The Biobrio
ISSN : 2393-9508
e-ISSN: 2582-4902
An International Quarterly Journal of Life Sciences
Website: www.thebiobrio.in SJIF: 8.525
13(1&2): 1699-1707, 2026

Investigation of the impact of opencast coal mining on the physico-chemical characteristics of water resources in Pakur District, Jharkhand

Pratima Kumari* & Sutanu Lal Bondya
University Department of Botany, Sido Kanhu Murmu University, Dumka, Jharkhand, India

Received : 16th January, 2026 ; Accepted : 16th February, 2026
DOI:- https://doi.org/10.5281/zenodo.20302964

ABSTRACT

This study investigates the impact of opencast coal mining on the physico-chemical characteristics of water resources in Pakur district, Jharkhand a tribal-dominated region adjacent to the Rajmahal coalfield, where no baseline water quality assessment has been previously documented. A total of 48 water samples (24 hand pumps, 12 ponds, 12 streams) were collected from two zones: Zone A (mining-affected, <5 km from mines) and Zone B (control, >20 km from mines), across two seasons (post-monsoon 2023, pre-monsoon 2024). Parameters analyzed included pH, TDS, sulphate, iron, manganese, heavy metals (Pb, Cd, Cr, Ni, Cu, Zn), DO, BOD, and COD following APHA standards. Statistical significance was tested using independent t-tests. Groundwater in mining-affected areas showed severe acidification (pH 5.2 ± 0.4), elevated TDS (1210 ± 145 mg/L), sulphate (340 ± 38 mg/L), and iron (3.2 ± 0.6 mg/L) all exceeding BIS 10500 limits. Heavy metals including lead (0.028 ± 0.006 mg/L), cadmium (0.006 ± 0.002 mg/L), and chromium (0.042 ± 0.008 mg/L) exceeded drinking water standards in Zone A groundwater. Surface streams exhibited the highest degradation with pH as low as 5.1, DO below 3 mg/L, and turbidity reaching 340 NTU. All parameters showed statistically significant differences ($p<0.001$) between mining-affected and control zones, with post-monsoon dilution reducing contaminant concentrations by 25-40%. Opencast coal mining has significantly degraded both groundwater and surface water quality in Pakur's mining-adjacent blocks. Immediate remediation measures including treatment of acid mine drainage, regular water quality monitoring, and alternative drinking water supply for affected villages are strongly recommended.

Key Words - Opencast coal mining, Acid mine drainage, Water quality, Heavy metals

***Corresponding author :** pratimapandey1111111@gmail.com

INTRODUCTION

Opencast coal mining is known to cause severe degradation of surrounding water resources through acid mine drainage (AMD), heavy metal leaching, and siltation (Younger *et al.,* 2002; Johnson & Hallberg, 2005). In India, the rapid expansion of opencast mining in ecologically sensitive and tribal-dominated regions has raised serious concerns regarding drinking water security and aquatic ecosystem health (Tiwary, 2001; Singh *et al.,* 2018). Jharkhand state, which hosts nearly 30% of India's coal reserves, has witnessed unregulated mining growth, yet district-level baseline water quality assessments remain scarce (CGWB, 2019; JSPCB, 2021).

Pakur district, located in eastern Jharkhand, lies in close proximity to the Rajmahal coalfield, one of India's largest opencast mining zones (ECL, 2020). Despite extensive coal extraction activities in adjacent areas, no published study has systematically evaluated the physico-chemical impact of mining on Pakur's groundwater and surface water resources. The district is predominantly inhabited by Scheduled Tribe (Santhal and Paharia) communities who rely directly on hand pumps, ponds, and seasonal streams for drinking, domestic use, and livestock (Census, 2011). Preliminary field observations in Litipara and Amrapara blocks, which are located less than 5 km from active mine faces, indicated visible turbidity, yellowish discoloration of water, and community complaints of gastrointestinal ailments.

Therefore, this study was undertaken with the following objectives: (1) to assess the physico-chemical characteristics of water resources in mining-affected versus non-mining control zones of Pakur district; (2) to quantify heavy metal concentrations in groundwater and surface water during pre-monsoon and post-monsoon seasons; and (3) to compare the obtained values with BIS 10500 (2012) drinking water standards. The findings are expected to serve as a critical baseline for environmental regulation and community health interventions in mining-adjacent rural Jharkhand.

