EEET ECOLOGICAL ENGINEERING & ENVIRONMENTAL TECHNOLOGY

Ecological Engineering & Environmental Technology, 2026, 27(2), 305–314
https://doi.org/10.12912/27197050/216363
ISSN 2719–7050, License CC-BY 4.0

Received: 2025.12.05
Accepted: 2026.01.13
Published: 2026.02.07

Assessment of adsorption parameters of zinc and copper from landfill leachate using *Gracilaria changii*

Nur Amanina Azmir[1*], Shreeshivadasan Chelliapan[1], Mohd Farizal Ahmad Kamaroddin[2], Aznah Nor Anuar[3], Nur Syamimi Zaidi[4], Fatehah Mohd Omar[5]

[1] Department of Smart Engineering and Advanced Technology, Faculty of Artificial Intelligence, Universiti Teknologi Malaysia, Jalan Sultan Yahya Petra, 54100, Kuala Lumpur, Malaysia
[2] Department of Biosciences, Faculty of Science, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia
[3] Disaster Preparedness and Prevention Centre, Malaysia-Japan International Institute of Technology, Universiti Teknologi Malaysia, Jalan Sultan Yahya Petra, 54100, Kuala Lumpur, Malaysia
[4] Centre for Environmental Sustainability and Water Security (IPASA), Universiti Teknologi Malaysia (UTM), 81310 Johor Bahru, Johor, Malaysia
[5] School of Civil Engineering, Universiti Sains Malaysia, Nibong Tebal, 14300, Pulau Pinang, Malaysia
* Corresponding author's e-mail: amanina@graduate.utm.my

ABSTRACT

Landfill leachate contains complex mixtures of organic matter and toxic heavy metals that pose significant environmental and public health risks; therefore, this study aimed to evaluate the potential of *Gracilaria changii*, a locally available red seaweed, as a low-cost and sustainable biosorbent for zinc (Zn^{2+}) and copper (Cu^{2+}) removal from real landfill leachate. Batch adsorption experiments were conducted using leachate collected from Jeram Landfill, Malaysia, which was spiked with Zn^{2+} and Cu^{2+} to ensure controlled concentrations, and the effects of key operational parameters including pH (2.5–8.0), biosorbent dosage (5–25 g), and contact time (30–180 min) were systematically investigated using a jar test apparatus at room temperature. The results demonstrated that pH significantly influenced biosorption performance, with maximum removal efficiencies of 71.89% for Zn at pH 2.5 and 44.50% for Cu at pH 5.5. Increasing the *G. changii* dosage enhanced metal removal due to the greater availability of active binding sites, achieving optimum removals of 99.14% for Zn and 80.75% for Cu at a dosage of 25 g. Adsorption efficiency increased with contact time and reached equilibrium between 150 and 180 min for both metals, indicating favorable biosorption kinetics. Although the study was limited to batch-scale laboratory experiments and focused on two heavy metals, the findings provide strong evidence of the biosorption capability of *G. changii* under controlled conditions. The use of this seaweed presents practical value as an environmentally friendly and cost-effective alternative to conventional adsorbents, with potential for integration into existing landfill leachate treatment systems. Notably, this study represents the first reported application of *Gracilaria changii* for Zn and Cu removal from real landfill leachate, offering original and significant insights into seaweed-based biosorption for sustainable wastewater treatment.

Keywords: landfill leachate, seaweed, *Gracilaria changii*, bio-adsorbent, heavy metals.

INTRODUCTION

Municipal solid waste (MSW) refers to the everyday waste generated from households, businesses, and institutions. In Malaysia, MSW management remains a significant environmental concern, with the country producing approximately 38,427 metric tons of waste daily, equivalent to 1.17 kg per capita (MIDA, 2022). About 82.5% of this waste is disposed of in landfills, most of which are non-sanitary, leading to pollution and sustainability challenges. Food waste, plastics, and paper make up the majority of MSW, representing 31%, 22%, and 15%, respectively

(Fatimah, 2023). Despite efforts to improve recycling, over 65% of waste in Malaysia still ends up in landfills (Hassan, 2024). Properly engineered sanitary landfills are designed to prevent groundwater contamination, manage leachate, and control gas emissions, yet many existing sites exceed their capacity and pose environmental risks due to poor infrastructure and limited enforcement of regulations (Hussein et al., 2021).

