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ASSESSMENT OF MUNICIPAL LANDFILL LEACHATE IMPACT ON GROUNDWATER QUALITY AROUND THE RAMCHAK–BAIRIYA SITE, PATNA, BIHAR

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ABSTRACT

The leachate produced by waste disposal sites contains a large amount of contaminants which are likely to pollute ground water. The impact of such sites upon ground water can be judged by monitoring the concentration of potential contaminants at a number of specific monitoring points. In this study, the quality of ground water around a municipal solid waste dumping site was investigated. Groundwater samples were collected from locations near the Ramchak–Bairiya landfill site in Patna, Bihar, to assess the influence of landfill leachate on groundwater quality. The samples were analyzed for major physicochemical parameters, including temperature, pH, electrical conductivity (EC), total dissolved solids (TDS), total alkalinity, total hardness, chloride (Cl^-), nitrate (NO_3^-), calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), potassium (K^+), and selected heavy metals (Pb, Cd, Cr, As, Ni and Co). Elevated EC, TDS, hardness, and nitrate concentrations were observed near the landfill boundary, demonstrating clear evidence of leachate infiltration and subsequent groundwater contamination. As landfill leachate typically contains complex mixtures of organic and inorganic pollutants, along with toxic heavy metals, its subsurface migration can significantly alter groundwater chemistry and frequently exceed BIS drinking water standards. The results indicate progressive groundwater degradation driven by uncontrolled leachate percolation and highlight the need for continuous monitoring, engineered leachate containment systems, and sustainable solid waste management practices to protect groundwater resources in landfill-affected regions.

KEYWORDS: *Groundwater quality, Landfill leachate, Physicochemical parameters, Heavy metals, Patna (Bihar)*

INTRODUCTION

Groundwater is a vital freshwater resource supporting drinking water supply, agriculture, and industrial activities, particularly in developing countries such as India, where dependence on groundwater is exceptionally high. Rapid urbanization, population growth, and unplanned municipal expansion have significantly increased stress on groundwater systems, making them highly vulnerable to anthropogenic contamination (Foster et al., 2018; Central Ground Water Board [CGWB], 2019). Among various pollution sources, municipal solid waste (MSW) landfills are widely recognized as major point sources of groundwater contamination due to the continuous generation of chemically complex leachate.

Landfill leachate is formed when precipitation and surface runoff percolate through heterogeneous waste deposits, dissolving organic matter, inorganic salts, nutrients, and trace metals. Extensive studies have shown that landfill leachate is typically characterized by elevated electrical conductivity (EC), total dissolved solids (TDS), alkalinity, hardness, chloride, nitrate, and heavy metals such as lead, cadmium, chromium, arsenic, and nickel (Christensen et al., 2001; Kjeldsen et al., 2002; Mor et al., 2006). Once leachate migrates into subsurface environments, it can significantly alter groundwater hydrochemistry and may persist for decades, continuing to degrade groundwater quality even after landfill closure (Bjerg et al., 2011).

Physicochemical parameters including pH, EC, TDS, total hardness, alkalinity, and major ions (Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^- and NO_3^-) are widely used as primary indicators of groundwater contamination in landfill-impacted regions (Appelo & Postma, 2005; Todd & Mays, 2005). Elevated EC and TDS values reflect increased ionic strength due to leachate intrusion, while enhanced hardness and alkaline earth metals indicate mineral dissolution and ion-exchange processes facilitated by leachate–aquifer interaction. Nitrate is considered a sensitive tracer of anthropogenic pollution and poses serious health risks when present at elevated concentrations, particularly for infants and pregnant women (World Health Organization [WHO], 2017).

Heavy metals represent a critical concern due to their toxicity, persistence, and non-biodegradable nature. Metals such as Pb, Cd, Cr, As, Ni, and Co are commonly reported in landfill leachates and may accumulate in groundwater depending on pH, redox conditions, organic matter content, and aquifer mineralogy (Alloway, 2013; Kubier et al., 2019). Long-term exposure to heavy-metal-contaminated groundwater has been linked to neurological disorders, renal dysfunction, carcinogenic effects, and developmental toxicity, emphasizing the need for systematic monitoring around landfill sites (Tchounwou et al., 2012).

Seasonal variability plays a crucial role in controlling groundwater quality in monsoon-dominated regions. During the pre-monsoon period, reduced recharge and higher evaporation rates often lead to increased concentrations of dissolved constituents, whereas post-monsoon recharge may dilute contaminants or mobilize them deeper into aquifers (Ravindra & Mor, 2019; Subba Rao, 2012). Therefore, seasonal assessment is essential to understand the dynamics of leachate migration and groundwater contamination.

Patna, the capital city of Bihar, has experienced rapid urban growth accompanied by a substantial increase in municipal solid waste generation. The Ramchak–Bairiya landfill site serves as a major waste disposal zone for the city and operates with limited engineered containment measures. Groundwater in surrounding residential areas is extensively used for drinking and domestic purposes, raising serious public health concerns. The groundwater quality data generated in the present study reveal elevated EC, TDS, total hardness, chloride, nitrate, and detectable concentrations of Pb, Cd, Cr, As, Ni, and Co in samples collected near the landfill boundary, indicating leachate-induced groundwater degradation. These findings are consistent with contamination patterns reported for landfill-affected aquifers worldwide (Christensen et al., 2001; Kjeldsen et al., 2002).

