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HEAVY METALS POLLUTION IN DRINKING WATER SOURCES: A CASE STUDY FROM KULIM HI-TECH PARK, MALAYSIA

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Abstract

Introduction: *Heavy metal content within drinking water poses significant risks to health and the environment. Given industrial impact on Kulim's water quality, this study determined the concentrations of iron (Fe), manganese (Mn), zinc (Zn), cadmium (Cd), and nickel (Ni) in various water sources around Kulim Hi-Tech Park (KHTP) and assess associated with chronic heath risks.* ***Methods:*** *We measured these five heavy metals in 30 water samples from tap water, rivers, and ponds, within and around Kulim Hi-Tech Park (KHTP), using Atomic Absorption Spectroscopy. Non-carcinogenic risk was assessed by calculating Hazard Quotient (HQ) and Hazard Index (HI), while carcinogenic risk used Excess Lifetime Cancer Risk (ELCR).* ***Results and Discussion:*** *Mean concentrations averaged between 0.0177 ± 0.0017 mg/L and 0.8652 ± 0.0606 mg/L; nickel showed the highest mean, followed by iron, zinc, manganese, and cadmium. Notably, concentrations of nickel, and in some instances iron and cadmium, exceeded regulatory limits. HQ and HI suggested no immediate adverse health effects from exposure to iron, manganese, and zinc. However, ELCR values for cadmium and nickel surpassed acceptable levels, indicating potential carcinogenic risks from long-term exposure. It is important to note that risk assessment for iron, manganese, and zinc is based on mean concentrations that include proportion of samples below the Limit of Quantification (LOQ), warranting cautious interpretation.* ***Conclusion:*** *This study provides crucial baseline data on heavy metals in KHTP water resources, underscores more investigation and potential remediation strategies to safeguard public and environmental health.*

INTRODUCTION

Heavy metal contamination is a widespread and significant concern for both environmental well-being and human health. These persistent, bioaccumulative toxic elements pose a continuous threat (1). Their prevalence, often from industrial water discharges, significantly risks plants, animals, and humans. Diverse industries contribute to contamination through inadequate waste treatment, exposing agricultural, industrial, and residential populations through ingestion, inhalation, and

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dermal contact (2). Children are particularly vulnerable to ingestion (3). The consensus among researchers underscores the dual impact of natural processes and human activities in perpetuating environmental degradation and compromising public health.

Various heavy metals, such as arsenic (As), cadmium (Cd), nickel (Ni), mercury (Hg), chromium (Cr), and lead (Pb), significantly threaten Malaysian public health through drinking water contamination (4). These persistent substances accumulate in organisms, causing long-term health risks like increased cancer susceptibility (5). They also harm aquatic ecosystems by inducing oxidative stress, disrupting hormones, and impairing immunity (6), leading to reduced survival, stunted growth, and human health hazards via food chain biomagnification. Their non-biodegradability causes continuous accumulation (7). Health risk assessments in China, India, and Iran highlighted the need to evaluate heavy metal exposure (8–10). Hg, Cd, and Pb identified as carcinogens by the International Agency for Research on Cancer (IARC) with prolonged exposure can cause muscular dystrophy, Alzheimer's, various cancers, and multiple sclerosis, underscoring the urgent need for mitigation (11–13).

Recent findings indicate that around 40% of the world's lakes and rivers suffer from heavy metal contamination, primarily due to urbanization, industrialization, and other anthropogenic activities (14). This widespread pollution poses a significant threat to aquatic ecosystems, while conventional physical and chemical remediation methods are often expensive and can cause further environmental damage. This concern is pressing in rapidly urbanizing and industrializing area, like in Kulim, Malaysia, where pollution is increasing (15). Heavy metals in drinking water are a major human exposure route. Heavy metals in drinking water are a major human exposure route, and studies have indicated the presence of elevated levels of these contaminants in some water sources, underscoring the urgency for ongoing monitoring and comprehensive risk assessment protocols (16). As Kulim has become a key industrial center, vigilant tracking of heavy metal levels in drinking water is vital for safeguarding human and environmental health. Many of the water bodies in and around this area serve as essential raw water sources for the region's drinking water supply.

Given the potential for industrial activities to impact drinking water quality in Kulim (17), this study aims to determine the concentrations of iron (Fe), manganese (Mn), zinc (Zn), cadmium (Cd), and nickel (Ni) in various water sources around Kulim Hi-Tech Park (KHTP) and also assessing the chronic health risks linked to prolonged exposure. The findings of this research will provide valuable insights into the extent of industrial contamination and inform strategies for safeguarding drinking water quality in the region. To our best knowledge, comprehensive studies specifically investigating the concentrations of these five heavy metals (Fe, Mn, Zn, Cd, Ni) in various drinking water sources and assessing associated human health risks within and around Kulim Hi-Tech Park published in the last five years are scarce. This study therefore addresses a critical knowledge gap by providing recent and detailed data essential for understanding heavy metal contamination in this industrially significant area. The selection of these specific heavy metals (Fe, Mn, Zn, Cd, Ni) as parameters is driven by their prevalence in industrial activities and their known potential as environmental pollutants with significant health implications. Kulim Hi-Tech Park, being a hub for electronics, semiconductors, and other manufacturing industries, often involves processes that can lead to the release of these metals. For instance, nickel and cadmium are commonly associated with battery manufacturing and electroplating and zinc is widely used in galvanizing and electronic, while elevated iron and manganese can originate from metal processing, corrosion, or runoff from altered land use within such an industrial landscape (18).

