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Comparative Study Of Adsorption Materials For Heavy Metal Ion Removal From Industrial Wastewater In Damonjodi

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This paper is aimed towards the effectiveness of red mud, which is an aluminium and other low-cost adsorbents such as fly ash in removing heavy metal ions from wastewater. In the present paper, "Damonjodi", Odisha would be the focus area because increases in industrial activities like that in "Damonjodi" have led to an enhancement in toxic heavy metal content in water bodies and also posed severe ecological and public health dilemmas. Industrial by-products can find applications as the adsorbent, which might be environmental friendly and more economical way for wastewater treatment. A paper discusses here the adsorption experiments from a batch process on removing efficiency concerning red mud and fly ash under different experimental conditions viz. pH contact time dosage of adsorbent as well as the agitation speed. Results show that fly ash is more efficient in the removal of lead ions at near neutral to slightly alkaline pH, whereas red mud has better preference in more complicated wastewater settings due to the capability of multilayer adsorption. This comparative analysis underlines the advantage of each material, giving an insight into their suitability for large-scale industrial wastewater treatment in areas heavily influenced by aluminium processing. These by-products should be beneficially applied in practice so as to advance both solutions to water treatment and a more efficient circular economy: reduction through reuse.

Keywords: Red mud, Fly ash, Heavy metal removal, Wastewater treatment, Environmental remediation, Damanjodi.

1. Introduction

In 2004, as well as the concentration of pollutants in the Nile stream water entering Nigerian exceeded 50 μg. In 2013, the concentrations of heavy metals in the water of the country's "Korotoa" River were documented at 1 μg L one for "cadmium" (Cd), 35 μg L one for lead (Pb), 83 μg L−1 in "chromium" (Cr), and 46 μg L−1 for "arsenic".. The heightened levels of contaminants in surface water, due to their accumulation, biological enlargement, and hazardous impacts, have generated significant concern among both governments and the public. Metallic compounds can derive through sources that are anthropogenic or natural.The primary natural sources predominantly arise from foundation erosion. Human-caused causes include industrial production, fertiliser usage, and waste management. The harvesting of natural resources via mining and processing in factories, together with its subsequent application in agricultural and industrial sectors, has led to elevated concentrations of metallic element[3].

In the region of Yunnan, China, element extraction and manufacturing were the principal causes of the presence of heavy metals in groundwater. In "Manzala Lake", Egypt, for instance, contamination with heavy metals in the water predominantly stemmed from agricultural runoff, drainage of sewage, and industrial waste. Diverse strategies have been implemented to alleviate the origins of heavy metal pollution in aquatic areas.

The phenomena of industrialisation and financial growth have exacerbated the production of "city waste garbage (MSW)" worldwide. In the twenty-first century, handling of "municipal solid waste" (MSW) has emerged as a significant environmental concern, and MSW management remains a considerable ecological challenge. Figure 1 illustrates that "Eastern Asian and Pacific" regions are the leading producers of garbage, succeeded by Latin America. Caribbean region, Eastern and Northern Asian nations, South Asian area, "Middle Eastern and North African countries", and sub-Sahara African states. The global generation of municipal solid waste is anticipated to rise from the current 1.3 billion tonnes to a staggering 2.2 billion tonnes annually (World Bank 2012). The worldwide trash generation rate is projected to rise by around one million tonnes per day as a result of sustained economic expansion. The prevailing circumstances in developing countries are critical owing to the ongoing mismanagement of trash. Despite adequate collection, garbage frequently fails to reach specified disposal locations and is instead disposed of in dispersed, unregulated landfills [7]. Alongside the substantial quantity of controlled dumps, corporate municipal and hazardous materials are occasionally combined and disposed of together, leading to hazardous, toxic conditions due to the mingling of different types of trash.

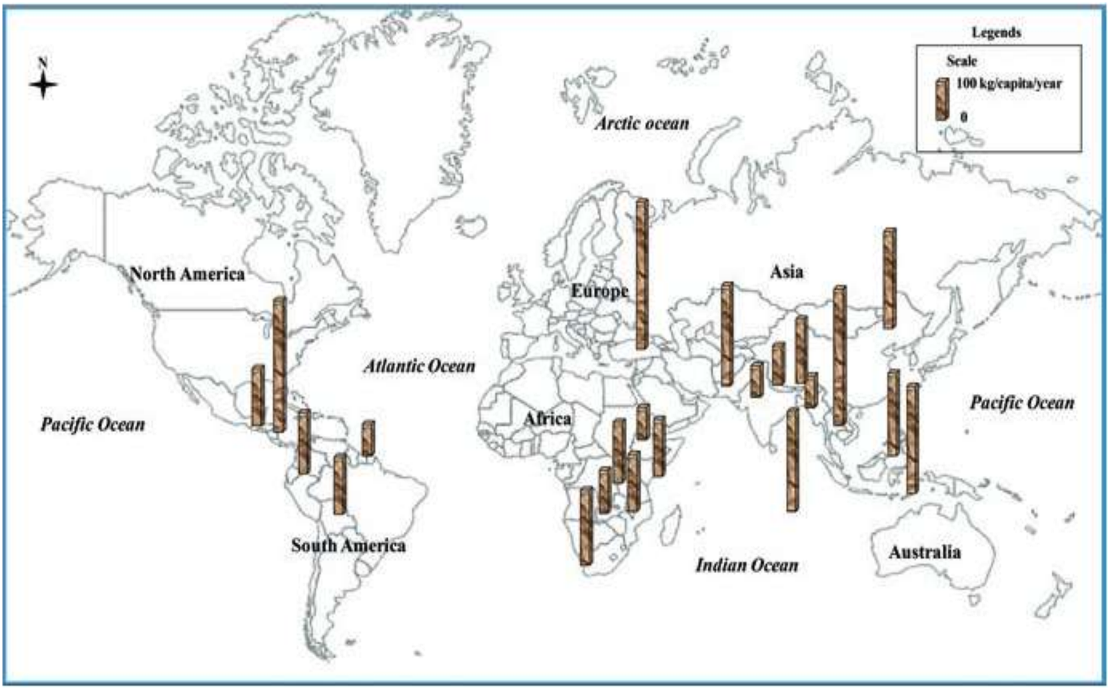


Fig: 1 Global map showing the quantity of annual solid waste generation (in kg/capita/year)

An essential yet frequently overlooked element of "municipal solid waste" disposal in developing nations is the establishment of environmentally sound in-situ waste treatment facilities.

