_bara.pdf (Accessed: October 11, 2025).

Krogulec, E. *et al*. (2025) "Changes in groundwater vulnerability due to land reclamation in mining areas: An assessment using the DRASTIC method," *Water*, 17(5), 702. Available at: https://doi.org/10.3390/w17050702.

Li, S. *et al*. (2025) "Model test study on the rainfall erosion mechanisms and reclamation potential of open-pit coal mine dump soil improved by fly ash and polyacrylamide," *Engineering Geology*, 344, 107837. Available at: https://doi.org/10.1016/j.enggeo.2024.107837.

Li, T. *et al*. (2025) "Efficient removal of metals and resource recovery from acid mine drainage by modified chemical mineralization coupling sodium sulfide precipitation," *Journal of Environmental Sciences*, 156, pp. 399–407. Available at: https://doi.org/10.1016/j.jes.2024.10.019.

Ma, T. *et al.* (2021) "Integrated ecological risk assessment of heavy metals in an oil shale mining area after restoration," *Journal of Environmental Management*, 300, 113797. Available at: https://doi.org/10.1016/j.jenvman.2021.113797.

Mariyam, S., Putra Satria, A. and Samsudin, M. (2023) "What are the forms and obstacles of community participation in environmental damage prevention?," *Administrative and Environmental Law Review*, 4(2), pp. 115–126. Available at: https://doi.org/10.25041/aelr.v4i2.2992.

Marquez, J.E. *et al.* (2018) "Effect of cadmium, copper and lead on the growth of rice in the coal mining region of Quang Ninh, Cam-Pha (Vietnam)," *Sustainability*, 10(6), 1758. Available at: https://doi.org/10.3390/su10061758.

Meftah, S. *et al.* (2025) "Heavy metal polluted water: Effects and sustainable treatment solutions using bio-adsorbents aligned with the SDGs," *Discover Sustainability*, 6(1), 137. Available at: https://doi.org/10.1007/s43621-025-00895-6.

Moyo, A. *et al.* (2024) "Acid mine drainage and metal(loid) risk potential of South African coal processing wastes," *Minerals Engineering*, 215, 108825. Available at: https://doi.org/10.1016/j.mineng.2024.108825.

Nurlaela *et al.* (2020) "The impact of nickel management on community socio-economic conditions in Morosi District Konawe Regency," *Indonesian Journal of Social and Environmental Issues (IJSEI)*, 1(1), pp. 1–4. Available at: https://doi.org/10.47540/ijsei.v1i1.4.

Pambudi, P.A. (2025) "The paradox of nickel investment in Indonesia," *Environmental Pollution Journal*, 5(3), pp. 299–319. Available at: https://doi.org/10.58954/epj.v5i3.339.

Pambudi, P.A. *et al.* (2023a) "Coal mining reclamation as an environmental recovery effort: A review," *Journal of Degraded and Mining Lands Management*, 10(4), pp. 1001–1011. Available at: https://doi.org/10.15243/jdmlm.2023.104.4811.

Pambudi, P.A. *et al.* (2023b) "Implikasi tambang batubara pada kehidupan masyarakat lokal [Coal mining implication on local community life]," *Humanis: Jurnal Ilmu-Ilmu Sosial Dan Humaniora*, 15(2), pp. 48–58.

Pambudi, P.A. *et al.* (2023c) "Potential social conflict in coal mining areas and alternative solutions in Indragiri Hulu Regency, Riau Province," *Aspirasi: Jurnal Masalah-Masalah Sosial*, 14(2), pp. 155–171. Available at: https://doi.org/10.46807/aspirasi.v14i2.3615 https://vs-dprexternal3.dpr.go.id/index.php/aspirasi/article/view/3615/pdf (Accessed: October 15, 2025).

Pambudi, P.A., Utomo, S.W. and Handoko, R.S. (2025) "Coal mining reclamation: Lessons learned from tropical and subtropical countries," *Journal of Environmental Science and Sustainable Development*, 8(1), pp. 148–184. Available at: https://doi.org/10.7454/jessd.v8i1.1299.