METHODS

This study employed a comprehensive observational and analytical approach to assess heavy metal contamination and associated health risks in various water sources around Kulim Hi-Tech Park (KHTP). The methodology involved systematic water sample collection, laboratory analysis for targeted heavy metals using Atomic Absorption Spectroscopy, and subsequent human health risk assessment through established models.

Selection of Sampling Locations and Seasonal Considerations

The selection of the 30 sampling locations was based on a combination of factors to ensure a representative assessment of potential drinking water sources within and around the Kulim Hi-Tech Park (KHTP). These locations included: (1) points representing various types of water sources (tap water, rivers, ponds) used for or with the potential for drinking water; (2) locations proximal to potential industrial discharge points within KHTP; (3) residential areas potentially impacted by industrial activity; and (4) control sites relatively distant from industrial activity to establish a baseline.

River samples were collected during the Northeast Monsoon period (December-March) of 2022/2023. This timing is significant because during this period of higher rainfall, increased surface runoff can potentially wash accumulated pollutants from industrial and urban areas into rivers, influencing their heavy metal concentrations. While ideally, sampling across different rainfall patterns would provide a more comprehensive picture, this initial study provides a crucial baseline assessment for future monitoring efforts within the prevailing hydrological conditions.

Sample Collection and Preparation

During the sampling procedure, the types of water samples and their conditions were recorded. For each sampling location, a high-density polyethylene (HDPE) bottle was used to collect about 500 mL of water. HDPE is a common type of plastic, known for its strength, durability, and resistance to chemicals and impacts. Water samples were then filtered through 47 mm glass fiber GF/F filters, nominal cut-off size of 0.7 μm (Whatman, Fontenay Sous Bois, France) and were acidified with 3 mL nitric acid for pre-treatment before being sealed in HDPE bottles. All water samples were transported in dark, cool containers and at room temperature prior to analysis at the Faculty of Health Science, Universiti Teknologi Mara (UiTM), Puncak Alam, Selangor. All samples at each location were collected in triplicate following established protocols for trace metal analysis in water by American Public Health Association(19)

Sample Analysis

Cadmium (Cd), manganese (Mn), nickel (Ni), iron (Fe), and zinc (Zn) in water samples were determined by an atomic absorption spectroscopy (AAS) AA800 (Perkin Elmer, Foster City, CA, USA). To confirm the AAS calibration status, a calibration blank, independent calibration standards, and verification standards for Cd, Mn, Ni, Fe, and Zn were analysed alongside all samples. Calibration curves with a coefficient of determination (r^2) greater than 0.999 were deemed acceptable for quantification, and the reported results are the averages of three replicate measurements. The Limit of Quantification (LOQ) for Cd, Mn, Ni, Fe, and Zn was 0.05, 0.05, 0.05, 0.5 and 0.5 (mg/L), respectively. Quality control samples and blank solutions underwent the same preparation and analysis procedures as the samples.

Risk Assessment of Heavy Metals

Risk assessment involves estimating the probability of an event, or the chance that environmental hazard exposure will adversely affect human or animal health. In this study, the Chronic Daily Intake (CDI) parameters for heavy metal intake were estimated using Equation 1 below for non-carcinogenic and carcinogenic metals. For metals where a significant portion of samples were below the LOQ—specifically Cd, Fe, Zn, and Mn—a substitution method was employed for CDI calculation. Half of the LOQ value was used for any sample where the metal concentration was below the LOQ (20).

$$CDI = \frac{C \ x \ IR \ x \ EF \ x \ ED}{BW \ x \ AT} \quad \text{Equation 1}$$

The parameters for assessing human exposure, including ingestion rates (IR), exposure frequency (EF), exposure duration (ED), average body weight (BW), and averaging time (AT), were adopted from established guidelines by United States Environmental Protection Agency (USEPA) for environmental health risk assessment, and are detailed below.

The ingestion rate (IR) for children was 0.78 liters per day, while for male and female adults it was 2.26 and 1.97 liters per day, respectively. The exposure frequency (EF) was assumed to be 365 days per year for all age groups, and the exposure duration (ED) was 74 years for adults and 6 years for children. The average body weight (BW) was 69.95 kg for male adults, 62.59 kg for female adults, and 15 kg for children. In terms of time (AT), adults were assumed to have an average of 27,010 days per year, while children had 2,190 days per year (21-22).

To evaluate the likelihood of non-carcinogenic effects from a particular metal, the Hazard Quotient (HQ) was calculated as in Equation 2. The HQ represents the quotient of potential exposure and the exposure level at which adverse effects are not expected. An HQ value of less than 1 suggests that the exposure is unlikely to cause negative health outcomes.

$$HQ = \frac{CDI}{RFD} \quad \text{Equation 2}$$

The Fe, Mn, Zn, Cd, and Ni reference doses were determined as 7.0E-01, 1.4E-01, 3.0E-01, 5.0E-04, and 2.0E-01 mg/kg/day, respectively (23).