Waste tariffs account for approximately 30–40% of operational expenses, resulting in inadequate resources for capital investments [8-9]. The deficit is financed by allocations from government or municipal budgets. In the absence of initiative implementation, issues of trash disposal will exacerbate. This matter is especially pressing in metropolitan areas with constrained possibilities for landfill expansion. The UN Unit for "Sustainable Human Settlements" (UNCHS) asserts that solid waste management in emerging and underdeveloped countries is among the most inadequately administered services. Unregulated dumping of solid trash (UNCHS; Household Refuse Collected Vehicles for Established Nations; Nairobi 1991).The rising importation of electronic garbage (e-waste) for recycling by numerous Asian and African nations is leading to inadequate management of waste and indiscriminate disposal on refuse in shallow open land areas. To mitigate garbage development in garbage dumps open burning is commonly employed at dumpsites, especially in poor countries, resulting in the emission of dangerous substances such as dioxins,furans, and toxic metals into the atmosphere, consequently jeopardising human health. Increased concentrations of dioxin-like compounds "dl-PCBs" have been detected in the milk from breastfed babies of women living near the the city of Kolkata dumpsite, associated with their fish-based diet [10].

The mud that is red is the solid waste product resulting from the decomposition of "bauxite ores" with "caustic soda" during alumina (Al_2O_3) manufacture. Around between 35 and 40% of processed bauxite ore results in waste in the form of caustic red mud slurry, comprising 15–40% solids, with 0.8–1.5 tonnes of red mud generated every tonne of alumina created [11]. Annually, it is estimated that 70 million tonnes of muddy red is produced globally, including 0.7 million tonnes in Greece, 2 million tonnes in the nation of India, 30 million tonnes in Australia, and over 30 million tonnes in China. Red mud, as a solid waste, is typically disposed of in mud lakes as slurry impoundments or stacked in lagoons as dry mud nearby alumina factories, or it is immediately released via a pipeline into a neighbouring sea. The dumping of substantial amounts of red mud, characterised by fine particles, elevated alkalinity (pH 10–12.5), and trace metal concentration, has resulted in significant environmental issues, notably soil contamination, contamination of ground water, and the suspension of fine particles in marine environments. Furthermore, the deposition of red dirt to lakes or ponds consumes extensive land areas, and preserving of dry crimson mud can result in dust pollution, posing significant health risks to individuals residing near the mud's red storage sites. The expense of red mud removal is significant, representing around 2% of the aluminium price [14]. The alumina pricing in China is approximately US$439 per tonne, resulting in a red mud dumping cost of nearly US$9 every tonne of alumina produced.

Extensive research and development efforts on the storage, disposal, and utilisation of red mud are being conducted globally [15-16]. The research examines the global and Indian dimensions of bauxite production and red mud creation. It delineates the characterisation, disposal, various neutralisation techniques, and applications of red mud. It provides a comprehensive evaluation of the efforts undertaken to utilise red mud in construction, environmental mitigation, and metal recovery. This research examines issues related to the environmental implications of red mud disposal and its potential applications [17]. Environmental compliance standards have grown progressively challenging to meet in the discharge of wastewater and chemical management. Dyes in water alter its characteristics, obstructing sunlight penetration and diminishing the photosynthetic process. Certain dyes are poisonous and potentially cancerous. The traditional techniques for managing dye-laden wastewaters include flocculation, coagulation, reverse osmosis, and active carbon adsorption [18]. These devices exhibit negligible efficacy and economic benefits. Adsorption is the predominant technique for wastewater treatment owing to its simplicity and cost-effectiveness; nevertheless, utilising carbon carbon as adsorbents presents challenges due to the high expenses associated with its use and regeneration. The adsorption method will be a viable technology provided the sorbent is cost-effective and readily available for application [19-20]. The utilisation of corporate recyclables for the sterilisation of sewage from a different industry could benefit both the environment by addressing the disposal of solid waste issue and the economy [21]. Fly ash and red mud, two categories of solid waste, are predominantly generated by power generating and the alumina industry, respectively. Red mud is an unwanted outcome of the "Haber process". For each tonne of alumina generated, about 1 and 2 tonne (dry mass) of red mud byproducts are created. It consists mostly of small fragments of silica, aluminium, calcium, iron, and oxides of titanium and hydroxides. Red mud, owing to its elevated levels of calcium therefore sodium hydroxide, is quite hazardous and presents a significant pollution risk. Recent years have seen extensive research on the application of dark clay for water treatment, particularly in the removal of harmful heavy metals [22-23].

The aim of controlling water quality in industrial applications is to reduce the production of hazardous pollutants, including heavy metals. Numerous industrial operations in the plating sector utilise pollutants for metal finishing, necessitating effluent treatment before disposal [24]. A cost-efficient solution for metals-contaminated sewage is necessary due to increasingly rigorous environmental regulations. While conventional treatments like precipitation of chemicals or flotation can effectively remove heavy metals from organic effluent, each method possesses inherent limitations. Recently, adsorption has emerged as an alternate therapy option [25-26]. Adsorption techniques is a mass transfer process when a substance transitions from its liquid state to the surface of a solid, being affixed through physical or chemical reactions.

Activated carbon, characterised by its extensive surface area, elevated adsorption capacity, and surface reactivity, effectively removes metals like Ni(II) from inorganic wastewater, enabling the treated effluent to comply with rigorous metal discharge criteria in certain countries [27-28]. Nonetheless, the utilisation of carbon-based materials may incur significant expenses. The pursuit of economical adsorbents with metal-binding capabilities has escalated. Locally abundant materials, whether natural substances, agricultural residues, or industrial by-products, can serve as economical adsorbents. Certain materials can serve as adsorbents with minimal preparation. The transformation of these supplies into activated carbon, applicable as an adsorption material for water filtration, would enhance economic value, assisting industry in minimising waste disposal costs and provide a viable substitute for activated carbon [29-30].

Comparative Analysis of Red Mud and Other Adsorbents for Heavy Metal Removal in Damonjodi, Odisha" was a study put in the form of clearly defined objectives to enhance heavy metal removal efficiency from wastewaters, particularly wastewater containing lead, using material efficient and environmental-friendly materials. The aim is essentially to compare and evaluate the adsorption properties of the red mud by-product of the aluminum processing process with other readily available materials such as fly ash. It is, therefore, considered important in comparing the materials for lead ions removal capability under controlled conditions in the laboratory. More critical parameters that may dictate the adsorption properties involve pH, contact time, amount of adsorbent used, and agitation rate. Through research on these variables, the researchers identify what kind of circumstance each material would be most effective at working in.