Leachate is the contaminated liquid that forms when rainwater percolates through decomposing municipal solid waste (Afolabi et al., 2022). Its composition varies depending on landfill age, waste type, and environmental factors such as temperature and moisture (Mojiri et al., 2021). Typically, leachate contains high levels of organic and inorganic compounds, ammonium, and toxic heavy metals like Zn, Cu, Pb, Cd, and Cr (Josfirin et al., 2024). These substances pose serious threats to soil, groundwater, and aquatic ecosystems. In Malaysia, the Department of Environment (DOE) regulates leachate discharge under the Environmnetal Quality (Sewage) Regulations (2009), which set limits for pH (5.5–9.0), COD (200 mg/L), and heavy metals like mercury (0.001 mg/L) and cadmium (0.01 mg/L). Younger landfills generally produce more biodegradable leachate with higher COD and BOD levels, while older ones generate stabilized leachate with lower pollutant concentrations but increased humic substances (Lindamulla et al., 2022).

Leachate treatment typically involves a combination of physical, chemical, and biological processes, often used in conjunction for enhanced efficiency (Aziz and Ramli, 2018). Biological treatments, such as aerobic and anaerobic systems, use microorganisms to degrade organic pollutants, achieving COD and ammonia removal rates above 90% (Mojiri et al., 2021). Physical treatments include adsorption using activated carbon, membrane filtration (reverse osmosis, nanofiltration, ultrafiltration, microfiltration), and sedimentation, which effectively remove suspended solids and heavy metals (Siddiqi et al., 2022). Chemical methods like coagulation-flocculation, air stripping, and advanced oxidation processes (AOPs) are also common, but can produce sludge and incur high energy costs (Aragaw and Bogale, 2023). In Malaysia, integrated treatment systems combining these approaches are increasingly adopted to improve pollutant removal while minimizing operational costs and environmental impact (Kumara and Dayanthi, 2023).

Seaweed, or macroalgae, comprises multicellular marine organisms classified into brown (Phaeophyta), red (Rhodophyta), and green (Chlorophyta) groups (UNCTD, 2024). Seaweed's functional groups, which are carboxyl, hydroxyl, sulphate, and amino, allow it to bind heavy metals effectively, making it a promising biosorbent for wastewater treatment (Foday et al., 2021). Several studies have explored the use of seaweed for heavy metal removal from wastewater, particularly from landfill leachate (Pandya et al., 2017; Ali et al., 2020; Arumugam and Chelliapan, 2021; Selvam et al., 2019). Beyond industrial applications in food and pharmaceuticals, seaweed offers a sustainable, low-cost alternative to activated carbon for pollutant removal (Pereira and Cotas, 2024). Studies show red algae like *Gracilaria changii* can achieve significant removal of heavy metals through adsorption (Arumugam and Chelliapan, 2021).

The primary objective of this study is to explore the effectiveness of the naturally occurring seaweed *Gracilaria changii* in removing heavy metals, specifically Zn and Cu, from real landfill leachate. The study aims to determine the adsorption capabilities of *G. changii* under varying conditions of pH, adsorbent dosage, and contact time through controlled batch experiments. The key scientific goal is to generate new insights into the biosorption potential of *Gracilaria changii*, which has not previously been investigated for Zn and Cu removal in real leachate matrices. In addition, this research seeks to fill a significant gap in the current body of knowledge, as no prior studies have reported on the application of *Gracilaria changii* for the treatment of actual landfill leachate. The study is designed to uncover previously unknown relationships between experimental conditions and removal efficiencies, thereby improving the understanding of biosorption mechanisms involving marine macroalgae. It is hypothesized that *Gracilaria changii* possesses a high natural affinity for Zn and Cu ions, and that its biosorption capacity can be significantly influenced by operational parameters. It is expected that the results will not only validate this hypothesis but also support the development of *Gracilaria changii* as a cost-effective, environmentally sustainable biosorbent. Ultimately, the findings aim to contribute toward the advancement of eco-friendly technologies for heavy metal remediation in complex wastewater systems.

MATERIALS AND METHODS

Landfill leachate

The landfill leachate used in this study was collected from Jeram Landfill, Selangor, Malaysia. Figure 1 shows the landfill leachate collection pond. The samples were collected directly from the leachate discharge point, stored in a sealed high-density polyethylene (HDPE) bottles, and preserved at 4 °C to maintain their physicochemical integrity.

Metal solution

To ensure controlled metal concentrations for adsorption studies, the leachate was spiked with zinc (Zn^{2+}) and copper (Cu^{2+}) ions. The spiking process was essential to achieve the desired metal concentrations, as certain heavy metals were present at insufficient levels in the raw leachate. Stock solutions (100 mg/L) were freshly prepared daily using analytical-grade reagents from Merck, where zinc and copper powders were dissolved in hydrochloric acid (HCl) and nitric acid (HNO_3), respectively, and subsequently diluted with distilled water. All prepared solutions were stored at 4 °C until used for experimental work to ensure chemical stability and reproducibility.

