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Research article

Low-Cost Adsorbents (Potato Peels, Banana Peels and Eggshells) For the Treatment of Heavy Metals from Car Wash Wastewater

Mohammad Ridzuan Mohd Nidzam[1], Mohd Izwan Masngut[1*], Razi Ikhwan Md Rashid & Siti Norashikin Mohamad Shaifuddin[1,2]

[1] *Centre for Environmental Health and Safety Studies, Faculty of Health Sciences, Universiti Teknologi MARA (UiTM) Selangor Puncak Alam Campus, 42300 Puncak Alam, Selangor, Malaysia*
[2] *EcoPharmacovigilance, Universiti Teknologi MARA (UiTM), UiTM Cawangan Selangor, 42300 Puncak Alam, Selangor, Malaysia*

**Corresponding author: izwan7698@uitm.edu.my*

Abstract

Introduction: *The increasing demand for car wash services has led to the discharge of large volumes of wastewater containing heavy metals such as iron (Fe), manganese (Mn), and zinc (Zn) into the public water system. These contaminants primarily originate from the gradual wear of vehicle components such as brake pads, tires, and corroded metallic parts. Such metals pose significant risks to aquatic ecosystems, human health, and environmental sustainability. Conventional treatment methods are often costly and unsustainable, highlighting the need for alternative eco-friendly approaches.* ***Objective:*** *This study evaluated the potential of natural waste-derived biosorbents (banana peels, potato peels, and eggshells) for the removal of heavy metals from car wash wastewater.* ***Methodology:*** *Wastewater samples were collected from five commercial car wash premises and analysed in the laboratory. The biosorbents were processed into three particle sizes (0.5 mm, 1.0 mm, and 2.0 mm) and applied to the wastewater samples. Heavy metal concentrations before and after treatment were determined using Atomic Absorption Spectrometry (AAS), and data were statistically analysed using one-way ANOVA.* ***Results:*** *Among the tested biosorbents, eggshells demonstrated the highest removal efficiencies (dosage of 2.5g/100ml, contact time of 4hrs, pH4 at room temperature), achieving 88.30% for Fe, 54.44% for Mn, and 65.52% for Zn, outperforming Potato peels and banana peels.* ***Conclusion:*** *The findings underscore the potential of natural biosorbents, particularly eggshells, as cost-effective and sustainable alternatives for treating heavy metal-contaminated wastewater from car wash effluents. Adoption of such waste-derived materials may reduce reliance on conventional treatment methods while contributing to environmental protection and resource sustainability.*

Keywords: *biosorbents, carwash, heavy metals, removal efficiency, wastewater*

INTRODUCTION

Car washing is a widely practiced municipal service that requires substantial amounts of freshwater while simultaneously generating large volumes of wastewater (Ghali et al.,2021). On average, each car wash produces between 150–350 liters of wastewater (Mujumdar et al., 2020). The growing number of vehicles has intensified the demand for car wash services, resulting in a significant discharge of wastewater containing heavy metals such as iron (Fe), zinc (Zn), manganese (Mn), and lead (Pb), which pose considerable environmental risks to plants, animals, and humans (Cuput et al., 2024). When present at concentrations above permissible limits, heavy metals can disrupt aquatic ecosystems, bioaccumulate in organisms, and ultimately enter the human food chain, causing long-term health effects including kidney damage and neurological disorders (Briffa et al., 2020; Taslima et al., 2022).

The sources of heavy metal contamination in car wash wastewater are primarily linked to the gradual wear and tear of vehicle components such as brake pads, tyres, and corroded metallic parts (Gupta, V. (2019). For instance, tyres are a notable source of Zn, Cu, and Pb (Jeong, 2022). A study by Anyinkeng et al. (2020) reported Pb and Zn as the most prevalent metals in car wash wastewater, with average concentrations of 0.24 mg/L each, whereas Cu was detected at 0.12 mg/kg. Similarly, Fayed et al. (2023) observed that Zn and Cu are the most common heavy metals present, with concentrations ranging from 0.1–5 mg/L and 0.05–2 mg/L, respectively.

Conventional wastewater treatment methods such as chemical precipitation and ion exchange, although effective, are often economically unfeasible due to their high operational costs, energy demands, chemical usage, and generation of toxic sludge that requires additional disposal (Chakraborty et al., 2022). These limitations underscore the need for alternative treatment strategies that are both sustainable and cost-effective.

