Global Journal of Environmental Science and Management
(GJESM)

Homepage: https://www.gjesm.net/

Podcasts

ORIGINAL RESEARCH PAPER

Validation of heavy metals in geothermal to support water management practices and mitigation strategies

G.M. Idroes[1,2], D.P. Rezeki[3], K. Khairi[3], K. Khairan[4], R. Idroes[4], E. Suhartono[5], R. Prasetio[6], S.A. Rahman[7], S. Suhendrayatna[8,9*]

[1] *Graduate School of Mathematics and Applied Sciences, Universitas Syiah Kuala, Banda Aceh, 23111, Indonesia*

[2] *Department of Occupational Health and Safety, Faculty of Health Sciences, Universitas Abulyatama, Aceh Besar 23372, Indonesia*

[3] *Department of Chemistry, Faculty of Mathematics and Natural Sciences, Universitas Syiah Kuala, Banda Aceh 23111, Indonesia*

[4] *Department of Pharmacy, Faculty of Mathematics and Natural Sciences, Universitas Syiah Kuala, Banda Aceh 23111, Indonesia*

[5] *Department of Medical Chemistry/ Biochemistry, Faculty of Medicine, Lambung Mangkurat University, Banjarbaru 70124, Indonesia*

[6] *Research Center of Radiation Processing Technology, National Research and Innovation Agency, Puspiptek Serpong, South Tangerang, 15314, Indonesia*

[7] *Faculty of Chemical and Process Engineering Technology, Universiti Malaysia Pahang, Lebuhraya Persiaran Tun Khalil Yaakob, 26300 Gambang, Kuantan, Pahang, Malaysia*

[8] *Biochar and Forest Conservation Research Center, Universitas Syiah Kuala, Banda Aceh, Indonesia*

[9] *Department of Chemical Engineering, Faculty of Engineering, Universitas Syiah Kuala, Banda Aceh 23111, Indonesia*

ARTICLE INFO

Article History:
Received 18 June 2024
Revised 23 August 2024
Accepted 02 October 2024

Keywords:
Environmental contamination risks
Flame atomic absorption spectroscopy (FAAS)
Heavy metal analysis
Water quality assessment

ABSTRACT

BACKGROUND AND OBJECTIVES: This study aimed to evaluate and validate the concentrations of six heavy metals, specifically lead, cadmium, copper, chromium, zinc, and iron, found in geothermal water from the Mount Kembar Region in Gayo Lues Regency, Aceh Province. This study primarily sought to investigate the health risks that these heavy metals may present and to deliver vital information that would aid in the advancement of water management practices and mitigation strategies in the locality. Understanding the levels of these metals is essential for preventing long-term health effects on the local population and ensuring sustainable use of geothermal water resources.

METHODS: Water samples were taken from five geothermal sites in the region and analyzed with flame atomic absorption spectroscopy, a highly effective technique for the detection of trace metals. The flame atomic absorption spectroscopy technique was validated for precision, linearity, and accuracy, achieving R-squared values greater than 0.99, confirming the reliability of the analytical results. This confirmed that the identified concentrations of metals were reliable and could serve to evaluate the possible health risks faced by residents and users of the water source.

FINDINGS: The analysis revealed that copper, chromium, zinc, and iron concentrations were within the permissible limits for safe drinking water as established by national and international health guidelines. However, elevated concentrations of lead and cadmium were detected in multiple sampled locations, surpassing the recommended safety thresholds. This implies a substantial danger to the health of those who drink or are exposed to this water, as both lead and cadmium are associated with severe health complications, including damage to the nervous system and kidneys. The findings underscore the urgent need for targeted water treatment and continuous monitoring, providing critical data to support sustainable water management and mitigation strategies in geothermal regions.

CONCLUSION: The findings of this study underscore the urgent need for water treatment initiatives and continuous monitoring of geothermal water sources in the Mount Kembar Region. Although the analysis showed that the majority of metals were within safe ranges, the notably high levels of lead and cadmium require urgent measures to minimize health risks. Preventive measures, such as water filtration and public health advisories, should be implemented to safeguard the local population from the potential long-term exposure to these toxic metals.

DOI: 10.22034/gjesm.2024.10.SI.10

This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

NUMBER OF REFERENCES
50

NUMBER OF FIGURES
1

NUMBER OF TABLES
7

*Corresponding Author:
Email: *suhendrayatna@usk.ac.id*
Phone: +812 6 911 823
ORCID: 0000-0002-2673-0947

Note: Discussion period for this manuscript open until November 1, 2024 on GJESM website at the "Show Article".

INTRODUCTION

Geothermal energy is a renewable resource obtained from the heat located beneath the Earth's surface (Idroes *et al*., 2024a), primarily produced by volcanic activity and the natural radioactive decay of elements within the Earth's core (Idroes *et al*., 2024b). This thermal energy is extracted by utilizing underground sources of heated water (Shah *et al*., 2024) or steam (Lund and Toth, 2021), enabling the production of electricity or the provision of direct heating for diverse (Owebor *et al*., 2021). One of its key advantages is its ability to offer a consistent and reliable energy supply (Maulidar *et al*., 2024), unlike other renewable sources like solar and wind (Lin *et al*., 2021), which depend on weather conditions (Lund *et al*., 2022). Geothermal energy is particularly effective in regions with significant geothermal activity (Islam *et al*., 2022), such as Iceland, the United States (Azarpour *et al*., 2022), and New Zealand, and can play a vital role in these areas energy grids (Miranda *et al*., 2020). In addition to being stable, geothermal energy is environmentally friendly (Androniceanu and Sabie, 2022), emitting far fewer greenhouse gases than fossil fuels (Letcher, 2022). Its smaller land footprint compared to solar and wind farms also makes it ideal for regions where space is limited (Sayed *et al*., 2021). However, geothermal development comes with challenges (Kumar *et al*., 2022), particularly the high upfront costs associated with drilling and exploration and its geographical limitations, as it can only be effectively harnessed in specific locations (Santos *et al*., 2022). Despite the existing challenge, geothermal energy remains a viable long-term solution for sustainable energy generation (Bhagaloo *et al*., 2022). It provides significant environmental and economic benefits (Soltani *et al*., 2021) when applied in suitable circumstances (Hardi *et al*., 2024). Countries with significant volcanic activity, such as Iceland (Meirbekova *et al*., 2024), the Philippines, and the United States, have been leaders in successfully tapping into geothermal energy's vast potential (Gutiérrez-Negrín, 2024). By capitalizing on their specific geographical features, these nations have successfully tapped into geothermal resources for the production of electricity and heating (Anderson and Rezaie, 2019), which has significantly bolstered their energy independence and supported environmental sustainability efforts (Sharmin *et al*., 2023). Indonesia, which sits along the Pacific "Ring of Fire," holds the largest geothermal potential globally, with an estimated capacity of approximately 29.5 Gigawatt (Pambudi and Ulfa, 2024). Indonesia's significant geothermal resources are found in multiple geologically dynamic regions, including Sumatra, Java, Bali, and Sulawesi, thereby establishing the nation as an ideal candidate for large-scale geothermal energy initiatives (Pambudi, 2018). Despite possessing the world's largest geothermal potential, Indonesia faces significant barriers to fully utilizing this resource. Technological limitations hinder the efficient extraction and conversion of geothermal energy, while suboptimal policies and regulatory frameworks have slowed geothermal development (Darma, 2016). Environmental concerns arise from heavy metals in geothermal water (Rotich *et al*., 2024), posing risks to local ecosystems if not properly managed (de Jesus, 2016). To effectively tackle these challenges, Indonesia must leverage technological advancements, enhance governmental policies, and implement robust environmental protections. Such measures are essential for the nation to fully realize its geothermal energy potential and make a significant contribution to global renewable energy objectives (Zhang *et al*., 2019). The Aceh Province also has significant geothermal energy potential, particularly in the Seulawah (Idroes *et al*., 2019) such as Ie Seu'um (Bahri *et al*., 2023), Ie Jue (Aprianto *et al*., 2023) and Jaboi Geothermal areas in Sabang (Idroes *et al*., 2021). These regions are defined by active geothermal features, including fumaroles, hot springs, and volcanic activity, indicating the presence of substantial underground heat sources (Maulydia *et al*., 2024a). The Seulawah Geothermal area, located near the Seulawah Agam volcano, is considered one of the most promising sites for geothermal energy development in Aceh due to its high temperature geothermal reservoirs (Lala *et al*., 2024). The Jaboi Geothermal region located in Sabang has demonstrated significant potential, as research suggests it may be utilized for electricity generation (Rahman *et al*., 2024) as well as for direct use applications (Azhar *et al*., 2024). Together, these geothermal sites represent a critical opportunity for sustainable energy development in Aceh (Marwan *et al*., 2023), providing an eco-friendly alternative to fossil fuels and also enhances