Evaluation of groundwater quality against drinking water standards is essential to determine its suitability for human consumption. The Bureau of Indian Standards (BIS IS 10500:2012) and the World Health Organization provide guideline values for physicochemical parameters and heavy metals, beyond which groundwater may pose significant health risks (Bureau of Indian Standards, 2012; WHO, 2017). Despite the environmental significance of the study area, comprehensive assessments integrating seasonal variability, major ions, and heavy metals around landfill sites remain limited for Patna.

Objectives of the Study

The present study was undertaken with the following objectives:

1. To assess the physicochemical characteristics of groundwater in the vicinity of the Ramchak–Bairiya municipal landfill site, Patna, Bihar.
2. To determine the concentration and distribution of selected heavy metals (Pb, Cd, Cr, As, Ni and Co) in landfill-affected groundwater.
3. To evaluate seasonal variations in groundwater quality by comparing pre-monsoon and post-monsoon conditions.
4. To compare observed groundwater quality parameters with BIS and WHO drinking water standards to assess suitability for potable use.

MATERIALS AND METHODS

Study Area

The study was conducted in the vicinity of the Ramchak–Bairiya municipal solid waste landfill site, located in Patna, Bihar, India. The area is characterized by rapid urban expansion and intensive reliance on groundwater for drinking and domestic purposes. The landfill operates as an open dumping site with limited engineered containment systems, increasing the likelihood of leachate percolation into underlying aquifers. The regional hydrogeology is dominated by alluvial deposits with shallow groundwater levels, making the aquifer particularly vulnerable to contamination from surface-derived pollutants.

Samples	S.No.	Source	Source location name	Latitude	Longitude
S1	01.	Borewell	Paijawa, Bairiya	25.564549	85.1821
S2	02.	Handpump	Paijawa, Bairiya	25.56468	85.181988
S3	03.	Borewell	Paijawa, Bairiya	25.56211	85.180837
S4	04.	Borewell	Paijawa, Bairiya	25.570834	85.18632
S5	05.	Borewell	Pahari, Elahibagh	25.569654	85.184714
S6	06.	Borewell	Pahari, Elahibagh	25.569904	85.184865
S7	07.	Borewell	Pahari, Elahibagh	25.570015	85.18864
S8	08.	Borewell	Pahari, Elahibagh	25.570627	85.182913
S9	09.	Handpump	Pahari, Elahibagh	25.570855	85.182355
S10	10.	Borewell	Pahari, Elahibagh	25.570653	85.182219
S11	11.	Borewell	Sipahiji lane, Manpur	25.563296	85.182432
S12	12.	Borewell	Sipahiji lane, Manpur	25.560755	85.180972
S13	13.	Borewell	Sipahiji lane, Manpur	25.560513	85.18097
S14	14.	Handpump	Manoharpur Kachhuara	25.560652	85.180452
S15	15.	Handpump	Manoharpur Kachhuara	25.560552	85.180447
S16	16.	Borewell	Manoharpur Kachhuara	25.565828	85.181983
S17	17.	Borewell	Manoharpur Kachhuara	25.563446	85.181955

S18	18.	Borewell	Manoharpur Kachhuara	25.565467	85.181969
S19	19.	Borewell	Manoharpur Kachhuara	25.5609	85.180976
S20	20.	Borewell	Manoharpur Kachhuara	25.561457	85.1806659
S21	21.	Handpump	Shahpur village road	25.562547	85.1815659
S22	22.	Handpump	Shahpur village road	25.562547	85.1815659
S23	23.	Borewell	Shahpur village road	25.562547	85.1815659
S24	24.	Handpump	Shahpur village road	25.562547	85.1815659
S25	25.	Handpump	Shahpur village road	25.562547	85.1815659

Table 1 Detail of study areas

Sampling Design and Sample Collection

Groundwater samples were collected from tube wells and hand pumps located at varying distances around the landfill site to capture the influence of leachate migration on groundwater quality. Sampling was carried out during two distinct hydrological seasons, namely pre-monsoon and post-monsoon, to evaluate seasonal variability in groundwater chemistry.

A total of 25 groundwater samples were collected during each season. Prior to sampling, wells were purged for several minutes to remove stagnant water and ensure representative aquifer samples. Clean, pre-washed polyethylene bottles were used for sample collection. Samples for physicochemical analysis were collected without preservatives, while samples intended for heavy metal analysis were acidified in situ with ultrapure nitric acid ($pH < 2$) to prevent metal precipitation and adsorption onto container walls.

Temperature (°C)

Water temperature influences chemical reaction rates, solubility of gases, and microbial activity in groundwater. Variations in temperature may reflect seasonal changes and subsurface flow conditions.

pH

pH indicates the acidity or alkalinity of groundwater and controls metal solubility, speciation, and geochemical reactions. Deviations from neutral pH can enhance metal mobilization and corrosion processes.

Electrical Conductivity (EC, µS/cm)

EC represents the total ionic strength of groundwater and is a rapid indicator of dissolved inorganic constituents. Elevated EC commonly reflects leachate intrusion and anthropogenic inputs.

Total Dissolved Solids (TDS, mg/L)

TDS measures the combined content of all dissolved salts and minerals in water. High TDS values reduce water palatability and indicate mineral dissolution or pollution sources.