The following Equation 3 of ELCR (Excess Lifetime Cancer Risk) was used in this study to determine the potential for specific elements such as cadmium and nickel to cause cancer in a population. In the normal setting, value range between 1×10^{-4} to 1×10^{-6} is considered as an acceptable risk level.

$$ELCR = CDI \times CSF \qquad \text{Equation 3}$$

The Cancer Slope Factor (CSF) was used as an assumption for Cd and Ni at levels of 6.3 and 0.84 (mg/kg/day)$^{-1}$, respectively (23). To assess the potential for non-carcinogenic effects from the combined exposure to multiple heavy metals, the Hazard Index (HI) was calculated. The HI is the sum of the Hazard Quotients (HQs) for all metals that may affect the same target organ or have similar toxicological endpoints.

An HI value less than 1 suggests that adverse non-cancer health effects from the combined exposure are unlikely. An HI value equal to or greater than 1 indicates a potential risk of non-carcinogenic effects, and the likelihood of adverse effects may increase as the HI value increases.

Statistical Analysis

Each test was conducted three times, and the average of the triplicates was taken as the final value. Microsoft Excel 2016 was used for data tabulation and analysis. Results are presented as mean ± standard deviation (SD), and statistical analysis suitable for the type of data was performed for each parameter.

RESULTS

Sampling and Characterization

We collected 30 water samples from 30 distinct sites within and surrounding Kulim Hi-tech Park (KHTP). These included tap water, rivers, and ponds, all considered potential sources for drinking. All samples were labelled S1 through S30 (Figure 1). Table 1 shows the description of the collected water samples and their condition during the sampling.

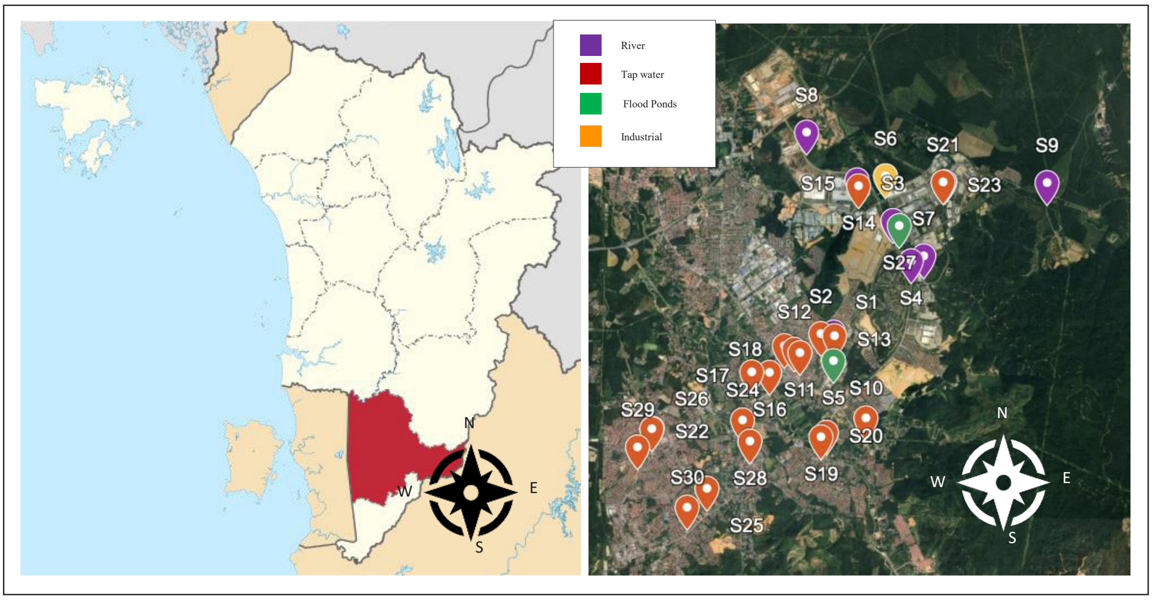

Figure 1. Overview of study area, Kulim, Kedah. Left: Regional map of Peninsular Malaysia with Kulim highlighted. Right: Detailed map of Kulim Hi-Tech Park (KHTP) showing the 30 water sampling locations (S1-S30).

Table 1. Location of Water Sampling and Sample Condition Collected from Different Locations in Kulim, Malaysia

Sampling point	Latitude	Longitude	Description of sample water	Location	Water condition
S1	5.39414	100.57284	R	Residential area	Slightly turbid & clear
S2	5.39382	100.57021	TW	Surau KTC (Muslim prayer place)	Clear
S3	5.41706	100.58508	R	Industrial zone phase 1	Clear
S4	5.40878	100.58886	R	Industrial zone phase 1	Clear
S5	5.38826	100.57282	FP	Reservoir	Slightly turbid with light brown
S6	5.426254	100.58355	IP	Industrial zone phase 1	Highly turbid and dark colour
S7	5.40980	100.59143	R	Industrial zone phase 1	Slightly turbid & clear
S8	5.435216	100.567267	R	Industrial zone phase 1	Slightly turbid & clear
S9	5.424847	100.616860	R	Waste disposal centre	Slightly turbid & clear
S10	5.37649	100.57951	TW	Residential area	Clear

