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LOW-COST ADSORBENTS FOR HEAVY METAL REMOVAL: A CASE STUDY USING FLY ASH AND RED MUD AT DAMONJODI

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ABSTRACT

This study assesses the efficacy of three inexpensive adsorbents—china clay, red mud, and fly ash—in removing chromium, lead, and cadmium from wastewater. In order to evaluate the adsorption capabilities of these materials, batch adsorption tests were carried out using water solutions that initially included 100 ppm of metal ions. The results indicated that red mud achieved the highest removal efficiencies: 91% for chromium, 94% for lead, and 89% for cadmium. China clay also demonstrated effective removal, with 89% for chromium, 86% for lead, and 90% for cadmium. Fly ash, though slightly less efficient, removed 84% of chromium, 89% of lead, and 83% of cadmium.\The adsorption process was found to be time-dependent, with removal efficiency increasing as contact time was extended, suggesting a gradual adsorption mechanism influenced by the availability of active sites on the adsorbent materials. These findings show that fly ash, red mud, and china clay are effective for removing heavy metals from contaminated water.

The study highlights the feasibility of using these low-cost, readily available materials as alternatives to expensive and less environmentally friendly adsorbents. These materials present a sustainable and economically viable option for large-scale wastewater treatment, offering a practical solution to address heavy metal pollution. This approach can contribute to more sustainable and cost-effective wastewater management, particularly in regions where affordable treatment options are critical for mitigating environmental contamination.

Key Words: Heavy metals, Adsorbents, Contact time, Agricultural waste, Wastewater treatment

1.1 Introduction

The discharge of toxic heavy metals such as chromium, copper, and lead into water bodies presents a significant environmental challenge with widespread implications for both ecological systems and human health. These metals, commonly introduced through industrial activities, remain persistent in the environment and pose severe risks to water quality, aquatic life, and public health. This abstract explores the sources, effects, and regulatory measures concerning these metals in water, while emphasizing the need for effective remediation strategies to mitigate their impact [1].

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Chromium, a toxic metal widely found in industrial effluents from processes like metal plating, leather tanning, and dyeing, is particularly hazardous in its hexavalent form (Cr^{6+}). This form is a known carcinogen and has severe health implications for humans, including respiratory issues, skin ulcers, and cancer, particularly when it contaminates drinking water. In aquatic ecosystems, high concentrations of chromium can lead to decreased reproductive rates and abnormal development in fish and other species, causing long-term ecological damage.

Copper, while an essential trace element for human health, becomes toxic when present in excessive amounts. It is often released into water systems through industrial discharge, mining activities, and the use of copper-based pesticides in agriculture [2]. While copper is necessary for biological processes, it's over accumulation can lead to copper poisoning in humans, resulting in symptoms like nausea, abdominal pain, and liver damage. Long-term exposure to high levels of copper in drinking water is also associated with kidney dysfunction and other serious health concerns. In aquatic environments, excessive copper concentrations can disrupt the growth and health of fish and other organisms, leading to broader ecological consequences [3].

Several sectors, including building, manufacturing, and plumbing, have relied on lead, a ubiquitous contaminant. Water bodies often become contaminated with lead due to the breakdown of lead-based paints, the leaching of lead from old pipes, and industrial runoff. Exposure to lead is particularly detrimental to infants and toddlers, as it causes cognitive impairments, behavioral issues, and deficiencies in development. Lead can cause heart disease, renal damage, and reproductive problems in adults if they are exposed to it for an extended period of time [4]. The Bureau of Indian Standards (ISI) has prescribed a maximum allowed quantity of 0.05 ppm for lead pollution in drinking water, which is subject to stringent regulation. Lead poisoning is still a major problem in communities with outdated infrastructure and insufficient water treatment facilities, even though these restrictions have been adopted.

The presence of these toxic metals in water bodies can have far-reaching consequences for aquatic ecosystems and human health. The bioaccumulation of heavy metals in organisms, including fish, shellfish, and plants, can disrupt food chains and biodiversity, ultimately affecting human populations that rely on contaminated water sources for drinking, agriculture, and fishing. Furthermore, the toxic effects of these metals on aquatic life can lead to reduced biodiversity, impaired reproductive rates, and the loss of valuable species that are crucial to ecosystem balance [5].

Addressing the growing concern of metal pollution in water requires immediate and coordinated action. Industrial activities that release untreated wastewater into water bodies must be better regulated to prevent the release of these metals. Governments and regulatory bodies must enforce stricter wastewater discharge standards to ensure the protection of water quality and the surrounding ecosystems. Moreover, industries must invest in advanced waste treatment technologies to effectively remove or neutralize toxic metals before they are discharged into the

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environment [6]. A shift toward more sustainable production practices, including the adoption of cleaner technologies and pollution prevention strategies, is essential to reduce the overall burden of metal pollution.