energy security in the area (Marwan *et al*., 2023). The geothermal manifestations in this region, such as fumaroles and solfataras, indicate significant geothermal activity (Maulydia *et al*., 2024b). Located in Gayo Lues, Aceh, Mount Kembar is an area with substantial geothermal potential that has yet to be fully explored. Based on initial hypotheses, this region is believed to contain heavy metals such as lead (Pb), cadmium (Cd), copper (Cu), chromium (Cr), iron (Fe), and zinc (Zn). These heavy metals can pose environmental risks, particularly to people living around the Mount Kembar geothermal area, who may be exposed to heavy metals by consuming contaminated water. The exploration of heavy metal concentrations in geothermal water and their environmental implications is notably underdeveloped. This is a matter of considerable concern, as the presence of heavy metals can result in serious health hazards for humans and contribute to environmental deterioration if not managed appropriately. Additional research is required to better understand the distribution and concentration of heavy metals in this region and their effects on the local ecosystem. The aim of the present study is to measure and analyze the concentrations of heavy metals such as Pb, Cd, Cu, Cr, Fe, and Zn in the geothermal water of the Mount Kembar Region, while assessing the potential environmental impacts of these contaminants on the local ecosystem and communities. This study aims to generate significant scientific information that can enhance the management and sustainable utilization of geothermal resources, with an emphasis on mitigating the environmental and health hazards associated with heavy metals. By studying a geothermal region that has not been thoroughly explored, the study aims to contribute to the broader understanding of heavy metal content in geothermal environments, supporting more effective environmental management practices. This research took place in Aceh Province, Indonesia, in 2024.

MATERIALS AND METHODS

Tools and materials

A thermo scientific iCE 3000 series atomic absorption spectrometer (AAS) in flame mode served as the main instrument for analyzing heavy metal concentrations in geothermal water samples. This instrument was selected due to its ability to accurately measure the concentrations of multiple heavy metals, including Pb, Cd, Cu, Cr, Zn, and Fe. The supporting equipment included a precision balance for accurate sample preparation, a temperature-controlled hotplate for sample preservation, and various glassware items such as beakers, flasks, and pipettes. All chemicals, including nitric acid (HNO_3) and standard solutions for the target metals, were supplied by E. Merck.

Sampling technique

Water samples were collected from five geothermal manifestation points in the Mount Kembar Region, Gayo Lues Regency, Aceh Province, Indonesia, with the coordinates being MK1: 3°46’21” N, 97°35’13” E; MK2: 3°46’19” N, 97°35’13” E; MK3: 3°45’02” N, 97°37’35” E; MK4: 3°45’02” N, 97°37’36” E; and MK5: 3°45’03” N, 97°37’37” E included in Table 1 and illustrated in Fig. 1. The collection of samples was performed with plastic scoops, and these samples were then transferred into polyethylene (PE) bottles that had been pre-cleaned and rinsed first with nitric acid and then with the sample water. The potential of hydrogen (pH) of the samples was adjusted to below 2 with nitric acid to prevent metal precipitation or degradation. They were then kept in a cooler box at 4 ± 2 degrees Celsius (°C) and taken to the laboratory for analysis (BSN, 2004).

Table 1: The water collection sites in the Mount Kembar *Region*

Code	Locations	Coordinate
MK1	Mount Kembar 1	3° 46' 21" N; 97° 35' 13" E
MK2	Mount Kembar 2	3° 46' 19" N; 97° 35' 13" E
MK3	Mount Kembar 3	3° 45' 02" N; 97° 37' 35" E
MK4	Mount Kembar 4	3° 45' 02" N; 97° 37' 36" E
MK5	Mount Kembar 5	3° 45' 03" N; 97° 37' 37" E