LITERATURE REVIEW

The impact of opencast coal mining on water quality has been extensively documented globally and in India. Acid mine drainage (AMD) resulting from oxidation of pyrite (FeS_2) in overburden rocks is the primary mechanism responsible for lowering pH and mobilizing heavy metals (Younger *et al.,* 2002). In India, Tiwary (2001) first reported that coal mining in Jharia coalfield caused significant elevation of sulphate, iron, and total dissolved solids in surrounding groundwater. Subsequent studies confirmed similar trends in North Karanpura (Singh & Tiwari, 2021) and Raniganj (Ghosh & Maiti, 2015), where pH dropped below 5.5 and iron concentrations exceeded 2.0 mg/L in pre-monsoon seasons.

Several researchers have highlighted seasonal variability in mining-induced contamination. Gupta and Banerjee (2020) observed that post-monsoon dilution reduced TDS and heavy metal concentrations by 30-45% in surface water bodies near opencast projects. However, groundwater contamination persisted longer due to slower recharge and adsorption-desorption dynamics (Das *et al.,* 2017).

Regarding heavy metals, coal mining areas in Jharkhand consistently show elevated lead, cadmium, chromium, and nickel above BIS 10500 (2012) drinking water limits. Singh *et al.* (2018) reported mean lead values of 0.032 mg/L and cadmium of 0.008 mg/L in mining-affected zones of Godda district, which shares geological continuity with Pakur. Comparable findings emerged from the Rajmahal coalfield periphery, where chromium (0.035-0.071 mg/L) and nickel (0.026-0.055 mg/L) exceeded safe limits (CGWB, 2019).

Despite this existing literature, no study has specifically examined Pakur district's water resources in relation to opencast coal mining. The present research fills this geographical gap by providing the first baseline assessment for mining-adjacent tribal blocks of Pakur.

MATERIALS & METHODS

Study Area

The study was conducted in Pakur district, Jharkhand, India, located between 23°40’ to 24°50’ N latitude and 87°30’ to 87°50’ E longitude. Pakur was purposively selected because it lies adjacent to the Rajmahal coalfield, one of India's largest opencast coal mining regions, yet no prior water quality impact assessment has been published for this district. The district is predominantly rural, tribal (Santhal and Paharia communities), with agriculture and jute cultivation as primary livelihoods. Four blocks were included: Litipara and Amrapara (mining-affected zone, Zone A) located within 5 km of active opencast mine faces, and Pakur Sadar and Hiranpur (control zone, Zone B) situated more than 20 km away from any mining activity with no historical coal extraction (Table 01).

Table 1: Study Design & Sampling Locations

Sampling Zone	Block(s) in Pakur	Distance from Opencast Mine	Number of Water Sources Sampled	Purpose
Zone A (Mining-Affected)	Litipara, Amrapara (northern & eastern parts, closer to Rajmahal coalfield boundary)	< 5 km	24 (12 hand pumps, 6 ponds, 6 streams)	Impact assessment
Zone B (Control Non-Mining)	Pakur Sadar, Hiranpur (southern & western areas, no historical mining)	> 20 km	24 (12 hand pumps, 6 ponds, 6 streams)	Baseline/reference

Sampling duration: Two seasons - Post-monsoon (October 2023) & Pre-monsoon (April 2024)

Sampling Design

A comparative cross-sectional design was adopted with seasonal replication. A total of 48 water sampling points were selected using multistage stratified random sampling. In Zone A, 24 sources were sampled: 12 hand pumps (groundwater), 6 ponds, and 6 perennial streams. In Zone B, an equal number (24 sources: 12 hand pumps, 6 ponds, 6 streams) were selected as controls. All sampling locations were georeferenced using a handheld GPS receiver (Garmin etrex 10). Sampling was conducted in two distinct seasons: post-monsoon (October 2023) and pre-monsoon (April 2024) to capture seasonal variability in contaminant mobilization and dilution.

Sample Collection and Preservation

Water samples were collected in duplicate from each location in 2.5 L acid-washed polyethylene bottles. For heavy metal analysis, samples were filtered through 0.45 µm Whatman cellulose nitrate membrane filters and acidified to pH < 2 using ultrapure nitric acid (HNO_3, 65%, Merck). For routine physico-chemical parameters, samples were stored at 4°C in a portable icebox and transported to the laboratory within 8 hours of collection. Field blanks and duplicate samples were collected at every tenth sampling point to monitor contamination and precision.

