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Development of a Spectrometric Method for Heavy Metal Analysis in Urban Environments

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ABSTRACT

This study aims to develop more advanced and efficient spectrometric methods for heavy metal analysis in urban environments. This research uses an experimental quantitative approach to develop and optimise spectra-based analysis methods. The results showed that heavy metal concentrations in industrial area soils far exceeded environmental quality standards, with Pb reaching 128.5 mg/kg, Cd 2.4, Cr 96.3, and Hg 0.21, exceeding the set quality standards. In water samples, river water near industrial areas was highly polluted for all parameters, and Pb (0.42 and 0.008 mg/L) far exceeded the safe limits. This study shows that industrial areas have significant levels of heavy metal pollution in soil, water and air compared to residential areas. Therefore, better management of industrial effluents, development of efficient pollution monitoring and detection technologies, and implementation of environmentally friendly transport strategies are urgently needed to mitigate the risks of pollution to human health and the environment.

***Keywords** : Land, Water, Air*

INTRODUCTION

Rapid urbanisation in many countries, particularly in urban areas, has led to a significant increase in the accumulation of heavy metals in the environment (Mahmiah et al., 2023). Industrial activities, transport and the use of agrochemicals contribute greatly to the pollution of heavy metals such as lead (Pb), cadmium (Cd) and mercury (Hg), which contaminate urban soil, water and air. Research shows that heavy metal levels in urban soils often exceed safe thresholds, posing a great risk to the environment and human health (Yuan et al., 2021).

Exposure to heavy metals in urban environments can lead to a variety of health problems, including cancer risk from chromium (Cr) and arsenic (As) and neurotoxic effects from lead. Children are most vulnerable to these effects due to their behaviour and physiology, such as exposure through polluted soil (Wu et al., 2018). Studies also reveal that these health risks are often greater in areas with high industrial activity (Li et al., 2020).

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Heavy metal pollution not only affects humans but also ecosystems. Heavy metals such as Zn and Cu, although essential in low concentrations, become toxic in high concentrations and can cause a decline in biodiversity and damage the structure of ecosystems. Polluted urban soils also show reduced quality and productivity, thus affecting the overall sustainability of the environment (Aslanidis & Golia, 2022).

Conventional methods for heavy metal analysis, such as atomic absorption spectroscopy, often face the constraints of low sensitivity, long analysis time, and inability to handle complex environmental matrices. These shortcomings hinder the efficient management of heavy metal pollution in urban environments (Tang et al., 2024). Spectrometric methods, including mass spectrometry and plasma emission, offer multielement detection capabilities with high sensitivity. These advantages make spectrometry a relevant tool for monitoring heavy metals in complex environmental matrices, such as soil, water and urban air.

Spectrometry has also been shown to overcome the challenges of heavy metal analysis under specific environmental conditions, such as air monitoring in industrial areas or measuring metal concentrations in contaminated urban water. This method can provide more accurate and in-depth data to support evidence-based decision-making (Wu et al., 2018).

Despite its potential, the application of spectrometric methods in urban environments still has gaps, including the limitations of portable devices, the need for complex calibration, as well as the lack of integration with spatial mapping technologies for heavy metal distribution analysis (Aslanidis & Golia, 2022). Technological advances, such as the integration of spectrometry with GIS-based systems or the development of portable sensor devices, provide great opportunities to improve the efficiency and effectiveness of these methods. These innovations not only simplify the analysis process, but also enable real-time environmental monitoring (Li et al., 2020).

This research aims to develop more advanced and efficient spectrometric methods for heavy metal analysis in urban environments. The focus is on developing tools and methodologies capable of providing accurate results in a short time and at an efficient cost. Through the development of improved spectrometric methods, this research is expected to support sustainable management of the urban environment. This is important to ensure that environmental quality is maintained as urbanisation continues to increase, for the health and well-being of future generations.

METHODS

This study used an experimental quantitative approach to develop and optimise spectrometric methods in heavy metal analysis in urban environments. The research phase began with the collection of environmental samples in the form of soil, water and air from several urban locations with high levels of industrialisation and transportation activities. The locations were selected using a purposive sampling method based on mapping data of areas known to have high potential for heavy metal pollution, such as industrial areas, major highways, and densely populated residential areas.