Fitted recognised isotherms of adsorption models, particularly the "Langmuir model" and the "Freundlich models", on the gathered data.This approach facilitates an in-depth knowledge of the adsorbent behaviours mixed maximum limits of red mud with fly ash of lead removal, thereby establishing a solid foundation for assessing the adsorption efficacy of each material. A primary objective of this research is to evaluate the viability of implementing these adsorbents on a broader scale, especially in industrialised areas like "Damonjodi", while significantly decreasing heavy metal contaminants from wastewater. It subsequently investigates the efficacy of red clay and fly ash as viable adsorbents, so addressing the complexities of waste material management, including the augmentation of environmental advantages through the repurposing of industrial waste for pollution mitigation. This method adheres to environmentally friendly waste reduction principles by converting potentially harmful industrial byproducts into valuable resources for wastewater treatment. The comparing framework of the research is anticipated to assist practitioners and policymakers in understanding the advantages and disadvantages of each adsorbent. Such results are likely to facilitate the selection of cost-effective and efficient options for the removal of heavy metals, hence promoting more efficient and resource-conserving practices in wastewater treatment.

The contrasting study of red mud along with additional adsorbents for eliminating heavy metals in "Damonjodi", Odisha, is significant due to its potential economic and industrial advantages for locations affected by heavy metal pollution from industrial activity.This research is economically significant; it tackles the critical issue of contamination with heavy metals in water, which poses threats to ecosystems, agricultural production, and human health. Lead and other hazardous metals from industrial wastewater can accumulate in aquatic ecosystems, adversely impacting marine life and infiltrating the food chain, hence posing detrimental impacts on wildlife and human health. This study contributes to sustainable wastewater treatment approaches aimed at reducing environmental dangers linked to metal loading by examining cost-effective, easily accessible materials such as red mud and fly ash for the removal of heavy metals.

The study is highly pertinent to companies, especially in regions such as Damonjodi, Odisha, where substantial industrial activities related to aluminium processing produce significant quantities of industrial by-products. The study addresses by-products from aluminium production, specifically red mud and combustion of coal fly ash, by transforming these materials into practical applications. This approach reduces the reliance on costly commercial adsorbents, lowers treatment expenses on an industrial scale, and promotes the recycling of products generated by industrial activities, thereby exemplifying the principles of a circular economy. The outcomes of this study would endorse cleaner production practices, so promoting sustainable growth in industrial regions such as Damonjodi, which confront persistent issues of industrial contamination and waste management. This work seeks to enhance environmental protection and resource efficiency through its model to be utilised in analogous industrial contexts, facilitating the environmentally responsible yet economically feasible removal of toxic metals from wastewater.

2. Literature of Review

Efficiency of Red Mud for Heavy Metal Adsorption

A review by H. Ali et al. (2013) provided an account of several methods for monitoring, managing, and reducing heavy metal pollution and emphasizes the difficulties that come along with the process of risk assessment and selection of proper remediation technology. Site-specific remediation, keeping in view the pollution levels and environmental conditions prevalent at the site, was the successful remediation of contaminated sites. Further, the authors have suggested an integrated approach to fortify the efficacy of the reduction of heavy metal contamination. In a related study, He et al investigated properties and hydration behavior of red mud-based geopolymer materials with the aim of optimized structural properties for construction applications using advanced techniques for analysis of dosage of red mud and SiO2/Na2O ratios. The parameters that influence the performance of adsorption are ion type, concentration, pH, red mud dosage, time, and temperature. The study by Bai et al. (2022) examines the static adsorption of heavy metal pollutants with treated red mud particles. Heavy metal removal preference ranked Pb > Cd > Cu from the solutions at 94.5% at pH 4.3 for Pb, 92.8% at pH 5.0 for Cd, and 78.1% at pH 3.6 for Cu. Yang et al. (2020) state that red mud is thermally treated in the range of 200 to 900 °C. The optimal temperature for the maximum adsorption capacity of 42.64 mg g^{-1} and a surface area of 32.77 m^2 g^{-1} was determined to be 500 °C. The authors affirm that specific sorption is the primary mechanism of Cd(II) removal, which is enhanced by the stability of the treated red mud. Lyu et al. (2021) worked out a hydrothermal procedure through colloidal silica in conjunction with sodium hydroxide for red mud where, in contrast to virgin red mud, about ten times improvement was reported of Pb(II) as regards adsorption, reaching as saturation level up to 551.11 mg/g; adsorption kinetics in general followed pseudo-firstand pseudo-secondorder kinetics with an isotherm studying on monolayer phys adsorption. Characterization techniques proved that there existed lead carbonate; thus, ion exchange and precipitation participated in the mechanism of adsorption. Last, Chen et al. in 2019 work out the potential utilization of red mud and granulated blast furnace slag in the manufacture of geopolymer-based pervious concrete to filter rainwater. Their findings determine the influence of a variable amount of red mud content, mole ratio Na2O/SiO2, and the amount of activator concentration in order to study mechanical characteristics as well as heavy metal ions' adsorption potential. Their results demonstrate that higher red mud content enhances the adsorption of heavy metal ions but reduces compressive strength, indicating the potential of red mud in sustainable construction materials for environmental remediation.

Chemical Modification of Red Mud for Enhanced Performance

Emphasize the various application potential and improvements of red mud in different fields. Recently, Feng et al., 2022 published works on modified red mud via NiO, MnO2, and CuO. The additions of 15 wt% NiO as well as 20 wt% CuO results have shown to enhance performance characteristics of coal combustion where enhancement in CO2 selectivity and carbon capture has a high rate with a supporting structural analysis through XRD and H2-TPR. Joseph et al. (2019) carried out a comprehensive review on the environmental application of red mud, where treatment methods were identified to enhance its properties for wastewater treatment and other industrial applications. Hu et al. (2024) synthesized modified red mud through hydrothermal methods with an increase in surface area up to 280.18 mg/g maximum methylene blue adsorption capacity, indicating it as an eco-friendly adsorbent. Sun et al. (2022) reported on the preparation of binder using red mud and bottom ash from incineration of municipal solid wastes, hydration behavior, and mechanical performance. Wu et al. (2023) attempted to review the filler nature of red mud in resin composites, with possible environmental risks, avenues of improving the properties of the filler, and improvement in performance. Finally, Wu et al. (2018) characterized Ce-doped red mud catalysts that indicated optimal treatments improved significantly the efficiency of denitration and NOx conversion rates, but noted adverse effects of SO2 on catalyst activity.