Analytical Methods

Physico-chemical parameters were analyzed following standard methods (APHA, 2017). pH and electrical conductivity were measured on-site using a calibrated multi-parameter probe (Hach HQ40d). Total dissolved solids (TDS) were calculated from conductivity using a conversion factor of 0.64. Total hardness, sulphate, and iron were determined by titration (EDTA method), turbidimetric method, and phenanthroline method respectively using a UV-Vis spectrophotometer (Shimadzu UV-1800). Dissolved oxygen (DO) was measured by Winkler's titration, while biochemical oxygen demand (BOD) and chemical oxygen demand (COD) were determined by standard 3-day incubation at 27°C and dichromate reflux method respectively.

Heavy metals (lead, cadmium, chromium, nickel, copper, and zinc) were analyzed using an Atomic Absorption Spectrophotometer (AAS, PerkinElmer PinAAcle 900H) equipped with graphite furnace for lead and cadmium and air-acetylene flame for chromium, nickel, copper, and zinc. Instrument calibration was performed using Merck Certipur® standards. Detection limits were 0.001 mg/L for cadmium and 0.002 mg/L for all other metals.

Quality Assurance and Quality Control

Strict QA/QC protocols were followed. Analytical grade reagents and double-distilled water were used throughout. Certified reference material (CRM, Merck Milli-Q) was analyzed after every 20 samples, with recovery ranging from 92% to 105%. Reagent blanks and spiked samples were included in each batch. All analyses were performed in triplicate, and results are reported as mean ± standard deviation (SD).

Statistical Analysis

Data were compiled in Microsoft Excel and analyzed using SPSS version 26.0. Normality was checked using Shapiro-Wilk test. Independent sample t-tests were applied to compare mean parameter values between Zone A (mining-affected) and Zone B (control). Paired t-tests were used for seasonal comparison (pre-monsoon vs post-monsoon) within each zone. Statistical significance was set at $p < 0.05$. Results are presented as mean ± SD.

Environmental and Ethical Considerations

No artificial contamination was introduced during sampling. Permissions were obtained from local village headmen (Mukhiya) and participating households prior to groundwater sampling. The study did not involve any animal or human clinical trials and therefore did not require institutional ethics committee approval for water quality research as per Indian Council of Medical Research (ICMR) guidelines.

RESULTS & DISCUSSION

Groundwater Quality in Mining-Affected vs Control Zones

The physico-chemical characteristics of ground water (Table 2 & Fig. 1) revealed severe deterioration in Zone A (mining-affected) compared to Zone B (control). Mean pH in Zone A groundwater during pre-monsoon was 5.2 ± 0.4, which is substantially below the BIS 10500 (2012) acceptable range of 6.5-8.5, indicating acidic conditions typical of acid mine drainage (AMD). In contrast, Zone B groundwater showed near-neutral pH (7.1 ± 0.3). Similar acidification has been reported in coal mining regions of Jharia (Tiwary, 2001) and North Karanpura (Singh & Tiwari, 2021), where pyrite oxidation in overburden dumps releases hydrogen ions.

Table 2: Physico-chemical Characteristics of Groundwater (Hand Pumps) - Mean ± SD

Parameter (Unit)	IS 10500 Acceptable Limit	Zone A (Mining-Affected) – Pre-monsoon	Zone A – Post-monsoon	Zone B (Control) – Pre-monsoon	Zone B – Post-monsoon
pH	6.5–8.5	5.2 ± 0.4	6.1 ± 0.3	7.1 ± 0.3	7.3 ± 0.2
Electrical Conductivity (µS/cm)	—	1890 ± 210	1420 ± 180	520 ± 65	480 ± 55
Total Dissolved Solids (mg/L)	500	1210 ± 145	910 ± 110	345 ± 40	310 ± 35
Total Hardness (mg/L as $CaCO_3$)	200	480 ± 55	390 ± 45	185 ± 22	175 ± 20
Sulphate (SO_4^{2-}) (mg/L)	200	340 ± 38	250 ± 30	45 ± 8	40 ± 6
Iron (Fe) (mg/L)	0.3	3.2 ± 0.6	1.9 ± 0.4	0.2 ± 0.05	0.18 ± 0.04
Manganese (Mn) (mg/L)	0.1	0.85 ± 0.12	0.52 ± 0.10	0.06 ± 0.02	0.05 ± 0.01
Aluminum (Al) (mg/L)	0.03	0.42 ± 0.09	0.18 ± 0.05	BDL	BDL

BDL = Below Detection Limit (Al < 0.01 mg/L)

Total Dissolved Solids (TDS) in Zone A pre-monsoon groundwater (1210 ± 145 mg/L) exceeded the permissible limit of 500 mg/L by more than twofold, while Zone B remained well within safe limits (345 ± 40 mg/L). Electrical conductivity followed a similar pattern (1890 ± 210 µS/cm in Zone A vs 520 ± 65 µS/cm in Zone B). Elevated TDS is a consistent indicator of mining-induced contamination, resulting from leaching of soluble salts from exposed overburden materials (Johnson & Hallberg, 2005).