Monitoring water quality and ensuring compliance with established safety standards are crucial for protecting public health. Regular monitoring of water sources can help detect early signs of contamination and provide the necessary data to inform appropriate mitigation measures [7]. Additionally, public awareness campaigns and education on the dangers of heavy metal contamination can empower communities to take action and advocate for better environmental policies.

1.2 Lead: Toxic Effects and Environmental Impact

Lead is a heavy metal that has been used for thousands of years in various industries, including the production of lead-based paints, batteries, and plumbing systems. It is a potent neurotoxin, and even low levels of lead exposure can result in severe health consequences. The main ways that lead gets into drinking water are through plumbing systems, lead-containing pipes, or aging lead-based paints that corrode over time [8].

1.3 Chromium: Health Risks and Environmental Concerns

There are two main types of the heavy metal chromium, and they are called trivalent and hexavalent chromium, respectively. In contrast to hexavalent chromium, which is extremely poisonous and carcinogenic, trivalent chromium is an important mineral that helps with glucose metabolism [9]. Both naturally occurring in soil and rocks and as an effluent from industrial operations like metal plating, leather tanning, and pigment manufacture are frequent places to find it. The most dangerous type of chromium, both for humans and ecosystems, is hexavalent chromium.

1.4 Copper: Health Effects and Ecological Impacts

Red blood cell creation, bone and nerve health, and other biological functions all necessitate copper, a trace mineral that must be present in the human diet. Nevertheless, copper becomes poisonous and can induce many health issues when present in excessive doses. The U.S. Environmental Protection Agency (EPA) states that drinking water copper levels cannot be higher than 1.3 mg/L, which is the limit considered safe for long-term usage.

1.5 Sources of Heavy Metal Contamination

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Industrial processes, mining, agricultural runoff, and urban infrastructure degradation are the main causes of heavy metal contamination in water bodies. Metal refining, chemical and dye production, and electronics manufacturing are among industrial activities that frequently discharge heavy metals like lead, chromium, and copper into the environment [10]. Heavy metal contamination is already a serious issue, and it is made worse by the improper disposal of industrial waste and the release of untreated wastewater into aquatic environments.

Mining operations, particularly those involving the extraction of metals such as copper, gold, and silver, also contribute to heavy metal contamination. Toxic metals are frequently released into surrounding water bodies by these activities, which may contaminate supplies of drinking water. Additionally, the use of heavy metals in agricultural practices, such as copper-based fungicides, can result in the runoff of these metals into surrounding water sources.

Urbanization and the deterioration of infrastructure also contribute to heavy metal pollution. Lead, for example, is commonly found in older plumbing systems, and the corrosion of lead pipes can result in the leaching of lead into drinking water. Additionally, the use of lead-based paints in older buildings and infrastructure contributes to lead contamination in the environment.

MATERIALS AND METHODS

Preparation of Adsorbents:

1: Fly ash

The Obera Thermal Power Plant in Mirzapur, Uttar Pradesh, India, was surveyed for fly ash. This fly ash was a byproduct of coal combustion in the power plant’s boilers and was obtained directly from the plant’s collection system. The collected fly ash was used without any pre-treatment.

Fly Ash Preparation:

The fly ash was sieved using a 53 μm pore size sieve to separate the finer particles. This fine fraction was selected for use in experiments due to its higher surface area, which enhances its ability to adsorb contaminants like heavy metals.

Chemical Analysis:

The findings of the analysis of the fly ash's chemical makeup are shown in Table 1:

ISBN Number: 978-93-95305-78-5

Constituent	Percentage by weight
SiO_2 (Silicon Dioxide)	56.04%
Al_2O_3 (Aluminum Oxide)	25.90%
CaO (Calcium Oxide)	2.22%
Fe_2O_3 (Iron Oxide)	1.26%
MgO (Magnesium Oxide)	0.94%
Loss of Ignition	13.64%

This study explores the utilization of untreated fly ash from the Obera Thermal Power Plant in Mirzapur, Uttar Pradesh. The fly ash, sieved through a 53 μm pore size, demonstrated favourable physical properties, including a surface area of 5.77 m^2/g, porosity of 0.360, and a density of 3.420 g/cm^3. The experimental procedure involved mixing the fly ash with water samples containing heavy metals, and measuring metal concentrations using Atomic Absorption Spectroscopy (AAS). Results indicate that fly ash is an effective, low-cost material for heavy metal removal, offering a sustainable solution for water treatment.