Environmental and Economic Implications

Taylor et al. (2022) review all available literature related to environmental assessments of open and closed nuclear fuel cycles, from the life cycle assessment to the waste arisings that focus on resource usage within SNF management and resulting environmental impacts due to its radioactive characteristics. Slorach et al. (2019) evaluated various waste management alternatives, and based on the per-tonne sustainability value, incineration is claimed to be the most viable option. On yearly basis of waste treated that might save up to £251 million a year, in addition, anaerobic digestion proved to be one of the best. Considering CO2 equivalent emissions this would reduce 490 kilotonnes a year which is supposed to increase benefit from waste avoidance options. Huang et al. 2017 applied a framework of systems modeling to predict the impacts that AM had on injection molding processes and realized possible cuts from 3% to 5% in primary energy consumption, 4% to 7% for GHG emissions, and lead times from 12% to 60% with potential cuts from 15% to 35% from costs within a cycle over one million, with importance given to integrating economic factors with environmental requirements. D'Agostino et al. (2019) proposed a multi-criteria selection approach with an outcome of 90% less in operational primary energy and a total energy dropbetween 55% to 67% within ten years with the objective that environmental as well as economic criteria shall be applicable to the designing process. Ferraz et al. (2018) studied the use of chicken eggshell waste in calcitic lime production. They found that, although it was slower-reacting because of larger particle size, the calcium oxide from eggshells showed a high reactivity that is comparable to commercial limestone. Another low mobility of REE, Y, and Sc within phosphogypsum stacks had been taken into consideration. Cánovas et al. (2018) pointed out that phosphate minerals can act as hosts of these elements and that possibly fluoride minerals can be linked to the solubility of them. Thus, phosphogypsum might emerge as a secondary source for these valuable elements.

3. Materials and Methods

This part of the research describes the materials used, the experimental setup taken for batch adsorption testing, the use of isotherms of adsorption, and the statistical approaches used in analyzing and verifying the results. Through all these aspects, it forms a complete guide towards the replication of the study, thus allowing the understanding of its methodological approach.

Materials

The two key materials under investigation in this study are red mud and fly ash. These two materials have been chosen primarily because of their availability as industrial by-products and due to the potential for such materials as cost-effective adsorbents for the removal of lead from wastewater. Red mud is a by-product generated from the aluminium production process, particularly through the Bayer process utilized by refineries, which makes it significantly relevant to the industrial region of Damonjodi, Odisha. This substance is alkaline with residual alumina, iron oxides, among other compounds, that may be causing the adsorption properties of this substance. For the purpose of the experiment, red mud samples were taken directly from the local refinery facility at Damonjodi. The samples were treated through a process of preparation steps: drying, grinding, and then sieving. Moisture was removed using a laboratory oven at 105°C, and sieving with a 75-125 µm mesh was done to provide uniform particle sizes for the batch experiments.

Fly ash was the second industrial by-product. Fly ash is the product of a local coal-fired power plant. It has been found to be a promising material for adsorption because it possesses a high surface area and pore structure. This sample was further dried at 105°C and then sieved to be the same as the particle size of red mud; the size is 75-125 µm. This standardization in terms of particle size helps bring out uniformity in their adsorption characteristics while undertaking the experiments. Samples prepared for red mud and fly ash were sealed in sealed jars to prevent any adulteration or absorption of moisture before their usage during experiments.

Experimental Procedure

The batch adsorption method was used in studying the ability of red mud and fly ash to remove lead ions from synthetic wastewater. In this method, synthetic wastewater containing a certain lead ion concentration is mixed in known quantities with adsorbents under controlled test conditions. The batch adsorption tests were conducted in 250 mL conical flasks. These conical flasks ensure proper mixing and reaction conditions. The rotary shaker was set at 150 rpm to maintain constant agitation.

- **Adsorbent Dosage**: Different doses of red mud and fly ash were used to understand the influence of the dosage of adsorbent quantity on the lead removal efficiency. Dosages tested are 0.5 g, 1.0 g, 1.5 g, 2.0 g, and 2.5 g per 100 mL synthetic wastewater.
- **Contact Time**: Batch experiments were conducted at different contact time intervals to study the kinetics of adsorption and identify how long it takes to reach equilibrium. The time periods utilized in a contact time experimentations include 30 minutes, 60 minutes, 90 minutes, 120 minutes, and 150 minutes. The observed equilibrium time was the period showing no increase in lead uptake.
- **pH Range**: pH is one of the most critical elements in adsorption; thus, the study was done with a range of pH conditions, which was shifted to acidic to basic conditions using 0.1 M NaOH or 0.1 M HCl before each experiment and studied at pH 2, 4, 6, 8, and 10. The ideal pH for lead removal based on the maximum observed removal percentage determined for each type of adsorbent used.
- **Agitation Speed**: In other tests, the agitation speed varied in an effort to bring about a total interaction of lead ions and the surface of the adsorbent. The changing speed made use of was 90, 120, 150, 180, and 210 rpm that compares for the same experimental value in order to understand what variable affects adsorption efficacy.

Subsequent to every experiment, the resulting solution underwent filtration to isolate the adsorbent, and the residual quantity of lead ions in the filtrate obtained was assessed via atomic absorption spectra (AAS). Each experiment was conducted thrice to verify data dependability, and the average values were utilised for analysis.

Adsorption Isotherms

The data was applied with two of the most frequent isotherms that have been used to model lead ions adsorption on both red mud and fly ash: Langmuir and Freundlich models. These are the mechanisms and capacities each material shows under different conditions.

$qe = QmaxbCe/1+bCe$

Where:

- Q e q _e q e is the amount of lead adsorbed per unit weight of adsorbent (mg/g),
- Q maxQ_{\text{max}}Qmax represents the maximum adsorption capacity (mg/g),
- Bbb is the Langmuir constant related to the affinity of binding sites (L/mg),
- CeC_eCe is the concentration of lead ions in the solution at equilibrium (mg/L).

  By plotting 1qe\frac{1}{q_e}qe1 versus 1Ce\frac{1}{C_e}Ce1, the constants QmaxQ_{\text{max}}Qmax and bbb can be derived from the slope and intercept, respectively.