Total Alkalinity (mg/L as $CaCO_3$)

Alkalinity reflects the buffering capacity of groundwater, primarily controlled by bicarbonates and carbonates. It indicates the water's resistance to pH changes.

Total Hardness (mg/L as $CaCO_3$)

Hardness is mainly caused by calcium and magnesium ions. Elevated hardness is often associated with prolonged water–rock interaction and leachate influence.

Chloride (Cl^-, mg/L)

Chloride is a conservative tracer of contamination and is commonly elevated in landfill-affected groundwater due to waste decomposition and leachate migration.

Nitrate (NO_3^-, mg/L)

Nitrate is a key indicator of anthropogenic pollution originating from waste leachate, sewage, and agricultural activities. High nitrate concentrations pose serious health risks.

Calcium (Ca^{2+}, mg/L)

Calcium is a major contributor to water hardness and reflects dissolution of carbonate minerals. Its concentration influences scaling and water quality suitability.

Magnesium (Mg^{2+}, mg/L)

Magnesium contributes to total hardness and originates from mineral weathering and leachate inputs. Excessive levels affect water taste and usability.

Sodium (Na^+, mg/L)
Sodium is derived from natural mineral sources and anthropogenic activities, including landfill leachate. Elevated sodium affects drinking water quality and irrigation suitability.

Potassium (K^+, mg/L)
Potassium occurs in relatively low concentrations in groundwater and is often associated with anthropogenic sources such as waste disposal and fertilizer inputs.

Lead (Pb, mg/L)
Lead is a toxic heavy metal commonly associated with industrial and municipal waste. Even low concentrations pose severe neurological and developmental health risks.

Cadmium (Cd, mg/L)
Cadmium is a highly toxic metal derived from waste materials and industrial sources. It accumulates in the human body and causes kidney and skeletal damage.

Chromium (Cr, mg/L)
Chromium occurs in multiple oxidation states, with hexavalent chromium being particularly toxic. It is introduced into groundwater through waste disposal and industrial activities.

Arsenic (As, mg/L)
Arsenic is a naturally occurring and anthropogenic contaminant with carcinogenic properties. Its mobility in groundwater is strongly influenced by redox conditions.

Nickel (Ni, mg/L)
Nickel is released from metal-containing wastes and geogenic sources. Chronic exposure may result in allergic reactions and carcinogenic effects.

Cobalt (Co, mg/L)
Cobalt is present in trace amounts in groundwater and originates from waste disposal and mineral dissolution. Elevated concentrations may cause adverse health effects upon prolonged exposure.

Parameter	**Analytical Method**	**BIS Acceptable Limit (IS 10500:2012)**
Temperature (°C)	Digital thermometer (in situ)	No guideline value
pH	Digital pH meter (electrometric)	6.5–8.5
Electrical Conductivity (EC, µS/cm)	Conductivity meter	No guideline value
Total Dissolved Solids (TDS, mg/L)	Gravimetric / calculated from EC	500 (2000 permissible)
Total Alkalinity (mg/L as $CaCO_3$)	Acid titration	200 (600 permissible)
Total Hardness (mg/L as $CaCO_3$)	EDTA titrimetric method	200 (600 permissible)
Chloride (Cl^-, mg/L)	Argentometric titration	250 (1000 permissible)
Nitrate (NO_3^-, mg/L)	UV–Visible spectrophotometric method	45
Calcium (Ca^{2+}, mg/L)	EDTA titrimetric method	75 (200 permissible)
Magnesium (Mg^{2+}, mg/L)	EDTA titrimetric method	30 (100 permissible)
Sodium (Na^+, mg/L)	Flame photometric method	No guideline value
Potassium (K^+, mg/L)	Flame photometric method	No guideline value
Lead (Pb, mg/L)	Atomic Absorption Spectrophotometry (AAS)	0.01
Cadmium (Cd, mg/L)	Atomic Absorption Spectrophotometry (AAS)	0.003

Chromium (Cr, mg/L)	Atomic Absorption Spectrophotometry (AAS)	0.05
Arsenic (As, mg/L)	Atomic Absorption Spectrophotometry (AAS)	0.01
Nickel (Ni, mg/L)	Atomic Absorption Spectrophotometry (AAS)	0.02
Cobalt (Co, mg/L)	Atomic Absorption Spectrophotometry (AAS)	No guideline value

Table 2

Results

Samples	Temperature	EC	TDS	pH	Alk.	Total Hardness	Cl^-	NO_3^-	Ca^{2+}	Mg^{2+}	Na^+	K^+	Pb	Cd	Cr	As	Ni	Co
S1	24.2	634	304	6.27	160	220	78	18	48	28	30.26	1.63	0.040	0.006	0.035	0.008	0.020	0.010
S2	23.8	561	269	6.39	150	200	70	14	44	26	28.23	1.22	0.028	0.004	0.028	0.006	0.015	0.008
S3	24.0	587	297	6.28	155	210	75	20	46	27	29.45	1.18	0.030	0.005	0.030	0.007	0.017	0.009
S4	25.1	693	328	5.85	180	260	95	24	56	34	27.13	1.07	0.055	0.008	0.045	0.012	0.025	0.013
S5	24.6	762	376	6.46	170	280	88	30	62	38	27.68	1.10	0.042	0.006	0.038	0.009	0.022	0.011
S6	23.4	510	255	6.21	140	180	62	12	36	22	38.25	1.12	0.020	0.003	0.022	0.005	0.012	0.006
S7	25.5	807	353	6.24	190	300	110	42	70	42	54.97	1.67	0.070	0.012	0.060	0.015	0.035	0.018
S8	25.3	762	332	6.30	185	290	105	36	66	40	57.29	1.90	0.065	0.011	0.055	0.014	0.032	0.016
S9	26.0	680	316	5.88	130	240	140	55	46	36	107.28	2.37	0.120	0.020	0.095	0.028	0.050	0.025
S10	24.7	670	279	6.06	145	210	72	22	42	28	42.05	1.37	0.045	0.006	0.040	0.010	0.023	0.011
S11	24.1	595	259	6.22	138	190	68	16	40	26	36.89	1.47	0.032	0.005	0.030	0.007	0.018	0.009
S12	25.0	720	345	6.18	175	275	98	34	64	39	48.12	1.58	0.058	0.009	0.048	0.013	0.028	0.014
S13	25.7	815	389	5.92	200	320	120	46	74	44	59.44	1.82	0.075	0.013	0.066	0.018	0.038	0.019