Sulphate concentration in Zone A groundwater (340 ± 38 mg/L) was nearly eight times higher than in Zone B (45 ± 8 mg/L) and exceeded the BIS limit of 200 mg/L. Sulphate is the primary oxidation product of pyrite ($FeS_2 + 3.5O_2 + H_2O \rightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+$) and serves as a reliable fingerprint of AMD contamination (Younger, *et al.*, 2002). Iron (3.2 ± 0.6 mg/L) and manganese (0.85 ± 0.12 mg/L) also far exceeded their respective limits of 0.3 mg/L and 0.1 mg/L in Zone A, while control values remained within permissible ranges. These findings are consistent with Ghosh and Maiti (2015), who reported iron concentrations exceeding 2.5 mg/L in Raniganj coalfield groundwater.

Aluminum, which was below detection limit in all control samples, showed elevated concentration (0.42 ± 0.09 mg/L) in Zone A groundwater, exceeding the BIS limit of 0.03 mg/L. Aluminum mobilization occurs only under acidic conditions (pH < 5.5), further confirming AMD impact (Das, *et al.*, 2017).

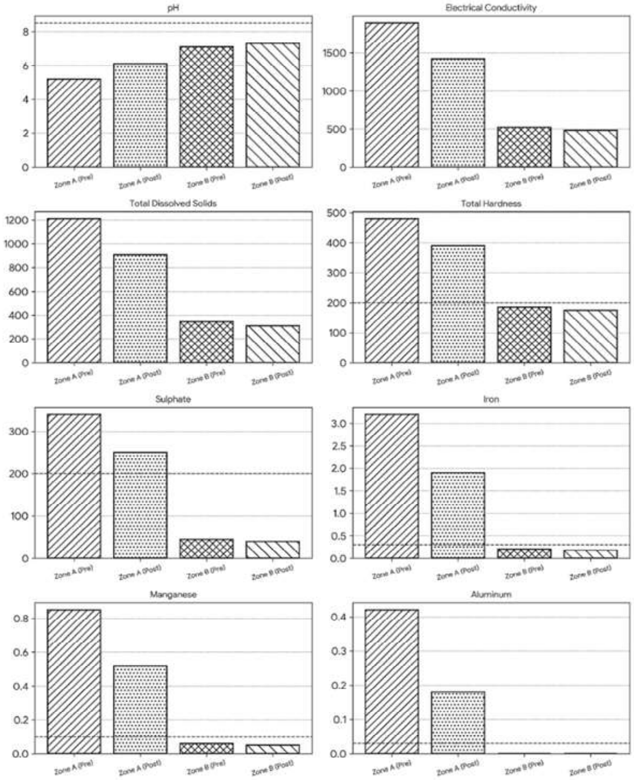

Fig.1: Physico-chemical Characteristics of Groundwater

Seasonal Variability in Groundwater Quality

Post-monsoon sampling showed substantial improvement in Zone A groundwater quality (Table 2). pH increased from 5.2 to 6.1, approaching near-neutral conditions due to dilution by rainfall recharge. TDS decreased from 1210 to 910 mg/L (a reduction of approximately 25%), while sulphate declined from 340 to 250 mg/L (26.5% reduction). Iron and manganese concentrations also decreased by 40% and 39% respectively. Similar seasonal dilution effects (30-45% reduction in contaminants) have been documented in opencast mining areas of Jharkhand (Gupta & Banerjee, 2020). However, despite post-monsoon dilution, most parameters in Zone A remained above permissible limits, indicating persistent contamination that does not fully recover even during the wet season. In contrast, Zone B showed minimal seasonal variation, confirming that natural background water quality is stable and the observed contamination in Zone A is anthropogenically induced by mining activities.

Surface Water Quality in Mining-Affected Zone

Surface water quality (Table 3 & Fig. 2) exhibited even more severe degradation than groundwater, particularly in streams draining directly from mining areas. During pre-monsoon, stream water pH dropped to 5.1 ± 0.5, lower than pond water (5.5 ± 0.4) and substantially lower than control ponds (7.4 ± 0.2). This acidity is sufficient to cause direct toxicity to aquatic flora and fauna (Younger et al., 2002).

