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Efficient Techniques for Adsorption-Based Heavy Metal Removal in East African Paint Industry Wastewater

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Abstract

Heavy metals such as lead (Pb), cadmium (Cd), chromium (Cr), and zinc (Zn) from paint industry effluents are main ecological and public health concern in East Africa. This study explores the application of efficient sustainable adsorption techniques as low-cost methods for heavy metalemoval in the paint manufacturing sector in the region. Biochar from agricultural waste, natural clays, and industrial by-products are all absorbents this review emphasizes their effectiveness, feasibility, and adaptability to resource-limited settings. It also explores the role of highly efficient nanomaterials such as Fe_3O_4 nanoparticles and graphene oxide for critical applications to evaluate the performance of hybrid systems combining electrocoagulation and membrane filtration for improved removal efficiency. Process optimization for the key process factors such as pH, contact time, and drug dosage are discussed. Technical, economic, and policy challenges may limit the implementation of such adsorption strategy in East Africa. By integrating technology, policy, and capacity-building efforts, adsorption could emerge as a viable route to cleaner industrial processes and sustainable environmental protection in the region.

Keywords: Heavy metals sources; wastewater treatment; Toxicity; low-cost adsorbents; East Africa.

1. Introduction

The East African paint manufacturing sector is a new industry that plays a role in economic growth, but it generates wastewater contaminated with the highly toxic heavy metals such as lead (Pb), chromium (Cr), cadmium (Cd), and zinc (Zn) [1]. These heavy metals cause a substantial environmental and public health risk to the ecosystem, such as water pollution, soil contamination, and chronic disease, when they enter the food chain [2]. Traditional wastewater treatment methods, such as chemical precipitation and ion exchange, are often expensive and ineffective for low metal levels, setting the demand for innovative technologies to fulfill the market requirements [3].

Adsorption is considered as an economical and environmentally friendly method for heavy metals removal due to its high efficiency, simple operation, and low cost of adsorbents [4]. Remediation studies emphasize the potential of local supporters, such as coconut shell activated carbon [5], Activated carbon from biomass for water filtration, biochar from agriculture [6] and modified clay minerals [7], for industrial wastewater treatment. While the field application of these methods in East Africa is limited, there are few studies on adapting adsorption processes to suit regional wastewater conditions [8]. Environmental studies indicate that the improper handling of industrial waste from paint manufacturing is contributing to the pollution of local rivers and lakes with heavy metals in East Africa, emphasizing a critical gap in environmental management that must be addressed [9].

Heavy metals such as lead (Pb), chromium (Cr), cadmium (Cd) and zinc (Zn) released from the paint industry are non-biodegradable and tend to accumulate in soil and water bodies causing hazards to health and the environment. Exposure to heavy metals from contaminated water or food can cause neurological disorders, kidney damage, respiratory problems and cancer. High concentrations of heavy metals in water bodies around paint factories have been associated with health issues among nearby communities in east Africa [10]. These impacts highlight the need for effective treatment and intensive control of industrial effluents to protect the environment and public health. Aquatic life is particularly vulnerable, as heavy metals bioaccumulate and biomagnetize, causing toxic effects on fish and wildlife. In East Africa, industrial effluents containing heavy metals, along with the contamination of water bodies, threatened

freshwater resources that are essential for agriculture and human use [11].

Furthermore, Exposure to lead can result in nerve damage, hinder childhood development, and contribute to heart disease. Chromium (VI) is a confirmed carcinogen that may harm the lungs and skin. Additionally, cadmium can result in kidney failure and bone fractures, while excessive zinc intake disrupts digestive processes, with even low exposure levels posing significant chronic health risks [12]. The reduction and control of heavy metal pollution from industrial effluents in East Africa is severely hampered. Lax enforcement of environmental laws, lack of financial and technical resources, and poor wastewater treatment facilities hinder effective industrial effluent control. Most industries lack effective monitoring systems for pollution, resulting in uncontrolled or ineffective discharges. In addition, the lack of nationally developed guidelines and standards for tolerable heavy metal concentrations makes control more challenging. The high cost of advanced treatment technologies and low awareness among stakeholders about sustainable practices limit mitigation efforts. Current studies highlight the need to build strong institutional frameworks, invest more in low-cost treatment options, and promote capacity-building programs to address these limitations and ensure environmental and public health protection [13].

This study evaluates the effectiveness of adsorption processes as a viable and sustainable approach for the removal of heavy metals – namely lead (Pb), chromium (Cr), cadmium (Cd) and zinc (Zn) – from East African paint industry wastewater.

Different adsorbents such as biochar, activated carbon and clay minerals will be considered under different operating conditions such as pH, contact time and dosage for process optimization and improvement of adsorbents recyclability for overall efficiency. Special attention is also paid to locally available low-cost materials such as industrial-by-products, natural clays and agro-wastes to ensure their economic viability in the region.

Adsorption will be compared with other traditional treatment processes including chemical precipitation and ion exchange to identify the benefits of adsorption in resource-limited environments. Finally, the study raises practical issues for wider application and provides suggestions for incorporating adsorption-based systems into wastewater treatment in East African paint industries.

2. Key Heavy Metals, Their Sources and Toxicity in East Africa's Paint Industry Wastewater

2.1 Key Heavy Metals

The East African paint industry plays an important sector in construction and manufacturing, however it generates hazardous heavy metals that pose a threat to the environment and public health. The following are the main pollutants and their sources from recent studies:

Lead (Pb) - Despite global reductions in lead-containing paint, lead from pigments, dyes, and corrosion inhibitors remains in wastewater [14]. Local paint manufacturers continue to occasionally use lead additives in small quantities [15].

Chromium (Cr) - Hexavalent chromium (Cr (VI)), a listed human carcinogen, enters wastewater streams through anti-corrosive primers and some colorants. An environmental study at 2023 in Tanzania identified Cr levels above the levels recommended by WHO in wastewater from the paint industry [16].

Cadmium (Cd) - Cadmium is used in bright red and yellow paints and leaches into wastewater during cleaning and production of equipment. In Kenya, research has identified high levels of Cd around paint factories, which are associated with untreated wastewater effluents.

Zinc (Zn) - Zinc pollution occurs due to the use of galvanized coatings and anti-corrosion additives. Although not particularly harmful, excess Zn can be toxic to aquatic life and can be deposited in sediments [17].

2.2 Sources and Toxicity of Heavy Metals in Paint Industry Effluents

Heavy metals such as lead (Pb), chromium (Cr), cadmium (Cd) and zinc (Zn) are common in effluents from paint companies throughout East Africa. The metals are derived from various raw materials and chemical additives used in the formulation, painting and manufacturing processes.

2.2.1 Sources

Lead (Pb) is often introduced through pigments such as lead chromate ($PbCrO_4$) and lead oxide (PbO), which are valued for their bright color, luminosity and stability. It also occurs in drying agents and anti-corrosion additives in protective coatings [18-19]. Chromium (Cr), especially the hexavalent state (Cr(VI)), is used for corrosion resistance and bright coloration, occurring in chrome-based pigments and inhibitors [20]. Cadmium (Cd) provides bright yellow and red pigments as cadmium sulfide (CdS), and cadmium selenide (CdSe) and acts as a stabilizing agent [21]. Zinc (Zn), usually in the form of zinc oxide (ZnO), is used both as a white pigment and as a corrosion inhibitor, particularly in primers and galvanizing paints [22]. During various stages of production, such as mixing, washing, and equipment cleaning, these metals are released into wastewater streams. In most East African paint factories, the antiquated infrastructure and lack of modern treatment systems often result in discharges exceeding acceptable environmental discharge levels [9, 23].

2.2.2. Toxicity

Toxicity of heavy metals have been documented; whereby, Lead (Pb) is a neurotoxin that is particularly harmful to children, causing mental retardation, behavioral changes, and developmental delays. Chronic exposure in adults can lead to kidney damage and hypertension [24]. Chromium (Cr (VI)) is a Group 1 human carcinogen according to the International Agency for Research on Cancer (IARC), causing lung cancer by inhalation, skin lesions and respiratory tract irritation [21]. Exposure to cadmium (Cd) has been associated with irreversible kidney damage, bone loss (Itay-Itay disease) and pulmonary carcinogenesis. Bioaccumulation in the human body poses a threat of long-term toxic effects [25]. Although zinc (Zn) is an essential trace element, toxic levels can cause nausea, vomiting and interfere with the absorption of other essential minerals. At high levels in the environment, zinc can cause disturbances in aquatic ecosystems and toxicity to fish and microorganisms.

