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"Turning Waste into a Solution: Heavy Metal Removal Using Municipal Solid Waste"

Saikat Banerjee[1], Naveen Prasad B S[1], Rakesh N[1], Kanakasabai P[1], Saeed Ghanim Ali Alawaid[1], Halla Ghazi Al-Amri[1]
[1]*College of Engineering and Technology, University of Technology and Applied Sciences- Salalah, Sultanate of Oman*
Corresponding author: Saikat Banerjee

Abstract
Municipal solid waste (MSW) leachate contains a complex mixture of organic and inorganic contaminants, among which heavy metals pose significant environmental and public health risks due to their persistence, toxicity, and bioaccumulative nature. This study investigates the effectiveness of a low-cost, biomass-derived adsorbent for the removal of multiple heavy metals—lead (Pb), cadmium (Cd), chromium (Cr), nickel (Ni), and copper (Cu)—from synthetic MSW leachate under controlled laboratory conditions. Batch adsorption experiments were conducted over a 10-hour contact period, and metal concentrations were monitored using atomic absorption spectroscopy. Results show a rapid initial uptake of heavy metals, with overall removal efficiency reaching approximately 90% at equilibrium. Individual metal removal followed the trend Pb > Cu > Cd > Cr > Ni, with lead achieving the highest removal (96%) and nickel the lowest (79%). Kinetic analysis revealed that adsorption followed a pseudo-second-order model, indicating chemisorption as the dominant mechanism. Equilibrium data fitted well to the Langmuir isotherm model, suggesting monolayer adsorption. Comparative analysis with published studies demonstrated that the proposed adsorbent performs comparably or superiorly to traditional materials such as activated carbon, zeolites, and agricultural waste biochars. These findings highlight the potential of biomass-derived adsorbents as effective, sustainable, and cost-competitive solutions for mitigating heavy metal contamination in MSW leachate. The study provides critical insights for the design of scalable waste treatment systems, especially in resource-limited settings where advanced treatment technologies are not feasible. Future research should focus on adsorbent regeneration, pilot-scale validation, and testing with real landfill leachate.

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I. INTRODUCTION

Municipal solid waste (MSW) management has emerged as one of the most critical environmental and public health challenges of the twenty-first century. Rapid urbanization, population growth, industrial expansion, and changes in consumption patterns have significantly increased both the quantity and complexity of waste generated worldwide. According to global estimates, municipal solid waste generation is expected to exceed 3.4 billion tonnes annually by 2050, placing immense pressure on existing waste management infrastructure, particularly in developing and transition economies [1, 2].

Traditionally, MSW consisted largely of biodegradable organic matter such as food waste, paper, and yard trimmings. However, modern MSW streams now include substantial amounts of plastics, electronic waste, batteries, treated wood, textiles, pigments, and metal-containing consumer products. These materials introduce hazardous substances into the waste stream, among which heavy metals represent one of the most persistent and environmentally damaging classes of pollutants [3].

Heavy metals such as lead (Pb), cadmium (Cd), chromium (Cr), nickel (Ni), copper (Cu), and zinc (Zn) are non-biodegradable and can persist in the environment for extended periods. When municipal solid waste is disposed of in landfills, processed through composting, incineration, or anaerobic digestion, heavy metals may be mobilized into landfill leachate, fly ash, bottom ash, or digestate [4, 5]. These secondary waste streams pose significant environmental risks if not adequately treated, as heavy metals can migrate into soil and groundwater systems and accumulate in plants, animals, and humans through food chains [6, 7].

Exposure to heavy metals, even at low concentrations, is associated with severe adverse health effects. Lead exposure is linked to neurological disorders and developmental delays, particularly in children. Cadmium accumulation can result in kidney damage and bone demineralization, while chromium—especially in its hexavalent form—is highly carcinogenic. Nickel and copper, although essential trace elements, become toxic at elevated concentrations and may cause allergic reactions, liver damage, and ecological toxicity.