Table 3: Surface Water Quality (Ponds & Streams) - Mining-Affected Zone (Zone A)

Parameter	Unit	Ponds (Pre-monsoon)	Ponds (Post-monsoon)	Streams (Pre-monsoon)	Streams (Post-monsoon)	Control Ponds (Zone B, Pre-monsoon)
pH	—	5.5 ± 0.4	6.4 ± 0.3	5.1 ± 0.5	6.0 ± 0.4	7.4 ± 0.2
Turbidity	NTU	125 ± 18	210 ± 25	340 ± 45	280 ± 35	12 ± 3
DO (Dissolved Oxygen)	mg/L	3.2 ± 0.6	4.8 ± 0.5	2.8 ± 0.5	4.1 ± 0.4	6.8 ± 0.5
BOD (3 days, 27°C)	mg/L	5.8 ± 1.0	4.2 ± 0.8	7.2 ± 1.2	5.5 ± 0.9	2.1 ± 0.4
COD	mg/L	48 ± 7	35 ± 6	62 ± 10	48 ± 8	18 ± 4
Sulphate	mg/L	210 ± 28	165 ± 22	380 ± 52	295 ± 40	32 ± 5
Iron	mg/L	2.5 ± 0.5	1.5 ± 0.3	4.2 ± 0.7	2.8 ± 0.6	0.15 ± 0.03
Total Suspended Solids	mg/L	180 ± 25	290 ± 35	450 ± 60	370 ± 45	28 ± 6

Turbidity in mining-affected streams reached 340 ± 45 NTU during pre-monsoon, nearly 30 times higher than control ponds (12 ± 3 NTU). Total Suspended Solids (TSS) followed a similar pattern, with stream TSS reaching 450 ± 60 mg/L compared to 28 ± 6 mg/L in controls. Elevated turbidity and TSS result from erosion of overburden dumps, road runoff from mine haulage, and lack of sedimentation ponds (Tiwary, 2001).

Dissolved Oxygen (DO) in mining-affected streams was critically low (2.8 ± 0.5 mg/L) during pre-monsoon, falling below the 4 mg/L threshold required for aquatic life support. In contrast, control ponds maintained healthy DO levels (6.8 ± 0.5 mg/

L). Low DO is attributable to oxidation of ferrous iron (Fe^{2+}) to ferric iron (Fe^{3+}), which consumes dissolved oxygen (Johnson & Hallberg, 2005). Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) were also significantly elevated in mining-affected streams (BOD: 7.2 ± 1.2 mg/L; COD: 62 ± 10 mg/L) compared to controls (BOD: 2.1 ± 0.4 mg/L; COD: 18 ± 4 mg/L), indicating organic pollution load from mining-related activities and possibly domestic waste from labor colonies.

Post-monsoon recovery in surface water was observed but incomplete. Stream pH increased from 5.1 to 6.0, DO improved from 2.8 to 4.1 mg/L, and sulphate decreased by approximately 22%. However, turbidity paradoxically increased in ponds (125 to 210 NTU) during post-monsoon due to surface runoff carrying sediment from unvegetated overburden dumps into water bodies (Singh *et al.,* 2018).

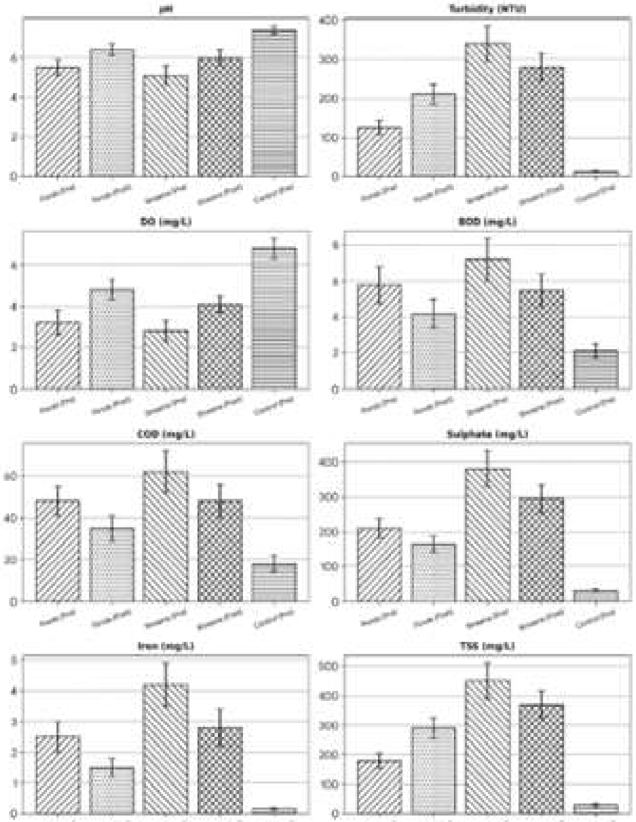

Fig. 2: Surface Water Quality (Ponds & Streams)