2: Red mud-

Red mud, a highly alkaline byproduct generated during the production of aluminum, poses significant environmental challenges due to its large volume and hazardous composition. However, its potential as an adsorbent material for environmental remediation has gained considerable attention. The purpose of this research is to determine whether red mud, a byproduct of the aluminum industry, can be used as an adsorbent to remove heavy metals and other pollutants from water [11]. In order to assess the adsorption potential of red mud, its physicochemical parameters were comprehensively examined. These properties include bulk density, particle size, porosity, water holding capacity, and surface area. Furthermore, adsorption experiments were performed to determine how well red mud removed harmful heavy elements, such as cadmium (Cd), lead (Pb), and chromium (Cr), from wastewater.

Red mud exhibits a variety of characteristics that make it a promising material for environmental remediation. The bulk density and particle size of red mud were found to be conducive for both practical handling and its application in large-scale remediation processes. Its relatively low bulk density ensures that it can be used in expansive applications without imposing significant logistical challenges. The surface area and porosity of red mud, key factors in determining the number of available adsorption sites, were found to be relatively high. These properties provide numerous active sites for the adsorption of contaminants, especially heavy metals, making red mud an

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effective adsorbent. The water holding capacity of red mud also contributes to its suitability, enhancing the material's ability to maintain optimal conditions for adsorption over time.

Chemical Analysis of Red Mud as Adsorbent

Constituent	Percentage by Weight
Fe_2O_3	39.45%
Al_2O_3	22.65%
TiO_2	13.80%
SiO_2	8.55%
CaO	5.20%
Loss of Ignition	10.25%

2.1 Batch adsorption studies:

The metal stock solutions used in batch adsorption experiments have a concentration of 1000 mg/L. In a 250 mL conical flask, 1.0 g of each adsorbent was added individually to 100 mL of each metal solution. To make sure the adsorbate and adsorbent were interacting properly, the mixture was agitated with a magnetic stirrer. To determine how well the adsorbent removed the metal ions from the solution, we tracked its progress over time and evaluated the metal concentrations once equilibrium was attained.

We evaluated the adsorption process over a wide range of contact periods, from 30 to 180 minutes, and changed the pH of the solutions as needed at room temperature. Once the adsorption period had passed, the solution was filtered through Whatman 42 filter paper. The concentration of the filtered solution was then ascertained using a PerkinElmer model 2380 atomic absorption spectrophotometer. Using the following formula, we were able to determine the percentage of metal ions removed:

Percentage Adsorption = $\frac{[Co-Ce]}{Co}$X100

Where,

Co = the solution's initial metal ion concentration (mg/l)

Ce = final metal ion concentration in the solution (mg/l).

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2.2 Impact of Adsorption of Heavy Metals on Contact Time:

The adsorption of metal ions was observed to increase continuously with time until equilibrium was reached at 180 minutes. The percentage removal of cadmium varied as follows: red mud (64%-89%), and fly ash (60%-83%) (Figure 1) [12]. This variation may be attributed to the presence of larger surface area active sites on the adsorbents. Similarly, the chromium removal rates were red mud (71%-91%), and fly ash (64%-84%) (Figure 2) [13]. Reduced adsorption efficiency, especially at the lower range, could be due to the limited availability of active sites on the adsorbents. For lead removal, the percentages for red mud, and fly ash were 63%-86%, 56%-94%, and 69%-89%, respectively (Figure 3) [14].

The rapid increase in removal rates for chromium, lead, and cadmium in red mud (91%, 94%, and 89%), and fly ash (84%, 89%, and 83%) suggests that activation of adsorption sites, possibly via a surface exchange mechanism, played a significant role in enhancing the adsorption [15]. Moreover, the higher adsorption rates in fly ash can be attributed to its smaller particle size, which allows better penetration of metal ions into the internal pore structure. In contrast, larger adsorbent particles exhibit slower adsorption due to higher diffusive resistance, limiting the mass transport of metal ions into the adsorbent.