Sampling point	Latitude	Longitude	Description of sample water	Location	Water condition
S11	5.38991	100.56589	TW	Public market	Clear
S12	5.39062	100.56470	TW	Public hall	Clear
S13	5.39339	100.57303	TW	Hospital	Clear
S14	5.42420	100.57800	TW	Sport Complex KHTP	Clear
S15	5.425412	100.577681	R	Sport Complex KHTP	Slightly turbid & clear
S16	5.38585	100.55963	TW	Shell (petrol station)	Clear
S17	5.38594	100.55597	TW	Stadium	Clear
S18	5.39135	100.56270	TW	Mosque	Clear
S19	5.37261	100.57024	TW	Residential area	Clear
S20	5.37353	100.57135	TW	Residential area	Clear
S21	5.42498	100.59543	TW	Eco Park KHTP	Clear
S22	5.37448	100.53547	TW	Petronas (petrol station)	Clear
S23	5.42509	100.59575	R	Industrial zone phase 1	Slightly turbid & clear
S24	5.37606	100.55407	TW	Caltex (petrol station)	Clear
S25	5.36202	100.54673	TW	Residential area	Clear
S26	5.37429	100.53536	TW	Residential area	Clear
S27	5.41602	100.58638	FP	Reservoir industrial zone phase 1	Slightly turbid & clear
S28	5.37172	100.55558	TW	Residential area	Clear
S29	5.37054	100.53240	TW	Public market	Clear
S30	5.35812	100.54263	TW	Residential area	Clear

R: Rivers; TW: Tap water; FP: Flood ponds; IP: Industrial ponds

Occurrence of Fe, Mn, Zn, Cd, and Ni in Water Samples

To evaluate the potential for human exposure to heavy metals via ingestion, water samples were characterized from various sources, including rivers, ponds, and industrial pools, in addition to tap water. Although tap water represents the most direct ingestion route, other sampled water bodies can contribute to human exposure through multiple pathways. Rivers and ponds may serve as direct water sources for some residents or for domestic uses like cooking and washing, leading to incidental ingestion. Moreover, these surface waters, potentially impacted by industrial activities, can indirectly affect human health by recharging groundwater or contributing to agricultural irrigation, thus transferring contaminants into the food chain. Industrial pools highlight specific areas of high contamination risk that could impact broader environmental water systems through seepage or overflow, ultimately influencing the overall water quality and potential for human intake.

Overall, all target pollutants were detected in all water samples collected. Table 2 presents the mean concentrations of Fe, Mn, Zn, Cd, and Ni for each location and as an overall mean concentration. However, it is important to note that while all target pollutants were detected, the majority of samples for Fe, Zn, and Cd fell below the LOQ. Specifically, all Cd samples, 21 Fe samples, and all but one Zn sample were below the LOQ. Ni was detected above the LOQ in all samples, and Mn was detected above the LOQ in three samples. Chronic daily intake (CDI) values for adults and children are shown in Figure 2. Due to the high proportion of samples below the LOQ for Cd, Fe, and Zn, the CDI calculations for these metals are unreliable and should be interpreted with extreme caution.

Table 2. Concentration of Heavy Metals from Water Samples in Kulim, Malaysia (Mean ± SD; n = 30)

Water Sample	Iron (Fe) (mg/L)	Manganese (Mn) (mg/L)	Zinc (Zn) (mg/L)	Cadmium (Cd) (mg/L)	Nickel (Ni) (mg/L)
S1	3.860 ± 0.0485	0.043 ± 0.0063	0.047 ± 0.0018	0.021 ± 0.0026	0.530 ± 0.0092
S2	2.183 ± 1.9456	0.001 ± 0.0035	0.030 ± 0.0008	0.018 ± 0.0024	0.728 ± 0.0332
S3	1.071 ± 0.0354	0.041 ± 0.0032	0.039 ± 0.0016	0.018 ± 0.0011	1.231 ± 0.0751
S4	0.817 ± 0.0148	0.036 ± 0.0039	0.035 ± 0.0032	0.017 ± 0.0015	0.849 ± 0.0499
S5	0.491 ± 0.0208	0.010 ± 0.0016	0.345 ± 0.0053	0.020 ± 0.0013	1.993 ± 0.0369
S6	0.024 ± 0.0060	0.006 ± 0.0026	0.024 ± 0.0013	0.021 ± 0.0010	0.637 ± 0.0503
S7	1.419 ± 0.7799	0.069 ± 0.0021	0.040 ± 0.0024	0.021 ± 0.0009	0.762 ± 0.0252
S8	0.374 ± 0.2833	0.003 ± 0.0043	0.037 ± 0.0016	0.019 ± 0.0023	0.801 ± 0.0956