Characterization of leachate

The leachate was characterised for its key parameters such as pH, COD, BOD, ammoniacal nitrogen, color, and heavy metal content. A calibrated pH meter (model: Accumet Portable, AP 61, Fisher Scientific) with values obtained was accurate to ± 0.02 units, according to APHA (2005) Method No. 4500-H+ B, was used to measure the pH. Heavy metal concentrations (Zn^{2+} and Cu^{2+}) in both untreated and treated leachate were determined using ICP-OES (model: Optima 8300), according to APHA Method 3111. The instrument was calibrated using multi-element standard solutions, and only calibration curves with $R^2 > 0.995$ were accepted. Blank and verification standards were analyzed periodically to ensure quality control. Chemical oxygen demand (COD) was measured according to APHA (2005) Method 5220 using the Standard Closed Reflux Method. A 2 mL filtered sample was added to a HACH reflux vial containing potassium dichromate and mercury sulfate, sealed, and refluxed for 2 hours at 150 °C in a HACH COD reactor. Leachate color before and after treatment was analyzed using APHA (2205) Method 2120 with a spectrophotometer to assess compliance with DOE standards.

Preparation of the adsorbent

The red macroalgae *Gracilaria Changii* was collected from a cultivation pond in Kota Kuala Muda, Kedah, Malaysia. The biomass was thoroughly washed with tap water followed by distilled water to remove salts and impurities, then oven-dried at 70 °C for 24 hours. The dried seaweed was ground and sieved to obtain powder with particle sizes ranging from 150 to 300 μm. A comprehensive characterization of the adsorbent was carried out to determine its physicochemical properties, including ash, crude fat, crude fiber, protein, moisture, and mineral composition, using standard analytical methods. Additional analyses, such as fatty acid profiling, pigment quantification, and vitamin content determination, were performed to evaluate the biochemical constituents relevant to its adsorption behavior. Figure 2 shows the cleaned seaweed, the dried seaweeds, and crushed seweed.

Figure 1. Actual photo of the leachate collection pond in Jeram Landfill, Selangor, Malaysia

Figure 2. (a) Cleaned *Gracilaria changii* before drying; (b) Oven-dried G. changii; (c) *Gracilaria changii* crushed into powder

Characterization of *Gracilaria changii*

The dried *Gracilaria changii* powder was analyzed for particle size, surface morphology, and mineral composition. Proximate analyses were conducted following standard methods. Ash content was determined gravimetrically after low-temperature oxidation at 550 °C for 18 hours. Crude fat was extracted using the Soxhlet method with petroleum ether and quantified after drying the extract at 80 °C. Crude fiber was measured using sequential acid–alkali hydrolysis (1.25% H_2SO_4 and 1.25% NaOH), followed by drying and weighing the residue. Moisture content was obtained by oven-drying samples at 60 °C to constant weight. Protein content was determined using the Kjeldahl method, and total protein was calculated by multiplying nitrogen content by 6.25. Nitrogen-free extract (NFE) was calculated using:

$$NFE\ (\%) = 100 - (ash + crude\ fat + crude\ fiber + protein) \tag{1}$$

For mineral analysis, freeze-dried samples were digested with concentrated HNO_3, $HClO_4$, and H_2SO_4, filtered, and analyzed using ICP-AES with a multi-element standard. Fatty acids were extracted using a direct-transmethylation method with methanol/DCM/HCl and analyzed by gas chromatography–FID. Pigment analysis (β-carotene, xanthophylls, and chlorophylls) involved solvent extraction with acetone–methanol, centrifugation, partitioning with diethyl ether, and HPLC-MS/MS detection. Fat-soluble vitamins (A, D, E, and K) were extracted following lipid saponification with methanolic KOH and analyzed by HPLC equipped with a C18 column. Vitamin C was quantified by iodine titration. Particle size distribution of the dried seaweed powder was determined using an Endecotts EFL 2000 sieve shaker.

Adsorption study

The objective of the preliminary investigation was to determine the optimal operating conditions for heavy metal adsorption using *Gracilaria changii*. Maximum removal efficiency was defined as the highest percentage of Zn^{2+} and Cu^{2+} removed under each operating condition. Batch adsorption experiments were conducted at room temperature using a jar test apparatus. A jar test was used in this study for the batch experiments as shown in Figure 3. The effects of pH (2.5–8, adjusted with 2 M NaOH or 2 M HCl), adsorbent dosage (5–25 g), and contact time (30–180 min) were evaluated. Table 1, 2, and 3 shows the details experimental conditions for each parameter evaluated.