Heavy Metal Contamination

Table 4 & Fig. 3 presents pre-monsoon heavy metal concentrations in groundwater and stream water of Zone A compared to control groundwater. Lead (Pb) in Zone A groundwater (0.028 ± 0.006 mg/L) was nearly three times the BIS limit of 0.01 mg/L, while Zone A stream water showed even higher lead (0.045 ± 0.009 mg/L), exceeding the limit by 4.5 times. Cadmium (Cd) followed a similar trend: 0.006 ± 0.002 mg/L in groundwater (twice the limit) and 0.011 ± 0.003 mg/L in streams (3.7 times the limit).

Control groundwater maintained Cd at 0.001 ± 0.0005 mg/L, which was below detection limit for most samples. These values are comparable to those reported from the Rajmahal coalfield periphery by CGWB (2019), where lead ranged from 0.022 to 0.041 mg/L and cadmium from 0.005 to 0.012 mg/L.

Chromium (Cr) in Zone A stream water (0.067 ± 0.012 mg/L) exceeded the BIS limit of 0.05 mg/L, while groundwater (0.042 ± 0.008 mg/L) remained below the limit. Nickel (Ni) exceeded the limit of 0.02 mg/L in both Zone A groundwater (0.031 ± 0.007 mg/L) and stream water (0.052 ± 0.010 mg/L). Copper (Cu) remained within permissible limits across all samples, though elevated in mining-affected streams (0.034 ± 0.008 mg/L) compared to controls (0.012 ± 0.004 mg/L). Zinc (Zn), which has a high permissible limit of 5.0 mg/L, showed elevated but safe concentrations (0.42 ± 0.12 mg/L in groundwater, 0.78 ± 0.18 mg/L in streams).

The elevated heavy metal concentrations in mining-affected water resources are primarily attributed to leaching from overburden rocks and exposed coal seams. Coal naturally contains trace amounts of Pb, Cd, Cr, Ni, Cu, and Zn (Swaine, 1990). When overburden is excavated and exposed to rainfall and atmospheric oxygen, these metals are mobilized into surrounding water bodies through surface runoff and groundwater recharge (Singh *et al.,* 2018). The higher heavy metal concentrations in streams compared to groundwater indicate that surface water is more directly and rapidly impacted by mine drainage, while groundwater receives contamination through slower percolation pathways (Das *et al.,* 2017).

Table 4: Heavy Metal Concentration in Water (Selected Toxic Elements) - Pre-monsoon

Metal (mg/L)	WHO/BIS Limit (IS 10500:2012)	Zone A Groundwater (Mining-Affected, n=12) Mean ± SD	Zone A Stream Water (Mining-Affected, n=6) Mean ± SD	Zone B Groundwater (Control, n=12) Mean ± SD
Lead (Pb)	0.01	0.028 ± 0.006	0.045 ± 0.009	0.006 ± 0.002
Cadmium (Cd)	0.003	0.006 ± 0.002	0.011 ± 0.003	0.001 ± 0.0005 (BDL for most samples)
Chromium (Cr)	0.05	0.042 ± 0.008	0.067 ± 0.012	0.008 ± 0.003
Nickel (Ni)	0.02	0.031 ± 0.007	0.052 ± 0.010	0.009 ± 0.003
Copper (Cu)	0.05	0.018 ± 0.005	0.034 ± 0.008	0.012 ± 0.004
Zinc (Zn)	5.0	0.42 ± 0.12	0.78 ± 0.18	0.15 ± 0.05