Water Sample	Iron (Fe) (mg/L)	Manganese (Mn) (mg/L)	Zinc (Zn) (mg/L)	Cadmium (Cd) (mg/L)	Nickel (Ni) (mg/L)
S9	0.238 ± 0.0120	0.012 ± 0.0027	0.041 ± 0.0027	0.021 ± 0.0022	0.832 ± 0.0787
S10	0.716 ± 0.0462	0.045 ± 0.0021	0.070 ± 0.0025	0.017 ± 0.0014	1.283 ± 0.0443
S11	1.144 ± 0.0073	0.096 ± 0.0012	0.037 ± 0.0010	0.020 ± 0.0003	0.786 ± 0.0245
S12	0.051 ± 0.0153	0.004 ± 0.0019	0.033 ± 0.0030	0.019 ± 0.0025	0.767 ± 0.0595
S13	0.046 ± 0.0010	0.010 ± 0.0033	0.031 ± 0.0027	0.019 ± 0.0025	0.705 ± 0.0738
S14	0.084 ± 0.0043	0.018 ± 0.0017	0.173 ± 0.0035	0.019 ± 0.0032	0.794 ± 0.0254
S15	0.234 ± 0.0171	0.006 ± 0.0042	0.201 ± 0.0060	0.015 ± 0.0007	0.741 ± 0.0582
S16	0.063 ± 0.0053	0.011 ± 0.0022	0.230 ± 0.0011	0.014 ± 0.0010	0.781 ± 0.0381
S17	0.212 ± 0.0859	0.072 ± 0.0017	0.826 ± 0.0036	0.020 ± 0.0007	0.910 ± 0.0111
S18	0.091 ± 0.0305	0.020 ± 0.0017	0.033 ± 0.0019	0.020 ± 0.0027	0.704 ± 0.0297
S19	0.058 ± 0.0048	0.018 ± 0.0044	0.460 ± 0.0054	0.020 ± 0.0019	0.730 ± 0.0465
S20	0.045 ± 0.0072	0.015 ± 0.0017	0.027 ± 0.0015	0.018 ± 0.0022	0.807 ± 0.1003
S21	0.070 ± 0.0062	0.017 ± 0.0003	0.020 ± 0.0044	0.016 ± 0.0025	0.913 ± 0.0968
S22	0.087 ± 0.0118	0.016 ± 0.0012	0.017 ± 0.0036	0.016 ± 0.0004	0.856 ± 0.1091
S23	0.446 ± 0.0194	0.021 ± 0.0024	0.156 ± 0.0021	0.013 ± 0.0024	0.850 ± 0.0223
S24	0.073 ± 0.0039	0.029 ± 0.0042	0.052 ± 0.0021	0.016 ± 0.0033	0.774 ± 0.0438
S25	0.212 ± 0.0097	0.016 ± 0.0016	0.069 ± 0.0005	0.018 ± 0.0011	0.751 ± 0.1822
S26	0.150 ± 0.0033	0.026 ± 0.0020	0.063 ± 0.0005	0.017 ± 0.0003	0.807 ± 0.0606
S27	1.272 ± 0.2593	0.055 ± 0.0038	0.011 ± 0.0007	0.014 ± 0.0020	0.851 ± 0.1015
S28	0.177 ± 0.0013	0.032 ± 0.0021	0.088 ± 0.0043	0.016 ± 0.0007	0.866 ± 0.0763
S29	0.070 ± 0.0092	0.015 ± 0.0011	0.269 ± 0.0014	0.012 ± 0.0008	0.950 ± 0.1025
S30	0.146 ± 0.0256	0.044 ± 0.0031	0.046 ± 0.0022	0.015 ± 0.0017	0.967 ± 0.0572
All	0.5308 ± 0.1240*	0.0269 ± 0.0026	0.1183 ± 0.0025	0.0177 ± 0.0017*	0.8652 ± 0.0606*
River	1.0574 ± 0.1513	0.0289 ± 0.0036	0.0745 ± 0.0027	0.0181 ± 0.0017	0.7616 ± 0.0518
Tap water	0.2988 ± 0.1171	0.0266 ± 0.0022	0.1355 ± 0.0024	0.0174 ± 0.0017	0.8357 ± 0.0639
Pond	0.5957 ± 0.0954	0.0237 ± 0.0027	0.1267 ± 0.0024	0.0183 ± 0.0014	1.1603 ± 0.0629
Residential area	0.4776 ± 0.1092	0.0266 ± 0.0023	0.1412 ± 0.0025	0.0177 ± 0.0017	0.8763 ± 0.0600
Industrial area	0.655 ± 0.1586	0.0277 ± 0.0032	0.0649 ± 0.0024	0.0177 ± 0.0016	0.8393 ± 0.0619

Notes: For samples where the concentration was below the LOQ, a value of half the LOQ was used for calculating mean concentrations presented in subsequent analyses. Therefore, mean values for these metals should be interpreted with caution due to the high proportion of data below the LOQ. LOQ: Cadmium (Cd) was 0.05 mg/L, Iron (Fe) was 0.5 mg/L, Manganese (Mn) was 0.05 mg/L, Nickel (Ni) was 0.05 mg/L, and Zinc (Zn) was 0.5 mg/L.

*Concentration exceed the limit set by the regulatory bodies

Across all samples, mean heavy metal concentrations varied between 0.0177 ± 0.0017 mg/L and 0.8652 ± 0.0606 mg/L. Notably, the order of mean concentrations was: Ni > Fe > Zn > Mn > Cd. Across all samples, the overall mean concentrations were determined as follows: Ni at 0.8652 ± 0.0606 mg/L, Fe at 0.5308 ± 0.1240 mg/L, Zn at 0.1183 ± 0.0025 mg/L, Mn at 0.0269 ± 0.0026 mg/L, and Cd at 0.0177 ± 0.0017 mg/L. This corresponds to the order of mean concentrations: Ni > Fe > Zn > Mn > Cd. However, the mean concentrations for Cd, Fe, and Zn are heavily influenced by the large number of samples below the LOQ and therefore, should be interpreted with caution.