Their cumulative, non-biological and bioaccumulative properties require immediate action. In the absence of proper wastewater treatment, the East African paint industry is a major source of heavy metal pollution that threatens human health and environmental stability [21, 23].

3. Environmental and Health Impacts of Heavy Metals in Paint Industry Effluents in East Africa

3.1 Environmental Impact

3.1.1. Water pollution and water toxicity

Heavy metals such as lead (Pb), hexavalent chromium (Cr (VI)), and cadmium (Cd) accumulate in rivers, lakes and groundwater, causing widespread ecological disturbances [26], as they accumulate naturally and increase over time [27]. Chromium, as a toxic compound Cr (VI) causes DNA damage in fish species, while inhibiting the growth of phytoplankton at concentrations as low as 0.5 mg/L [28]. Similarly, lead has bioaccumulative properties, accumulating in algae and fish populations. When ingested at higher trophic levels, the pollutants are transported through the food web, increasing their impact on aquatic organisms [29]. Zinc (Zn) and mercury (Hg) are toxic to fish, reducing biodiversity and affecting fisheries [30] (Fig 1).

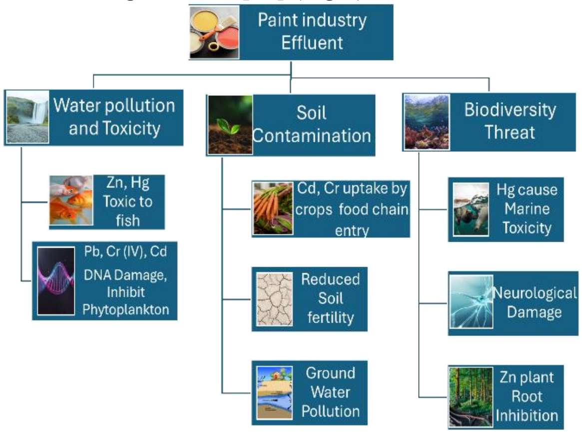

Figure 1. Environmental Impact of Heavy metals

3.1.2. Soil contamination

Industrial waste is frequently discharged onto agricultural land, and metals such as Cd and Pb are taken up by crops, directly entering the food chain [21]. Chronic contamination reduces the fertility of soil and microorganisms [31]. Improper management of paint sludge disposal has long-term implications for soil health, as its accumulation results in pollutants that inhibit microbial activity and crop yield, affecting long-term agricultural productivity [32]. The extended life span has serious implications for groundwater quality, which increases the risk of contamination that can affect ecosystems and human health [33] (Fig 1).

3.1.3. Threat to biodiversity

Metals such as Hg and Pb accumulate in water and enter the food chain through fish consumption, which can reach human populations [34]. Mercury (Hg) was once a traditional ingredient in antifouling paint applied to seabeds, but its presence has been shown to harm marine life. Mercury exposure causes neurological damage in marine mammals, impairing their cognitive and motor skills, which can have a significant impact on their survival and behavior [35-36]. Alternatively, zinc (Zn), which is less toxic than heavy metals such as mercury, is an environmental concern when present at high levels. Excess zinc inhibits root development in plants, limits their ability to absorb nutrients and water, and has negative effects on plant health and growth [37] (Fig 1).

3.2 Human Health Risks

Exposure to heavy metals poses significant risks to human health, ranging from neurological disorders to organ failure. Lead (Pb) is particularly toxic to children, causing cognitive impairment and delayed growth, and chronic exposure can cause kidney disease and hypertension [33, 38]. Hexavalent chromium (Cr (VI)) is a potent carcinogen that increases the risk of lung cancer when inhaled or ingested and causes skin diseases such as dermatitis and ulcers when exposed to it [40, 27]. Cadmium (Cd) preferentially accumulates in the kidneys, leading to kidney failure and bone diseases such as Itay-Itay disease; it is also classified as a Group 1 carcinogen by IARC [40, 41]. Although zinc (Zn) is essential for biological processes, excessive exposure can lead to nausea, anemia, and immune suppression [30]. Such health risks highlight the need for strong environmental regulations and regulatory measures (Fig 2).

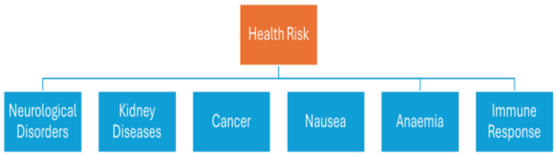

Figure 2. Health Risks of exposure to heavy metal pollution

A. Acute & Chronic Exposure Risks

Heavy metals pose significant health risks through various exposure pathways. Lead (Pb) is a neurotoxicant that can cause anemia and kidney damage, primarily through inhalation of dust or ingestion of contaminated water and food [42]. Chromium (Cr(VI)) exposure, often occurring in occupational settings such as paint factories or through contaminated drinking water, is linked to lung cancer and skin ulcers [43]. Cadmium (Cd) accumulates in the body over time, leading to kidney failure and bone demineralization, as seen in Itai-Itai disease; major exposure routes include contaminated seafood and tobacco smoke [28].

B. Vulnerable Populations

Some groups face higher risks from exposure to heavy metals due to physiological exposure or occupational hazards. Children are particularly vulnerable to lead (Pb) poisoning, as their developing nervous systems are susceptible to cognitive impairment, with long-term consequences such as reduced IQ and developmental delays [33]. Industrial workers, particularly in paint manufacturing, face higher risks of lung cancer due to long-term exposure to hexavalent chromium (Cr (VI)), a known carcinogen that contributes to chronic respiratory diseases, highlighting the need for strict workplace safety measures [41]. Pregnant women are at increased risk of developing mercury (Hg) exposure, which can cause serious harm to fetal development, brain damage and neurological disorders in newborns, reinforcing the need for environmental controls and preventive measures to protect the health of mothers and children [34]. Implementing protective policies and reducing exposure risks are crucial for these vulnerable demographics.

4. Regulatory and Mitigation Challenges for Heavy Metal Pollution from Paint Industry Wastewater in East Africa

Heavy metal pollution raises significant regulatory and mitigation challenges, particularly due to global disparities in environmental governance. In many developing countries, weak implementation and enforcement of effluent standards have resulted in widespread contamination of water and soil resources. Poor infrastructure and weak regulatory framework worsen the level of pollution, render it difficult to intervene effectively [44].

New materials are a technologically advanced solution that can reduce heavy metal pollution, improve water quality, and reduce the risk of toxic exposure [46]. Phytoremediation uses metal-accumulating plants used to clean up pollutants in contaminated areas. For example, sunflowers have proven to be very effective in removing lead (Pb) from soil, providing a sustainable and natural remediation method [45]. Another development in pollution control is the use of high-performance adsorbents such as graphene oxide, which has shown good performance in removing hexavalent chromium (Cr (VI)) from industrial wastewater.

4.1 Regulatory Challenges

The rules for industrial wastewater treatment In the East African Community (EAC) are sometimes inconsistent outdated, and poorly enforced, limiting its effectiveness in environmental preservation and public health. [47].

4.1.1. Disparate legal frameworks

The East African Community (EAC) has many effluent standards, making it easy for regulatory arbitrage and cross-border environmental protection. For example, Tanzania allows a lead (Pb) content of 0.1 mg/L in industrial effluents, while Kenya has a more stringent 0.05 mg/L standard, allowing industries to take advantage of regional variations [48]. Enforcement measures are also under pressure, with 78% of small and medium enterprises (SMEs) operating without a permit for wastewater discharges – not because they are not always enforced, but because agencies such as NEMA Kenya (2022) are chronically understaffed and have inadequate capacity to investigate and enforce [49]. Jurisdictional challenges further complicate pollution control, particularly in trans boundary water bodies such as Lake Victoria, where the lack of joint enforcement mechanisms allows pollution to move unchecked across international borders [50]. Filling these gaps requires harmonizing environmental policy and improving institutional capacity to ensure effective regulatory oversight.