Figure 3. Jar test experiment for adosorption study

Table 1. Experimental condition during the study of the effect of pH

pH of leachate solution	Leachate volume (mL)	Heavy metals	Heavy metal concentration (mg/L)	Mass of *Gracilaria changii* (g)	Contact time (min)	Rotational speed (rpm)
2.5, 3.5, 5.5, 6.5, 8	200	Zn^{2+}	20	10	180	100
2.5, 3.5, 5.5, 6.5, 8	200	Cu^{2+}	20	10	180	100

Table 2. Experimental condition during the study of the effect of dosage

pH of leachate solution	Leachate volume (mL)	Heavy metals	Heavy metal concentration (mg/L)	Mass of *Gracilaria changii* (g)	Contact time (min)	Rotational speed (rpm)
Previous result	200	Zn^{2+}	20	5, 10, 15, 20, 25	180	100
Previous result	200	Cu^{2+}	20	5, 10, 15, 20, 25	180	100

Table 3. Experimental condition during the study of the effect of contact time

pH of leachate solution	Leachate volume (mL)	Heavy metals	Heavy metal concentration (mg/L)	Mass of *Gracilaria changii* (g)	Contact time (min)	Rotational speed (rpm)
Previous result	200	Zn^{2+}	20	Previous result	30, 60, 100, 150, 180	100
Previous result	200	Cu^{2+}	20	Previous result	30, 60, 100, 150, 180	100

For each experiment, 1200 mL of leachate containing ±20 mg/L of heavy metals was prepared, and 200 mL of this solution was transferred into 500 mL beakers. A control sample without seaweed was maintained to determine the initial metal concentrations for QA/QC. The solutions were stirred at 100 rpm at 25 ± 1 °C. After the adsorption period, samples were filtered using Whatman No. 40 filter paper, and ICP-OES (Optima 8300) analyze the filtrates. Removal efficiency was calculated based on the amount of metal adsorbed per gram of biosorbent at equilibrium, (mg g^{-1}), using the following equation:

$$q_e = \frac{(C_i - C_e) \times V}{m} \quad (2)$$

where: C_i and C_e are the initial and equilibrium metal concentrations (mg/L), V is the solution volume (L), and m is the dry mass of *Gracilaria changii* (g).

Statistical analysis

Descriptive statistics were applied to summarize and present the experimental data, including measures such as mean values and standard deviations to describe the central tendency and variability of the results. To evaluate the significance of differences between groups, a comparative analysis was conducted using the t-test. This statistical test was employed to determine whether there was a statistically significant difference between the means of two groups under different experimental conditions. A p-value of less than 0.05 ($p < 0.05$) was considered statistically significant, indicating that the observed differences were unlikely to have occurred by chance

RESULT AND DISCUSSION

Characteristics of landfill leachate

The characterization results of the raw leachate, as presented in Table 1, indicate that the leachate collected from the Jeram landfill exhibits properties typical of an intermediate to stabilized leachate. The measured pH of 7.98 falls within the Department of Environment (DoE) Malaysia's allowable discharge range (5.5–9.0), signifying a near-neutral condition. The temperature of 32 °C is also within the acceptable limit of 40 °C, suggesting minimal thermal variation during collection. However, several other parameters exceeded the permissible limits, demonstrating the leachate's high pollution load. The chemical oxygen demand (COD) and biochemical oxygen demand (BOD) values were 2304 mg/L and 834 mg/L, respectively, far above the allowable discharge limits of 200 mg/L and 20 mg/L, indicating the presence of a substantial amount of biodegradable and non-biodegradable organic matter. Likewise, the colour intensity (11800 ADMI) and ammoniacal nitrogen concentration (638 mg/L) greatly surpassed the discharge limits of 80 ADMI and 5 mg/L, confirming the leachate's high organic strength and ammoniacal contamination, typical of aged landfill leachate (Table 4).

In contrast, the concentrations of targeted heavy metals, zinc (Zn) and copper (Cu), were measured at 0.05 mg/L and 0.02 mg/L, respectively, which are well below the allowable discharge limits of 2.0 mg/L (Zn) and 0.2 mg/L (Cu). Although the heavy metal concentrations were within permissible limits at the time of sampling, leachate characteristics can vary significantly depending on factors such as landfill age, waste composition, and rainfall conditions. Therefore, to evaluate the adsorption performance of *Gracilaria Changii* under controlled and representative conditions, the leachate was artificially spiked with additional Zn^{2+} and Cu^{2+} ions to achieve measurable concentrations suitable for adsorption studies. This approach ensured that the experimental setup accurately reflected the adsorption capacity and removal efficiency of the seaweed under various controlled parameters, allowing for a comprehensive evaluation of its potential in leachate treatment applications.

Characteristics of *Gracilaria changii*

The characterization results of the *Gracilaria changii*, as presented in Table 2 revealed that the proximate and biochemical analysis in *Gracilaria changii* contained a high moisture content of 89.9%, which is typical for fresh seaweed biomass. Although further drying at higher temperatures could reduce the moisture content, this approach is not recommended as it may degrade valuable phytochemical and bioactive compounds. The analysis also indicated that trace amounts of heavy metals such as Fe, Mn, Cu, and Zn are naturally present in minimal concentrations, suggesting that the seaweed is safe and suitable for environmental and adsorption applications.