When comparing mean concentrations to permissible limits (Table 3), Ni was found to surpass standards established by the United States Environmental Protection Agency (USEPA), Malaysia Recommended Raw Water Quality (MRRWQ), and Malaysia Drinking Water Quality Standard (MDWQS).Due to the LOQ limitations, the mean concentrations for Fe and Cd may not accurately reflect actual environmental levels.

Ni concentrations exhibited a relatively consistent trend between tap water and pond water samples. In contrast, river samples showed a distinct pattern, with Fe being the most abundant metal, followed by Ni, Zn, Mn, and Cd. Comparing residential and industrial areas, subtle differences were observed, primarily in Ni concentrations. Zn was slightly higher in residential areas, whereas Fe was elevated in industrial zones. It is important to remember that due to the high proportion of samples below the LOQ for Fe, Zn, and Cd, comparisons for these metals are unreliable.

Table 3. Permissible Limits (mg/L) for Heavy Metals in Water According to Different Regulatory Standards

Regulatory Standards	Iron (Fe) (mg/L)	Manganese (Mn) (mg/L)	Zinc (Zn) (mg/L)	Cadmium (Cd) (mg/L)	Nickel (Ni) (mg/L)
USEPA [a)] standards	0.3	0.05	5.0	0.005	0.1
MRRWQ [b)]	1.0	0.2	3.0	0.003	-
MDWQS [c)]	0.3	0.1	3.0	0.003	0.02

Regulatory bodies: a) United States Environmental Protection Agency; b) Malaysia Recommended Raw Water Quality; c) Malaysia Drinking Water Quality Standards

Risk Assessment of Fe, Mn, Zn, Cd, and Ni from the Sample Collected

Table 4 presents the estimated Chronic Daily Intake (CDI), Hazard Quotient (HQ),and Hazard Index (HI) for non-carcinogenic metals, as well as Excess Lifetime Cancer Risk (ELCR) for carcinogenic metals, across the studied sub-populations (adult males, adult females, and children). These values provide quantitative measures of potential human exposure and health risks. Figure 2 visually represents the CDI values for adults and children.

For Fe, Mn, Cd, and Zn, where a significant number of samples were below the LOQ, mean values used in the CDI equations were substituted with half of the respective LOQ values. Consequently, the HQ and HI values for these metals should be interpreted with caution and are considered unreliable, due to the inherent uncertainty introduced by the high proportion of data below the Limit of Quantification (LOQ).

Table 4. Carcinogenic and Non-Carcinogenic Risk of Heavy Metals from Water Intake of Different Sub-Populations in Kulim, Malaysia

Risk	Male Adult		Female Adult		Children	
Non-Carcinogenic	CDI (mg/kg/day)	HQ	CDI (mg/kg/day)	HQ	CDI (mg/kg/day)	HQ
Fe	0.0081	1.15E-02	0.0079	1.12E-02	0.0130	1.86E-02
Mn	0.0008	5.77E-03	0.0008	5.62E-03	0.0013	9.29E-03
Zn	0.0081	2.69E-02	0.0080	2.62E-02	0.0130	4.33E-02
Hazard Index (HI)	-	4.42E-02	-	4.30E-02	-	7.12E-02
Carcinogenic	CDI (mg/kg/day)	ELCR	CDI (mg/kg/day)	ELCR	CDI (mg/kg/day)	ELCR
Ni	2.80E-02	**0.0051**	2.72E-02	**0.0050**	4.50E-02	**0.0082**
Cd	0.0008	**0.0235**	5.56E-04	**0.0205**	9.19E-04	**0.1095**

CDI: Chronic Daily Intake; HQ: Hazard Quotient; ELCR: Excess Lifetime Cancer Risk. Values in bold exceed the ELCR threshold of 1 × 10-4.

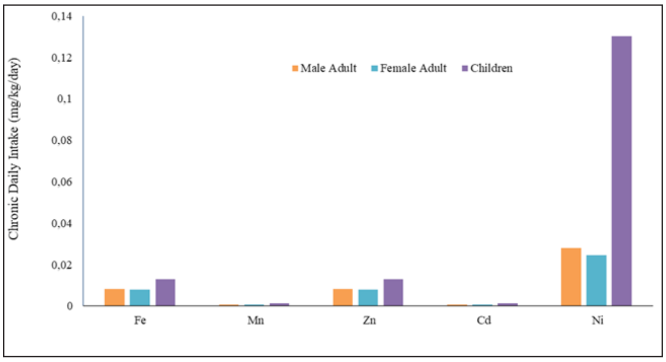

Figure 2. Chronic Daily Intake (CDI) (mg/kg/day) of heavy metals for different sub-populations, calculated using mean concentrations (half LOQ substituted for non-detects).

Note: CDI values were calculated using mean heavy metal concentrations (half LOQ substituted for non-detects for Cd, Fe, Mn, and Zn). The concentration ranges (mg/L) for each metal were:
Fe: Children, male and female adults: < 0.5 – 3.860 mg/L
Mn: Children, male and female adults: < 0.05 – 0.072 mg/L
Zn: Children, male and female adults: < 0.5 – 0.826 mg/L
Cd: Children, male and female adults: < 0.05 – 0.021 mg/L
Ni: Children, male and female adults: 0.530 – 1.993 mg/L

Regarding non-carcinogenic risks, the Hazard Quotient (HQ) was calculated for Fe, Mn, and Zn. For all sub-populations, the HQ values for Fe, Mn, and Zn were consistently below 1 (Table 4). Specifically, the HQ values for Fe ranged from 1.12E-02 to 1.86E-02, for manganese from 5.62E-03 to 9.29E-03, and for zinc from 2.62E-02 to 4.33E-02. An HQ value less than 1 indicates that daily exposure to these metals through drinking water is unlikely to pose a significant non-carcinogenic health risk. As previously noted, however, this conclusion for Fe, Mn, and Zn is subject to the limitations imposed by the high number of samples below the LOQ.