4.1.2. Outdated monitoring systems

Regional water quality monitoring is still outdated, with 92% of monitoring bodies still using sampling method that provides only temporary snapshots rather than the real-time data streams provided by modern sensor technology [51]. In addition, key environmental data continues to be hidden in national systems, and regional monitoring is thus hampered. For example, lead contamination incidents reported in Tanzania in 2022 were not uploaded to the EAC regional water quality portal, resulting in significant gaps in trans boundary pollution monitoring [52]. To overcome such limitations, it is necessary to introduce advanced monitoring technologies and encourage data sharing schemes to improve integrated environmental management.

4.1.3. The Policy-Implementation Divide

Despite good policies on paper, enforcement remains a chronic problem. While Uganda's 2019 Industrial Wastewater Regulations are well-written, they have failed to be implemented due to annual budget shortfalls and bureaucratic laxity, making them unpractical [53]. Meanwhile, the informal economy operates largely unregulated. In Nairobi, about 60% of small paint workshops, many involving heavy metals, are unregistered and unregulated, discharging their unregulated effluents into the city's drainage system, posing environmental and public health risks [54]. Enhancing enforcement mechanisms and including informal industries in compliance frameworks is crucial for effective pollution control.

4.2 Barriers to Mitigation

In East Africa, approaches to addressing industrial wastewater pollution are hampered not only by weak regulations but also by severe constraints on the ground. These range from technical to economic and institutional, creating barriers that can undermine even the best reforms [55].

Technical limitations, economic weaknesses, and lack of stakeholder coordination have contributed to the lack of effective wastewater management in the region. According to three certified industrial wastewater management experts in Rwanda, the prohibitive cost of sophisticated treatment equipment such as an electrocoagulation unit (US$250,000) makes it unaffordable for 89 percent of local industries [56, 57]. On the other hand, economic pressures encourage non-compliance, as Kenyan factories prefer to pay a fine of $50 per day compared to the $500 per day they would spend on legal effluent treatment, and the black market in illegal lead additives is 40% cheaper than the regulated versions, which undermines regulatory compliance [58, 59]. In addition to technical and financial challenges, it also hinders stakeholder alignment. Comparably, 82 percent of Tanzania's wastewater treatment research has not found its way to producers, and the Lake Victoria 2022 mercury pollution recommendations have not been met due to lack of public awareness [60, 61]. To address these regulatory challenges, enforcement must be strengthened, knowledge access increased, and stakeholder engagement strengthened.

4.3 New solutions and implementation barriers

Despite many obstacles, and despite the fact that implementation is still plagued by obstacles, innovation in industrial wastewater treatment continues to be driven by indigenous biotechnology and advanced digital technology. In Kenya, IBM Research has deployed a blockchain-enabled monitoring platform along the Athi River corridor to track effluent discharges in real time to enhance transparency and accountability [62]. Still, ongoing bottlenecks are hindering implementation—Kenya's only accredited heavy metal analyzer is facing a six-month trial period, which is delaying its implementation by regulators [63]. Policy hurdles remain, including the removal of toxic additives from the EAC Paint Sector Protocol, which is due to be implemented in 2021 due to differences between ministries and insufficient funding [64]. Financing remains a weak point in industrial wastewater transformation, with Tanzania's 2022 Industrial Cleanup Bond, which is 67% underfunded, and Uganda's Environmental Fund, which spends less than 5% of its budget on wastewater treatment, diverting funds to other conservation efforts [65, 66]. Closing these gaps will require dedicated funding, improved policy implementation, and efficient technology integration to translate innovation into action.

4.4 Case Studies

In 2023, Tanzania took decisive action against pollution in the Misimbazi River by closing 17 factories that violated chromium discharge limits, resulting in a 43% reduction in production and an economic loss of $28 million [67]. This action inadvertently led to the creation of 32 informal operators in the same industrial areas, which allowed pollution to continue uncontrolled [68]. To further strengthen environmental protection, policymakers are called upon to align the East African Community legislation with the European Union's REACH thresholds by 2025, a move that would strengthen compliance measures and close cross-border loopholes that undermine industry accountability [69]. Given the complexity of the industrial landscape, a gradual approach is needed, with penalties adjusted for the size of the factory and the severity of the risk. A good model is Kenya's 2024 Finance Bill, with a graduated penalty system, which lays out a blueprint for wider regional implementation [70]. South-South cooperation is essential to promote innovation and collaboration in managing industrial waste by providing large-scale solutions. The UNIDO-supported India Common Effluent Treatment Plant (CETP) concept is a cost-effective approach specifically designed for clustered industrial parks, improving waste management efficiency and reducing operating costs [71]. Other studies in Kenya, maize cob biochar was used as an adsorbent with conditions of pH 5, 2 g/L dosage, and a contact time of 30 minutes, remove up to 92% lead (Pb) from contaminated water [72-75]. Furthermore, in Tanzania, coconut shell columns were used for removal of chromium from contaminated wastewater, resulting in an 88% removal efficiency for Cr (VI) ions at pH 3[76]. Similarly, Uganda, innovative modular PVC bed systems achieved between 85% and 93% removal of cadmium (Cd) and lead (Pb) [77].

5. Key Heavy Metals, Their Sources and Toxicity in East Africa's Paint Industry Wastewater

5.1 Advantages of Adsorption for heavy metal removal

5.1.1. High Removal Efficiency

Adsorption has been proven to be a very effective method for heavy metal removal. Materials such as activated carbon, biochar, and clay minerals have large surface areas and many active sites, which allow strong physical and chemical interactions for metal binding [75]. Graphene oxide and other nanoscale materials have shown rapid adsorption properties, removing more than 95% of Pb (II) ions in less than 30 minutes, and can be applied in real-time water treatment processes [76]. These next-generation materials prove to be versatile, combining cationic heavy metals such as Pb^{2+} and Cd^{2+}, as well as anionic pollutants such as hexavalent chromium (CrO_4^{2-}), making them applicable in a variety of industrial and environmental situations [77].

5.1.2. Cost-Effectiveness

Compared to traditional alternatives such as chemical precipitation, ion exchange, and membrane filtration, adsorption is a cost-effective solution with potential savings of 40–60% in operational costs compared to chemical precipitation [78]. The fact that adsorbents can be obtained locally from agricultural residues and industrial by-products further minimizes costs, with adsorption cutting operating costs by 40–60% compared to chemical precipitation. In contrast to membrane filtration and electrochemical remediation, adsorption calls for little input of energy, increasing its scalability for mass pollution control [79]. Agricultural residue-derived biochar from rice husks and coconut shells has shown cost savings of 40–60%, further establishing its role as an economical large-scale solution for wastewater treatment [80].

5.1.3. Simplicity and adaptability

Adsorption operations are easy to design and operate, and do not require much technical expertise, making them suitable for small and medium-sized paint production units in East Africa. Their versatility allows treatment to be tailored to different wastewater compositions and volumes, making them applicable in a variety of industrial environments [81].

5.1.4. Environmental and operational advantages

Adsorption generates less secondary waste than chemical precipitation, which reduces sludge disposal issues. Most adsorbents are amenable to regeneration by drying, reducing material usage and ensuring sustainability [82]. The versatility of adsorption allows for the optimization of important parameters – pH, contact time, volume and temperature – to further improve treatment efficiency for industrial wastewater [83].

5.1.5. Scalability and sustainability

It reduces secondary pollution and reduces the amount of toxic chemicals needed to easily handle sludge, in line with environmental regulations governing hazardous waste reduction [84]. It is scalable, meaning that modular structures such as fixed bed columns can treat effluents ranging from 1 to 1,000 cubic meters per day, providing flexibility for a variety of industrial applications [32]. Due to its efficiency, low cost, and environmental benefits, adsorption remains an effective method for removing heavy metals in the East African paint industries, ensuring compliance with regulatory requirements and sustainable development goals [85]. Therefore, much of the recent research has aimed to optimize adsorption methods and explore local, cost-effective adsorbents to make this method more applicable in regional environments.