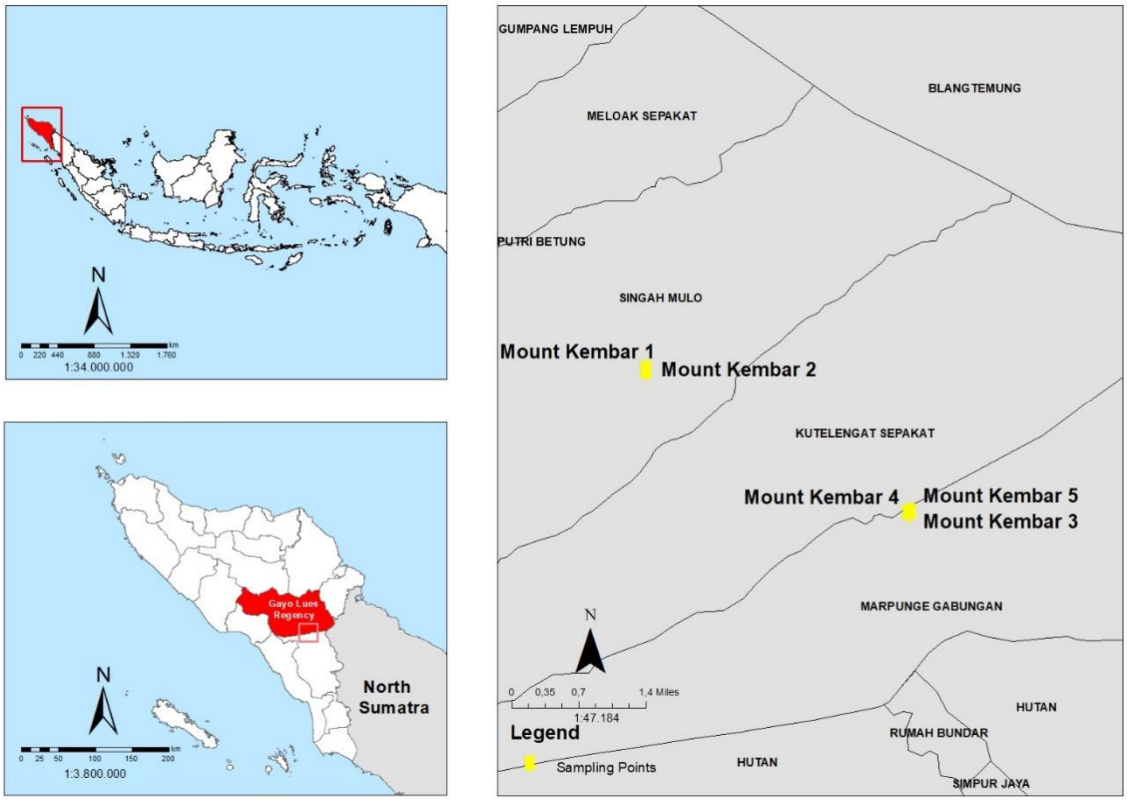


Fig. 1: Geographic position of the study area within the geothermal manifestation of Mount Kembar, located in Gayo Lues Regency, Aceh Province, Indonesia

Sample preparation

The water samples, upon their reception in the laboratory, were subjected to filtration through Whatman No. 42 filter paper to eliminate suspended particulates. The filtered samples were transferred into volumetric bottles for heavy metal analysis using flame atomic absorption spectroscopy FAAS. This filtering step was critical to ensure that only dissolved metals were measured in the analysis (BSN, 2004).

Heavy metal analysis

Flame FAAS was used to quantify the concentrations of six heavy metals. For each metal, calibration standards were formulated from certified stock solutions that have predetermined concentrations. The calibration curve was constructed for each metal using seven different concentration levels, ensuring accuracy across a wide range of metal concentrations prior to the analysis of the samples, the FAAS instrument underwent calibration with standard solutions, and each sample was analyzed in triplicate to guarantee accuracy. The concentrations of the heavy metals were expressed in milligram per liter (mg/L). The FAAS method was validated to confirm the accuracy, precision, linearity, and sensitivity of the measurements. To evaluate the reliability of the method in detecting trace amounts of heavy metals, the limit of detection (LoD) and limit of quantification (LoQ) for each metal were also established (Kassim *et al.*, 2022).

Method validation

The method was validated to confirm the accuracy and consistency of the measurements (Idroes *et al.*, 2024c). The verification of heavy metal concentrations in geothermal water samples requires the application of multiple critical laboratory methods to ensure both accuracy and reliability in

Table 2: The method for calculating measurement uncertainty

Name	Formula	Sources
Standard deviation (SD) of regression (Sr)	$S_r = \sqrt{\frac{S_{yy} - m^2 S_{xx}}{N-2}}$	(Christian *et al.*, 2013)
SD of slope (Sm)	$S_m = \sqrt{\frac{S_y^2}{\sum(X - X_i)}} = \sqrt{\frac{S_y^2}{\sum x_i^2 - (\sum X_i)^2/N}}$	
SD of intercept (Sb)	$s_b = s_y \sqrt{\frac{s_y \sum x_i^2}{N \sum x_i^2 - (\sum x_i)^2}} = s_y \sqrt{\frac{1}{N - \frac{(\sum x_i)^2}{\sum x_i^2}}}$	
SD of the concentration (Sc)	$S_c = \frac{S_i}{m}\sqrt{\frac{1}{M} + \frac{1}{N} + \frac{(Y_c - Y_{ave})^2}{m^2 S_{xx}}}$	
LoD	$\text{LoD} = 3.3 \times \frac{S_r}{\text{slope}}$	
LoQ	$\text{LoQ} = 10 \times \frac{S_r}{\text{slope}}$	

the results obtained. Atomic absorption spectroscopy (AAS) is utilized to measure the concentrations of metals, with calibration achieved through standard solutions of known concentrations. Calibration curves are constructed for each metal, showing strong linearity with R^2 values above 0.99. The assessment of recovery rates (%Recovery) is conducted through the analysis of spiked samples, in which specific amounts of metals are introduced, serving to confirm the method's precision. The sensitivity of the method, especially for trace metal detection, is determined by key parameters like the LoQ and LoD. The verification of precision is achieved through the repetition of measurements, while the estimation of method uncertainty incorporates potential errors. This validation framework ensures accurate, reliable measurements of heavy metals in geothermal water samples (Christian *et al.*, 2013). The corresponding equations are provided in Table 2.

Determination of the concentration

Standard deviation (SD) values and statistical data represented the uncertainty in the concentration measurement for each parameter. The dataset was utilized to conduct a linear regression analysis employing the least squares method (LINEST) in Microsoft Excel, aiming to determine the optimal line of fit for the provided data. These calculations yielded statistical outputs, including the regression standard deviation (Sr), coefficient of determination (R), slope (m) along with its standard deviation (Sm), intercept (b) with its standard deviation (Sb), and the concentration standard deviation (Sc) (Christian *et al.*, 2013). Table 2 provides a comprehensive overview of the equations employed for determining the standard deviation and other statistical functions.

RESULTS AND DISCUSSION

The in situ examination of water samples included measuring various parameters, such as temperature, salinity, total dissolved solids (TDS), pH, and electrical conductivity (EC) (Andres *et al.*, 2018). The specified parameters yield essential insights into the chemical and physical characteristics of water, facilitating the evaluation of its quality and appropriateness for diverse applications, including potable use, agricultural irrigation, and industrial purposes. The pH level indicates the acidity or alkalinity of the water, while TDS refers to the concentration of dissolved particles. Electrical conductivity (EC) is closely related to TDS, reflecting the water's ability to conduct electricity, which increases with higher ion concentrations (McCleskey *et al.*, 2023). The influence of temperature on other environmental variables is substantial, whereas salinity provides a measurement of total salt content, which is a key indicator for determining water quality in both freshwater and marine environments (Paepae *et al.*, 2021). The results from this comprehensive in situ analysis, which offer a detailed snapshot of the water's condition at the time of sampling, are presented in Table 3. This table consolidates the values recorded

Table 3: On-site data from water samples gathered in the field

Code	T ± SD (◦C)	pH ± SD	EC ± SD Microsiemens per centimeter (µS/cm)	TDS ± SD (mg/L)	Salinity ± SD (‰)
MK1	38.54 ± 0.080	6.30 ± 0.0080	2.43 ± 0.01	386 ± 1.60	0.91 ± 0.030
MK2	45.80 ± 0.008	5.71 ± 0.0008	2.89 ± 0.01	326 ± 0.70	1.39 ± 0.008
MK3	53.76 ± 0.020	6.65 ± 0.0040	3.75 ± 0.01	2083 ± 1.14	1.50 ± 0.007
MK4	87.42 ± 0.140	6.34 ± 0.0040	4.67 ± 0.01	4046 ± 0.40	2.49 ± 0.008
MK5	89.59 ± 0.08	6.26 ± 0.0010	4.77 ± 0.02	4062 ± 0.90	2.59 ± 0.008

for each parameter, thereby enabling comparisons across diverse samples or locations and illuminating potential environmental or contamination-related issues.