Langmuir Isotherm

Assuming that monolayer adsorption occurs on a uniform surface with a finite number of identical sites, it gives the Langmuir model, which is described with the following equation:

$Qe = KfCe1/n$

Taking the logarithmic form, the equation becomes:

Log (qe) = log (K f) + 1nlog (C e) \ log (q _e) = \log(K_ f) + \ frac {1}{n} \log(C_ e) log (qe) = log (K f) + n1log(Ce)

Where:

- KfK_fKf is the Freundlich constant indicative of adsorption capacity (mg/g)(L/mg)^(1/n),
- nnn is a constant representing adsorption intensity.

A plot of log(qe)\log(q_e)log(qe) versus log(Ce)\log(C_e)log(Ce) provides the constants KfK_fKf and 1/n1/n1/n, with KfK_fKf indicating adsorption capacity and nnn showing adsorption favorability (with values between 1 and 10 suggesting favorable adsorption).

Data Analysis

Data analysis was performed to interpret red mud and fly ash for adsorption efficiency under the different conditions. The experimental data obtained were verified in terms of fitting to different isotherm models with the help of statistical approaches to ensure the validity of the data.

Regression Analysis

Regression analysis is done on the linearized versions of both Langmuir and Freundlich isotherms to obtain constants as well as the coefficient of correlation, R2. The higher the R^2 value, the more appropriate will be the selected model, as it fits the data better.

Analysis of Variance

ANOVA was done to determine the significance of experimental variables, namely pH, contact time, and dosage of the adsorbent for lead removal efficiency. In this analysis, various parameters that affect the efficiency of adsorption are identified mostly.

Error Evaluation

The average of the error bars were applied to the data collected during experiments to derive the standard deviation for each experiment. The changes in leads ion adsorption efficiency at varying pH values were consistently of statistical significance and reproducible.

Optimization

Optimization techniques have been used to compare the efficiency of adsorption with varying experimental parameters for identifying the most favorable conditions for lead removal. Both red mud and fly ash as adsorbents had optimum conditions identified in this approach.

With these data analysis procedures, the research aimed to provide a critical evaluation of adsorption behavior and generate a valid comparison of red mud with fly ash concerning lead removal from synthetic wastewater. Careful planning at every stage of materials preparation, the experimental setup, and data analysis helped in making the study more reliable and valid, making this research credible for industrial and environmental applications.

4. Results

The chapter summarizes key results gathered during the study with specific reference to red mud and fly ash which are to be tested for adsorption in the lead removal of water streams. Further probes their fitness for known adsorption models and evaluates how various aspects of experimentation-including the factors of pH, dosage, and contact time-affected the efficiency of percent adsorption. Finally, comparative analysis is given between red mud and fly ash through tables and graphs for proper representation of the data at better depth.

Adsorption Capacity

The adsorption capacity of red mud and fly ash was studied for the removal of lead ions from synthetic wastewater at various experimental conditions. In this process, the initial concentration of lead and the amount of adsorbent were changed to set up the optimal conditions for both materials. The fly ash had a higher adsorption capacity than that of red mud, more so in pH close to neutral or slightly alkaline, thus suggesting that there is possibly a higher attraction of fly ash towards the lead ion at these certain conditions. For example, at pH 8, the percentage removal of lead by fly ash was recorded to be 85% while red mud recorded only about 82%. However, the removal efficiencies of both materials were satisfactory, indicating potential alternatives to more expensive adsorbents.

The increased dosage of each adsorbent would increase the capacity for adsorption because the available active sites for binding lead ions would be in higher numbers. For both red mud and fly ash, an optimal dosage range was identified where the lead removal efficiency peaked and then leveled off at a dosage of more than 2.5 grams per 100 mL of solution. This implies that at this threshold, further additions of the adsorbent material did not enhance the rates of removal, perhaps due to saturation of the adsorption sites.

Isotherm Model Fit

Two adsorption models were used for data analysis: Langmuir and Freundlich isotherms, which could enlighten the mechanisms involved in the adsorption at the surface. They enable the quantification of the lead adsorption capacity of each material.

1. Langmuir Model:

- Q_{text{max}} = 4.464, text{mg/g} Q_{text{max}} = 4.464 , \ext{mg/g} Qmax=4.464mg/g and b = 2.29, text{L/mg} b = 2.29 , text{L/mg} b=2.29L/mg, and R^2=0.9802. It reflects a highly high value of R^2 that might be viewed to be quite closely fitted towards the Langmuir model and shows adsorption to have taken place at the level of monolayer and on an apparently uniform surface.
- Fly ash had a greater adsorption capacity, with QmaxQ_{text{max}}Qmax = 9.4697 mg/g and bbb = 4.6354 L/mg, and R^2 = 0.9936. With a high R^2 value for fly ash, this further proved an even more perfect fit of monolayer adsorption as that found in red mud, implying a more consistent interaction with the surface.

2. Freundlich Model:

    - For red mud was measured to be 1.67, the heterogeneity factor nnn was at 2.226 while the R^2 value recorded was 0.9996. That is really close fit, therefore, implying that the Freundlich model, which presupposes the adsorption surface to be heterogeneous, can better express the behavior of red mud.

In summary, the Freundlich model is applicable to fly ash in which the Freundlich constant was Kf=1.0297 with n=2.22, and R^2 was found to be 0.9948, so again the Freundlich model works well for fly ash albeit with fit slightly lower compared to the Langmuir model.

Both models showed good fit for the data of each of the adsorbents. In the case of fly ash, the Langmuir model performed slightly better than the Freundlich one to indicate monolayer adsorption, but for the red mud, the adsorption surface had to be better represented by the Freundlich model as it depicted a heterogeneous adsorption surface.

pH:

Lead ions adsorption efficiencies by fly ash and red mud proved to depend on the experimental variable, pH. The pH range for optimum removal in both was a slight alkaline to nearly neutral with the optimal pH as 8. At that pH, the removal is at 85% of fly ash and 82% for red mud. Lower pH decreased the percentage removal because hydrogen ions competed for the binding sites available with lead ions and interfered with lead adsorption. In higher pH, the surface charge of adsorption increased, contributing to a high uptake of lead.

Adsorbent Dosage:

For both red mud and fly ash, an increase in dosage of adsorbent from 0.5 g to 2.5 g increased lead removal. More binding sites contributed to higher percentages of lead removal. However, at dosages higher than 2.5 g per 100 mL of solution, adsorption efficiency leveled off. For example, at a dosage of 2.5 g, fly ash removed about 85% of lead, whereas red mud removed about 83%. Increasing the dosage from this point did not produce further significant improvement, which should be attributed to saturation of the binding sites.