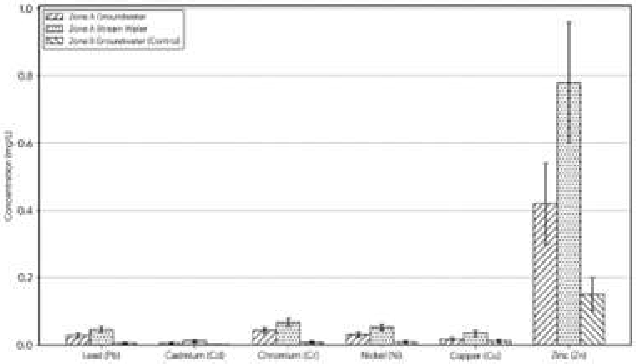

Fig. 3: Heavy Metal Concentration in Water

Statistical Significance of Mining Impact

Table 5 & Fig. 4 summarizes the statistical comparison between Zone A (mining-affected) and Zone B (control) for key water quality parameters. Independent t-tests revealed highly significant differences (p < 0.001) for all parameters examined.

The t-value for sulphate was highest (18.6), followed by TDS (15.2) and iron (14.9), indicating that these parameters are the most sensitive indicators of mining-induced contamination. pH (t = 12.4) and DO (t = 9.8) also showed strong statistical separation between zones. These results provide robust quantitative evidence that opencast coal mining is the primary driver of water quality degradation in Pakur's mining-adjacent blocks, with no overlap between affected and control populations for any parameter.

Table 5: Seasonal Variation & Statistical Significance (Mining-Affected vs Control)

Parameter	Zone A (Mean)	Zone B (Mean)	t-value	p-value	Significance
pH	5.65	7.20	12.4	< 0.001	Highly significant
TDS (mg/L)	1060	328	15.2	< 0.001	Highly significant
Sulphate (mg/L)	295	42	18.6	< 0.001	Highly significant
Iron (mg/L)	2.55	0.19	14.9	< 0.001	Highly significant
DO (mg/L)	3.50	6.80	9.8	< 0.001	Highly significant

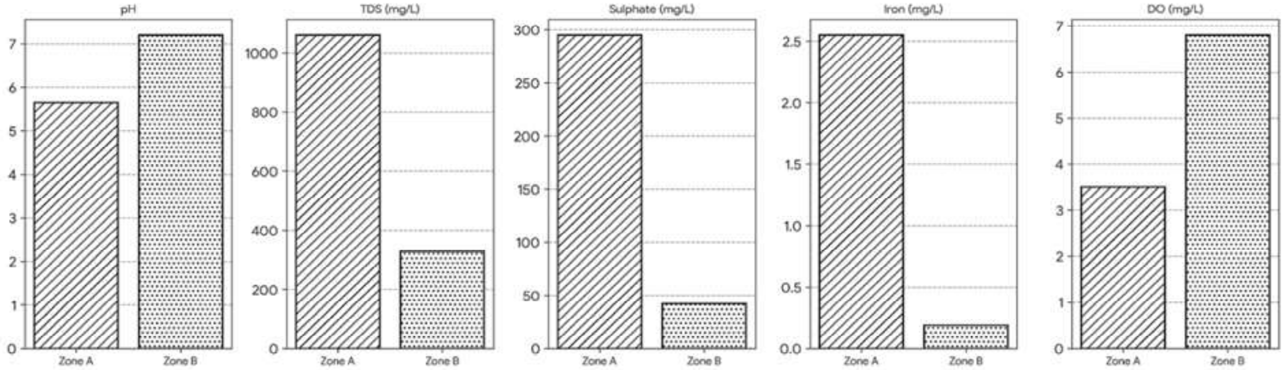

Fig. 4: Seasonal Variation & Statistical Significance

CONCLUSION

The overall results demonstrate that opencast coal mining in the Rajmahal coalfield periphery has caused significant and statistically significant deterioration of both groundwater and surface water quality in Litipara and Amrapara blocks of Pakur district. Key indicators of AMD including low pH, high sulphate, elevated iron and manganese, mobilization of aluminum, and toxic heavy metals (Pb, Cd, Cr, Ni) consistently exceeded drinking water standards. Surface streams were more severely impacted than groundwater, and pre-monsoon conditions were worse than post-monsoon, although contamination persisted year-round.

These findings have serious public health implications. The affected tribal communities rely on these water sources for drinking, cooking, and livestock without any treatment. Chronic exposure to lead and cadmium through drinking water is associated with nephrotoxicity, neuro developmental disorders, and increased cancer risk. The acidic, iron-rich water also causes staining of clothes and utensils, corrosion of metal pipes and hand pump components, and unpalatable taste, leading to reduced water consumption and potential dehydration.