The analysis of water samples from five geothermal points (MK1 to MK5) at Mount Kembar in Table 3 reveals variations in critical parameters such as temperature, pH, electrical conductivity (EC), total dissolved solids (TDS), and salinity. The recorded temperatures varied between 38.54°C and 89.59°C, substantially surpassing the acceptable limits for potable water, which suggests considerable geothermal activity in the area. The pH levels were slightly acidic at most points, with values between 5.71 and 6.65, except for MK3, which met the minimum standard of 6.5 outlined in Regulation of the Minister of Health No. 492/2010 for drinking water (Kementerian Kesehatan, 2010). Electrical conductivity showed significant mineral presence, especially at MK4 and MK5, further confirmed by the high TDS values, which ranged from 326 mg/L at MK2 to over 4000 mg/L at MK5. According to Regulation of the Minister of Health No. 492/2010, the maximum acceptable TDS for drinking water is 500 mg/L, meaning only MK1 and MK2 meet this requirement. The elevated TDS and salinity values, particularly at MK3, MK4, and MK5, suggest high mineral content, possibly from geothermal processes, making the water unsuitable for direct human consumption without treatment. Further corroboration is found in the elevated salinity levels, with MK5 demonstrating a concentration of 2.59 percent (%), indicative of a considerable amount of dissolved salts. While the water from MK1 and MK2 may have the potential for limited use after treatment, the remaining points would require extensive purification. Notwithstanding this, the geothermal properties identified suggest a promising opportunity for energy generation or various industrial uses, thereby necessitating additional investigation and evaluation of this resource. In geothermal regions like Mount Kembar, geothermal water, often containing elevated levels of heavy metals such as Pb and Cd, can flow into rivers used by local communities for drinking and daily activities. This contamination poses serious health risks, including neurological and kidney damage. The study emphasizes the necessity for persistent monitoring and the implementation of effective water treatment strategies to avert exposure to heavy metals.

Uncertainty measurement

Critical factors in establishing the accuracy and reliability of the analytical method include the linearity and uncertainty of the calibration curve. The calibration curve establishes a quantitative correlation between the response of the instrument and the concentration of the analyte. The linearity of the calibration curve for each metal ion was evaluated by calculating the slope, intercept, and coefficient of determination (R^2). To gain a clearer understanding of the method's precision, uncertainties pertaining to the slope and intercept were assessed. The following table summarizes the slope, intercept, SD of the slope and intercept, coefficient of determination (R^2), SD of regression, sum of squares regression, and sum of square residual for six metal ions: Cd, Pb, Cu, Cr, Zn, and Fe (Table 4).

The results in Table 4 demonstrate that the calibration curves for all the analyzed metals (Cd, Pb, Cu, Cr, Zn, and Fe) exhibit excellent linearity, as reflected by high R^2 values above 0.99, indicating a strong correlation between instrument response and analyte concentration. The slope values exhibit variability among the different metals, indicating distinct levels of sensitivity. The intercepts are close to zero, suggesting minimal response at zero concentration and further validating the accuracy of the calibration model. The uncertainties in both the slope and intercept, as represented by their SDs, are

Table 4: The calibration curve heavy metal standards

Name	Results					
	Cd	Pb	Cu	Cr	Zn	Fe
Slope	0.0575	0.0323	0.0973	0.0519	0.0421	0.0529
Intercept	0.0007	-0.0014	-0.00003	0.00002	0.00002	-0.000002
SD of slope (Sm)	0.0005	0.0015	0.0010	0.0003	0.0008	0.0007
SD of Intercept (Sb)	0.0004	0.0011	0.0008	0.0002	0.0006	0.0005
Coefficient of determination (R^2)	0.9998	0.9935	0.9997	0.9999	0.9990	0.9995
SD of regression (Sr)	0.0004	0.0013	0.0009	0.0002	0.0007	0.0006
Sum of square regression	13369.0558	461.7802	9045.9556	34457.6491	3128.6964	5881.4812
Sum of square residual	3.0000	3.0000	3.0000	3.0000	3.0000	3.0000

Table 5: Detection and quantification limits of heavy metals

Parameter	Heavy metals (mg/L)					
	Cd	Pb	Cu	Cr	Zn	Fe
LoD	0.021	0.113	0.026	0.013	0.043	0.032
LoQ	0.064	0.343	0.077	0.040	0.132	0.096

minimal, reflecting the precision and consistency of the method. The sum of square regression values being much higher than the sum of square residuals confirms that most variations in the data are well-explained by the regression model. Overall, the data demonstrate that the calibration curves are dependable, showing low levels of uncertainty, which reinforces the robustness of this method for the accurate detection and quantification of the designated metal ions.

Limit of detection and limit of quantification

The LoD and limit of quantification LoQ are key factors in evaluating the sensitivity of an analytical technique. The LoD represents the minimum concentration of a substance that can be detected with confidence, even if it cannot be accurately measured. Conversely, LoQ specifies the minimum concentration that can be accurately and precisely measured. These limits are important for evaluating the method's capacity to detect and quantify trace levels of heavy metals in samples. The LoD and LoQ were determined for six heavy metals: Cd, Pb, Cu, Cr, Zn, and Fe, as presented in Table 5.

The results in Table 5 demonstrate the detection limits (LoD) and quantification limits (LoQ) for six heavy metals, where chromium (Cr) shows the lowest values at 0.013 mg/L for LoD and 0.040 mg/L for LoQ, highlighting the method high sensitivity in detecting and quantifying Cr at low concentrations. Conversely, Pb exhibits the highest LoD and LoQ values, at 0.113 mg/L and 0.343 mg/L, indicating that higher concentrations of Pb are required for reliable detection and quantification. These findings imply that the method is adequately sensitive for identifying and measuring trace concentrations of heavy metals, with sensitivity varying according to the specific type of metal analyzed. The LINEST function in Microsoft Excel was used to calculate the LoD and LoQ values, based on calibration curve data, ensuring an accurate assessment of the method's sensitivity and precision for detecting and quantifying the heavy metals at low concentrations.

Precision and accuracy

The assessment of the analytical method's precision and accuracy was conducted by examining the percentage recovery (% Recovery) and the relative standard deviation (RSD) for the analyzed heavy metals. The results imply that the method demonstrates a high degree of sensitivity for both the detection and quantification of trace amounts of heavy metals, with sensitivity levels differing based on the specific metal analyzed. Table 6 presents the %Recovery and RSD values for the six heavy metals (Pb, Cd, Cu, Cr, Zn, Fe).

As shown in Table 6, the %Recovery for the samples, which were spiked with 30 µg/L standard solutions of

Fe, Cr, Cd, Zn, Pb, and Cu, fell within the acceptable range of 70–125%. This indicates that the preparation method used for the samples is appropriate for analyzing these metals. Precision testing with 30 µg/L standard solutions for Cd, Pb, Cu, Cr, Zn, and Fe demonstrated high precision, with a RSD of less than 2% for each metal.

Heavy metals analysis in water samples

The concentrations of Fe, Cr, Cd, Zn, Pb, and Cu in water samples collected from the geothermal manifestation area of Mount Kembar, Aceh, were assessed using the validated method. The analysis revealed that Fe, Cr, Cd, Zn, Pb, and Cu were present in all the water samples at different levels (as shown in Table 7).