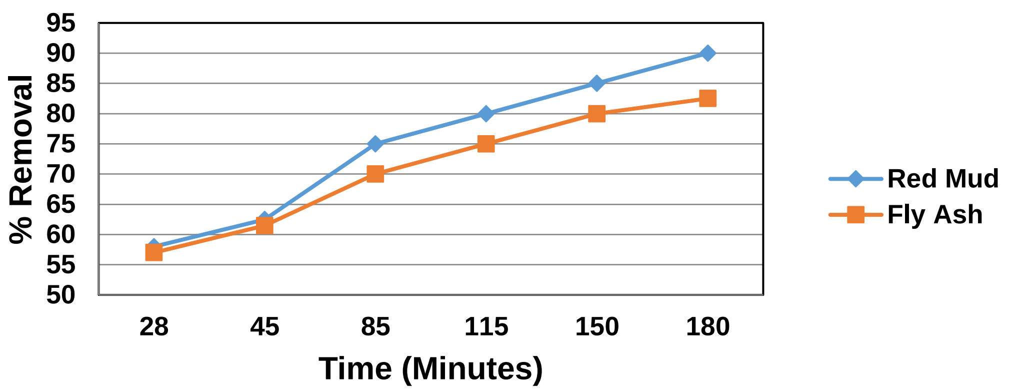

Fig 1 percentage removal of cadmium from different adsorbents

ISBN Number: 978-93-95305-78-5

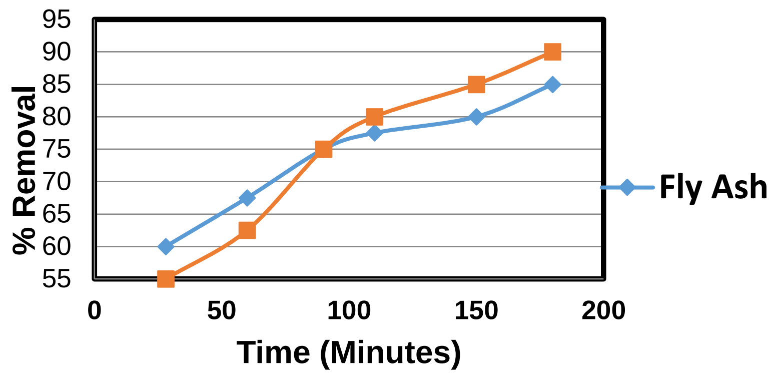

Fig 2 percentage removal of Chromium from different adsorbents

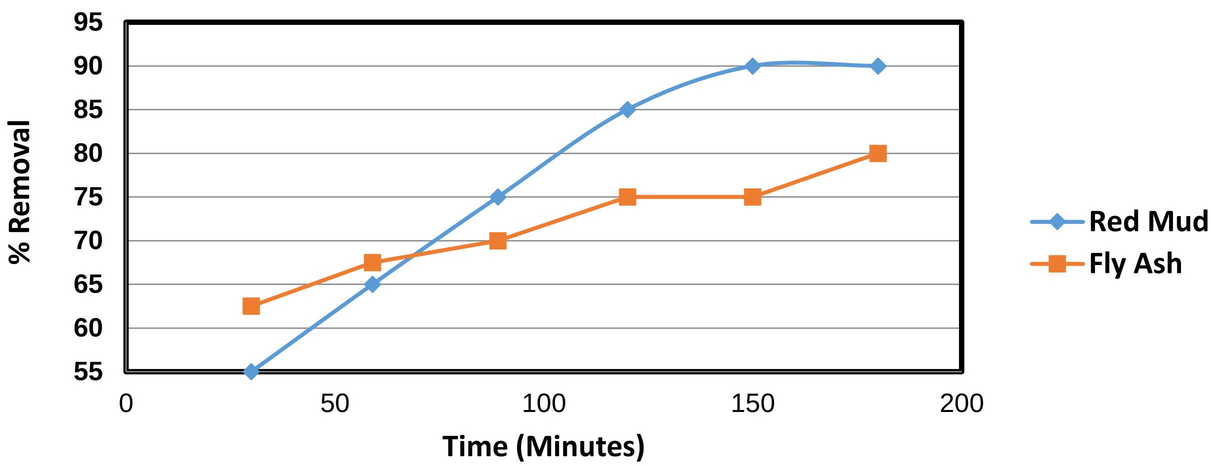

Fig 3 percentage removal of Lead from different adsorbents

CONCLUSION

Heavy metals like cadmium, lead, and chromium were selected for the current study's batch adsorption method of removing them from aqueous solutions [16]. The findings showed that adsorbents' adsorption effectiveness was greatly increased by decreasing their particle size. For the elimination of these metals, a particle size of 53 µm was shown to be quite effective. Because smaller particles have more surface area, there are more active sites available for adsorption, increasing removal efficiency. This emphasizes how crucial particle size is to raising an adsorbent's adsorption capability.

In order to remove lead, cadmium, and chromium from water and wastewater, the study used a variety of adsorbents, such as fly ash and red mud, all of which showed encouraging results [17]. These materials were determined to be cost-effective, environmentally beneficial, technically possible, and user-friendly, which made them perfect for widespread industrial water treatment applications. Their high adsorption effectiveness guarantees little environmental impact in addition to lowering the concentration of hazardous metals in wastewater.

The use of these adsorbents in treating industrial effluents before discharge is crucial for preventing contamination of water bodies. By removing hazardous metals like Chromium, Lead, and Cadmium from wastewater, the risk of environmental and health hazards is significantly reduced. As industries continue to expand, the need for effective wastewater treatment methods becomes more critical, and the use of these eco-friendly adsorbents presents a viable solution for sustainable water treatment [18]. Thus, implementing these materials at an industrial scale could contribute to cleaner, safer water resources and a healthier environment.

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