In addition, *Gracilaria changii* exhibited a rich composition of minerals, pigments, and essential fatty acids, including omega-3 and omega-6, enhancing its nutritional and medicinal value. The presence of β-carotene pigments contributes to the characteristic coloration of the seaweed, while chlorophyll pigments play a

Table 4. Characteristics of landfill leachate

Parameter	Unit	Value	Allowable discharge Limit
pH	-	7.98	5.5–9.0
Temperature	°C	32	40
COD	mg/L	2304	200
BOD	mg/L	834	20
Colour	ADMI	11800	80
Ammoniacal nitrogen (AN)	mg/L	638	5.0
Zinc (Zn)	mg/L	0.05	2.0
Copper (Cu)	mg/L	0.02	0.2

crucial role in photosynthesis and possess significant therapeutic and antioxidant properties. These attributes highlight the potential multifunctional use of *Gracilaria vhangii* in both environmental remediation and bioproduct development. For adsorption experiments, the seaweed biomass was ground and sieved to a particle size range of 150–300 μm, a size range that was consistently used throughout this study (Table 5).

Effect of pH

The pH level of leachate is a crucial factor in determining the maximum adsorption capacity of an adsorbent, as it directly affects metal solubility, the adsorbent's surface charge, and the ionization of functional groups on cell walls. To evaluate this relationship, an investigation was conducted by varying the leachate pH from 2.5 to 8 to observe its influence on metal ion removal efficiency, as illustrated in Figure 1. The results revealed that Cu achieved its highest removal efficiency at pH 5.5, with a maximum percentage removal of 44.50%, while Zn exhibited a gradual yet stable removal trend throughout the pH range. Interestingly, zinc removal exhibited a gradual improvement as the pH increased, with the lowest percentage removal (69.05%) detected at pH 8, down from a maximum of 71.89% at pH 2.5. These findings are consistent with previous research showing that the biosorption capacity of red seaweed generally improves with increasing pH, primarily due to enhanced availability of negatively charged binding sites that promote the attraction of positively charged metal ions.

The effect of pH on biosorption is fundamentally governed by the competition between hydrogen ions (H^+) and metal ions for the same adsorption sites. At low pH values, the high concentration of H^+ ions suppress metal ion adsorption by occupying the negatively charged functional groups, such as carboxyl, hydroxyl, and amine groups, on the *Gracilaria changii* surface (Isam et al., 2019). As the pH increases, these groups undergo deprotonation, leading to a more negatively charged adsorbent surface, which enhances the electrostatic attraction between metal cations and the biosorbent. This mechanism explains the improvement in copper removal efficiency at moderately acidic to near-neutral pH, where binding site accessibility and electrostatic interactions are most favourable (Sumaiya et al., 2014). In contrast, zinc's relatively stable adsorption trend across different pH values suggests that factors beyond surface charge, such as ionic size or coordination properties, also play a role in determining its affinity toward the seaweed surface (Figure 4).

Table 5. Characteristic of *Gracilaria changii*

Analysis	Result
Ash	4.8%
Crude fat	0.6%
Crude fiber	4.3%
Moisture	89.9%
Nitrogen free extract	4.0%
Protein (N × 6.25)	0.9%
Fatty acid composition:	Per 100 g:
Omega 3	5 mg
α-Linolenic acid	5 mg
Eicosapentaenoic acid	0 mg
Docosahexaenoic acid	0 mg
Omega 6:	75 mg
Linolenin acid	35 mg
ɣ-Linolenic acid	0 mg
Dihomo -ɣ- Linolenic acid	0 mg
Arachidonic acid	40 mg
Pigments	
B-Carotane	25.8 mg
Xanthophyll	2.4 mg
Chlorophyll	5.5 mg

Effect of seaweed dosage

Seaweed dosage is essential because it directly influences the efficiency of heavy metal removal in biosorption processes. Increasing the dosage of seaweed provides more active sites for metal ions to bind, resulting in greater uptake and improved purification rates for contaminated water. The graph illustrates the relationship between seaweed dosage and the percentage removal of Zn and Cu from leachate solutions using *Gracilaria changii* under optimized pH conditions, which is 5.5 for copper and 2.5 for zinc. As seaweed dosage increases from 5 g to 25 g, both metals show improved removal efficiencies. Zinc removal exhibits a significant increase from 44.62% at 5 g dosage to almost complete removal at 99.14% for 25 g dosage. Copper removal also follows an upward trend, starting at 65.99% and reaching 80.75% at the highest seaweed dosage.