The concentrations of heavy metals, namely Pb, Cd, Cu, Cr, Fe, and Zn, found in water samples from five sites (MK1 to MK5) in the geothermal area of Mount Kembar are summarized in Table 7. The measured concentrations were compared to the Clean Water Quality Standards and Drinking Water Quality Standards specified in the Regulation of the Minister of Health of the Republic of Indonesia No. 32/2017 (Kementerian Kesehatan, 2017). The analysis revealed that lead and cadmium levels in most of the samples exceeded the allowed limits for both clean and drinking water, with MK5 showing the highest concentrations of Pb (0.1408 ± 0.178 mg/L) and Cd (0.0126 ± 0.007 mg/L), highlighting a significant health risk if consumed without proper treatment. In contrast, the levels of copper, chromium, iron, and zinc were found to be within the permissible limits for drinking water quality. Copper levels, ranging from 0.0065 ± 0.009 mg/L to 0.0126 ± 0.009 mg/L, were well below the maximum allowable limit of 2 mg/L. Similarly, zinc concentrations remained safely under the three mg/L limit for drinking water, with the highest concentration recorded at MK5 (0.0353 ± 0.012 mg/L). Chromium levels across all samples were lower than the drinking water limit of 0.05 mg/L, although MK5 approached this threshold with a concentration of 0.0420 ± 0.004 mg/L. Iron concentrations, while under the drinking water limit of 0.3 mg/L, were highest at MK5 (0.0662 ± 0.012 mg/L), requiring periodic monitoring. A limitation of this study is the use of Flame FAAS for heavy metal analysis. Despite its effectiveness, FAAS is not as sensitive or precise as more advanced analytical techniques, including Inductively coupled plasma optical emission spectroscopy (ICP-OES). ICP-OES could provide more accurate detection of trace metals, offering a broader and more detailed analysis (Hossain *et al*., 2021). Future research would benefit from utilizing ICP-OES to achieve greater precision in assessing contamination levels. The evidence presented in this study suggests that geothermal water from the Mount Kembar Region is not safe for

Table 6: Heavy metal with precision (RSD) and accuracy (recovery) values

Sample	Recovery(%)	RSD
Pb	99.67	0.78
Cd	99.16	0.48
Cu	99.88	0.26
Cr	100.11	0.85
Zn	100.03	0.66
Fe	99.98	0.33

Table 7: Heavy metals concentrations in geothermal water samples

Code	(Pb) Concentration (mg/L) ± Sc	(Cd) Concentration (mg/L) ± Sc	(Cu) Concentration (mg/L) ± Sc	(Cr) Concentration (mg/L) ± Sc	(Fe) Concentration (mg/L) ± Sc	(Zn) Concentration (mg/L) ± Sc
MK1	0.0914 ± 0.109	0.0000 ± 0.0000	0.0085 ± 0.009	0.0170 ± 0.004	0.0303 ± 0.008	0.0258 ± 0.012
MK2	0.1068 ± 0.130	0.0039 ± 0.007	0.0065 ±0.009	0.0228 ±0.004	0.0397 ±0.009	0.0163 ± 0.012
MK3	0.1223 ± 0.152	0.0074 ± 0.007	0.0096 ±0.009	0.0362 ±0.004	0.0265 ±0.009	0.0234 ±0.012
MK4	0.1099 ± 0.135	0.0057 ± 0.007	0.0075 ±0.009	0.0266 ±0.004	0.0624 ±0.011	0.0281 ±0.012
MK5	0.1408 ± 0.178	0.0126 ± 0.007	0.0126 ±0.009	0.0420 ±0.004	0.0662 ±0.012	0.0353 ±0.012

direct human consumption, owing to the concerning levels of lead and cadmium detected. These metals are known to cause severe health issues, including neurological impairments and kidney damage, particularly when consumed over prolonged periods. The significant levels of these hazardous metals emphasize the pressing requirement for swift intervention, necessitating the establishment of robust water treatment solutions and extensive monitoring frameworks. Continuous surveillance of water quality in the region is essential to mitigate the health risks posed by heavy metal contamination. While metals like copper, chromium, zinc, and iron were within safe drinking limits, elevated levels of lead and cadmium are likely due to geothermal activity mobilizing these toxic metals into surface water. A frequent concern in areas with significant geothermal activity is the potential for interactions with the Earth's crust to result in the emission of harmful contaminants. Geothermal fluids can cause corrosion, requiring effective management, while impact assessments often overlook health risks and long-term community effects, highlighting the need for more thorough evaluations (Rotich *et al.*, 2024). Potential mitigation strategies include advanced filtration techniques like ion exchange and reverse osmosis, which are effective but can be costly and resource-intensive. Innovative alternatives such as nanotechnology-based filtration using graphene oxide for more efficient removal, and electrocoagulation, which uses electrical currents to precipitate metals, offer promising solutions with reduced waste and energy demands. Phytoremediation, an environmentally friendly approach that uses plants to absorb heavy metals, provides a cost-effective option for regions with limited infrastructure. Employing a combination of these technologies could lead to improved sustainability and effectiveness in water management within geothermal zones. The observed variations in metal concentrations at different sampling sites imply that geological factors, such as the diversity in mineral composition and the routes taken by geothermal fluids, may substantially affect the distribution and levels of heavy metals present in the water. Addressing these concerns will require a nuanced approach, taking into account both the geothermal processes and the geological diversity of the region. It is equally important to consider the economic and logistical feasibility of the proposed solutions. The formulation of targeted water management strategies necessitates a careful equilibrium between technical efficacy, cost-effectiveness, and practical execution. This approach aims to secure the long-term safety of the local water supply while ensuring that the methods employed are both sustainable and economically feasible for the region.

CONCLUSION

This study successfully achieved its primary objective of evaluating and validating the concentrations of heavy metals in geothermal water from the Mount Kembar Region, with a particular focus on Pb, Cd, Cu, Cr, Fe, and Zn. The analytical method developed for this purpose demonstrated excellent accuracy and precision, with strong linearity ($R^2 > 0.99$), ensuring its reliability for detecting and quantifying these metals in geothermal water samples. The findings indicated that the concentrations of copper, chromium, zinc, and iron fell within the acceptable standards for drinking water; however, the levels of lead and cadmium surpassed the permissible thresholds. This raises significant public health concerns, as exposure to elevated levels of lead and cadmium is associated with serious health risks, including neurological damage and kidney dysfunction. The results highlight the urgent necessity for prompt water treatment measures and continuous surveillance to mitigate the health hazards associated with heavy metal pollution in the area. The method's exceptional sensitivity, particularly in detecting even trace amounts of chromium, provides a valuable advantage for early contamination detection in geothermal environments. This makes the method a powerful tool for environmental monitoring and ensures that harmful levels of metals can be identified promptly. This study presents a validated and highly sensitive method for detecting heavy metals in the relatively underexplored Mount Kembar Region, offering important new insights into the environmental quality of geothermal waters in Aceh Province. The region exhibits considerable geothermal potential that has not been fully harnessed, highlighting the importance of precise evaluations of water quality for the sustainable advancement of its geothermal resources. The study suggests that the elevated levels of lead and cadmium are likely linked to local geothermal activity, which may release these toxic

metals from underground reservoirs into surface water systems. Variations in metal concentrations across different sampling sites suggest that geological factors could be influencing the distribution of these contaminants in the region. Moving forward, future research should prioritize continuous, long-term monitoring of geothermal water quality, particularly in areas with high geothermal activity. Engaging in these monitoring activities would yield valuable insights into the temporal dynamics of heavy metal contamination, ultimately advancing our comprehension of the potential health risks faced by local populations. It is crucial to develop advanced water treatment technologies specifically designed to address the unique challenges of heavy metal contamination in geothermal waters, ensuring both public health protection and the sustainable, safe utilization of geothermal resources in the region. These technologies will play a vital role in promoting environmentally responsible geothermal energy development, aligned with the broader goals of sustainable resource management. Local authorities are required to implement forward-thinking actions to address the risks posed by geothermal activity on water resources. This approach is crucial for safeguarding public health and promoting sustainable development initiatives.