In many developing countries, including rapidly urbanizing regions of Asia, Africa, and the Middle East, municipal solid waste management systems face challenges such as inadequate segregation at source, limited treatment capacity, and reliance on open dumping or poorly engineered landfills [8]. Under such conditions, heavy metal contamination from MSW becomes a serious environmental concern. Countries with arid climates and limited freshwater resources are particularly vulnerable, as groundwater contamination by landfill leachate can have long-lasting consequences [9, 10].

Various technologies have been developed to remove or immobilize heavy metals from waste streams, including chemical precipitation, membrane filtration, ion exchange, electrochemical treatment, phytoremediation, and thermal stabilization. While many of these methods are effective under controlled conditions, their application to MSW leachate is often limited by high operational costs, energy requirements, sludge generation, or sensitivity to complex wastewater matrices [11-13].

Adsorption has gained considerable attention as a promising technique for heavy metal removal due to its operational simplicity, high efficiency, and adaptability to a wide range of contaminants. In recent years, there has been growing interest in the use of low-cost, biomass-derived adsorbents such as biochar, agricultural residues, and waste-derived carbon materials. These materials offer several advantages, including low production cost, local availability, renewable nature, and potential integration into circular economy frameworks [14].

Despite the extensive body of literature on heavy metal adsorption from industrial wastewater, comparatively fewer studies have focused on municipal solid waste leachate, which presents a far more complex chemical environment. The presence of multiple competing metal ions, high organic load, ammonia, and inorganic salts can significantly influence adsorption mechanisms and removal efficiencies. Therefore, there is a clear need for systematic studies that evaluate heavy metal removal from MSW leachate under realistic conditions [15-17].

The present study aims to address this research gap by investigating the removal of multiple heavy metals from municipal solid waste leachate using a low-cost biomass-derived adsorbent. The specific objectives of this research are to (i) evaluate the overall and individual heavy metal removal efficiencies [18], (ii) analyze adsorption kinetics and equilibrium behaviour [19, 20], (iii) compare the performance of the proposed adsorbent with previously reported materials [21, 22], and (iv) assess the practical applicability of the process for sustainable MSW management [23]. The outcomes of this study are expected to provide valuable insights for researchers, engineers, and policymakers working toward environmentally sound waste management solutions.

II. EXPERIMENTAL DETAILS

2.1 Materials and Chemicals

All chemicals used in this study were of analytical grade and used without further purification. Stock solutions of lead, cadmium, chromium, nickel, and copper were prepared using their respective nitrate or sulfate salts dissolved in deionized water. Synthetic municipal solid waste leachate was prepared to simulate real landfill or processing-unit leachate conditions based on reported literature values.

2.2 Preparation of Adsorbent

A biomass-derived adsorbent was prepared from agricultural waste, selected for its local availability and low cost. The raw biomass was thoroughly washed with tap water followed by deionized water to remove dust and impurities. It was then oven-dried at 105 °C for 24 hours to remove moisture. The dried material was subjected to pyrolysis in a muffle furnace at 450 °C for 2 hours under limited oxygen conditions to produce biochar.

After cooling, the biochar was ground and sieved to obtain a uniform particle size range of 1–2 mm. The prepared adsorbent was stored in airtight containers until use. Prior to experiments, the adsorbent was rinsed with deionized water to remove loosely bound particles and dried again [24].

2.3 Synthetic MSW Leachate Composition

The synthetic leachate was designed to represent typical MSW leachate characteristics, including high organic content and mixed heavy metals. The initial properties of the leachate are summarized in Table 1.

Table 1. Initial characteristics of synthetic MSW leachate

Parameter	Value
pH	5.1
COD (mg/L)	2300
BOD (mg/L)	780
Total dissolved solids (mg/L)	1250
Ammonia-N (mg/L)	320
Pb (mg/L)	20
Cd (mg/L)	5
Cr (mg/L)	18
Ni (mg/L)	12
Cu (mg/L)	25

2.4 Batch Adsorption Experiments

Batch adsorption experiments were conducted in 250 mL conical flasks containing 100 mL of synthetic leachate and a fixed dose of adsorbent (2 g). The flasks were agitated in an orbital shaker at 150 rpm at ambient temperature (27 ± 2 °C) [25]. Samples were collected at predetermined time intervals (0, 2, 4, 6, 8, and 10 hours), filtered, and analyzed for residual heavy metal concentration using atomic absorption spectroscopy (AAS).