Table 1 present the different metal removing technologies with different strengths (fig 3) and weaknesses depending on environmental conditions, costs, and scale requirements. Adsorption is still cost-effective compared to waste-derived biochar-based adsorbents, but with high energy requirements, membrane filtration is more efficient. Electrocoagulation, which is moderately efficient, has sludge disposal problems that require additional treatment processes [88].

Table 1: Comparison of Metal Removing Technologies

Method	Cost	Efficiency	Scalability	Limitations	Ref
Adsorption	Low	High (90–99%)	High	Periodic regeneration	[89]
Membranes	High	95–99%	Moderate	Fouling, high energy use	[90]
Electrocoagulation	Moderate	85–95%	Low	Sludge production	[91]

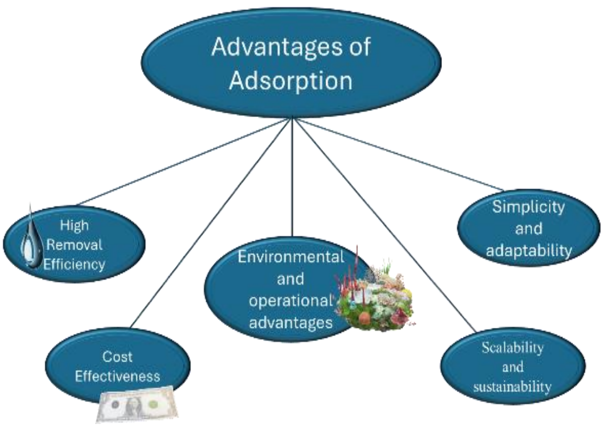

Figure 3. Advantages of adsorption for heavy metal removal.

6. Optimizing Process Parameters and Adsorbent Regeneration for Sustainable Heavy Metal Removal

6.1 Optimizing process parameters for maximum adsorption

Adjusting parameters such as pH, contact time, concentration and temperature can improve metal removal and treatment efficiency for effective removal from industrial wastewater. In East Africa, heavy metal removal from paint industry wastewater requires efficient adsorption processes for sustainable and cost-effective recovery methods. Key parameters and new recovery methods that can be implemented according to regional constraints have been identified in recent studies.

In East Africa, where industrial growth is challenging the environment, optimizing key process parameters has become a cornerstone of sustainable wastewater treatment. Since metal pollution poses a significant threat to water quality, scientific research in the region is focusing on improving the removal of heavy metals by adsorption. All parameters – pH, contact time, concentration and temperature – play a critical role in determining the efficiency of the process. The rapid industrialization of East Africa has increased heavy metal emissions from the paint, mining, and textile industries [89]. Low-cost, flexible advertising is now the new front-line approach.

6.2 Optimization of Critical Process Parameters

6.2.1. pH Adjustment

The solution pH is a major variable for the adsorption dynamics of ions. For lead (Pb^{2+}) and cadmium (Cd), adsorption occurs under mildly acidic conditions that is, in the pH range of 5 to 6, as shown in Table 3. As a result, wastewater often enters treatment systems at low pH, which impairs removal efficiency [91]. Lead (Pb^{2+}) and cadmium (Cd^{2+}) optimum adsorption detected at pH 5–6, where they primarily exist as free cations in solution. Their removal occurs mainly through electrostatic attraction to protonated hydroxyl (–OH) and carboxyl (–COOH) functional groups present on biochar surfaces [95]. Chromium (Cr (VI)) is most effectively adsorbed at acidic conditions (pH 2–3), where it exists predominantly as $HCrO_4^-$. The adsorption mechanism in this case involves ligand exchange as well as redox reactions that reduce Cr (VI) to the more stable and less toxic Cr (III) form [55].

6.2.2. Contact Time and Adsorbent Dose

Biochar-alginate complexes have shown great promise, with studies showing up to 85% removal of Zn^{2+} at 0.062 g and a temperature of 313.5 K. Equilibrium was generally achieved between 60 and 90 minutes, supporting batch treatment [92].

Environmental technologies have also been developed. University of Nairobi studies have shown that effective rice husk biochar can reduce Pb content in crop residues by 78% at 2 g/L, a major breakthrough in low-cost treatment technologies [93]. Extensive environmental reviews also suggest that biochar can be applied to sustainable agricultural practices, such as wastewater treatment [94].

6.2.3. Thermal effects

Endothermic adsorption is a common optimization feature for most of the heavy metal adsorption methods. Studies on Cd^{2+} removal using modified clay materials show positive thermal changes ($\Delta H > 0$), confirming that the adsorption efficiency increases with increasing temperature usually between 30°C and 40°C [95].

To overcome the inconsistent grid power, Tanzanian researchers have pioneered solar-powered adsorption systems, using the region's abundant sunlight to increase the adsorption efficiency by up to 15%. This approach represents a low-cost innovation that is compatible with environmental sustainability [96].

6.2.4. Improving Adsorbent Performance and Operating Conditions

Evaluating the adsorption performance of various adsorbents, such as biochar, activated carbon, and clay minerals, for the removal of heavy metals, such as lead (Pb), chromium (Cr), cadmium (Cd), and zinc (Zn) from wastewater is essential for developing efficient treatment methods. Parameters such as pH, contact time, and adsorption capacity have a significant impact on adsorption efficiency [97]. For example, potassium hydroxide-activated biochar derived from the stem of Syzygium cumini has been reported to remove Pb (II) at a dose of 0.5 to 1.5 g/L. One study showed that increasing the biochar dose from 0.5 to 1.5 g/L improved the Pb (II) removal efficiency from 86% to 97% at pH 5 with a contact time of 360 min. Increasing the dosage to 3.0 g/L, however, reduced the removal efficiency due to limited mass transfer between the adsorbate and adsorbent phases [98-99]. Similarly, a study on modified activated carbon showed that the adsorption efficiency of Pb^{2+} increased from 50.8% at pH 3 to 90.0% at pH 5, with an optimum contact time of 2 h. At higher pH, the efficiency dropped or slightly decreased due to precipitation of lead as hydroxide [100 – 101].

These data highlight the importance of fine-tuning the operating parameters for the removal of heavy metals from wastewater with different adsorbents.

As shown in Tables 2 and 3, optimization of operating parameters (e.g. pH, flow, and sludge management) is essential for heavy metal removal in wastewater treatment. Precipitation methods especially biochar are superior to chemical precipitation, with higher Pb^{2+} removal (92% vs. 85%), lower sludge yield (0.5 g/L vs. 5 g/L), and lower operating costs ($0.10/kg biochar vs. $0.50/kg for precipitation). Although chemical precipitation is less expensive in terms of capital costs (0.3–1.5/m³), long-term costs are increased by the high sludge volume (30–50% treated volume) and non-recyclable residues. Adsorption offers similar improved operational flexibility, with biochar operating at pH 4–6 and general adsorption at pH 3–9, while precipitation requires tight control of pH (8–11). These results position biochar adsorption as a cost-effective and environmentally friendly option, subject to adjustment of parameters to suit specific contaminants and economic conditions. Adsorption continues to be a space-saving option suitable for plants with inadequate infrastructure. Electrocoagulation, on the other hand, has good metal removal capabilities but requires additional energy inputs and regular maintenance. Both are used depending on the type of contaminant, operating conditions, and long-term sustainability.