AUTHOR CONTRIBUTIONS

G.M. Idroes contributed to manuscript preparation, conducted data analysis, and interpreted the results. D.P. Rezeki also performed data analysis and assisted with writing the manuscript. K. Khairi was responsible for creating figures and interpreting the results. K. Khairan prepared figures, interpreted results, and contributed to writing the manuscript. R. Idroes participated in result interpretation and manuscript preparation. E. Suhartono contributed by preparing figures and interpreting results. R. Prasetio participated in preparing the manuscript and interpreting the results. S.A. Rahman was involved in figure preparation, result interpretation, and manuscript writing. S. Suhendrayatna, the corresponding author, contributed to manuscript preparation, supervised data analysis, and interpreted the results.

ACKNOWLEDGEMENT

This study was funded by Direktorat Riset, Teknologi, dan Pengabdian Kepada Masyarakat, Direktorat Jenderal Pendidikan Tinggi, Riset, dan Teknologi, Kementerian Pendidikan, Kebudayaan, Riset, dan Teknologi and Universitas Syiah Kuala through "Penelitian Disertasi Doktor" scheme with grant number [094/E5/PG.02.00.PL/2024].

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

OPEN ACCESS

©2024 The author(s). This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third-party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit: http://creativecommons.org/licenses/by/4.0/

PUBLISHER'S NOTE

GJESM Publisher remains neutral with regard to jurisdictional claims in published maps and institutional afflictions.

ABBREVIATIONS

%	Percent
^{o}C	Degree Celsius
µg/L	Micrograms per liter
µS/cm	Microsiemens per centimeter (Unit of conductivity)

AAS	Atomic absorption spectroscopy
Cd	Cadmium
Cr	Chromium
Cu	Copper
EC	Electrical conductivity
FAAS	Flame atomic absorption spectroscopy
Fe	Iron
MK	Mount kembar (Sampling point code)
HNO_3	Nitric Acid
LINEST	Regression analysis using the least squares method
LoD	Limit of detection
LoQ	Limit of quantification
mg/L	Milligrams per liter
Pb	Lead
pH	potential of hydrogen
R^2	Coefficient of determination
RSD	Relative standard deviation
Sb	Standard deviation of intercept
Sc	Standard deviation of concentration
SD	Standard deviation
Sm	Standard deviation of slope
Sr	Standard deviation of regression
Sxx	Sum of squares of the x-values
Syy	Sum of squares of the y-values
T	Temperature
TDS	Total dissolved solids
Zn	Zinc

REFERENCES

Anderson, A.; Rezaie, B., (2019). Geothermal technology: Trends and potential role in a sustainable future. Appl. Energy. 248: 18–34 **(17 pages).**

Andres, L.; Boateng, K.; Borja-Vega, C.; Thomas, E., (2018). A review of in-situ and remote sensing technologies to monitor water and sanitation interventions. Water. 10: 756 **(13pages).**

Androniceanu, A.; Sabie, O.M., (2022). Overview of green energy as a real strategic option for sustainable development. Energies. 15: 8573 **(35 pages).**

Aprianto, A.; Maulana, A.; Noviandy, T.R.; Lala, A.; Yusuf, M.; Marwan, M.; Perucha, R.; Afidh, F.; Irvanizam, I.; Nizamuddin, N.; Idroes, G.M., (2023). Exploring geothermal manifestations in Ie Jue, Indonesia: Enhancing safety with unmanned aerial vehicle. Leuser J. Environ. Stud., 1: 2023 **(8 pages).**

Azarpour, A.; Mohammadzadeh, O.; Rezaei, N.; Zendehboudi, S., (2022). Current status and future prospects of renewable and sustainable energy in north America: Progress and challenges. Energy Convers. Manage. 269: 115945 **(37 pages).**

Azhar, F.; Misbullah, A.; Lala, A.; Idroes, G.M.; Kusumo, F.; Noviandy, T.R.; Irvanizam, I.; Idroes, R., (2024). Evaluating geothermal power plant sites with additive ratio assessment: Case study of Mount Seulawah Agam, Indonesia. Heca J. Appl. Sci., 2: 19–26. **(8 pages).**

Bahri, R.A.; Noviandy, T.R.; Suhendra, R.; Idroes, G.M.; Yanis, M.; Yandri, E.; Nizamuddin, N.; Irvanizam, I., (2023). Utilization of drone with thermal camera in mapping digital elevation model for Ie Seu'um geothermal manifestation exploration security. Leuser J. Environ. Stud. 1: 25–33 **(9 pages).**

Bhagaloo, K.; Ali, R.; Baboolal, A.; Ward, K., (2022). Powering the sustainable transition with geothermal energy: A case study on Dominica. Sustainable Energy Technol. Assess., 51: 101910 **(14 pages).**

BSN, (2004). Air dan air limbah–Bagian 8: Cara uji timbal (Pb) dengan Spektrofotometri Serapan Atom (SSA)-Nyala. SNI 06-6989.8-2004 **(1 page).**

Christian, G.D.; Dasgupta, P.K.; Schug, K.A., (2013). Analytical chemistry. John Wiley and Sons. **(850 pages).**

Darma, S., (2016). Indonesia, in: Geothermal power generation. Elsevier. 609–643 **(35 pages).**

de Jesus, A.C., (2016). Environmental benefits and challenges associated with geothermal power generation, in: Geothermal power generation: Dev. innovation. Elsevier Inc. 477–498 **(22 pages).**

Gutiérrez-Negrín, L.C.A., (2024). Evolution of worldwide geothermal power 2020–2023. Geotherm. Energy. 12: 14 **(60 pages).**

Hardi, I.; Idroes, G.M.; Hamaguchi, Y.; Can, M.; Noviandy, T.R.; Idroes, R., (2024). Business confidence in the shift to renewable energy: A country-specific assessment in major Asian economies. J. Econ. Technol., **(38 pages).**

Hossain, M.; Karmakar, D.; Begum, S.N.; Ali, S.Y.; Patra, P.K., (2021). Recent trends in the analysis of trace elements in the field of environmental research: A review. Microchem. J., 165: 106086 **(18 pages).**