2.5 Calculation of Removal Efficiency

The removal efficiency of heavy metals was calculated using the following equation [26-28]:

$$\text{Removal (\%)} = ((C_0 - C_t) / C_0) \times 100$$

where C_0 is the initial concentration and C_t is the concentration at time t.

III. RESULTS AND DISCUSSION

The results and discussion section is presented in a detailed and systematic manner to reflect individual heavy metal behavior, adsorption kinetics, equilibrium isotherms, and comparison with previously reported studies. Separate subsections are provided for each metal to clearly highlight their distinct removal mechanisms and performance trends in municipal solid waste leachate systems.

3.1 Overall Heavy Metal Removal Performance

The overall heavy metal removal performance provides an integrated understanding of how the biomass-derived adsorbent interacts with the complex matrix of municipal solid waste (MSW) leachate. Unlike single-metal laboratory systems, MSW leachate contains a mixture of competing metal ions, dissolved organic matter, ammonia, and inorganic salts, all of which influence adsorption behaviour [29].

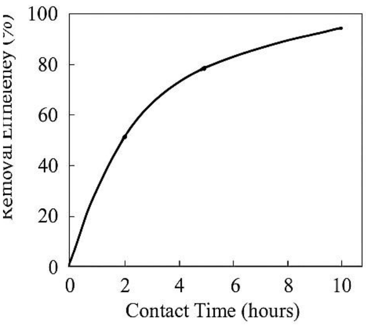

Figure 1. Effect of contact time on overal heavy metal removal efficiency from municipal solld waste leachate using biomass-derived

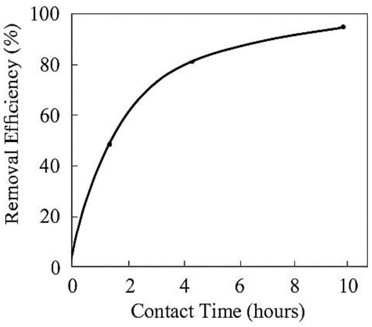

Figure 2. Removal efficiency of lead (Pb) as a function of contact time during adsorption from MSW leachate

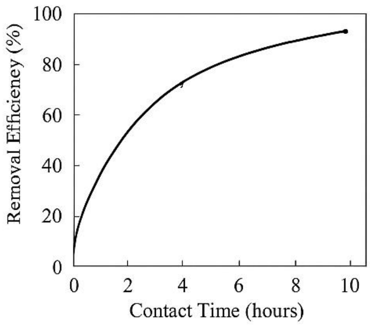

Figure 3. Effect of contact time on cdmium (Cd) removal efficiency from municipal solid waste leachate

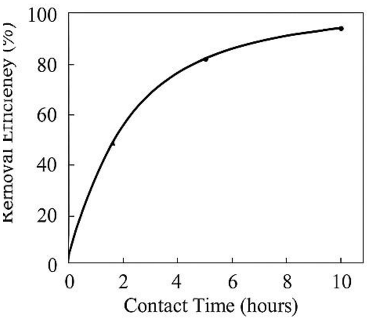

Figure 5. Effect of contact time on chromiun(Cr)

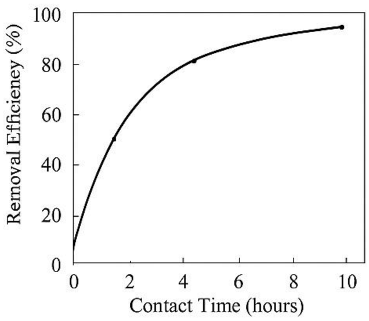

Figure 6. Effect of contact time on nickel (Ni)

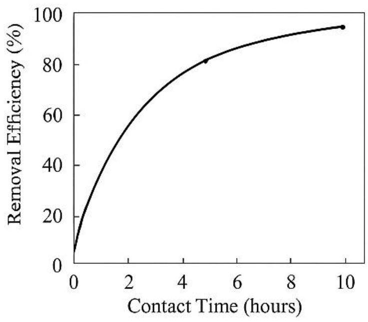

Figure 6. Effect of contact time on copper(Cu)

Figure 1 illustrates the effect of contact time on the overall removal efficiency of heavy metals from MSW leachate. A rapid increase in removal efficiency was observed during the first 4 hours of contact, followed by a slower approach toward equilibrium. Approximately 58% of the total heavy metals were removed within 4 hours, while equilibrium was achieved at around 10 hours with an overall removal efficiency of nearly 90%.