Adsorption has emerged as a promising technique for heavy metal removal due to its simplicity, effectiveness, low cost, and environmental compatibility (Chakraborty et al., 2022). The process involves the transfer of metal ions from the liquid phase onto the surface of an adsorbent through physical or chemical interactions, forming a coating of adsorbate on the adsorbent surface (Seleman et al., 2023). Adsorption not only exhibits high efficiency in removing trace levels of heavy metals but also offers advantages such as reversibility, renewability, and design flexibility (Aschale et al., 2021).

In line with the need for sustainable solutions, this study investigates the application of natural byproducts specifically potato peels, banana peels, and eggshells as adsorbents for heavy metal removal from car wash wastewater. Eggshells, composed mainly of calcium carbonate ($CaCO_3$), possess a highly porous structure and negatively charged functional groups that enhance their ion exchange and electrostatic adsorption capacities. Banana peels and potato peels, on the other hand, contain lignocellulosic compounds and functional groups such as hydroxyl (–OH), carboxyl (–COOH), and phenolic groups that can effectively bind metal cations through complexation or surface adsorption.These materials, which are abundantly available as household waste, are inexpensive, biodegradable, and environmentally friendly thus making them ideal for large-scale applications in developing countries.

The objective of this study is to evaluate the efficiency of potato peels, banana peels, and eggshells as natural adsorbents in removing Fe, Zn, and Mn from car wash wastewater. A comparative analysis will be conducted to determine the percentage removal and adsorption efficiency of each material, thereby identifying the most effective low-cost biosorbent for potential large-scale application.

METHODOLOGY

Biosorbent and wastewater collection

The biosorbents used in this study (potato peels, banana peels, and eggshells) were collected (500 g each) from local cafeterias and roadside stalls in Puncak Alam, Selangor, and stored separately in clean polyethylene bags. Car wash wastewater samples were obtained from five commercial car wash premises in the same area. The wastewater was collected in labeled 1 L polyethylene bottles, transported to the laboratory in a cool box, and preserved by adding nitric acid (HNO_3) to adjust the pH to <2 before storage in a chiller at 4°C to prevent precipitation (Chen et al., 2020). As a quality control measure, all wastewater samples were collected exclusively from premises serving petrol vehicles. The sample shall later being compared with Standard B as the sampling area were located outside water catchment zone.

Preparation of biosorbent and batch adsorption experiments

Banana peel (BP), potato peel (PP), and eggshell (ES) were washed thoroughly with distilled water, oven-dried at 90 °C for 24 hours until a constant weight was achieved, ground into powder, and sieved to particle sizes of 0.5 mm, 1 mm, and 2 mm following the procedure described by Notzir et al. (2022). Batch adsorption experiments were then performed to evaluate the adsorption capacity of the biosorbents for heavy metals in car wash wastewater following the method prescribed by Chen et al. (2018), where 2.5 g of biosorption sample were mixed with 100 mL of wastewater (adsorbent-adsorbate mixture) and incubated for 4 hours before undergoing filtration process. The pH was set at 4. Distilled water was used as a control, undergoing the same adsorption process to ensure the reliability of results. The whole process were done at room temperature.

Acid digestion and heavy metals analysis

Wastewater samples (before and after treatment) were digested with nitric acid following the APHA 3030F method prior to analysis. Heavy metal concentrations were determined using Atomic Absorption Spectrometry (AAS, Perkin Elmer PinAAcle 900T).

Data analysis

The percentage removal of heavy metals by each biosorbent was calculated using the formula:

$$\% \text{ Removal} = [(C_i - C_f) / C_i] \times 100$$

Where, C_i is the initial concentration and C_f is the final concentration of the heavy metals. Statistical analysis was conducted using SPSS version 29.0. A one-way ANOVA was performed to compare the adsorption efficiencies among the biosorbents. Statistical significance was set at p<0.05.

RESULTS AND DISCUSSION

The concentrations of iron (Fe), manganese (Mn), and zinc (Zn) in wastewater from five carwash premises (CW1–CW5) in Puncak Alam, Selangor, were analyzed and compared against the Environmental Quality (Industrial Effluent) Regulations 2009 (Standard B for inland waters). Among the three metals, Fe exhibited the highest concentrations across all samples, followed by Zn, while Mn consistently showed the lowest values (Table 1).