Contact Time:

The contact time that was required to reach equilibrium slightly differed between red mud and fly ash. The rate of equilibration by fly ash was faster at about 120 minutes. Red mud, however took a little close to 150 minutes in order to attain similar degrees of lead removal. Adsorption during the initial period was steep and indicated an immediate uptake of lead where available binding sites were utilized. Once equilibration is attained, further adsorption would not be realized, hence indicating that all available sites for adsorption were utilized.

Agitation Speed:

Agitation speed also varied the adsorption efficiency. With agitation speeds of 90 to 210 rpm, the rate of adsorption was increased. In fact, both red mud and fly ash achieved their greatest efficiency at an agitation speed of 150 rpm. This might have optimized contact between the adsorbent particles and lead ions leading to higher adsorption efficiency. Beyond this agitation level of 150 rpm, little improvement in efficiency was found in the case of both materials, meaning that it would be at the highest possible agitation level to attain a maximum level of removal.

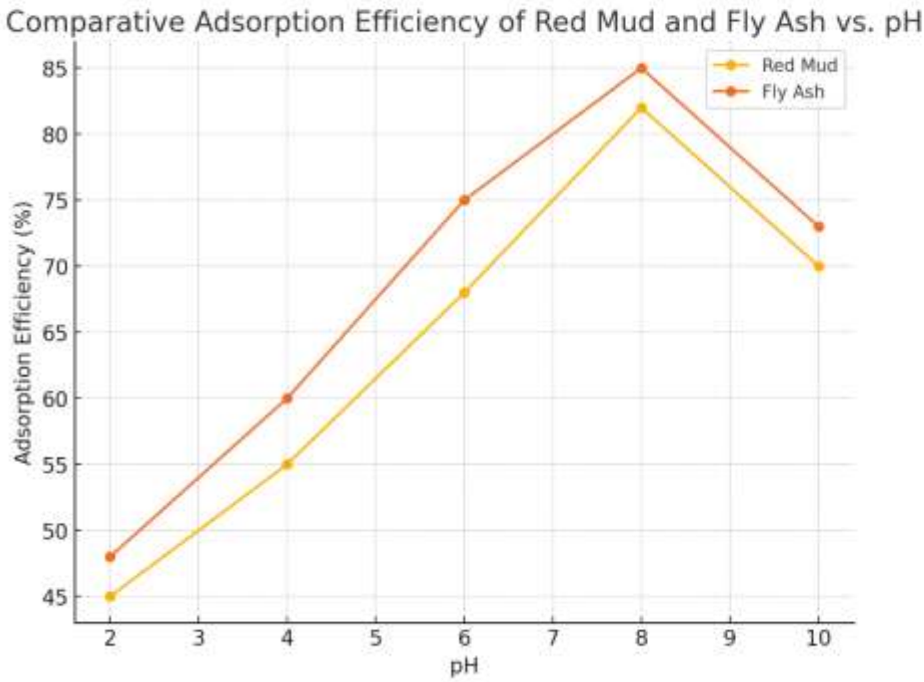
Comparative Performance

To understand and make the comparative performance clearly between red mud and fly ash, several graphs summarizing some of the essential data and trends from experiments have been incorporated. A transparent insight of how either one of these materials will demonstrate strengths as well as potential weaknesses regarding the elimination of lead can be well shown here.

Efficiency vs. pH Advertisement:

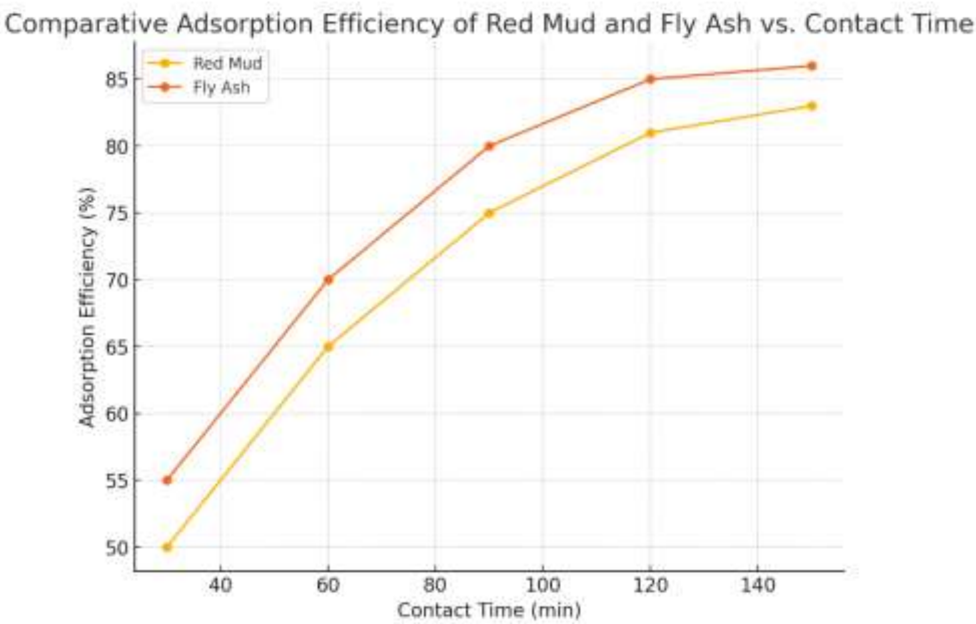
This graph illustrates lead removal efficiencies of red mud and fly ash at different pH levels, and both materials reached maximum efficiency at pH 8.

Adsorption Efficiency vs. Contact Time:



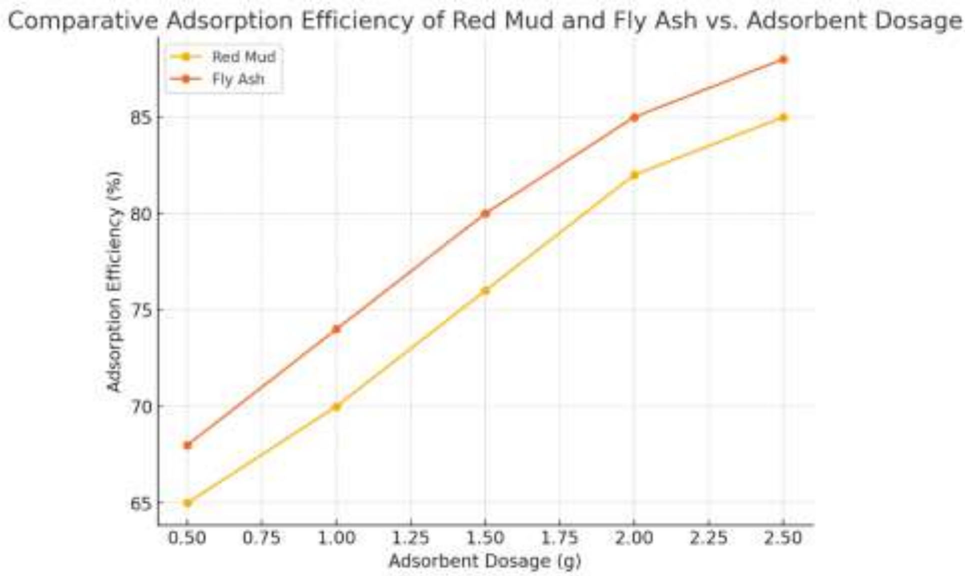
This line graph is used to compare how long each adsorbent requires to reach equilibrium. Comparing the time to achieve equilibrium, fly ash requires less time than red mud to reach equilibrium. Hence, it may be considered superior in time-dependent applications.

Adsorption Efficiency vs. Adsorbent Dosage:



This graph of lead removal efficiency as a function of dosage depicts that the efficiency increases with quantity, and both the materials leveled off at 2.5 g.

Adsorption Efficiency vs. Agitation Speed:



This is the graph showing agitation impact on adsorption efficiency. For this case, optimum speed is 150 rpm for both materials.

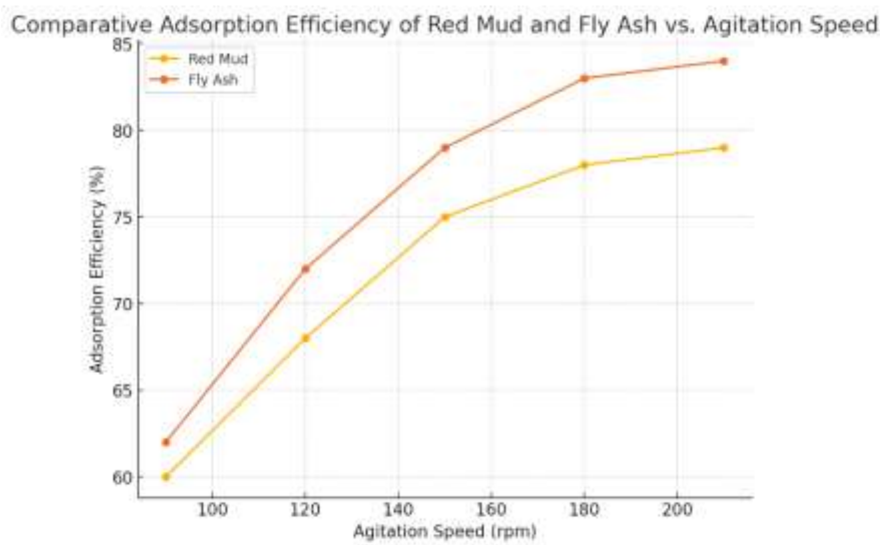


Table of Isotherm Constants:

Adsorbent	Langmuir Q_max (mg/g)	Langmuir b (L/mg)	Langmuir R^2	Freundlich K_f (mg/g)(L/mg)^(1/n)	Freundlich n	Freundlich R^2
Red Mud	4.464	2.29	0.9802	1.67	2.226	0.9996
Fly Ash	9.4697	4.6354	0.9936	1.0297	2.22	0.9948

A table summarizing the Langmuir and Freundlich constants with R^2 values for each adsorbent helps in a more quantitative comparison of how good each model describes the behaviour of the adsorption process.

The results of this study show that both red mud and fly ash are good adsorbents for lead ions in wastewater, and under optimal conditions, fly ash is a little better than red mud. The Langmuir model is best fitted for the adsorption behavior of fly ash, which shows that monolayer adsorption is dominant, whereas the Freundlich model better describes red mud, suggesting a more heterogeneous surface of adsorption. The maximum adsorption occurs at a pH of 8. The desirable dosage of the adsorbent is 2.5 g, and equilibrium times are observed to fall within the range of 120-150 minutes.

The present comparative analysis aims at the possibility of using red mud and fly ash as viable, cost-effective alternatives for the removal of heavy metals from wastewater. These adsorbents have their performance well under a range of conditions, which allows them to be practically applied in the field of environmental management in industries.

5. Discussion

This paper presents a detailed comparison of red mud and fly ash as adsorbents for the removal of lead from wastewater. Their efficiencies and mechanisms of adsorption will be reported along with the practical implications of such material use. Brief discussions about limitations and possible future research directions will also be considered.

Analysis of efficiency of an adsorbent

Comparing red mud and fly ash both indicated their effectiveness in adsorption capacities for the removal of lead ions under experimental conditions but with individual merits, and fly ash invariably produced a slightly higher capacity as compared to red mud but primarily at near neutral or slightly alkaline pH conditions. For example, optimizing the pH at 8, fly ash was established to have efficiency about 85% for removing lead, whereas that of red mud was about 82%. Such differences are likely to arise from quite subtle reasons, such as physical properties and surface chemistry characteristics of both the adsorbent materials.

The combustion product of fly ash is generally having greater surface area and pore, so more potential sites than red mud. A broad chemical composition of the components such as silica, alumina, and variety metal oxides in the content of fly ash explains many aspects of adsorption and properties in solution under some pH dependence on charge developed at the surface. Further, the high Langmuir QmaxQ_{text{max}}Qmax value of fly ash, 9.4697 mg/g, suggests that it has more lead ions in a single layer. This can be seen in the assumptions made in the Langmuir model. Red mud has a lower monolayer capacity under similar conditions and its Langmuir QmaxQ_{text{max}}Qmax value is 4.464 mg/g.

However, red mud Freundlich model constants indicate a different strength since a KfK_f value of 1.67 and an nnn of 2.226 value indicates that the surface favors multilayer adsorption, which is suitable for complex wastewater with a varied range of metal concentrations. Such inferences are that even though fly ash may be favored in such scenarios demanding high capacity and fast adsorption, its multilayer adsorption capability makes red mud far more versatile while handling effluents with intricate natures.

Adsorption Mechanisms

Probably, the adsorption of lead ions by red mud and fly ash is affected by several physical and chemical interactions. The primary mechanisms involved in the adsorption by these materials are ion exchange, electrostatic attraction, and surface complexation. Each of these mechanisms varies with the properties of the adsorbents.