The data in Figure 2 indicate that the biosorption capacity of *Gracilaria changii* enhances

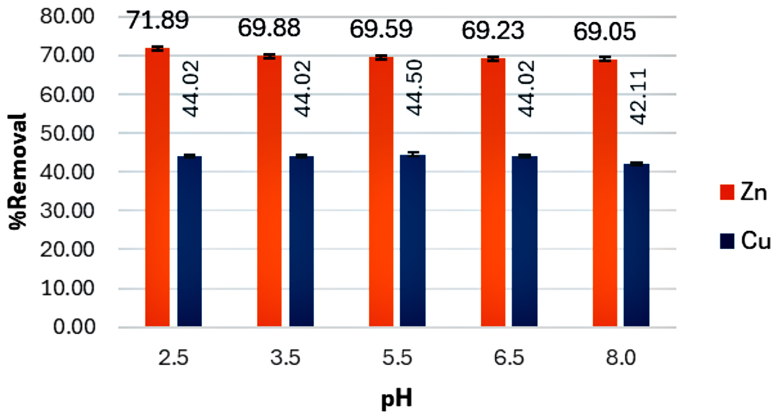

Figure 4. Effect of pH on the removal of Zn and Cu

with higher biomass availability, providing more active sites for metal binding. This positive correlation suggests that increasing the biosorbent dosage improves the interaction between the seaweed's functional groups and metal ions, resulting in higher heavy metal uptake (Znad et al., 2022). The difference in removal efficiency between zinc and copper could be attributed to the intrinsic binding affinity differences and metal speciation at the optimal pH. Zinc shows a sharper increase in removal, suggesting a stronger or more accessible binding mechanism to the seaweed biomass at low pH. Copper, while still showing a clear enhancement, has a more graduated increase, likely influenced by different ionization states and competition at the biosorption sites (Figure 5).

Effect of contact time

Contact time is a critical variable in biosorption studies because it determines how long the adsorbent is exposed to heavy metal ions, directly influencing the overall removal efficiency and uptake capacity (Ávila et al., 2025). Sufficient contact time allows for optimal interaction between the adsorbent's active sites and metal ions, enhancing adsorption before saturation or equilibrium is reached. The graph in Figure 3 depicts the effect of contact time on the percentage removal of Zn and Cu from leachate solutions using *Gracilaria changii* under optimized pH (5.5 for copper and 2.5 for zinc) and fixed seaweed dosage (25g). Zinc removal shows a substantial increase from 85.33% at 30 minutes to nearly complete removal (~94.89%) at 150 minutes, after which it plateaus through to 180 minutes. Copper removal also demonstrates a clear increasing trend, starting at 54.35% at 30 minutes and reaching 68.84% after 180 minutes.

The data suggest that extended contact time promotes greater metal uptake by the seaweed until an equilibrium state is reached. This increase in removal efficiency with time can be attributed to the biosorption process, where initially abundant