The Hazard Index (HI), which assesses the cumulative non-carcinogenic risk from combined exposure to these metals, was calculated by summing the individual HQs for Fe, Mn, and Zn. The HI for all sub-populations was also consistently below 1 (e.g., 2.94E-02 for male adults, 2.74E-02 for female adults, and

7.21E-02 for children). An HI value less than 1 indicates that adverse non-cancer health effects from combined exposure are unlikely. Again, it is crucial to recognize the impact of LOQ limitations on the overall HI value.

Excess Lifetime Cancer Risk (ELCR) was determined for Cd and Ni due to their established carcinogenic potential. The ELCR values indicated that Cd generally had higher values than Ni across all sub-populations. Specifically, the ELCR for nickel was 0.0051 for male adults, 0.0050 for female adults, and 0.0082 for children. For cadmium, the ELCR was 0.0235 for male adults, 0.0205 for female adults, and 0.1095 for children (Table 4). In the normal setting, an ELCR value range between 1×10^{-4} (0.0001) to 1×10^{-6} (0.000001) is considered an acceptable risk level. All calculated ELCR values for both Ni and Cd, across all sub-populations, exceeded the upper acceptable threshold of 1×10^{-4}. This suggests a significant potential carcinogenic risk from both cadmium and nickel exposure over a lifetime, based on the estimated concentrations. However, it is important to reiterate that the ELCR values for Cd are subject to considerable uncertainty due to the high proportion of samples below the LOQ. Thus, while both Cd and Ni show elevated cancer risks based on these calculations, the interpretation for Cd requires extreme caution given the data limitations. Further research with more sensitive analytical methods is needed to determine the true impact of the data below the LOQ on the ELCR values, particularly for Cd. Further research is needed to determine the impact of the data below the LOQ on the ELCR values.

DISCUSSION

This study assessed water quality in Kulim Hi-Tech Park (KHTP) which is an industrial area by analyzing 30 water samples from diverse sources (rivers, tap water, ponds) across residential and industrial areas. Turbidity varied significantly, requiring filtration for accurate analysis. The impact of land use patterns on surface water quality, including parameters like turbidity, is a key consideration in watershed management (24). While parameters like biological oxygen demand (BOD), chemical oxygen demand (COD), and ammonia nitrogen (NH_3-N) were not assessed due to equipment limitations, research has demonstrated their complex relationships with heavy metal distribution. For example, a study identified COD and BOD as key factors influencing heavy metal concentrations, potentially linked to non-point sources like mining activities (25).

In terms of mean concentration, heavy metals ranked as follows:nickel (Ni) > iron (Fe) > zinc (Zn) > manganese (Mn) > cadmium (Cd). Consistent trends were observed between tap and pond water, suggesting shared contamination sources. River samples were slightly deviated, with Fe dominating, likely influenced by riverine dynamics and anthropogenic activities along riverbanks. Minor distinctions were observed between residential and industrial areas, with higher Zn in residential and Fe in industrial zones, hinting at localized influences or the infrastructure on heavy metal distribution.

Crucially, the reliability of the mean concentrations for Fe, Zn, and Cd is severely compromised by the high proportion of samples below the Limit of Quantification (LOQ). Specifically, 21 out of 30 Fe samples, all but one Zn sample, and all Cd samples were below the LOQ. This significantly impacts the accuracy of comparisons to regulatory standards and the interpretation of trends. The use of half the LOQ as a substitute for these values, while a common practice, introduces significant uncertainty and limits the robustness of our conclusions.

While Fe concentrations exceeded regulatory limits in seven locations, primarily in river samples, this finding must be interpreted with extreme caution due to the LOQ limitations. This limitation significantly affects the reliability of the mean Fe concentrations and the comparison to regulatory standards. Despite the limitations of our Fe data, it is important to note that Fe contamination is a widespread global issue as evidenced by studies in the South Kalimantan, Indonesia (26), in Hodh El Chargui in Mauritania (27), the Sylhet district in Bangladesh (28) and also in wastewater in Malaysia (29) These studies collectively highlight the widespread nature of Fe contamination, affecting residential areas, water bodies, and industrial zones alike. However, given the data limitations in this study, further research using more sensitive analytical methods is essential to accurately assess Fe contamination in Kulim and to determine if the observed exceedances are genuine or artifacts of the data handling. The potential health complications associated with excessive Fe intake—including liver tumors, metabolic disorders, cardiovascular diseases, and reproductive issues(30), as well as the aesthetic impact of high Fe concentrations on water quality (31)—further emphasize the need for accurate assessment.