1. **Fly Ash Mechanisms:**

- The adsorption performance of fly ash may be ascribed mainly to its high silica and alumina content, which endows it with a high surface area and considerable porosity. The physical characteristics promote electrostatic interactions between the negatively charged surface of fly ash and the positively charged lead ions, especially in slightly alkaline conditions. Increased pH promotes a greater negative charge on fly ash, leading to enhanced lead uptake.
- The oxides in fly ash create a mechanism for surface complexation: Lead ions can form chemical bonds with the oxygen atoms on the surface. Surface bonding stabilizes the lead ions adsorbed since bbb of Langmuir constant for fly ash is somewhat high, indicating a certain affinity of lead ions toward binding sites on the fly ash.

Mechanism of Red Mud:

This red mud consists mainly of iron and aluminum oxides and trace amount of some alkali elements and comes under specific adsorption mechanisms especially in mild acidic conditions up to the neutral condition. The Freundlich models for red mud indicate heterogeneous surfaces, hence favor the multilayer adsorptions. Such multilayer adsorption may further be due to ion exchanges in which the leadions exchange other cations so far bound at the surfaces, and it adds an additional layer of binding upon ion exchange.

The layered mechanism of red mud adsorption is particularly applicable to waters with changing concentrations of heavy metals. Such a characteristic allows adsorption in multiple layers. The total adsorption capacity might be lower as compared to that of fly ash; however, this variability makes it suitable across different kinds of wastewater that is highly useful in diverse treatment cases.

These mechanisms reveal that the adsorption mechanisms for both materials are rather complex, depending on the particular surface features, charge density, and chemical composition. Fly ash, particularly due to its higher surface area and pore structure, is best suited for single-layer rapid adsorption; however, red mud, in turn, is better suited for multilayer adsorption because of its heterogeneous surface.

Environmental and Practical Implications

This research study has crucial environmental and practical implications, especially in industrial regions like Damonjodi, Odisha, which have a large amount of red mud and fly ash by-products from industries. Using these by-products as adsorbents in wastewater treatment will help solve two of the environmental challenges: water pollution by heavy metals and finding sustainable ways to use industrial waste.

Waste Reduction and Resource Reuse

Such a research supports the sustainability in waste management, especially industrial by-products such as red mud and fly ash being used as adsorbents. These materials will not be stored in the landfill or storage facilities which risk the environment; it is turned into resources in the removal of heavy metal contamination. It then efficiently tackles the question of a circular economy emerging by converting waste into a source to tackle pollution at the very origin.

Cost-Effectiveness of Wastewater Treatment

Another important advantage of red mud and fly ash as adsorbents is their cost-effectiveness. Compared to commercial adsorbents, which are usually expensive products of costly production processes, red mud and fly ash are readily available in industrial areas and require minimal preparation. Their use as adsorbents reduces reliance on more costly commercial solutions, making this approach feasible in regions with limited financial resources for water treatment. Large-scale application in wastewater treatment becomes practical with the available by-products. Results here would lay a basis for the pilot projects or even field trials in an industrial set-up, and with useful inputs for other similar situations facing heavy metal polluting the environment. Mass applications will change the dynamics on the management of the industrial by-products to usher into cleaner industrial processes without so much environmental damage.

6. Limitations

- **Specificity to Lead Ions** It focused on studying the lead ion adsorption specifically. In industrial wastewater, there is usually a mixture of contaminants; therefore, the effectiveness of these adsorbents to remove other heavy metals like cadmium, chromium, and mercury should be determined in future studies to be able to provide a general understanding of their capabilities.

- **Complex Interactions in Wastewater** In the actual world, such wastewater systems contain some pollutants that might interact with each other through adsorption sites and can compete thereby lowering the levels of red mud and fly ash. Testing these two adsorbents in multi-pollutant systems provides the more realistic data and the possibility of altering the protocol for adsorption in terms of managing varied amounts of different pollutants.
- **Critical issues under real-world conditions** Laboratory-controlled variables such as pH and temperature may not be the same in real life, where fluctuations in the content of wastewater are more of a norm. Therefore, field trials in industrial wastewater treatment facilities are suggested to validate these findings and refine the treatment conditions for practical application.
- **Environmental Impact of Used Adsorbents** Another environmental factor is the environmental disposal of saturated adsorbents. Used adsorbents containing heavy metals require additional handling to avoid secondary pollution. Future research should therefore explore regeneration or safe methods of disposing of these materials, perhaps by developing mechanisms to release and recover the absorbed metals.
- **Regeneration Potential** Regeneration of the red mud and fly ash may also help in their economic viability by developing regenerating processes. The ability to reuse the adsorbents will minimize costs as well as increase the duration of every batch. Several regeneration methods could be developed: thermal treatment or chemical regeneration to revive adsorption sites for several cycles of utilization.

7. Conclusion

This paper discusses a comparison of red mud and fly ash as industrial by-products used as adsorbents for lead removal from wastewater, considering the performance of each material under different conditions and their possible applications. The results of the experiment demonstrated that, compared with large surface area, pore structure, and specific chemical properties, fly ash can adsorb lead up to a nearly 85% efficiency at a pH level of 8. Such makes it possible to attain a high-capacity adsorption with consistent performance. Conversely, red mud was efficient in more complex wastewater systems, especially those rich in diverse pollutants, due to the multilayer adsorption capability.To understand better these behaviors, the Langmuir and Freundlich adsorption models were applied. The fly ash was characterized to fit the Langmuir model, which suggests monolayer adsorption, while red mud was found to fit well with the Freundlich model, suggesting it has a heterogeneous surface and the ability to perform multilayer adsorption. This, therefore, points out the fact that fly ash will be better for rapid and high-capacity adsorption, while red mud would be advantageous when dealing with complex wastewater with various heavy metals.

The benefits for industries that are producing red mud and fly ash in large quantities, for instance, in Damonjodi, Odisha are the by-products can be utilized as adsorbents. It decreases the expense for the treatment of wastewater, and also the environmental burden due to waste disposal decreases. This method is quite practical for regions where there are limited financial and infrastructural resources and low-cost materials available in the area are to be used.

This could be done through the use of batch or continuous flow systems, applied at the primary stages of treatment, when the lead concentration is at its highest, to maximize contact time, pH balance, and dosage. Red mud and fly ash mixtures could also be an effective solution for more complex mixtures of contaminants. Continuous monitoring and regeneration techniques should be carried out to achieve a maximum life cycle of adsorbents, thus fostering sustainable wastewater treatment and less environmental impact.

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