Idroes, Ghalieb Mutig.; Hardi, I.; Hilal, I.S.; Utami, R.T.; Noviandy, T.R.; Idroes, R., (2024a). Economic growth and environmental impact: Assessing the role of geothermal energy in developing and developed countries. Innov. Green Dev., 3: 100144 **(12 pages).**

Idroes, Ghalieb Mutig.; Hardi, I.; Rahman, M.H.; Afjal, M.; Noviandy, T.R.; Idroes, R., (2024b). The dynamic impact of non-renewable and renewable energy on carbon dioxide emissions and ecological footprint in Indonesia. Carbon Res., 3: 35 **(21 pages).**

Idroes, Ghazi Mauer.; Suhendrayatna, S.; Khairan, K.; Suhartono, E.; Prasetio, R.; Riza, M., (2024). Ensuring accuracy: Critical validation techniques in geochemical analysis for sustainable geothermal energy development. Leuser J. Environ. Stud. 2: 19–29 **(11 pages).**

Idroes, R.; Marwan, M.; Yusuf, M.; Muslem, M.; Helwani, Z., (2021). Geochemical investigation on Jaboi manifestation, Jaboi Volcano, Sabang, Indonesia. Int. J. Geomate., 20: 170–185 **(16 pages).**

Idroes, R.; Yusuf, M.; Saiful, S.; Alatas, M.; Subhan, S.; Lala, A.; Muslem, M.; Suhendra, R.; Idroes, G.M.; Marwan, M.; Mahlia, T.M.I., (2019). Geochemistry exploration and geothermometry application in the North Zone of Seulawah Agam, Aceh Besar District, Indonesia. Energies. 12: **(17 pages).**

Islam, M.T.; Nabi, M.N.; Arefin, M.A.; Mostakim, K.; Rashid, F.; Hassan, N.M.S.; Rahman, S.M.A.; McIntosh, S.; Mullins, B.J.; Muyeen, S.M., (2022). Trends and prospects of geothermal energy as an alternative source of power: A comprehensive review. Heliyon. 8: e11836 **(17 pages).**

Kassim, N.S.A.; A. I. S. M. Ghazali, S.; Liyana Bohari, F.; A. Z. Abidin, N., (2022). Assessment of heavy metals in wastewater plant effluent and lake water by using atomic absorption spectrophotometry. Mater. Today Proc. 66: 3961–3964 **(4 pages).**

Kementerian Kesehatan, (2017). Peraturan Menteri Kesehatan Republik Indonesia Nomor 32 Tahun 2017 **(31 pages).**

Kementerian Kesehatan, (2010). Peraturan Menteri Kesehatan Republik Indonesia Nomor 492/MENKES/PER/IV/2010 **(9 pages).**

Kumar, L.; Hossain, M.S.; Assad, M.E.H.; Manoo, M.U., (2022). Technological advancements and challenges of geothermal energy systems: a comprehensive review. Energies. 15: 9058 **(18 pages).**

Lala, A.; Yusuf, M.; Suhendra, R.; Maulydia, N.B.; Dharma, D.B.; Saiful, S.; Idroes, R., (2024). Characterization of geochemical and isotopic profiles in the Southern Zone geothermal systems of Mount Seulawah Agam, Aceh Province, Indonesia. Leuser J. Environ. Stud. 2: 30–40 **(11 pages).**

Letcher, T.M., (2022). Global warming, greenhouse gases, renewable energy, and storing energy, in: Storing Energy. Elsevier. 3–12 **(10 pages).**

Lin, X.-M.; Kireeva, N.; Timoshin, A.V.; Naderipour, A.; Abdul-Malek, Z.; Kamyab, H., (2021). A multi-criteria framework for designing of stand-alone and grid-connected photovoltaic, wind, battery clean energy system considering reliability and economic assessment. Energy. 224: 120154 **(15 pages).**

Lund, J.W.; Huttrer, G.W.; Toth, A.N., (2022). Characteristics and trends in geothermal development and use, 1995 to 2020. Geothermics., 105: 102522 **(10 pages).**

Lund, J.W.; Toth, A.N., (2021). Direct utilization of geothermal energy 2020 worldwide review. Geothermics., 90 **(31 pages).**

Marwan, Isa, M.; Idroes, R.; Nursyafira, Idris, S.; Yanis, M.; Ghani, A.A.; Paembonan, A.Y., (2023). Geoelectrical model of geothermal spring in ie jue seulawah deriving from 2d vlf-em and dc resistivity methods. J. Appl. Eng. Sci., 21: 59–69 **(11 pages).**

Marwan, Syukri, M.; Idroes, R.; Ismail, N., (2019). Deep and shallow structures of geothermal Seulawah Agam based on electromagnetic and magnetic data. Int. J. Geomate. 16: 141–147 **(7 pages).**

Maulidar, P.; Fadila, S.; Hafizah, I.; Zikra, N.; Idroes, G.M., (2024). Enhancing environmental quality: Investigating the impact of hydropower energy consumption on CO_2 emissions in Indonesia. Ekonomikalia J. Econ., 2: 53–65 **(13 pages).**

Maulydia, N.B.; Idroes, R.; Khairan, K.; Tallei, T.E.; Mohd Fauzi, F., (2024a). Ecotoxicological insight of phytochemicals, toxicological informatics, and heavy metal concentration in Tridax procumbens L. in geothermal areas. Global J. Environ. Sci. Manage., 10: 369–384 **(16 pages).**

Maulydia, N.B.; Khairan, K.; Tallei, T.E.; Mohd Fauzi, F.; Idroes, R., (2024b). Analysis of geothermal impact on metabolite compounds of heat-tolerant plant species using clustering and similarity cliff. Global J. Environ. Sci. Manage., 10: 1827–1842 **(16 pages).**

McCleskey, R.B.; Cravotta, C.A.; Miller, M.P.; Tillman, F.; Stackelberg, P.; Knierim, K.J.; Wise, D.R., (2023). Salinity and total dissolved solids measurements for natural waters: An overview and a new salinity method based on specific conductance and water type. Appl. Geochemistry. 154: 105684 **(13 pages).**

Meirbekova, R.; Bonciani, D.; Olafsson, D.I.; Korucan, A.; Derin-Güre, P.; Harcouët-Menou, V.; Bero, W., (2024). Opportunities and challenges of geothermal energy: A comparative analysis of three European Cases—Belgium, Iceland, and Italy. Energies. 17: 4134 **(27 pages).**

Miranda, M.M.; Raymond, J.; Dezayes, C., (2020). Uncertainty and risk evaluation of deep geothermal energy source for heat production and electricity generation in remote northern regions. Energies. 13: 4221 **(35 pages).**

Owebor, K.; Diemuodeke, E.O.; Briggs, T.A.; Imran, M., (2021). Power situation and renewable energy potentials in Nigeria – A case for integrated multi-generation technology. Renew. Energy. 177: 773–796 **(24 pages).**

Paepae, T.; Bokoro, P.; Kyamakya, K., (2021). From fully physical to virtual sensing for water quality assessment: A comprehensive review of the relevant state-of-the-art. Sensors. 21: 6971 **(35 pages).**

Pambudi, N.A., (2018). Geothermal power generation in Indonesia, a country within the ring of fire: Current status, future development and policy. Renew. Sustainable Energy Rev., 81: 2893–2901 **(9 pages).**