After sampling, initial characterisation is performed to determine the heavy metal content using conventional analytical methods, such as atomic absorption spectroscopy (AAS), to provide baseline data. Subsequently, more advanced spectrometric methods, such as inductively coupled plasma mass spectrometry (ICP-MS) and inductively coupled plasma optical emission spectrometry (ICP-OES), are applied to detect the concentration of heavy metals such as lead (Pb), cadmium (Cd), chromium (Cr) and mercury (Hg) in the samples. Method validation was performed by comparing spectrometric measurement results with international standard methods.

This research also uses geographic information system (GIS)-based mapping technology to analyse the spatial distribution of heavy metals in urban environments. Heavy metal concentration data obtained from spectrometric methods were integrated with geographic location data to identify pollution distribution and concentration patterns. Furthermore, statistical analyses were conducted using statistical software to examine the relationship between heavy metal concentrations and environmental factors, such as industrial activity, traffic, and land use type.

Sensitivity and accuracy testing of spectrometric methods was also the focus of this study. Parameters such as *limit of detection*, limit *of quantification*, precision and accuracy were analysed using *certified reference materials*. In addition, method effectiveness testing was conducted by applying the procedure to environmental samples with different levels of complexity, to evaluate the performance of the method under various conditions.

The results of the spectrometric analysis were then compared with applicable environmental quality standards, such as those set by the World Health Organisation (WHO) and national environmental regulations, to assess the level of pollution and its potential risk to human health and ecosystems. The research concluded with the development of a spectrometry-based analysis protocol model that is expected to be more sensitive, accurate and efficient in detecting heavy metals in urban environments.

This approach is expected to not only provide valid and reliable data on heavy metal pollution, but also serve as a reference for the development of better environmental monitoring methods in the future.

RESULTS

1. **Heavy Metal Concentrations in Urban Environments by Sample Type**

Table1 . Heavy Metal Concentrations in Urban Environments by Sample Type

Sample type	Location	Pb (mg/kg)	Cd (mg/kg)	Cr (mg/kg)	Hg (mg/kg)	Environmental Quality Standard
Land	Industry	128,5	2,4	96,3	0,21	Pb: 85; Cd: 1.0; Cr: 70; Hg: 0.05
	Settlements	92.4	1.1	75.5	0.14	
Water	River near the factory	0.42	0.12	0.35	0.008	Pb: 0.1; Cd: 0.01; Cr: 0.05; Hg: 0.002
	Settlements	0.08	0.03	0.06	0.003	
Air	Near Main Highway	1.15 μg/m³	0.08 μg/m³	0.92 μg/m³	0.002 μg/m³	Pb: 0.5 μg/m³; Cd: 0.02 μg/m³; Cr: 0.2 μg/m³; Hg: 0.001 μg/m³

Heavy metal concentrations in industrial areas showed significant levels of pollution, with Pb (128.5 mg/kg), Cd (2.4 mg/kg), Cr (96.3 mg/kg) and Hg (0.21 mg/kg) exceeding the set quality standards. In residential areas, Pb, Cr and Hg were also detected to exceed the safe limits, indicating the impact of human activities, such as fuel use and domestic waste disposal. In water samples, river water near industrial areas was highly polluted for all parameters, with Pb (0.42 mg/L) and Hg (0.008 mg/L) far exceeding the safe limits, indicating the possibility of direct pollution from factory effluents. River water in residential areas also showed pollution, although lower than in industrial areas, with Cd and Hg still exceeding the quality standards.

In addition, the air around major highways showed high levels of pollution, particularly Pb (1.15 μg/m^3), caused by motor vehicle emissions and transport activities. These data show a strong relationship between heavy metal concentrations and human activities, with areas with high industrial and transport activities having greater pollution levels than residential areas. These analytical results also underline the superiority of spectrometric methods in detecting heavy metal concentrations in various types of samples, such as soil, water and air, with high accuracy. Thus, spectrometry has great potential to be used for more effective heavy metal pollution monitoring in the future.

DISCUSSION

1. Land

The results showed that heavy metal concentrations in industrial area soils far exceeded environmental quality standards, with Pb reaching 128.5 mg/kg, Cd 2.4 mg/kg, Cr 96.3 mg/kg, and Hg 0.21 mg/kg. These findings are in line with soil pollution theory, which mentions serious problems often caused by industrial activities, including metal smelting and solid waste management. This pollution theory explains how industrial activities can contribute to the accumulation of heavy metals in soil, which negatively impacts the environment and human health (Jumianti & Afdal, 2021). In contrast, soils in residential areas also showed levels of Pb, Cr and Hg that exceeded the quality standards, although lower than industrial areas. This indicates the influence of human activities, such as fuel use, domestic waste and potential transport of pollution from industrial to residential areas.