Table 2: Comparison of Adsorption vs. Chemical Precipitation for Heavy Metal Removal

Parameter	Adsorption	Chemical Precipitation	Ref
Cost	Low-moderate ($0.5-2/m³)	Low ($0.3-1.5/m³)	[105]
Efficiency	80-99% removal	70-95% removal	[106]
Sludge Production	Minimal	High (30-50% of treated volume)	[105]
pH Sensitivity	Works in wider pH range (3-9)	Requires strict pH control (8-11)	[107]
Metal Recovery	Possible via desorption	Difficult. sludge often landfilled	[108]

Table 3: Comparison of Biochar Adsorption vs Hydroxide precipitation for heavy metal removal

Parameter	Biochar Adsorption	Hydroxide Precipitation	Technical Notes	Ref
Pb^{2+} Removal	92%	85%	Biochar: Microporous structure enhances Pb^{2+} binding. Precipitation Efficiency drops at low Pb^{2+} concentration	105
Sludge Generated	0.5 g/L	5 g/L	Biochar sludge can often be reused. Precipitation sludge requires waste disposal	109
Operating Cost	$0.10/kg (local biochar)	$0.50/kg NaOH/lime	Costs exclude sludge handling, which is 3–5× higher for precipitation.	110
pH Sensitivity	Effective at pH 4–6	Requires pH 9–11	Precipitation fails if pH fluctuates; biochar tolerates mild variations.	105]
Regeneration	Possible (acid washing)	Not feasible	Biochar can be reused 3–5 times; precipitation sludge is unrecoverable.	109

7. Effective Adsorbents Innovation for Heavy Metal Removal from Paint Industry Wastewater

7.1 Effective Adsorbents

Effective adsorbents are key to the success of adsorption treatment methods for the removal of heavy metals from wastewater, such as wastewater from the paint industry. Their effectiveness depends largely on properties such as large surface area, porosity, surface functional groups, and chemical stability. Activated carbon, biochar, and clay minerals have shown high binding affinity for heavy metals such as lead (Pb), chromium (Cr), cadmium (Cd), and zinc (Zn), which can reduce high metal concentrations in the effluent. [108]

The selection of adsorbents is important not only to achieve effective removal but also to make the process economically valuable and sustainable, especially in areas such as East Africa. Agro-wastes and natural clays available in most African countries, are low-cost alternatives with high adsorption capacities. Chemical activation and surface functionalization are some of the modifications that can further improve adsorption. Recent studies have emphasized that optimizing the adsorption properties and process conditions leads to high metal adsorption, efficient, scalable, and environmentally friendly reduction of heavy metal pollution [109]. Efficient adsorbents play a crucial role in the treatment of wastewater from the paint industry loaded with toxic heavy metals such as lead (Pb), chromium (Cr), cadmium (Cd), and zinc (Zn). These metals are non-biodegradable and can persist in the environment for long periods, posing significant environmental and health risks. Adsorbents are designed to adsorb and adsorb metal ions from aqueous solutions, and their performance is based on surface area, porosity, functional groups, and ion-exchange capacity [110].

7.1.1. Activated carbon

Activated carbon is widely used due to its high surface area, microporosity, and surface reactivity. It can be used to remove a wide range of heavy metals. However, it is relatively expensive and requires regeneration. Modified versions of activated carbon have been shown to perform better in the removal of Pb^{2+} and Cr^{6+} from paint effluents under controlled laboratory conditions [111].

7.1.2. Biochar

Biochar synthesized from pyrolyzed biomass such as rice husks, soybean hulls, and sawdust is a low-cost, sustainable, and highly selective adsorbent for heavy metals. Chemically or physically activated biochar can greatly improve removal efficiency. For example, KOH-activated biochar prepared from agro-waste has been shown to remove more than 90% of Pb under optimized conditions. Biochar has emerged as a promising candidate for heavy metal removal due to its cost-effectiveness, environmental friendliness, and high affinity for metals [112-113].

7.1.3. Clay minerals

Clay minerals find wide application in heavy metal recovery due to their inherent ion exchange capacity and remediation capabilities. Bentonites and kaolinites are common in East Africa, they have good adsorption properties due to the porous nature of these materials and the high exchange capacity of kaolinites. These materials are particularly suitable for small-scale industries seeking economical alternatives [114].

7.1.4. Industrial waste products

Industrial waste products such as fly ash, red mud, and slag from adjacent industries are being screened for their heavy metal binding affinity. Depending on the chemical makeup and pretreatment [115], these materials offer the dual benefit of waste utilization and pollution reduction. Fly ash and red mud industrial by-products are considered effective adjuvants for the remediation of heavy metals based on waste valorization to increase environmental sustainability [116].

7.1.5. Composite Adsorbents

Recent developments include composite adsorbents that combine two or more materials. For example, biochar-alginate beads and clay-carbon composites have improved mechanical strength, surface area, and recyclability. These are particularly promising for large-scale applications in industrial wastewater conditions [117-118].

7.1.6. Nanomaterials

Nanomaterials have revolutionized heavy metal recovery due to their superior adsorption and separation properties [119].

A: Graphene oxide (GO)

With a large surface area of 2630 m^2/g, GO has excellent metal adsorption properties, with >95% Pb(II) and Cd (II) removal by surface complexation and electrostatic attraction. It is therefore a potential material for next-generation water purification systems [120].

B: Magnetic nanoparticles (Fe_3O_4)

These nanoparticles facilitate easy separation by external magnetization, facilitating recovery after treatment and removing 98% of Hg (II) from contaminated water sources. Their magnetic nature facilitates effective recycling and reuse [103], promoting sustainability.

In the East African paint manufacturing sector, it is crucial to select efficient, readily available and cost-effective adsorbents. Adsorbents such as biochar and clay are highly effective in increasing the removal efficiency and are environmentally friendly and economical. Current research aims to bring these materials to mass use, and to further enhance their potential to support sustainable industrial wastewater management [104].

Fly ash and bentonite clay are inexpensive but have moderate efficiencies, whereas graphene oxide provides exceptional performance at a significantly higher price. Biochar and activated carbon are priced reasonably and have high removal rates, making them widely used in wastewater treatment. Activated carbon is highly effective for removing Pb (II) and Cd (II), with a cost range of $5–50 per kilogram, removal efficiencies between 90–98% [124]. Biochar provides a more economical option at $1–5 per kilogram and is particularly suitable for Cr (VI) and Cu (II), with removal efficiencies of 85–95% [125]. Bentonite clay, priced at $0.5–2 per kilogram, is effective for Zn (II) and Cu (II), offering removal rates of 70–90% [126]. Fly ash represents one of the cheapest adsorbents, costing only $0.1–0.5 per kilogram, and is used for Pb (II) and Cr (VI) removal with efficiencies of 60–85% [127]. On the other hand, graphene oxide, though expensive at $50–200 per kilogram, demonstrates superior performance by removing over 95% of Pb (II) and Hg (II) ions [128].

7.2 Emerging Trends in Heavy Metal Adsorption

The alarm bells about industrial pollution have been raised, especially in rapidly industrializing parts of the world such as East Africa, which has led to the development of heavy metal adsorption technologies. Current research aims to develop low-cost, efficient adsorbents (e.g., banana peel biochar, volcanic tuff) to enhance sustainability and reduce imports [126]. Technologies such as nanocomposite adsorbents (e.g., Fe_3O_4-biochar hybrid) have shown 20–30% increased metal removal capacity compared to traditional materials for magnetic recovery [127]. Machine learning is also improving the optimization of parameters (pH, contact time) and reducing trial and error costs for small-scale industries. [128]. Pilot projects in Kenya and Tanzania have demonstrated the feasibility of these technologies, with modular adsorption systems removing 85-95% of Pb^{2+}/Cr^{6+} at a cost of 40% less than ion exchange [129]. However, challenges remain, highlighting the need for policy support in material quality standards and training of local operators [130].

7.2.1. Development of nanomaterial-based adsorbents

Graphene oxide, carbon nanotubes, and magnetic nanoparticles are being studied due to their unusually high surface area, controlled surface chemistry, and high adsorption activity. Such materials have the ability to adsorb heavy metals such as Pb^{2+} and Cd^{2+} in trace amounts and are particularly important in advanced treatment systems [131].

7.2.2. Functional and modified biochar:

Scientists are also turning from raw biochar to chemical or physical treatments with acids, bases, and oxidizing agents. Such treatments increase the metal binding sites, thereby increasing the adsorption capacity and selectivity. Removal efficiencies of over 95% for Pb and Zn have recently been reported in a study with KOH-activated biochar from agro-waste [112].