Pambudi, N.A.; Ulfa, D.K., (2024). The geothermal energy landscape in Indonesia: A comprehensive 2023 update on power generation, policies, risks, phase and the role of education. Renew. Sustainable. Energy Rev., 189: 114008 **(17 pages).**

Rahman, I.F.; Misbullah, A.; Irvanizam, I.; Yusuf, M.; Maulana, A.; Marwan, M.; Dharma, D.B.; Idroes, R., (2024). Optimizing geothermal power plant locations in Indonesia: A multi-objective optimization on the basis of ratio analysis approach. Infolitika J. Data Sci., 2: 1–8. **(8 pages).**

Rotich, I.K.; Chepkirui, H.; Musyimi, P.K.; Kipruto, G., (2024). Geothermal energy in Kenya: Evaluating health impacts and environmental challenges. Energy Sustainable Dev., 82: 101522 **(9 pages).**

Santos, L.; Dahi Taleghani, A.; Elsworth, D., (2022). Repurposing abandoned wells for geothermal energy: Current status and future prospects. Renew. Energy. 194: 1288–1302 **(15 pages).**

Sayed, E.T.; Wilberforce, T.; Elsaid, K.; Rabaia, M.K.H.; Abdelkareem, M.A.; Chae, K.-J.; Olabi, A.G., (2021). A critical review on environmental impacts of renewable energy systems and mitigation strategies: Wind, hydro, biomass and geothermal. Sci. Total Environ., 766: 144505 **(15 pages).**

Shah, M.; Prajapati, M.; Yadav, K.; Sircar, A., (2024). A comprehensive review of geothermal energy storage: Methods and applications. J. Energy Storage. 98: 113019 **(10 pages).**

Sharmin, T.; Khan, N.R.; Akram, M.S.; Ehsan, M.M., (2023). A state-of-the-art review on geothermal energy extraction, utilization, and improvement strategies: Conventional, hybridized, and enhanced geothermal systems. Int. J. Thermofluids. 18: 100323 **(25 pages).**

Soltani, M.; Moradi Kashkooli, F.; Souri, M.; Rafiei, B.; Jabarifar, M.; Gharali, K.; Nathwani, J.S., (2021). Environmental, economic, and social impacts of geothermal energy systems. Renew. Sustainable Energy Rev. 140: 110750 **(25 pages).**

Zhang, Q.; Chen, S.; Tan, Z.; Zhang, T.; Mclellan, B., (2019). Investment strategy of hydrothermal geothermal heating in China under policy, technology and geology uncertainties. J. Clean. Prod. 207: 17–29 **(13 pages).**

AUTHOR (S) BIOSKETCHES

Idroes, G.M., Ph.D., Candidate, Graduate School of Mathematics and Applied Sciences, Universitas Syiah Kuala, Banda Aceh, 23111, Indonesia.
- Email: *idroesghazi@gmail.com*
- ORCID: 0000-0001-6217-9067
- Web of Science ResearcherID: HSI-2075-2023
- Scopus Author ID: 57201859084
- Homepage: https://usk.ac.id/

Rezeki, D.P., B.Sc., Department of Chemistry, Faculty of Mathematics and Natural Sciences, Universitas Syiah Kuala, Banda Aceh 23111, Indonesia.
- Email: *deaputrii12razekii@gmail.com*
- ORCID: 0009-0007-1837-4464
- Web of Science ResearcherID: NA
- Scopus Author ID: NA
- Homepage: https://usk.ac.id/

Khairi, K., Ph.D., Associate Professor, Department of Chemistry, Faculty of Mathematics and Natural Sciences, Universitas Syiah Kuala, Banda Aceh 23111, Indonesia.
- Email: *khairi@usk.ac.id*
- ORCID: 0000-0001-5366-4423
- Web of Science ResearcherID: NA
- Scopus Author ID: 56524475200
- Homepage: https://fsd.usk.ac.id/khairi/

Khairan, K., Ph.D., Associate Professor, Department of Pharmacy, Faculty of Mathematics and Natural Sciences, Universitas Syiah Kuala, Banda Aceh 23111, Indonesia.
- Email: *khairankhairan@usk.ac.id*
- ORCID: 0000-0003-3028-6022
- Web of Science ResearcherID: GPS-9955-2022
- Scopus Author ID: 37016941000
- Homepage: https://fsd.usk.ac.id/kkh/

Idroes, R., Ph.D., Professor, Department of Pharmacy, Faculty of Mathematics and Natural Sciences, Universitas Syiah Kuala, Banda Aceh 23111, Indonesia.
- Email: *rinaldi.idroes@usk.ac.id*
- ORCID: 0000-0003-2264-6358
- Web of Science ResearcherID: S-8983-2016
- Scopus Author ID: 57192873366
- Homepage: https://fsd.usk.ac.id/rinaldi.idroes/

Suhartono, E., Ph.D. Professor, Department of Medical Chemistry/Biochemistry, Faculty of Medicine, Lambung Mangkurat University, Banjarbaru 70124, Indonesia
- Email: *ekoantioxidant@gmail.com*
- ORCID: 0000-0002-1239-6335
- Web of Science ResearcherID: AAG-9351-2019
- Scopus Author ID: 56951281500
- Homepage: https://brin.go.id/

AUTHOR (S) BIOSKETCHES

Prasetio, R., Ph.D. Researcher, Research Center of Radiation Processing Technology, National Research and Innovation Agency, Puspiptek Serpong, South Tangerang, 15314, Indonesia.
- Email: *rasi.prasetio@brin.go.id*
- ORCID: 0000-0002-6682-653X
- Web of Science ResearcherID: LJL-3979-2024
- Scopus Author ID: 55352219500
- Homepage: https://ulm.ac.id/

Rahman, S.A., Ph.D., Associate Professor, Faculty of Chemical & Process Engineering Technology, Universiti Malaysia Pahang, Lebuhraya Persiaran Tun Khalil Yaakob, 26300 Gambang, Kuantan, Pahang, Malaysia.
- Email: *sunarti@ump.edu.my*
- ORCID: 0000-0003-0986-5548
- Web of Science ResearcherID: NA
- Scopus Author ID: 57218826247
- Homepage: https://www.umpsa.edu.my/en

Suhendrayatna, S., Ph.D., Professor, Department of Chemical Engineering, Faculty of Engineering, Universitas Syiah Kuala, Banda Aceh 23111, Indonesia.
- Email: *suhendrayatna@usk.ac.id*
- ORCID: 0000-0002-2673-0947
- Web of Science ResearcherID: I-7750-2017
- Scopus Author ID: 7409901056
- Homepage: https://fsd.usk.ac.id/suhendrayatna/

HOW TO CITE THIS ARTICLE

Idroes, G.M.; Rezeki, D.P.; Khairi, K.; Khairan, K.; Idroes, R.; Suhartono, E.; Prasetio, R.; Rahman, S.A.; Suhendrayatna, S., (2024). Validation of heavy metals in geothermal to support water management practices and mitigation strategies. Global J. Environ. Sci. Manage., 10(SI): 153-166.

DOI: 10.22034/gjesm.2024.10.SI.10

URL: https://doi.org/10.22034/GJESM.2024.SI.10