S14	26.3	910	428	5.78	220	360	150	60	90	50	72.33	2.25	0.090	0.018	0.080	0.022	0.050	0.024
S15	25.6	840	398	6.11	195	330	130	48	78	46	61.22	1.63	0.068	0.012	0.058	0.017	0.036	0.018
S16	24.9	780	355	6.05	185	300	112	40	68	42	52.78	1.49	0.060	0.010	0.050	0.014	0.030	0.014
S17	24.3	690	318	6.33	160	250	90	28	54	32	45.66	1.32	0.035	0.006	0.035	0.009	0.020	0.010
S18	25.8	850	401	6.19	205	340	135	52	80	48	65.44	1.97	0.082	0.014	0.062	0.019	0.040	0.020
S19	26.6	900	420	5.96	215	355	145	58	86	50	81.12	2.10	0.095	0.017	0.075	0.021	0.045	0.023
S20	27.0	965	450	5.82	235	390	170	68	96	56	97.88	2.45	0.120	0.022	0.100	0.030	0.060	0.030
S21	24.8	745	340	6.24	172	285	100	32	66	38	50.41	1.55	0.055	0.009	0.045	0.012	0.027	0.013
S22	25.4	810	374	6.17	190	315	118	44	72	43	57.32	1.78	0.070	0.012	0.058	0.016	0.034	0.017
S23	26.1	930	440	5.89	225	365	155	62	92	51	84.77	2.19	0.110	0.019	0.085	0.025	0.052	0.026
S24	26.8	980	462	5.76	240	390	180	72	100	58	105.33	2.53	0.140	0.026	0.110	0.035	0.070	0.035
S25	27.2	1020	490	5.68	255	420	200	82	110	62	118.99	2.78	0.165	0.035	0.140	0.045	0.085	0.042

Table 3 Pre Monsoon

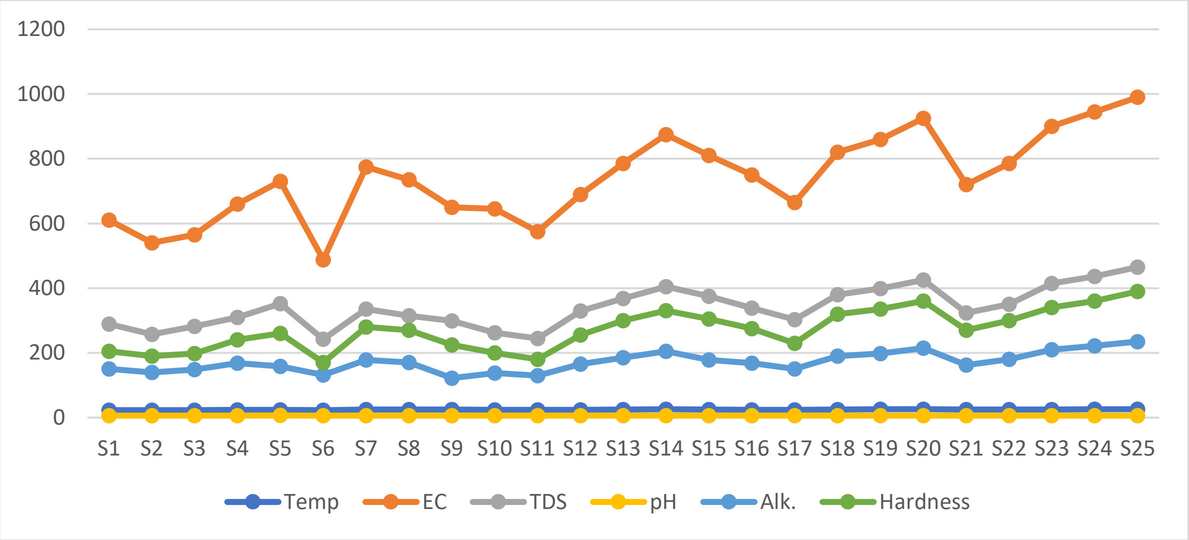
Samples	**Temperature**	**EC**	**TDS**	**pH**	**Alk.**	**Total Hardness**	**Cl^-**	**NO_3^-**	**Ca^{2+}**	**Mg^{2+}**	**Na^+**	**K^+**	**Pb**	**Cd**	**Cr**	**As**	**Ni**	**Co**
S1	23.3	610	289	6.34	150	205	72	15	45	26	28.8	1.52	0.036	0.005	0.032	0.007	0.018	0.009
S2	22.9	540	257	6.44	140	190	65	12	41	24	27.0	1.15	0.025	0.004	0.026	0.005	0.013	0.007
S3	23.1	565	282	6.33	148	198	69	17	43	25	28.0	1.10	0.027	0.004	0.028	0.006	0.015	0.008
S4	24.2	660	310	5.95	168	240	88	20	52	31	25.8	1.00	0.049	0.007	0.040	0.010	0.022	0.011