Fe concentrations were particularly notable at CW3, which recorded the highest level of 2.413 mg/L. Although this value remained within the Standard B limit of 5.0 mg/L, it was substantially higher than concentrations at CW1, CW2, CW4, and CW5 (0.313–0.833 mg/L). Such variations suggest that site-specific operational practices and wastewater management strategies may significantly influence Fe contamination.

Mn concentrations ranged between 0.025 mg/L (CW1) and 0.090 mg/L (CW3), whereas Zn concentrations were relatively consistent across premises, varying from 0.108 mg/L (CW5) to 0.145 mg/L (CW3). Both metals remained well below the regulatory threshold of 1.0 mg/L for Mn and 2.0 mg/L for Zn, indicating minimal risk of environmental pollution from these contaminants.

These findings align with previous studies, which reported elevated Fe levels as a common feature in carwash effluents due to cleaning agents, vehicle runoff, and metal corrosion (Ghaly et al 2021; and Chuput et al., 2024). While Mn and Zn contamination appears negligible, the elevated Fe concentration at CW3 underscores the importance of regular monitoring and implementing targeted treatment strategies to reduce localized environmental impacts.

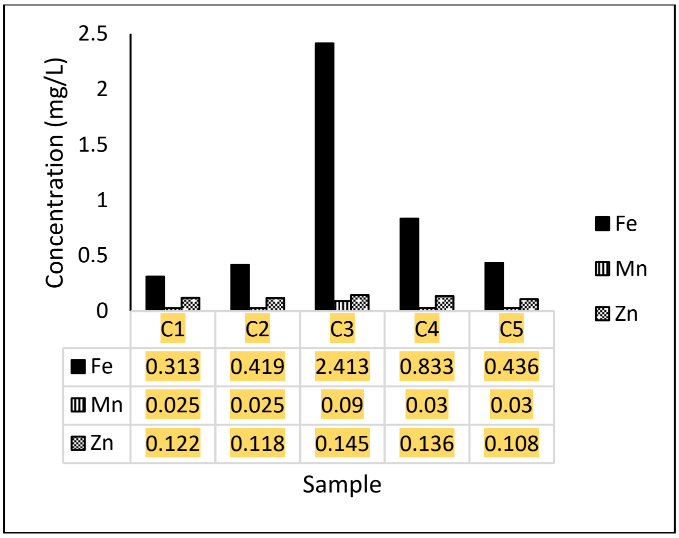

Figure 1: Heavy Metal (Fe, Mn and Zn) Concentration from the Car Wash Premises in Puncak Alam, Selangor
Note: All the value is within the limit for Standard B Environmental Quality (Industrial Effluent) Regulations 2009

The average concentrations of Fe, Mn, and Zn in wastewater from the five carwash premises revealed clear disparities in contamination levels (Figure 1). Iron exhibited the highest mean concentration (0.8828 mg/L), largely influenced by the elevated level at CW3 (2.413 mg/L). Although this average remains within the Standard B limit of 5.0 mg/L, the localized peak at CW3 highlights the potential for site-specific pollution. In comparison, Mn showed a low mean concentration of 0.04 mg/L, with the highest value of 0.090 mg/L (CW3) still well below the Standard B limit of 1.0 mg/L. Similarly, Zn displayed a uniform distribution across all premises, with an average of 0.1458 mg/L, far below the permissible threshold of 2.0 mg/L. These findings suggest that Fe is the primary contaminant of concern, whereas Mn and Zn pose minimal environmental risk in the study area.

Given the elevated heavy metal levels at CW3, wastewater from this site was selected for adsorption experiments. Three biosorbents—banana peels (BP), potato peels (PP), and eggshells (ES)—were tested at particle sizes of 0.5 mm, 1.0 mm, and 2.0 mm. Adsorption efficiencies were evaluated for Fe, Mn, and Zn and compared with Standard B limits (Table 2). Among the biosorbents, eggshells consistently demonstrated the highest removal efficiency across all metals, followed by potato peels and banana peels. These results confirm the potential of low-cost agricultural waste materials, particularly eggshells, as effective adsorbents for mitigating heavy metal contamination in carwash effluents.

The adsorption efficiencies of Fe, Mn, and Zn using banana peels (BP), potato peels (PP), and eggshells (ES) at different particle sizes (0.5, 1.0, and 2.0 mm) are presented in Table 2. The results demonstrate distinct variations in adsorption performance across biosorbents and particle sizes.