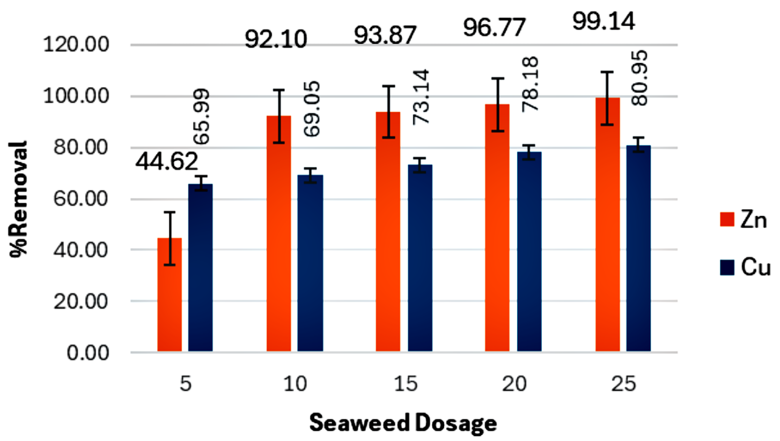

Figure 5. Effect of seaweed dosage on the removal of Zn and Cu

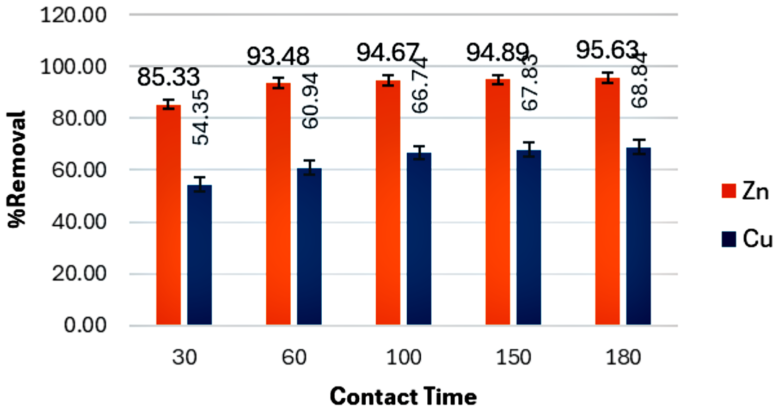

Figure 6. Effect of contact time on the removal of Zn and Cu

active sites on the *Gracilaria changii* biomass rapidly adsorb available metal ions (Fawzy, 2020). As time progresses, these sites become saturated, and the rate of uptake slows, resulting in the observed plateau in removal percentages. Zinc reaches near-complete removal more quickly than copper, implying stronger or faster biosorption kinetics for zinc under these conditions, which may be related to differences in metal ion properties or affinity for binding sites on the seaweed (Figure 6).

CONCLUSIONS

Based on the experimental results across all graphs, this study demonstrates that *Gracilaria changii* is an effective biosorbent for removing heavy metals from leachate solutions, with removal efficiencies strongly impacted by pH, seaweed dosage, and contact time. Optimal pH conditions maximized biosorption, as confirmed by the highest removal rates for copper and zinc at pH 5.5 and 2.5, respectively. Increasing the dosage of seaweed markedly enhanced metal removal, attributed to the greater availability of active binding sites, until a point of diminishing returns when maximal adsorption was approached. Furthermore, the removal efficiency for both copper and zinc increased with longer contact times, reaching equilibrium after 150–180 minutes, indicating the importance of allowing sufficient interaction time for maximum biosorption. These findings are consistent with biosorption kinetic models and support the need to optimize operational variables for industrial-scale applications. Overall, the synergy between pH control, appropriate biomass dosage, and adequate contact time enables *Gracilaria changii* to remove harmful metals from leachates efficiently. The study provides a scientific basis for employing red seaweed as a sustainable and cost-effective solution in environmental management, contributing to safer water discharge and aligning with regulatory standards for heavy metal contamination.

Acknowledgements

We would like to acknowledge the financial support from the Ministry of Higher Education Malaysia (MOHE) through the Fundamental Research Grant Scheme (Reference Code: FRGS/1/2024/TK08/UTM/01/5), and Universiti Teknologi Malaysia (Vote Number: R.K130000.7857.5F716).

REFERENCES

1. American Public Health Association (APHA) (2005). *Standard Methods for the Examination of Water and Wastewater (21st ed., 1220 p)*. Washington DC: American Public Health Association.
2. Afolabi, O. O., Wali, E., Ihunda, C., Orji, M. C., Emelu, V. O., Bosco-Abiahu, L. C., Ogbuehi, N. C., Asomaku, S. O., Wali, O. A. (2022). Potential environmental pollution and human health risk assessment due to leachate contamination of groundwater from anthropogenic impacted site, *Environmental Challenges*, *9*, 100627. https://doi.org/10.1016/j.envc.2022.100627
3. Ali, H. S., Kandil, N. F. E. S., Ibraheem, I. B. M. (2020). Biosorption of pb2+ and cr3+ ions from aqueous solution by two brown marine macroalgae: An equilibrium and kinetic study. *Desalination and Water Treatment*, *206*, 250–262. https://doi.org/10.5004/dwt.2020.26314
4. Aragaw, T. A., Bogale, F. M. (2023). Role of coagulation/flocculation as a pretreatment option to reduce

colloidal/bio-colloidal fouling in tertiary filtration of textile wastewater: A review and future outlooks, *Frontiers in Environmental Science, 11*, 1142227. https://doi.org/10.3389/fenvs.2023.1142227