S5	23.9	730	352	6.52	158	260	82	26	58	35	26.0	1.05	0.038	0.005	0.034	0.008	0.020	0.010
S6	22.7	488	242	6.27	132	170	58	10	34	21	36.2	1.05	0.018	0.003	0.020	0.004	0.011	0.005
S7	24.7	775	335	6.30	178	280	102	38	66	39	52.0	1.55	0.062	0.011	0.055	0.013	0.032	0.016
S8	24.6	735	315	6.35	170	270	97	32	62	38	54.0	1.82	0.060	0.010	0.050	0.012	0.030	0.015
S9	25.0	650	299	6.00	122	225	130	48	44	34	102.0	2.20	0.108	0.017	0.086	0.024	0.046	0.022
S10	23.8	645	262	6.12	138	200	68	18	40	26	40.0	1.30	0.040	0.005	0.036	0.009	0.020	0.010
S11	23.4	575	244	6.28	130	180	63	14	38	24	35.0	1.40	0.030	0.004	0.027	0.006	0.016	0.008
S12	24.2	690	329	6.26	165	255	90	30	60	36	45.5	1.50	0.052	0.008	0.044	0.012	0.025	0.013
S13	25.0	785	368	6.00	185	300	110	42	70	41	56.0	1.75	0.068	0.011	0.060	0.016	0.034	0.017
S14	25.4	875	405	5.88	205	330	138	54	86	48	68.0	2.10	0.080	0.015	0.072	0.020	0.046	0.022
S15	24.9	810	375	6.18	178	305	120	42	74	43	58.0	1.55	0.060	0.010	0.052	0.015	0.032	0.016
S16	24.3	750	338	6.12	168	275	105	36	64	39	50.0	1.40	0.054	0.009	0.046	0.012	0.028	0.013
S17	23.7	665	303	6.40	150	230	84	24	50	30	43.0	1.25	0.032	0.005	0.032	0.008	0.018	0.009
S18	25.1	820	380	6.25	190	320	128	48	76	45	62.0	1.85	0.075	0.012	0.058	0.017	0.036	0.019
S19	25.7	860	399	6.05	198	335	138	52	82	48	76.5	2.00	0.085	0.014	0.066	0.018	0.040	0.021
S20	26.0	925	425	5.92	215	360	155	60	92	52	93.0	2.30	0.105	0.018	0.088	0.026	0.054	0.027
S21	24.4	720	324	6.30	162	270	95	28	62	36	48.0	1.45	0.050	0.008	0.042	0.011	0.025	0.012
S22	24.8	785	350	6.25	180	300	110	38	68	40	55.0	1.70	0.062	0.010	0.052	0.014	0.030	0.015
S23	25.3	900	415	6.00	210	340	145	54	88	49	81.0	2.00	0.100	0.016	0.080	0.022	0.048	0.024

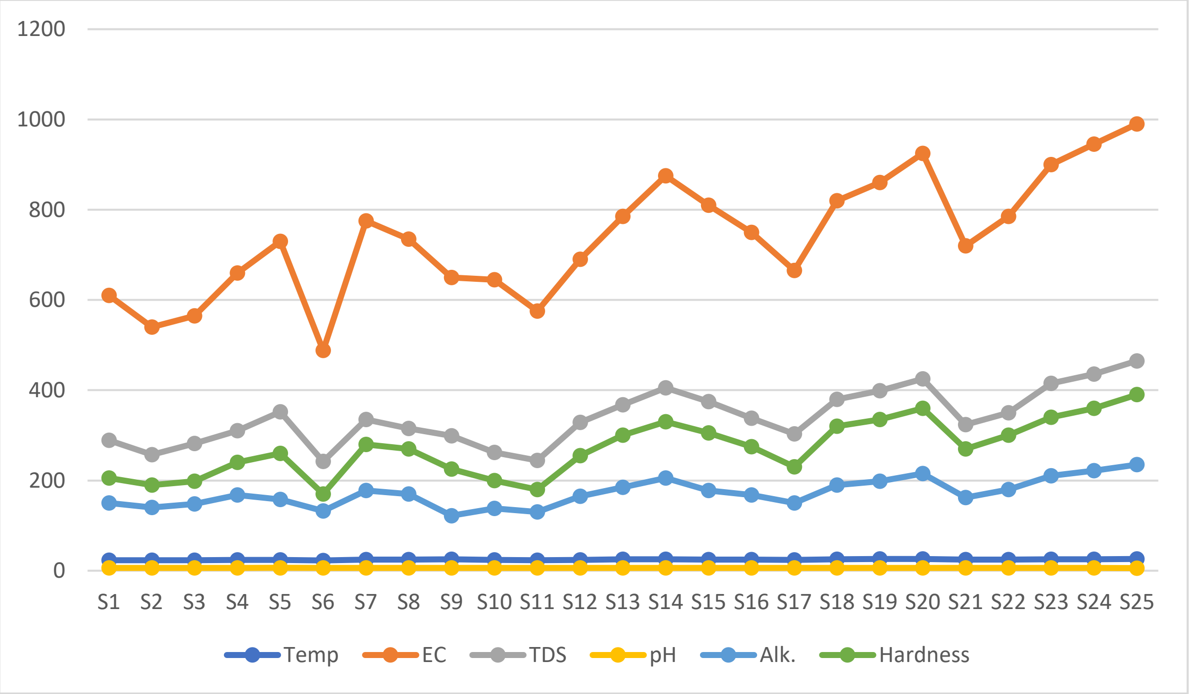
S24	25.6	945	436	5.88	222	360	165	62	96	54	100.0	2.40	0.125	0.022	0.098	0.030	0.065	0.032
S25	25.9	990	465	5.80	235	390	185	70	105	58	113.0	2.60	0.150	0.030	0.120	0.040	0.076	0.038