7.2.3. Composite and hybrid adsorbents

The synthesis of composite adsorbents prepared by combining biochar with polymers (e.g., alginate, chitosan), clays (e.g., montmorillonite), or iron oxides (e.g., Fe_3O_4, MnO_2) is a revolutionary approach for heavy metal removal. The composites benefit from the synergistic effects: biochar provides high surface area and polymers increase mechanical strength, and iron oxides provide selective binding sites [132]. For example, alginate-biochar beads achieve 95% Pb^{2+} removal due to the alginate carboxyl groups and porous nature of biochar, but they are resistant to dissolution in flow systems [133]. Similarly, clay-carbon composites (e.g. kaolin-biochar) have 20–30% higher adsorption capacities than their pure counterparts due to the clay ion-exchange capacity and carbon functional groups [134]. Such hybrids also perform better in terms of recyclability. Magnetic Fe_3O_4-biochar composites retain >85% efficiency after 10 cycles of acid washing [135]. Pilot-scale trials in Nigeria and Kenya have demonstrated their feasibility, with hybrid systems reducing treatment costs by 40% with activated carbon [136]. However, scaling up and achieving a standardized integrated system for a wide range of industrial effluents remains a challenge [137].

7.2.4. Magnetic adsorbents for easy separation:

Metal-based composites and magnetic biochar's allow for easy separation from treated water using simple magnets, eliminating the need for sophisticated filtration systems. This is particularly useful in industries with complex infrastructure and facilitates low-maintenance and scalable operations [138].

7.3 Data-driven process optimization

There is a growing focus on reusable and renewable adsorbents that do not suffer from significant loss in efficiency while promising sustainability. Processes such as microwave digestion and low-energy thermal regeneration are being tested for their applicability in industrial environments [139].

The application of artificial intelligence (AI), machine learning (ML), and modeling software to predict optimal operating parameters – pH, dosage, and contact time – is increasingly being used. These tools reduce trial and error, reduce costs, and increase the speed of process development [140].

New directions in heavy metal adsorption focus on material design innovation, process efficiency, and sustainability. These improvements are particularly important in regions such as East Africa, where the demand for low-cost, scalable, and environmentally friendly wastewater treatment solutions is increasing.

8. Mechanisms and Influencing Factors of Heavy Metal Adsorption

8.1 Mechanisms of Heavy Metal Adsorption

Removal of heavy metals like lead (Pb), chromium

(Cr), cadmium (Cd), and zinc (Zn) from paint industry wastewater by adsorption is based on multiple distinct physicochemical mechanisms. These mechanisms dictate how the metal ions bind on the adsorbent surface and affect the adsorption capacity, selectivity, and potential for regeneration of the adsorbent material [141]. These mechanisms depend on how the metal ions bind to the adsorbent surface and affect the adsorption capacity, selectivity and reactivity of the adsorbent material [141] (Fig 4).

8.1.1. Physical Adsorption

This is a non-specific process in which heavy metal ions are adsorbed to the adsorbent surface by weak van der Waals forces. It is usually reversible and very rapid, especially at low temperatures. High surface area and adsorbents such as activated carbon and biochars promote efficient physical adsorption [108] (Fig 4).

8.1.2. Chemical Adsorption

Chemisorption is the process of strong chemical bonding - i.e. covalent or ionic bonding - between metal ions and functional groups of the adsorbent surface (e.g. -COOH, -OH, $-NH_2$). This process generally results in a more specific and larger adsorption capacity. For example, acid- or base-treated modified biochar increase the availability of binding sites for metals such as Cr (VI) and Cd(II) [130] (Fig 4).

8.1.3. Ion Exchange

Metal ions exchange their positions in solution with surface-bound ions (e.g., H^+, Na^+, Ca^{2+}). Natural materials such as zeolites and clay minerals have high ion exchange capacities due to their crystalline nature. Ion exchange is particularly important in multi-component wastewaters such as those from the paint industry [138] (Fig 4).

8.1.4. Electrostatic attraction

At some pH values, the adsorbent surface becomes negatively charged, which attracts cationic metal ions (e.g., Pb^{2+}, Zn^{2+}). This process is highly dependent on the pH and ionic strength of the solution. For example, Pb^{2+} adsorption is enhanced at pH 5–6 due to reduced competition from H^+ ions [137] (Fig 4).

8.1.5. Surface complexation

Metal ions form covalent bonds with electron-donating functional groups on the surface of adsorbents. This is a highly selective process and plays a role in the high-stability metal adsorption. Functional biochar and polymer-based adsorbents rely on surface complexation to efficiently bind metals [142] (Fig 4).

8.1.6. Precipitation

Under certain conditions (usually high pH), metal ions can precipitate as insoluble hydroxides or carbonates on the adsorbent surface. Although adsorption is undesirable, this makes a net contribution to metal removal. However, Precipitation is not desirable, as it can lead to misinterpretation of adsorption performance [143]. Heavy metal adsorption is controlled by a combination of methods, with physical adsorption providing rapidity and reversibility, and chemical methods such as complexation and ion exchange providing high selectivity and capacity. Improving these processes by modifying the surface and controlling procedures. The amount of adsorbent determines the amount of active sites available. Increasing the dosage tends to increase the removal efficiency to an optimal level, after which the rate decreases or decreases due to particle aggregation that reduces the effective surface area.ss conditions is crucial to optimizing adsorption efficiency – a major concern in the East African painting sector where affordable and environmentally friendly treatment solutions are urgently needed (Fig 4).

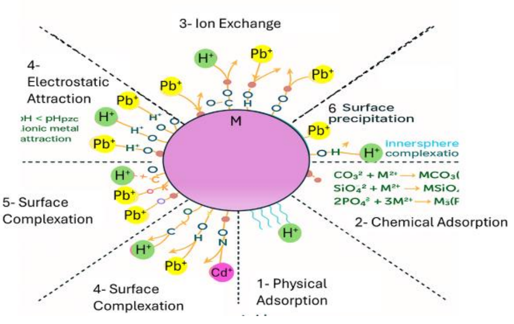

Figure 4. Heavy Metal Adsorption Mechanisms

8.2 Factors Affecting Adsorption Efficiency

The adsorption efficiency of heavy metals such as lead (Pb), chromium (Cr), cadmium (Cd) and zinc (Zn) from wastewater—particularly in applications such as the East African paint industry is controlled by a number of interrelated physical, chemical and operational parameters. Understanding and optimizing these parameters is essential to provide optimal pollutant removal at the lowest cost [144].

8.2.1. Solution pH

One of the most important parameters in adsorption that affect the surface charge of metal ions on the adsorbent and their chemical specificity is pH. For example, Pb^{2+} and Cd^{2+} adsorption decreases as pH increases to 5–6 due to competition for H^+ ions. At extremely high pH values, metal precipitation can occur, leading to misleading interpretations of adsorption capacity [110].

8.2.2. Contact Time

Sufficient contact time allows for an equilibrium between the metal ions and the adsorbent surface. Many studies have shown that initial rapid adsorption is followed by gradual filling of the active sites. For example, biochar has been shown to achieve >90% Pb removal in as little as 120 min [139]. Adsorption is progressive, with metal ions being adsorbed to the sites of interest. Although some materials, such as nanoparticles, are rapidly adsorbed within minutes, others, such as biochar, require a longer period of time (30–180 min) to reach optimal removal efficiency.

8.2.3. Adsorbent Dosage

The amount of adsorbent determines the amount of active sites available. Increasing the dosage tends to increase the removal efficiency to an optimal level, after which the rate decreases or decreases due to particle aggregation that reduces the effective surface area.

8.2.4. Temperature and Initial Metal Concentration

Increasing metal concentration can lead to a decrease in the percentage of binding sites. At higher concentrations, however, the adsorption capacity (mg/g) can increase, indicating the need to optimize the pollutant loading with the adsorbent capacity. Temperature affects adsorption kinetics and equilibrium. In most cases, increasing temperature enhances adsorption by accelerating diffusion and favoring endothermic reactions. For example, the adsorption of Zn^{2+}-doped biochar was enhanced by increasing temperature to 313 K [138]. Higher temperature can increase the adsorption rate by improving surface diffusion, but in some cases, it can also precipitate weakly bound metals. The initial metal concentration determines the adsorption kinetics - higher concentrations can lead to saturation more quickly, requiring higher adsorbent doses for complete removal. (143-145).

8.2.5. Surface area and adsorbent porosity

Adsorbents with a larger surface area and a more developed pore structure have more active sites for binding metal ions. Activated carbon and nanostructured materials are better adsorbed than raw materials due to their better structural properties [146].