Peraturan (2017) *Peraturan Menteri Kesehatan nomor 32 tahun 2017 tentang standar baku mutu kesehatan lingkungan dan persyaratan kesehatan air untuk keperluan higiene sanitasi, kolam renang, solus per aqua, dan pemandian umum [Regulation of the Minister of Health of the Republic of Indonesia Number 32 of 2017 concerning environmental health quality standards and water health requirements for sanitation hygiene purposes, swimming pools, solus per aqua and public baths]*. Available at: https://peraturan.bpk.go.id/Details/112092/permenkes-no-32-tahun-2017 (Accessed: November 09, 2025).

Peraturan (2021) *Peraturan Pemerintah Republik Indonesia nomor 22 tahun 2021 tentang penyelenggaraan perlindungan dan pengelolaan lingkungan hidup [Government regulation number 22 of 2021 concerning guidelines for environmental protection and management]*. Available at: https://peraturan.bpk.go.id/Details/161852/pp-no-22-tahun-2021 (Accessed: October 15, 2025.

Pickering, W.F. (1980) "Zinc interaction with soil and sediment components," in J.O. Nriagu (ed.) *Zinc in the environment – Part 1: Ecological cycling*. Hoboken: John Wiley & Sons.

Raj, K. and Das, A.P. (2023) "Lead pollution: Impact on environment and human health and approach for a sustainable solution," *Environmental Chemistry and Ecotoxicology*, 5, pp. 79–85. Available at: https://doi.org/10.1016/j.enceco.2023.02.001.

Sahoo, B.P. *et al.* (2023) "Assessment of metal pollution of overburden in a tropical coalfield, Ib valley, India: A case study," *Journal of the Geological Society of India*, 99(1), pp. 37–46. Available at: https://doi.org/10.1007/s12594-023-2264-6.

Sudaryatno, S. *et al.* (2025) "The geovisualization of settlement and cattle distribution in the Krasak River, Indonesia, Post the 2010 Merapi Eruption," *Romanian Journal of Geography*, 69(1), pp. 119–133. Available at: https://doi.org/10.59277/RRG.2025.1.08.

Takarina, N.D. (2020) "Mangrove root diversity and structure (cone, pencil, prop) effectiveness in accumulating Cu and Zn in sediments and water in River Blanakan," *IOP Conference Series: Earth and Environmental Science*, 550(1), 012009. Available at: https://doi.org/10.1088/1755-1315/550/1/012009.

USEPA (2017) *Assessing and managing chemicals under TSCA. Evaluating risk of existing chemicals under TSCA*. Washington, D.C.: United States Environmental Protection Agency. Available at: https://19january2017snapshot.epa.gov/assessing-and-managing-chemicals-under-tsca/evaluating-risk-existing-chemicals-under-tsca_.html#chemical%20names (Accessed: October 10, 2025).

Wu, Q. *et al.* (2025) "Research on influencing factors and improvement methods for air pollution in rural houses of severe cold region of China," *Journal of Building Engineering*, 99(73), 111491. Available at: https://doi.org/10.1016/j.jobe.2024.111491.

Zeng, Q. *et al.* (2022) "Investigation of the distribution of heavy metals in the soil of the Dahuangshan Mining Area of the Southern Junggar Coalfield, Xinjiang, China," *Minerals*, 12(10), 1332. Available at: https://doi.org/10.3390/min12101332.

Zhang, L. *et al.* (2022) "Surface coal mining impacts on land use change and ecological service value: a case study in Shengli coalfield, Inner Mongolia," *International Journal of Coal Science and Technology*, 9(1), 65. Available at: https://doi.org/10.1007/s40789-022-00518-9.

Zhou, M. *et al.* (2022) "Dilution or enrichment: The effects of flood on pollutants in urban rivers," *Environmental Sciences Europe*, 34(1), 61. Available at: https://doi.org/10.1186/s12302-022-00639-7.