Table 2: Adsorption Percentages for Heavy Metals

Adsorbent	Particle Size (mm)	Adsorption (%)		
		Fe	Mn	Zn
BP	0.5	77.92	10.00	2.07
BP	1.0	75.01	5.56	4.14
BP	2.0	65.26	3.33	1.38
PP	0.5	75.01	21.11	4.14
PP	1.0	73.98	13.33	12.41
PP	2.0	74.03	16.67	2.07
ES	0.5	87.20	53.33	60.00
ES	1.0	85.51	52.22	65.52
ES	2.0	88.33	54.44	57.93

BP – Banana Peels, PP – Potato Peels , ES – Egg Shells

BP exhibited its highest Fe removal (77.92%) at 0.5 mm, with efficiency decreasing at larger particle sizes, likely due to the reduction in surface area and available active sites. However, its adsorption of Mn and Zn remained very low, indicating limited affinity of banana peels for these ions.

PP showed relatively stable Fe adsorption (73–75%) across particle sizes, reflecting consistent performance, possibly due to its fibrous structure. For Mn and Zn, adsorption was modest, with Mn peaking at 21.11% (0.5 mm) and Zn at 12.41% (1.0 mm), suggesting selective but limited adsorption potential.

In contrast, ES consistently outperformed BP and PP for all metals. Fe adsorption remained high across particle sizes (85–88%), while Mn reached a maximum of 54.44% (2.0 mm). Zn adsorption peaked at 65.52% (1.0 mm), highlighting the strong affinity of eggshells for both Mn and Zn ions. The superior performance of ES is attributed to its calcium carbonate composition, which provides abundant active sites and facilitates ion exchange mechanisms.

To statistically evaluate the differences in adsorption efficiencies, Analysis of Variance (ANOVA) was applied to the particle size with the highest removal for each biosorbent. Using a significance threshold of $p < 0.05$, the results (Table 3) confirmed that ES had significantly higher adsorption capacities compared to BP and PP. This reinforces the potential of eggshells as the most effective low-cost biosorbent for heavy metal removal from carwash wastewater.

Table 3: Results of Adsorption Efficiency of Different Types of Adsorbents on Selected Heavy Metals Comparison

Comparison	Metal	Mean Difference (%)	p-value
BP vs ES	Fe	14.2833	0.0103*
BP vs PP	Fe	1.61	0.8732
ES vs PP	Fe	-12.6733	0.0177*
BP vs ES	Mn	47.0333	0*
BP vs PP	Mn	10.74	0.012*
ES vs PP	Mn	-36.2933	0*
BP vs ES	Zn	58.62	0*
BP vs PP	Zn	3.6767	0.5306
ES vs PP	Zn	-54.9433	0*

*Significant (p <0.05)

Experimental evidence further supports the superior adsorption performance of eggshells compared with other agricultural wastes. Statistical analysis confirmed that eggshells (ES) were the most effective biosorbent for Fe, Mn, and Zn removal compared to banana peels (BP) and potato peels (PP). For Fe, ES significantly outperformed BP and PP, with mean differences of 14.28% ($p = 0.0103$) and 12.67% ($p = 0.0177$), respectively, while no significant difference was observed between BP and PP ($p = 0.8732$). The highest Fe removal efficiency (88.33% at 0.5 mm particle size) was achieved by ES, attributed to its high $CaCO_3$ content, large surface area, and porous structure that facilitate ion exchange and electrostatic adsorption as explained by Chakraborty R. (2022). In contrast, BP showed moderate Fe adsorption (65–78%), likely limited by fewer active binding sites and lower porosity (Hossain et al., 2012;Seleman et al., 2023), while PP exhibited relatively stable adsorption (74–75%) due to fibrous structures and functional groups such as carboxyl and hydroxyl, although still less efficient than ES (El-Azazy et al., 2019; Ashfaq et al., 2021). Across all biosorbents, smaller particle sizes produced higher adsorption efficiencies, highlighting the crucial role of surface area in enhancing metal uptake (Hamood et al 2025).