8.2.6. Presence of competing ions

In real wastewater, there are many ions, and these can compete for the same adsorption sites, thus affecting the selectivity. This is especially true in industrial wastewater where sodium, calcium and other metal ions are present [147].

8.2.7. Functional groups on the adsorbent surface

Chemical groups such as hydroxyl (-OH), carboxyl (-COOH) and amino ($-NH_2$) play an important role in metal binding through complexation and ion exchange mechanisms. Surface modification can be used to increase the density and accessibility of these groups [148].

Optimizing adsorption efficiency is a complex process that requires optimizing and controlling process variables such as pH, drug dosage, and contact time. For regions such as East Africa where cost and infrastructure constraints are a major concern, it helps industries find ways to convert adsorption systems into sustainable and efficient heavy metal removal.

9. Regeneration, Reusability, and Performance Evaluation of Adsorbents for Heavy Metal Removal: Case Studies from East African Paint Factories

9.1 Regeneration and reuse of adsorbents for heavy metal removal

Regeneration and reuse of adsorbents are crucial for establishing long-term cost-effectiveness, sustainability and environmental footprint of adsorption-based wastewater treatment technologies. Particularly for industrial processes such as the East African paint industry – where operating costs and material availability are major concerns – efficiently recycled adsorbents can offer significant benefits [149].

9.1.1. The importance of regeneration

Regeneration allows the adsorbent to be restored to its original adsorption capacity following loading with heavy metals such as Pb^{2+}, Cr^{6+}, Cd^{2+} and Zn^{2+}. This extends the life of the adsorbent, reduces the need for continuous raw material supply, and reduces the environmental impact of adsorbent disposal [150].

9.1.2. Aggregate regeneration techniques

A number of methods are used to regenerate metal-loaded adsorbents, each suited to specific adsorbent types and target metals. Chemical leaching, with acids (e.g., HCl, HNO_3) or bases (e.g., NaOH), readily dissolves the bound metals, but may partially destroy the associated matrix (151). Thermal treatment, at 300–800°C under controlled atmospheric conditions (e.g., N_2, CO_2), regenerates adsorbents such as activated carbon and biochars, although repeated heating may degrade surface functional groups [152]. Newer technologies such as microwave and ultrasonic regeneration offer faster cycles with reduced energy consumption. Microwave regeneration, in fact, uses 2.45 GHz (500–1500 W), dielectric polarization to generate local "hot spots" that break metal-adsorbent bonds but retain functional groups (-COOH, -OH). This method uses 40–60% less energy (1.5–2.5 kWh) than 3–5 kg/h [127, 153, 154]. Biological regeneration, using microorganisms or enzymes to degrade metal complexes, is still under investigation but offers an environmentally friendly use [155].

9.1.3. Recyclability performance

The ability of the material to maintain its adsorption capacity over multiple cycles is one of the most important performance parameters. For example, biochar-alginate composites have shown stable Zn^{2+} removal efficiencies (~80–85%) over 3–5 cycles when regenerated with 0.1M HCl. Polymer-based adsorbents have achieved >90% desorption of several metals within 30 min and have maintained >85% removal efficiencies after 5 regeneration cycles [156]. However, natural materials such as untreated agricultural wastes may show a decrease in performance after repeated use due to structural damage or loss of active areas.

9.1.4. Limitations and Considerations

The durability of adsorption systems encounters some challenges, such as leaching of residual chemicals, reduced adsorption efficiency after multiple cycles, and the safe disposal and handling of metal-containing desorption solutions [157-158]. To conquer these challenges, it is important to choose the right regeneration strategy that balances efficiency, cost, and environmental safety. Regeneration and reuse in adsorption systems greatly increase their applicability in industrial wastewater treatment, especially in the East African paint industry. Regenerated adsorbents with low cost, low toxic by-products can reduce economic and environmental costs. As illustrated in Table 7, reducing regeneration cycles and optimizing thermal conditions can alleviate the efficiency loss and make thermal regeneration a feasible way to recover. Furthermore, balancing material stability and energy consumption [159] is essential for sustainable use in water treatment processes [160]. By addressing these issues, researchers and industry can introduce cost-effective and environmentally friendly heavy metal removal solutions.

10. Case Studies, Challenges of Heavy Metal Adsorption in Different Areas

10.1 Regeneration and reuse of adsorbents for heavy metal removal

Controlling heavy metal pollution, particularly lead (Pb), chromium (Cr), cadmium (Cd) and zinc (Zn), from East African paint factories is a growing environmental and regulatory issue. In order to find feasible, low-cost and efficient solutions for wastewater treatment, several regional case studies have examined the performance of various adsorbents. Biochar from agricultural wastes such as rice husk and sorghum straw has shown good performance in removing heavy metals from paint effluents. A Kenyan study showed that rice husk biochar removed up to 94% of Pb (II) under optimized conditions of pH 5 and contact time of 180 min [166-167]. Activated carbon derived from coconut shells and other biomass materials has also been extensively tested in Ugandan study finding that over 98% of Cr (VI) was removed by applying activated carbon made from coconut shells. Although the costs of production and regeneration still limit the use of small-scale production plants [168]. Natural clays and bentonite, removed up to 86% of Zn (II) in the treatment of a Tanzanian paint factory effluent, acid treatment boosted the removal efficiency by increasing the surface charge and pore size [169].

In Ethiopia, acidified red mud has been shown to be capable of removing 70-80% of heavy metals from paint wastewater [170]. These comparative studies show that although activated carbon is still the most effective, natural clay-based adsorbents and biochar offer cost-effective and viable alternatives for use in the paint industries of East Africa.

The performance depends on the metal type, operating conditions and adsorbent configuration. Therefore, the selection of a locally suitable, resource-based adsorbent is essential for successful and sustainable service in the region.

The study in Table 4 shows that nanomaterials have superior performance in removing trace heavy metals, achieving removal efficiencies of mercury (Hg) and lead (Pb) even at trace levels. Alternatively, biochar offers the desired compromise between performance and cost, with removal rates ranging from 85% to 95%. Its economic and sustainable nature brings it as a suitable choice for large-scale applications. At the same time, industrial wastes such as fly ash, while not very effective in removing metals, have the major advantage of being very cheap. Such materials may be appropriate for primary or large-scale treatments where cost considerations are a priority over high accuracy. These data facilitate the selection of adsorbents according to application requirements, achieving a tailored balance between efficiency, sustainability, and cost of metal removal operations.

In Table 5, clear patterns are seen in the metal removal behavior under different conditions. pH is a key factor, and cationic metals such as lead (Pb^{2+}) and cadmium (Cd) are best removed at neutral pH values, while anionics such as chromate (CrO_4^{2-}) require more acidic conditions to see good adsorption. Contact time also has a significant impact on performance - the nanoparticles separate, reaching adsorption equilibrium in less than 30 minutes, indicating a high reactive interaction with the contaminant. Among the materials studied, Fe_3O_4 nanoparticles have the highest adsorption capacity, which is due to their exceptionally high surface area at the nanoscale.

Table 4: Removal Efficiencies of Different Adsorbents

Adsorbent	Heavy Metal	Max Removal (%)	Initial Conc. (mg/L)	Ref
Activated Carbon (Coconut Shell)	Pb (II)	98.2	100	[169]
Magnetic Biochar (Rice Husk)	Cd (II)	94.5	50	[175]
Bentonite Clay	Cr (VI)	88.7	20	[176]
Fe_3O_4 Nanoparticles	Hg (II)	99.1	10	[177]
Fly Ash	Zn (II)	76.3	200	[178]

Table 5: Optimal Conditions for Maximum Adsorption

Adsorbent	Optimal pH	Dosage (g/L)	Time (min)	Temp (°C)	Capacity (mg/g)	Target Metal	Ref
Activated Carbon	5.0–6.0	2.0	90	25	48.7	Pb (II)	[179]
Biochar	6.0–7.0	5.0	120	30	32.4	Cd(II)	[180]
Bentonite	4.5–5.5	10.0	180	25	18.9	Cr(VI)	[181]
Fe_3O_4 NPs	3.0–4.0	1.5	30	35	112.5	Hg(II)	[182]

10.2 Paint Industry Case (India)

Biochar and bentonite have been employed to remediate heavy metal contamination in the treatment of paint industry wastewater. A study in India showed that a biochar-bentonite mixture removed 91% of lead (Pb) and chromium (Cr) from wastewater, making it an economical treatment option. According to UNIDO (2023), this method was achieved at a cost of $1.2 per cubic meter, demonstrating the economic benefits of implementing sustainable adsorbents in industrial remediation. Improved metal adsorption can be achieved through the combined interaction between bentonite and biochar without increasing the cost (179–180).