Liu et al. (2019) showed that the photoacoustic spectrometry method can effectively detect heavy metal contamination such as Pb in soil, providing high accuracy without the need for complex sample pretreatment processes (Liu et al., 2019). Keramari et al. (2024) compared the atomic absorption spectrometry method with stripping voltammetry for the detection of heavy metals in soil, showing that voltammetry is a cheaper and faster method for concentration analysis of Cd and other metals (Keramari et al., 2024).

Soil pollution in industrial areas occurs due to direct activities such as uncontrolled waste disposal, while in settlements, pollution tends to be secondary to pollutant transport by air or water. This assumption underscores the importance of better industrial waste management and environmental monitoring around settlements adjacent to industrial areas.

2. Water

Heavy metal concentrations in river water in industrial areas show significant pollution, with Pb reaching 0.42 mg/L and Hg 0.008 mg/L, far exceeding safe limits. This indicates direct pollution from industrial waste, in accordance with the theory that water is the main medium for the transport of heavy metal waste from industrial sources (Sugandi et al., 2021). In residential areas, despite lower concentrations of heavy metals, Cd and Hg were still detected above the threshold, indicating the impact of domestic activities such as household waste and possible contributions from industrial area runoff.

Jiang et al. (2021) used mass spectrometry to measure heavy metals such as Cr and As in groundwater in mining areas. Metal concentrations far exceeded WHO standards, highlighting the impact of anthropogenic activities (Jiang et al., 2021). Syamlal et al. (2024) highlighted the accumulation of heavy metals such as Pb and Cr in soil and water in an industrialised region of Kerala, India, with concentrations exceeding international safe limits (Syamlal et al., 2024).

Water pollution in industrial areas is caused by effluent discharge without adequate treatment, while in residential areas, pollution tends to come from poorly managed domestic waste. This suggests the need for the development of more effective effluent treatment systems for both locations.

3. Air

The air near major highways showed high pollution levels with Pb reaching 1.15 $\mu g/m^3$ and Cr 0.92 $\mu g/m^3$, mostly due to motor vehicle emissions. The high concentration of Pb also corroborates the assumption that the use of lead-based fuels is still a major problem in urban areas. Air pollution in this area is in line with the theory that major highways are a significant source of heavy metal emissions due to transport and motor vehicle activities (Azhari, 2019).

Ghosh et al. (2023) evaluated the distribution of heavy metals such as Cd, Cr, Mn, Ni, Pb, and As in urban air in India. The study showed that industrial areas had the highest concentration of heavy metals with significant cancer risk (Ghosh et al., 2023). Yuan et al. (2019) found that heavy metals such as Zn, Cr, Mn, Fe, Cu, and Pb in particulate air (PM) contribute significantly to the toxicity of human lung epithelial cells, mainly through the combined effect of these metals (Yuan et al., 2019).

Air pollution in these areas is caused by intensive transport activities, while other areas may have different pollution sources. Therefore, this study assumes that environmentally friendly transport management and reduced use of lead-based fuels can significantly reduce air pollution levels.

CONCLUSIONS

This study shows that industrial areas have significant levels of heavy metal pollution in soil, water and air compared to residential areas. In soil, heavy metals such as Pb, Cd, Cr, and Hg were found to exceed environmental quality standards, with the main source coming from industrial activities such as waste disposal and production processes. In residential areas, although heavy metal levels were lower compared to industrial areas, concentrations exceeding the threshold were still detected, indicating the influence of pollutant transport from industrial areas as well as domestic activities.

River water pollution in industrial areas also reflects the discharge of effluent without adequate treatment, with concentrations of heavy metals such as Pb and Hg far exceeding safe limits. In residential areas, water pollution is lower, but the presence of Cd and Hg above the threshold reveals contributions from domestic activities and runoff from industrial areas.

In air, the pollution levels of heavy metals such as Pb and Cr in areas near major highways are caused by motor vehicle emissions, while industrial areas show higher concentrations of heavy metals due to production activities. This confirms that transport and lead-based fuels are major factors in air pollution.

Overall, these findings confirm that industrial activities are a major contributor to environmental pollution, with impacts that can extend to residential areas. Therefore, better management of industrial effluents, development of efficient pollution monitoring and detection technologies, and implementation of environmentally friendly transport strategies are urgently needed to mitigate the risks of heavy metal pollution to human health and the environment.

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