5. Arumugam, N., (2021). *Treatment performance of heavy metals in landfill leachate using gracilaria changii*. PhD Thesis, Universiti Teknologi Malaysia, Malaysia.
6. Ávila, F. G., Cabrera-Sumba, J., Valdez-Pilataxi, S., Villalta-Chungata, J., Valdiviezo-Gonzales, L., Alegria-Arnedo, C. (2025). Removal of heavy metals in industrial wastewater using adsorption technology: Efficiency and influencing factors. *Cleaner Engineering and Technology, 24*, 100879. https://doi.org/10.1016/j.clet.2025.100879
7. Aziz, H. A., Ramli, S. F. (2018). Recent development in sanitary landfilling and landfill leachate treatment in Malaysia. *International Journal of Environmental Engineering*, *9*(3/4), 201. https://doi.org/10.1504/ijee.2018.10018737
8. Environmnetal Quality (Sewage) Regulations (2009). (accessed on 12 September 2024) Available online:
9. https://www.doe.gov.my/wpcontent/uploads/2021/08/Environmental_Quality_Sewage_Regulations_2009_-_P.U.A_432- 2009.pdf.
10. Fatimah, Z. (2023). *The high price of not recycling*. TheStar. (accessed on 19 December 2023). Available online: https://www.thestar.com.my/news/nation/2023/12/19/the-high-price-of-not-recycling
11. Fawzy, M. A. (2020). Biosorption of copper ions from aqueous solution by Codium vermilara: Optimization, kinetic, isotherm and thermodynamic studies, *Advanced Powder Technology*, *31*(9), 3724–3735. https://doi.org/10.1016/j.apt.2020.07.014
12. Foday, E. H., Bo, B., Xu, X. (2021). Removal of toxic heavy metals from contaminated aqueous solutions using seaweeds: A review, *Sustainability, 13*(21). https://doi.org/10.3390/su132112311
13. Hassan, H. (2024). *Waste incinerator plan sparks protests, highlights Malaysia's landfill shortage*. (accessed on 29 January 2024). Available online: https://www.straitstimes.com/asia/se-asia/waste-incinerator-plan-sparks-protests-highlights-malaysia-s-landfill-shortage
14. Hussein, M., Yoneda, K., Mohd-Zaki, Z., Amir, A., Othman, N. (2021). Heavy metals in leachate, impacted soils and natural soils of different landfills in Malaysia: An alarming threat, *Chemosphere*, *267*, 128874. https://doi.org/10.1016/j.chemosphere.2020.128874
15. Josfirin, U. R., Sharifah, N. S. I., Irniza, R., Karmegam, K. (2024). Estimation of leachate volume and treatment cost avoidance through waste segregation programme in Malaysia. *Pertanika Journal of Science & Technology*, *32*(1), 339–364. https://doi.org/10.47836/pjst.32.1.19
16. Kumara, K. K. P. S., Dayanthi, W. K. C. N. (2023). Waste materials composited intoãnãdsorbent for landfill leachate treatment. *Journal of Water and Health*, *21*(12), 1871–1897. https://doi.org/10.2166/wh.2023.310
17. Lindamulla, L., Nanayakkara, N., Othman, M., Jinadasa, S., Herath, G., Jegatheesan, V. (2022). Municipal solid waste landfill leachate characteristics and their treatment options in tropical countries, *Current Pollution Reports, 8*, 273–287. https://doi.org/10.1007/s40726-022-00222-x
18. Mojiri, A., Zhou, J. L., Ratnaweera, H., Ohashi, A., Ozaki, N., Kindaichi, T., Asakura, H. (2021). Treatment of landfill leachate with different techniques: An overview, *Journal of Water Reuse and Desalination*, *11*(1), 66–96. https://doi.org/10.2166/wrd.2020.079
19. Pandya, K., Patel, R., Jasrai, R., Brahmbhatt, N. (2017). Optimization of Cr and Cu biosorption by green marine algae *Caulerpa racemosa*Var. Cylindracea & Ulva lactuca. *International Journal of Advanced Research*, *5*(8), 923–939. https://doi.org/10.21474/IJAR01/5138
20. Pereira, L., Cotas, J. (2024). Seaweed: a sustainable solution for greening drug manufacturing in the pursuit of sustainable healthcare, *Exploration of Drug Science*, *2*(1), 50–84. https://doi.org/10.37349/eds.2024.00036
21. Selvam, S. B., Chelliapan, S., Din, M. F. M., Kamyab, H., Albati, S. K., Othman, N., Yuzir, A., Nasri, N. S. (2019). Landfill leachate treatment by an anaerobic process enhanced with recyclable uniform beads (RUB) of seaweed species of Gracilaria. *Desalination and Water Treatment*, *143*, 208–216. https://doi.org/10.5004/dwt.2019.23520
22. MIDA (2021). *Waste to Energy for A Sustainable Future*. MIDA e-Newsletter December 2021. Available online: https://www.mida.gov.my/waste-to-energy-for-a-sustainable-future/
23. Siddiqi, S. A., Al-Mamun, A., Baawain, M. S., Sana, A. (2022). A critical review of the recently developed laboratory-scale municipal solid waste landfill leachate treatment technologies. *Sustainable Energy Technologies and Assessments*, *52*(Part A), 102011. https://doi.org/10.1016/j.seta.2022.102011
24. UNCTD (2024). *An ocean of opportunities : the potential of seaweed to advance food, environmental and gender dimensions of the SDGs*. United Nations Publications, Geneva.
25. Znad, H., Awual, M. R., Martini, S. (2022). The utilization of algae and seaweed biomass for bioremediation of heavy metal-contaminated wastewater, *Molecules, 27*(4) 1275. https://doi.org/10.3390/molecules27041275