10.3 US Superfund Site

Activated carbon has been widely applied in the remediation of highly contaminated sites. Activated carbon column systems were used to treat 500 cubic meters of lead-containing wastewater at a US Superfund site, successfully reducing Pb levels to environmental levels [181]. These applications demonstrate the effectiveness and versatility of adsorption technologies in addressing heavy metal contamination issues. With a variety of adsorbents and treatment systems, industries and environmental organizations can successfully remove contaminants without sacrificing cost-effectiveness and sustainability.

11. Challenges and Future Directions in Heavy Metal Adsorption

11.1 Bridging the adoption gap for industrial wastewater treatment in East Africa

This study examines the practical challenges faced by the East African paint industry in upgrading adsorption-based wastewater treatment systems. These range from technical constraints such as adsorbent regeneration and disposal to economic issues such as initial investment and operating costs, as well as environmental compliance and regulatory compliance. Furthermore, challenges such as the feasibility of providing a consistent quality adsorbent and integration with existing treatment infrastructure are key issues that need to be addressed. This study emphasizes that overcoming these barriers requires a multi-stakeholder strategy that includes government policy support, industry input and capacity building for sustainable deployment [182]. These recommendations would facilitate adaptation approaches that promote efficient, cost-effective and environmentally sound wastewater treatment in line with regional needs.

11.2 Implications for Adsorption Application: Operational and Material Challenges

Metal removal most prominent problem is the variable quality and availability of adsorbents, especially agro-waste and natural material-based adsorbents. The lack of current availability and standard processing methods make it uncertain about the quality and reproducibility of adsorption [183-184]. Furthermore, the lack of technical resources in small and medium-sized paint plants hinders the optimization, monitoring, and continuous regeneration of adsorbents – features that are associated with long-term efficiency and cost-effectiveness [185].

11.3 Economic and Regulatory Barriers to Advertising Adoption

While there are many low-cost advertisers, the capital required to set up advertising units, design advertisements, and handle maintenance or renewal is not accessible for industrial operating due to tight financial situations [186]. Regulatory barriers further complicate adoption; most East African countries lack comprehensive guidelines specifically designed for advertising-based healthcare systems, thus hindering policy integration and implementation [187].

11.4 Innovation and Opportunities for Sustainable Adoption

Nanotechnology-enhanced adsorbents, composites, and bio-based materials with improved adsorption capacity and selectivity [188] are promising innovations. New approaches that combine adsorption with other treatment processes to increase overall removal efficiency constructed wetlands and electrochemical systems are also emerging [189]. The growing concern about environmental pollution, with the support of international development partners, is prompting pilot schemes and capacity-building programs for knowledge transfer and adaptation of local technologies (190). Multi-stakeholder engagement is essential to make adsorption technologies sustainable in the East African paint manufacturing sector. Coordination between policymakers, industry, researchers, and local communities is essential. With focused investment, regulatory guidance, and ongoing innovation, adsorption has great potential as an economical, scalable, and eco-friendly solution for industrial wastewater treatment in the region.

12. Future Roadmap for Heavy Metal Adsorption Technologies in East Africa

12.1 Local production and Standardization of Adsorbents

The future of heavy metal adsorption technologies in East Africa is to move from small-scale, dispersed applications to integrated, policy-supported, and industry-driven adoption. The road map for the future is to start with local production of adsorbents, focusing on the development of low-cost materials such as agro-wastes (e.g. rice husks, palm kernel shells, coconut shells) and natural clays [183, 184]. Standardization of the preparation and characterization of these materials is essential to achieve consistent adsorption performance across different industrial environments [188].

12.1.1. Capacity Building and Industry-Academia Collaboration

Capacity building and technical training are essential to equip local engineers, plant operators, and technicians with the skills to effectively design, operate, and maintain adsorption systems. Academic institutions, research institutions, and industry players can work together to support pilot-scale experiments and in-plant demonstrations that validate laboratory results under real-world plant operating conditions [185].

12.1.2. Policy Change and Fiscal Incentives

At the same time, policy and regulatory environments need to be changed to publicly recognize and enable the use of admixture as an acceptable wastewater treatment technology. This includes setting clear emission standards for heavy metals, encouraging regulators to adopt green technologies, and providing fiscal mechanisms such as subsidies or tax incentives to encourage industries to adopt sustainable treatment methods [187, 190].

12.1.3. Innovation in Advanced Adsorbents and Hybrid Systems

The roadmap should facilitate research into next-generation adsorbents, including functional biochar, nano-enabled materials, and composite systems with improved selectivity, capacity, and reusability [188]. Combining hybrid systems—such as electrocoagulation, membrane filtration, or phytoremediation—has also been shown to be beneficial in increasing removal efficiency in complex industrial effluents [189].

12.1.4. Regional Collaboration and Knowledge Transfer

The creation of regional clusters of excellence and innovation in wastewater treatment can foster cross-border collaboration, promote knowledge and technology exchange, and tailor solutions to the environmental, technical, and economic conditions of East Africa [190].

12.1.5. A Path Forward to Sustainable Wastewater Management

By combining technological innovation, regulatory environments, and industrial practices, East Africa can create a sustainable and scalable foundation for heavy metal treatment through ad-based technologies, enabling clean industrialization and long-term environmental resilience.

13. Conclusion and Recommendation

The East African paint industry plays a major role in economic growth but also generates hazardous wastewater containing toxic heavy metals such as lead (Pb), chromium (Cr), cadmium (Cd) and zinc (Zn). The toxins pose significant environmental and public health risks, including environmental pollution, food chain bioaccumulation and long-term health effects such as cancer, neurological syndromes and kidney disorders. Conventional treatment methods such as chemical precipitation are expensive, suboptimal for low metal concentrations, and produce large amounts of sludge, accordingly there is a need to develop sustainable alternatives.

Due to their high efficiency (80-99% removal), cost-effectiveness and ease of use in local conditions, they are the best choice for introduction. Scientific evidence shows that low-cost, locally available materials such as agricultural waste biochar, coconut shell activated carbon and modified clay minerals can be effective in removing heavy metals. Best practice, however, remains challenging in applying adsorption processes to the unique characteristics of East African wastewater, i.e., pH sensitivity, adsorbent regeneration, and size capacity.

This paper emphasizes the need for further research on locally available adsorbents, process improvements, and policy regulations to facilitate large-scale implementation. East African paint industries can achieve green and cost-effective heavy metal treatment by integrating adsorption-based technologies while meeting local requirements. Policymakers, researchers, and industry stakeholders should work together to strengthen monitoring, invest in low-cost technologies, and raise awareness of green treatment options. Ultimately, adopting adsorption techniques will help ensure water resources, protect public health, and promote regional industrial development in an environmentally sustainable manner. To make wastewater treatment more effective and sustainable, some useful recommendations emerge from the analysis. The development of locally available adsorbents should be encouraged first. By applying agricultural and industrial wastes, areas can generate low-cost, effective materials to remove pollutants, converting potential pollutants into useful products.

Secondly, it is necessary to optimize treatment processes through regional inspections. Understanding the optimal conditions for parameters such as pH, dosage, and contact time can greatly improve treatment efficiency and versatility in industrial and local applications. At the same time, regulatory compliance is strengthened. Strict effluent discharge standards, combined with strict monitoring regulations, will drive compliance and force industries to adopt improved wastewater management.

Public-private partnership support is also crucial. Encouraging collaboration between public and private organizations can help unlock new sources of finance and transfer new and advanced technologies to areas of need. Finally, continuous improvement relies on awareness and training. Training stakeholders in sustainable practices builds capacity to implement efficient and sustainable practices.

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