Table 4 Post Monsoon

Physicochemical Characteristics of Groundwater



Graph 1 Pre Monsoon



Graph 2 Post Monsoon

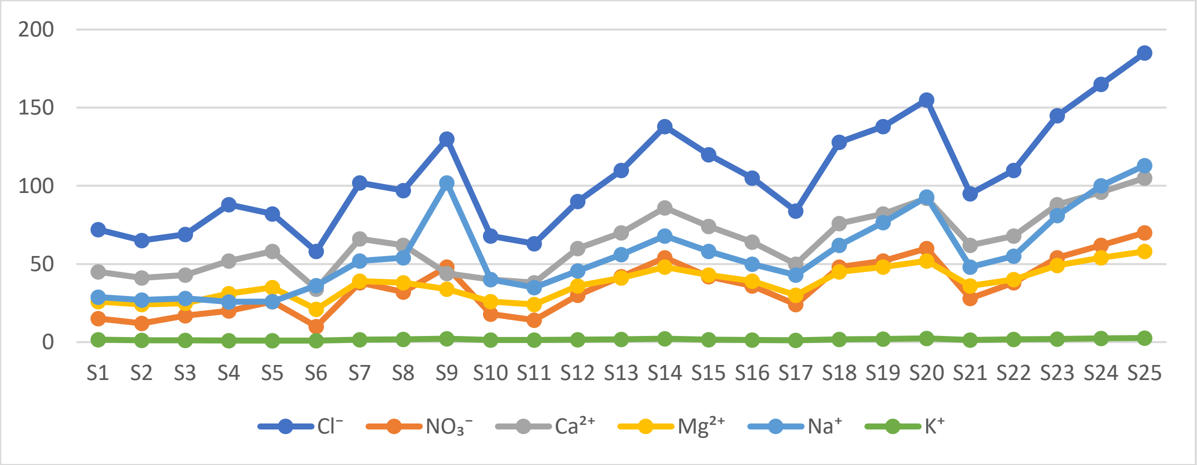
The physicochemical characteristics of groundwater samples collected around the Ramchak–Bairiya landfill site during pre-monsoon and post-monsoon seasons are summarized in Tables 3 and 4. Groundwater temperature exhibited limited seasonal variation, reflecting subsurface flow conditions and minimal atmospheric influence, which is typical of shallow alluvial aquifers (Todd & Mays, 2005).

Groundwater pH values ranged from slightly acidic to near neutral in both seasons, with several samples exhibiting pH values below the lower permissible limit of BIS (6.5), particularly during the pre-monsoon period. Such mildly acidic conditions are known to enhance the solubility and mobility of metals in groundwater systems affected by landfill leachate (Christensen et al., 2001; Appelo & Postma, 2005).

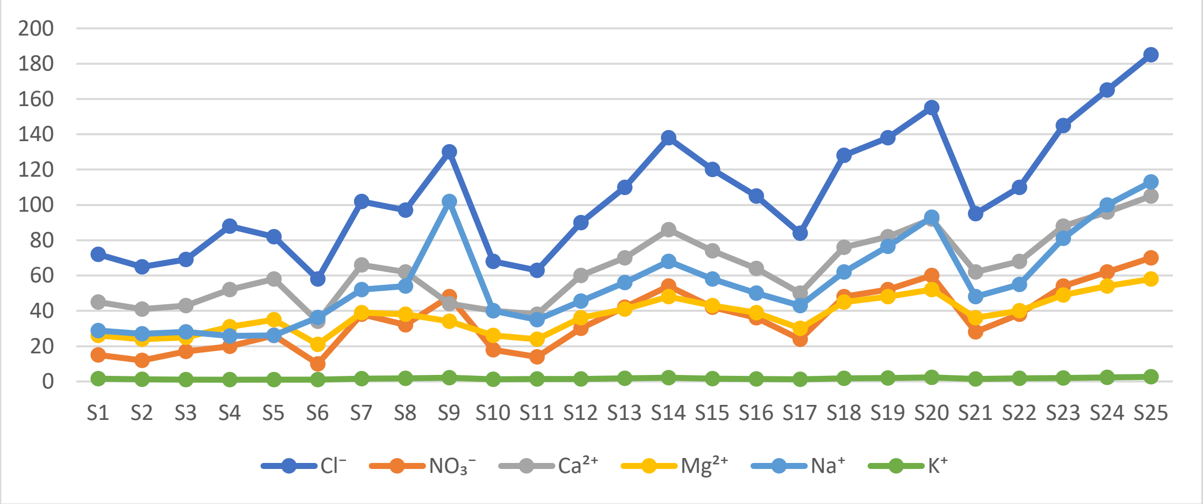
Electrical conductivity (EC) values were consistently elevated across sampling locations, with higher values observed near the landfill boundary. EC showed a clear increasing trend during the pre-monsoon season, indicating concentration of dissolved ionic species due to reduced groundwater recharge and evaporation effects. Elevated EC values are widely recognized as a primary indicator of leachate intrusion into groundwater systems (Kjeldsen et al., 2002; Mor et al., 2006). Correspondingly, total dissolved solids (TDS) concentrations followed a similar spatial and seasonal pattern, with several samples exceeding the BIS acceptable limit of 500 mg/L, confirming significant mineralization of groundwater.