Mn concentrations were within acceptable regulatory limits of Malaysia Recommended Raw Water Quality (MRRWQ) at 0.2 mg/L and Malaysia Drinking Water Quality Standard (MDWQS) at 0.1 mg/L. However, it is important to note that only three out of 30 Mn samples were above the LOQ. Consequently, the observed similarity in Mn levels between residential and industrial areas should be viewed with skepticism. The limited reliable data makes it difficult to draw definitive conclusions about Mn distribution and potential sources. Despite the data limitations, the significance of Mn in human health and physiological functions cannot be overstated. Mn is crucial for many biological processes, such as immune response, blood sugar control, cellular energy, reproduction, digestion, bone development, blood clotting, hemostasis, and antioxidant defense (32). Disruptions to Mn are also linked to various neurological conditions (33). Further research, using more sensitive analytical methods, would be needed to determine if the similar Mn levels observed are accurate.

Zn concentrations were generally low, with only one out of 30 samples above the LOQ. Therefore, the following conclusion should be interpreted with extreme caution. The observed trends between residential and industrial areas are likely artifacts of the data limitations and require further investigation with more sensitive methods. The essential nature of Zn for bodily functions underscores the importance of accurate monitoring, even at low concentrations. This study aligns with prior research indicating low Zn levels in groundwater and attributing human activities as major contributors to environmental Zn disposal (34). However, the discrepancy between our findings and those of previous studies, particularly regarding the higher Zn concentrations in residential areas compared to industrial zones, warrants further investigation (35-36).

Though all Cd concentrations were below the LOQ, suggesting that Cd was not able to be quantified, the potential for Cd contamination in these water sources remains a concern. The presence of industries in Kulim that utilize Cd, and the serious health risks associated with Cd exposure, necessitate further investigation using more sensitive methods to determine if Cd is present, even at trace levels. While a study in Iran have shown that agricultural activities can contribute to Cd contamination (37), and Kulim is home to various industries, including agro-tech and electronics facilities, we cannot confidently conclude that the water resources in this study were contaminated by Cd. It is important to acknowledge that even if Cd is present at very low levels, Cd in water is undesirable and can lead to severe health consequences. Acute cadmium exposure can cause symptoms such as diarrhea, vomiting, fever, lung damage, and muscle soreness. Chronic Cd exposure can lead to illnesses, including renal disease, bone damage, reproductive issues, and potentially cancer (38), as further detailed in a recent review of cadmium's effects on human health (39). Due to the data limitations, further research, using more sensitive analytical methods, is needed to determine the Cd concentrations within the water samples.

Ni concentrations also exceeded limits of the United States Environmental Protection Agency (USEPA) and Malaysia Drinking Water Quality Standard (MDWQS), with the highest average concentration observed in pond water (1.1603 ± 0.0629 mg/L). While the industrial area sample exhibited a relatively high Ni concentration (0.8393 ± 0.0619 mg/L), some river samples also showed comparable levels (0.7616 ± 0.0518 mg/L). The tap water and residential areas also showed relatively high concentrations of Ni (0.8357 ± 0.0639 mg/L and 0.8763 ± 0.0600 mg/L, respectively). The elevated Ni levels in pond water, and the relatively high levels found in other water sources, indicates a need for further investigation to determine the sources and pathways of Ni contamination. Studies in other industrial regions in Pakistan have highlighted the presence of elevated nickel levels in drinking water (40). As an immunotoxic and carcinogenic element, prolonged nickel exposure is linked to various health issues including contact dermatitis, cardiovascular disease, asthma, lung fibrosis, and respiratory tract cancer (41). To mitigate these risks, it is essential to implement stricter regulations on the discharge of industrial effluents, particularly from battery production facilities, targeting Ni concentrations. Furthermore, promoting the use of alternative, less hazardous materials in industrial processes is crucial to reduce Ni contamination in the water bodies of Kulim.

The health risk assessment, based on Hazard Quotient (HQ), Hazard Index (HI), and Excess Lifetime Cancer Risk (ELCR), is significantly impacted by the LOQ limitations. The non-carcinogenic conclusions for Fe, Mn, and Zn, and the potential cancer risks associated with Cd and Ni, are unreliable due to the high proportion of data below the LOQ. When facing environmental uncertainty, such as the unknown concentrations below the detection limit, the precautionary principle suggests taking preventative measures (42). Further research with more sensitive methods is crucial to validate these findings and inform remediation efforts. The high ELCR value for Ni, which was found in higher concentrations near industrial areas, indicates a need for immediate and targeted remediation efforts.

The limitations of this study, including the small sample size and the focus on only five heavy metals, necessitate further research. Future studies should employ larger sample sizes, include a broader range of metals (e.g., lead, arsenic), and implement long-term monitoring to track changes in metal concentrations. The use of more sophisticated statistical methods for handling censored data, such as survival analysis techniques, should also be considered.

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CONCLUSION

This study detected Fe, Cd, Ni, Zn, and Mn in water resources in Kulim Hi-Tech Park. However, due to the substantial limitations imposed by the high proportion of data below the LOQ, particularly for Fe, Zn, and Cd, the conclusions regarding these metals are unreliable. While Ni concentrations exceeded permissible limits and the ELCR calculations suggested potential cancer risks for Cd and Ni, these findings require further validation with more sensitive analytical methods. To protect public health, regulatory actions, such as stricter industrial discharge regulations and enhanced monitoring protocols, should be implemented. To strengthen future studies, a larger sample size is recommended, expanding the analysis to include other potentially harmful metals, and implementing long-term monitoring to track changes in metal concentrations over time.

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