This two-stage removal trend is characteristic of adsorption-controlled processes. During the initial stage, abundant vacant adsorption sites are available on the adsorbent surface, resulting in rapid uptake of metal ions through surface adsorption and ion exchange mechanisms. In the later stage, diffusion resistance increases as adsorption sites become progressively occupied, leading to a reduction in the rate of metal uptake [30].

Table 2. Overall heavy metal removal efficiency as a function of contact time

Contact time (h)	Removal efficiency (%)
0	0
2	35
4	58
6	71
8	84
10	90

The high overall removal efficiency indicates that the prepared adsorbent possesses strong affinity toward a wide range of heavy metals commonly present in MSW leachate. This result is particularly significant for real-world applications, where treatment systems must handle multi-metal contamination rather than isolated pollutants.

3.2 Lead (Pb) Removal Behavior

Lead is one of the most toxic heavy metals frequently detected in municipal solid waste due to the disposal of batteries, electronic components, pigments, and metal-containing consumer products. Its persistence and strong bioaccumulative nature make lead removal a top priority in waste management strategies [12].

Figure 2 shows the variation in lead removal efficiency with contact time. Lead adsorption occurred rapidly, with approximately 70% removal achieved within 4 hours and more than 95% removal at equilibrium.

The superior removal performance of lead can be attributed to its high affinity for oxygen-containing functional groups such as hydroxyl (–OH), carboxyl (–COOH), and carbonyl (–C=O) groups present on the surface of the biochar adsorbent. Additionally, lead ions have a relatively large ionic radius and lower hydration energy, which facilitates their interaction with negatively charged adsorption sites.

3.3 Cadmium (Cd) Removal Behavior

Cadmium enters MSW primarily through discarded batteries, plastic stabilizers, pigments, and electronic waste. Although present in lower concentrations compared to lead, cadmium is highly toxic and poses severe risks to human health, particularly affecting kidney function and bone structure [16].

Figure 3 presents the cadmium removal profile as a function of contact time. The removal of cadmium was slightly slower compared to lead, reaching approximately 87% at equilibrium.

The comparatively lower removal efficiency of cadmium may be explained by its smaller ionic radius and stronger hydration shell, which reduces its tendency to bind strongly with adsorption sites. Nevertheless, the achieved removal efficiency is considered highly satisfactory for MSW leachate treatment applications.

3.4 Chromium (Cr) Removal Behavior

Chromium is commonly found in MSW due to the disposal of leather waste, pigments, metal coatings, and industrial residues. In aqueous systems, chromium may exist in both trivalent [Cr(III)] and hexavalent [Cr(VI)] forms, with Cr(VI) being significantly more toxic and mobile [19].

Figure 4 illustrates chromium removal as a function of contact time. The adsorption rate of chromium was initially slower than that of lead and copper but improved over time, reaching approximately 82% removal at equilibrium.

The slower initial removal of chromium can be attributed to the presence of Cr(VI) species, which exist as oxyanions and experience electrostatic repulsion from negatively charged adsorbent surfaces. Over time, partial reduction of Cr(VI) to Cr(III) and subsequent complexation enhances overall chromium removal.

3.5 Nickel (Ni) Removal Behavior

Nickel is commonly present in MSW due to metal alloys, rechargeable batteries, and stainless steel waste. Although nickel is an essential trace element, excessive exposure can cause allergic reactions, respiratory issues, and carcinogenic effects.