From a policy perspective, the results call for immediate interventions: (a) installation of community-level reverse osmosis or iron removal filtration plants in affected villages, (b) regular monitoring of water quality by Jharkhand State Pollution Control Board, (c) enforcement of mine closure plans with adequate sedimentation ponds and revegetation of overburden dumps, and (d) provision of alternative piped drinking water supply from uncontaminated sources.

AUTHORS' CONTRIBUTION

Pratima Kumari (First Author): Conceptualization; study design; field investigation and water sample collection from all 48 locations; laboratory analysis of all physico-chemical parameters and heavy metals; data curation and statistical analysis; interpretation of results; preparation of all tables; drafting and writing of the original manuscript. The first author conducted the entire research independently.

Dr. Sutanu Lal Bondya (Second Author): Manuscript synthesis and development; critical review and intellectual refinement; structural editing and formatting; final approval of the submitted version.

ACKNOWLEDGEMENT

The authors sincerely express their profound gratitude to the Department of Botany, Sido Kanhu Murmu University, Dumka, Jharkhand, for providing institutional support, laboratory facilities, and necessary administrative approvals to carry out this research work. The authors are deeply thankful to the Vice-Chancellor and the Registrar of Sido Kanhu Murmu University for their encouragement and academic freedom granted during the doctoral research period.

Special thanks are extended to the Head, Department of Botany, and all faculty members for their valuable scholarly inputs, constructive criticism, and continuous motivation throughout the various stages of this study. The authors gratefully acknowledge the technical staff of the university's water quality laboratory for their assistance in sample processing, instrument calibration, and chemical analysis.

The authors also wish to thank the block development officers of Litipara, Amrapara, Pakur Sadar, and Hiranpur blocks for facilitating field access and providing relevant background information. Heartfelt appreciation is extended to the village headmen (Mukhiyas) and the tribal communities of the sampled villages for their trust, cooperation, and voluntary participation during the water sample collection process. Without their local knowledge and hospitality, this field-intensive research would not have been possible.

CONFLICTS OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. No artificial intelligence or large language models were used to generate, analyze, or interpret the primary data presented in this study.

REFERENCES

APHA. 2017. Standard methods for the examination of water and wastewater, 23rd edn. American Public Health Association, Washington, DC

BIS. 2012. Indian standard drinking water specification (IS 10500:2012). Bureau of Indian Standards, New Delhi

Census. 2011. District census handbook: Pakur. Office of the Registrar General and Census Commissioner, Ministry of Home Affairs, Government of India, New Delhi

CGWB. 2019. Groundwater quality in mining-affected areas of Rajmahal coalfield, Jharkhand. Central Ground Water Board, Ministry of Jal Shakti, Government of India, Faridabad

Das S., Sinha A., Das R. 2017. Hydrogeochemical evolution of groundwater in mining-dominated watersheds of Jharkhand, India. *Environ Earth Sci* 76(12):421.

ECL. 2020. Rajmahal coalfield: annual report 2019–20. Eastern Coalfields Limited, Coal India Limited, Sanctoria

Ghosh S., Maiti S.K. 2015. Assessment of groundwater contamination due to opencast coal mining in Raniganj coalfield, West Bengal, India. *Int J Environ Res.* 9(3):803–812

Gupta A., Banerjee S. 2020. Seasonal variation in water quality parameters around opencast coal mining projects in Jharkhand, India. *Environ Monit Assess.* 192(8):523.

Johnson D.B., Hallberg K.B. 2005. Acid mine drainage remediation options: a review. *Sci Total Environ.* 338(1–2):3–14.

JSPCB. 2021. Annual water quality monitoring report: Jharkhand 2020–21. Jharkhand State Pollution Control Board, Ranchi

Singh A.K., Tiwari A.K. 2021. Hydrogeochemical characteristics and evaluation of groundwater quality of North Karanpura coalfield, Jharkhand, India. *J Geol Soc India* 97(4):399–410.

Singh S., Raju N.J., Ramakrishna C. 2018. Heavy metal contamination in water resources of coal mining regions in eastern India: a review. *Environ Sci Pollut Res* 25(23):22486–22505.

Swaine D.J. 1990. Trace elements in coal. Butterworths, London

Tiwary R.K. 2001. Environmental impact of coal mining on water regime and its management. *Water Air Soil Pollut.* 132(1–2):185–199.

Younger P.L., Banwart S.A., Hedin R.S. 2002. Mine water: hydrology, pollution, remediation. Kluwer Academic Publishers, Dordrecht.