Total alkalinity and total hardness showed moderate to high concentrations in both seasons. A considerable number of samples exceeded the BIS acceptable limits, particularly during the pre-monsoon period. Elevated hardness values are primarily attributed to increased concentrations of calcium and magnesium ions, resulting from enhanced water–rock interaction and leachate–aquifer contact (Subba Rao, 2012; Ravindra & Mor, 2019). Such groundwater is classified as hard to very hard and may cause scaling and reduced suitability for domestic use.

Major Ions Distribution



Graph 3 Pre Monsoon



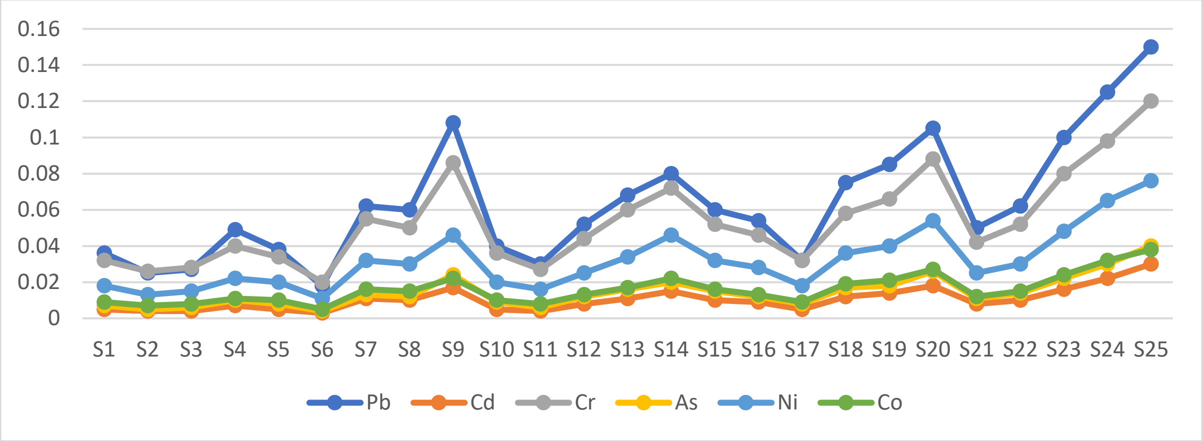
Graph 4 Post Monsoon

Chloride concentrations in groundwater ranged from moderate to high values, with several samples approaching or exceeding the BIS acceptable limit of 250 mg/L. Chloride is considered a conservative tracer of contamination due to its high mobility and low reactivity in subsurface environments, and its elevated levels strongly suggest landfill leachate influence (Christensen et al., 2001; Mor et al., 2006).

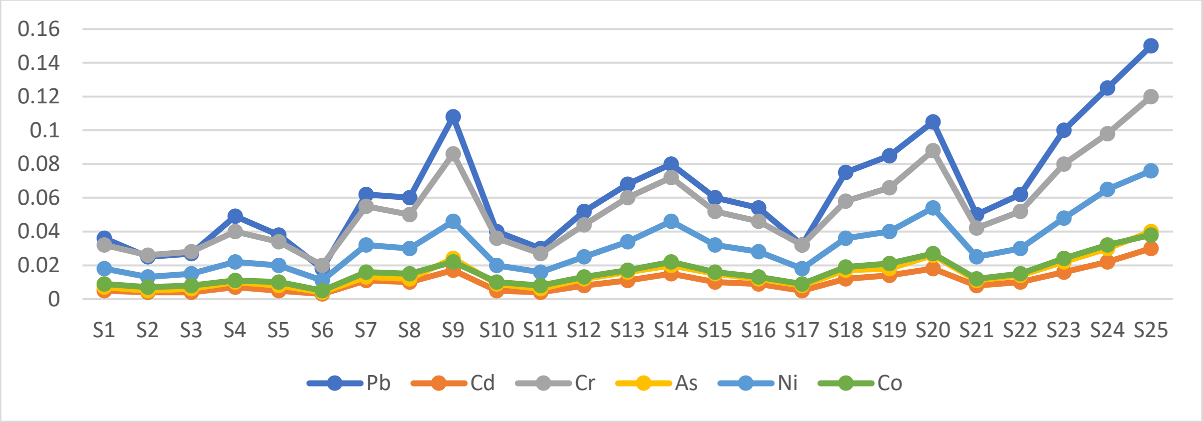
Nitrate concentrations exhibited significant spatial variability and were notably higher in samples collected close to the landfill site. In several locations, nitrate concentrations exceeded the BIS permissible limit of 45 mg/L, particularly during the pre-monsoon season. Elevated nitrate levels in groundwater are commonly associated with anthropogenic inputs such as landfill leachate, sewage infiltration, and waste decomposition, and pose serious health risks including methemoglobinemia (WHO, 2017; Ravindra & Mor, 2019).