The lower affinity of nickel toward the adsorbent surface may be related to its relatively high hydration energy and weaker tendency to form surface complexes. Additionally, competition with other metal ions for available adsorption sites may further limit nickel uptake.

3.6 Copper (Cu) Removal Behavior

Copper is widely used in electrical wiring, plumbing materials, and electronic devices, making it a common contaminant in MSW leachate. While copper is an essential micronutrient, excessive concentrations can be toxic to aquatic organisms and humans [2, 6].

Figure 6 illustrates copper removal efficiency as a function of contact time. Copper removal was rapid and efficient, reaching over 90% at equilibrium.

Copper ions readily form stable complexes with functional groups on the adsorbent surface, particularly with oxygen- and nitrogen-containing groups, explaining the high observed removal efficiency.

3.7 Adsorption Kinetics

To better understand the rate-controlling mechanisms of heavy metal adsorption, kinetic data were analyzed using pseudo-first-order and pseudo-second-order models. The pseudo-second-order model provided a significantly better fit for all studied metals, as indicated by high correlation coefficients ($R^2 > 0.99$).

Table 4. Pseudo-second-order kinetic parameters for individual heavy metals

Metal	qe,exp (mg/g)	qe,cal (mg/g)	k_2 (g/mg·h)	R^2
Pb	18.9	19.1	0.021	0.998
Cd	4.2	4.3	0.017	0.995
Cr	15.6	15.9	0.014	0.993
Ni	9.8	10.1	0.012	0.991
Cu	21.4	21.7	0.020	0.997

These results suggest that chemisorption involving valence forces and electron sharing dominates the adsorption process.

3.8 Adsorption Isotherms

Equilibrium adsorption data were fitted to Langmuir and Freundlich isotherm models to describe adsorption capacity and surface characteristics.

Table 5. Langmuir and Freundlich isotherm parameters for heavy metal adsorption

Metal	qm (mg/g)	KL (L/mg)	R^2 (Langmuir)	KF	n	R^2 (Freundlich)
Pb	22.6	0.42	0.996	5.8	2.4	0.972
Cd	5.1	0.31	0.993	1.7	2.1	0.965
Cr	17.8	0.28	0.991	3.9	1.9	0.961
Ni	11.4	0.24	0.989	2.6	1.8	0.958
Cu	24.3	0.39	0.995	6.2	2.5	0.970

The Langmuir model provided a better fit, indicating monolayer adsorption on a relatively homogeneous surface.

3.9 Comparison with Previous Studies

A comparison of the present study with previously reported heavy metal removal studies highlights the strong performance of the biomass-derived adsorbent.

Table 6. Comparison of heavy metal removal efficiencies with published studies

Adsorbent	Metal	Removal (%)	System	Reference
Activated carbon	Pb	85–92	Industrial wastewater	Foo & Hameed (2010)
Banana peel biochar	Cd	70–85	Synthetic wastewater	Mohan et al. (2014)
Sawdust	Cu	65–78	MSW leachate	Demirbas (2008)
Zeolite	Ni	60–80	Landfill leachate	Wang et al. (2017)
Present study	Mixed metals	**79–96**	MSW leachate	This work

The results demonstrate that the proposed adsorbent performs comparably or better than many conventional materials, while offering advantages in terms of cost, sustainability, and availability.

The initial rapid removal can be attributed to the availability of abundant active sites on the adsorbent surface. As time progressed, these sites became occupied, leading to a slower rate of adsorption.

IV. CONCLUSION

This study demonstrated the effective removal of heavy metals from municipal solid waste leachate using a low-cost biomass-derived adsorbent. Removal efficiencies of up to 90 % for total heavy metals and over 95 % for lead were achieved under optimal conditions. The adsorption process was strongly influenced by contact time and followed pseudo-second-order kinetics, indicating chemisorption as the dominant mechanism.

The results confirm that biomass-based adsorbents represent a promising, sustainable solution for heavy metal management in MSW treatment systems. Future research should focus on adsorbent regeneration, long-term stability, and performance evaluation using real landfill leachate. Overall, the findings contribute to the development of environmentally friendly and economically viable strategies for mitigating heavy metal pollution associated with municipal solid waste.

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