For Mn and Zn, the same trend was observed. ES achieved the highest adsorption efficiencies, significantly surpassing BP and PP (Mn: mean difference = 47.03%, $p < 0.0001$; Zn: $p < 0.0001$), while PP performed slightly better than BP for Mn removal ($p = 0.012$), suggesting some selective affinity related to its surface chemistry. Under optimal conditions, ES removed 54.44% Mn and 65.52% Zn, confirming its superior sorption performance.

Ion exchange effects of absorbent materials

Structurally, eggshells consist mainly of calcium carbonate ($CaCO_3$), with smaller proportions of calcium phosphate and an organic matrix containing proteins and polysaccharides (Chowdhury et al., 2020). These constituents provide functional groups such as carbonate (CO_3^{2-}), hydroxyl (–OH), and carboxyl (–COOH), which serve as active sites for metal ion binding. In the ion exchange process, divalent metal cations, such as Pb^{2+}, Cd^{2+}, Cu^{2+}, Zn^{2+}, Fe^{2+}, and Mn^{2+} in wastewater replace calcium ions (Ca^{2+}). This mechanism involves both surface adsorption and chemical substitution within the eggshell matrix, forming insoluble metal carbonates or surface complexes (Guru et al., 2014; Harripersadth, C. (2021). The porous microstructure of eggshells as compared to potato peels and banana peels also enhances this process by increasing surface area and the accessibility of reactive sites.

Electrostatic attraction

Alongside ion exchange, electrostatic attraction acts as a complementary mechanism that initiates metal ion adsorption. The eggshell surface bears numerous negatively charged sites, mainly derived from carbonate and hydroxyl groups, which attract positively charged metal ions through Coulombic forces (Guru et al, 2014). The strength of this attraction is strongly influenced by the solution pH. Under acidic conditions, hydrogen ions (H^+) compete with metal cations for binding sites, diminishing the net surface charge and weakening electrostatic attraction. Conversely, at neutral to slightly alkaline pH, deprotonation of surface functional groups increases negative charge density, thereby enhancing cation adsorption (Wang et al 2013).

Overall, the synergistic effects of ion exchange and electrostatic attraction endow eggshells with a high affinity for heavy metal cations, resulting in greater removal efficiency than other natural biosorbents. This dual mechanism underscores the potential of eggshells as a sustainable and effective material for wastewater remediation, transforming a common agricultural waste into a valuable environmental resource.

Quantitative comparisons with previous studies

Results from this study were compared with others to further validate the findings. Chakraborty et al. (2020) reported Fe(II) removal of 90.5% using powdered eggshell at pH 6.5, closely aligning with the current Fe removal of 88.33% while Tariq et al. (2018) observed 78% Fe, 62% Mn, and 69% Zn removal using calcined eggshells. In contrast, Afolabi et al. (2021) recorded Fe(II) adsorption of 70–80% with modified banana peel, and Ashfaq et al. (2021) reported Fe(II) removal of 73% by raw potato peel and up to 82% after modification, corresponding closely with the 74–75% removal in this study. Similarly, Harripersadth, C. (2021) reported Mn and Zn removal efficiencies of 50–70% using eggshell-derived $CaCO_3$ materials, consistent with current results of 54.44% and 65.52%, respectively.

Collectively, the findings establish eggshells as the most robust biosorbent for heavy metal removal, with superior adsorption efficiency and stability across particle sizes. PP showed moderate performance, while BP was the least effective, particularly for Mn and Zn.

CONCLUSION

This study demonstrates the potential of natural biosorbents derived from domestic waste for the removal of heavy metals from carwash wastewater. Among the tested materials, eggshells (ES) exhibited the highest adsorption efficiency for Fe, Mn, and Zn, followed by potato peels (PP) and banana peels (BP). These findings highlight the viability of eggshells as a low-cost, eco-friendly, and sustainable alternative to conventional wastewater treatment methods, owing to their high calcium carbonate content, porous structure, and strong ion exchange and electrostatic properties.

However, the present study was limited to batch adsorption experiments. In addition, kinetic and isotherm analyses were not conducted, which are essential for understanding adsorption rates, equilibrium behavior, and binding capacities of heavy metals on biosorbent surfaces.

Future studies should therefore focus on optimizing adsorption parameters such as dosage, contact time, and temperature, while also performing kinetic and isotherm modelling to better explain adsorption mechanisms. Moreover, pilot-scale and continuous-flow investigations are recommended to evaluate the practical scalability of eggshell-based biosorbents.

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