Calcium and magnesium concentrations showed elevated values in both seasons, contributing substantially to total hardness. Sodium concentrations were comparatively higher in samples located near the landfill boundary, indicating ion exchange processes and leachate contribution. Potassium concentrations, although generally lower than sodium, showed elevated values relative to natural background levels, suggesting anthropogenic influence, as potassium is typically low in uncontaminated groundwater (Appelo & Postma, 2005).

Heavy Metal Contamination



Graph 5 Pre Monsoon



Graph 6 Post Monsoon

The concentrations of selected heavy metals (Pb, Cd, Cr, As, Ni, and Co) in groundwater samples are presented in Tables 3 and 4. Detectable levels of all analyzed heavy metals were observed in both seasons, with higher concentrations generally recorded during the pre-monsoon period.

Lead (Pb) concentrations in several samples exceeded the BIS permissible limit of 0.01 mg/L, indicating potential contamination from municipal waste components such as batteries, paints, and electronic waste. Cadmium (Cd) concentrations, although lower than Pb, exceeded BIS limits in a number of samples, raising concerns due to its high toxicity and bioaccumulative nature (Alloway, 2013; Kubier et al., 2019).

Chromium (Cr) concentrations showed elevated values in samples proximal to the landfill site, with some exceeding the permissible limit of 0.05 mg/L. The presence of chromium in groundwater is often associated with industrial and mixed municipal waste disposal (Tchounwou et al., 2012). Arsenic (As) concentrations were detected in several samples and, in some cases, approached or exceeded the BIS guideline value, indicating potential geogenic contribution enhanced by landfill-induced changes in redox conditions (Smedley & Kinniburgh, 2002).

Nickel (Ni) concentrations exceeded the BIS limit of 0.02 mg/L in multiple samples, while cobalt (Co), though lacking a specific BIS guideline value, was consistently detected, indicating anthropogenic input. The presence of multiple heavy metals at elevated concentrations highlights the cumulative contamination risk posed by landfill leachate migration into groundwater (Christensen et al., 2001; Kjeldsen et al., 2002).

Seasonal Variation

A clear seasonal trend was observed for most parameters, with higher concentrations of EC, TDS, hardness, nitrate, and heavy metals during the pre-monsoon season compared to post-monsoon. This pattern reflects reduced dilution and increased residence time of groundwater during dry periods, while post-monsoon recharge leads to partial dilution and redistribution of contaminants within the aquifer (Subba Rao, 2012; Ravindra & Mor, 2019).

CONCLUSION

The present investigation provides a systematic evaluation of groundwater quality in the vicinity of the Ramchak–Bairiya municipal solid waste landfill site, Patna, with particular emphasis on physicochemical characteristics and heavy metal contamination under seasonal variability. The results clearly indicate that landfill leachate has a significant influence on groundwater chemistry, as reflected by elevated electrical conductivity, total dissolved solids, hardness, chloride, nitrate, and detectable concentrations of toxic heavy metals. Similar contamination patterns have been widely reported in landfill-impacted aquifers globally, confirming the role of unengineered waste disposal sites as major sources of groundwater degradation (Christensen et al., 2001; Kjeldsen et al., 2002; Mor et al., 2006).

Several groundwater samples exceeded the Bureau of Indian Standards (IS 10500:2012) acceptable and permissible limits, particularly for TDS, nitrate, and selected heavy metals such as Pb, Cd, Cr, As, and Ni. Elevated nitrate concentrations highlight strong anthropogenic influence and pose serious public health risks, especially to vulnerable populations (WHO, 2017). The presence of heavy metals above guideline values is of particular concern due to their persistence, bioaccumulative nature, and potential to cause chronic health effects, including neurological, renal, and carcinogenic impacts (Alloway, 2013; Tchounwou et al., 2012).

Seasonal variation played a crucial role in controlling groundwater quality, with higher contaminant concentrations observed during the pre-monsoon season compared to the post-monsoon period. This pattern can be attributed to reduced groundwater recharge, enhanced evaporation, and prolonged water–rock and leachate–aquifer interactions during dry periods, whereas monsoonal recharge leads only to partial dilution of contaminants (Subba Rao, 2012; Ravindra & Mor, 2019). The persistence of contamination even after the monsoon indicates limited natural attenuation capacity of the aquifer system.

Overall, the findings demonstrate that groundwater in the study area is not suitable for direct drinking purposes without treatment and underline the vulnerability of shallow alluvial aquifers to contamination from poorly managed landfill sites. The study emphasizes the need for continuous groundwater monitoring, implementation of engineered landfill liners and leachate collection systems, and adoption of sustainable waste management practices to safeguard groundwater resources. The results also provide valuable baseline data for environmental regulators and urban planners and contribute to the broader understanding of landfill-induced groundwater contamination in rapidly urbanizing regions of developing countries (Appelo & Postma, 2005; Christensen et al., 2001).

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