EEET ECOLOGICAL ENGINEERING & ENVIRONMENTAL TECHNOLOGY

Ecological Engineering & Environmental Technology, 2026, 27(9), 391–403
https://doi.org/10.12912/27197050/226163
ISSN 2719–7050, License CC-BY 4.0

Received: 2026.07.13
Accepted: 2026.08.03
Published: 2026.08.15

Removal of copper(II) ion using modified guava (*Psidium guajava* L.) leaves powder as a biosorbent in synthetic wastewater

Cristopher Bombane Parmis[1*], Jenilie Granado Velasco[1], Diana Rose Berongoy Bridio[1*], Shaira Mae Solitario Hernane[1], Jackielyn Jurado Lopera[1]

[1] Technological University of the Philippines-Taguig, East Service Road Western Bicutan, Taguig City, Philippines
* Corresponding author's e-mail: dianarosebridio@gmail.com

ABSTRACT

The elevated concentration of copper (II) ions in wastewater has become a serious environmental and public health concern, highlighting the need for affordable and efficient treatment methods. In this study, modified guava leaf powder was utilized as a biosorbent for the removal of Cu^{2+} ions from synthetic wastewater. The guava leaves were treated sequentially with sodium hydroxide and tartaric acid to enhance their surface properties and improve adsorption performance. The prepared biosorbent was characterized using scanning electron microscopy (SEM) and Fourier transform infrared spectroscopy (FTIR), along with iodine number analysis to evaluate surface area and porosity. Batch adsorption experiments were conducted to assess the influence of operational variables, including pH levels (4, 7, and 10), contact time (30, 45, and 60 minutes), and biosorbent dosage (0.4, 0.7, and 1.0 g). Optimization of the adsorption process was performed using response surface methodology (RSM) combined with a Box-Behnken Design. A quadratic model was developed to describe the relationship between the independent variables and Cu^{2+} removal efficiency, showing strong statistical validity and close agreement between predicted and experimental values. Optimal conditions were identified at pH 7, a contact time of 45 minutes, and a biosorbent dosage of 0.7 g, achieving a maximum copper removal efficiency of 97.122% with a desirability value of 1.000. Kinetic analysis indicated that the adsorption followed a pseudo-second-order model (R^2 = 0.9998), suggesting that chemisorption played a dominant role in the process. Isotherm studies further showed that the Freundlich model (R^2 = 0.5864) provided a better fit compared to the Langmuir model, implying that adsorption occurred on a heterogeneous surface. Overall, the results demonstrate that modified guava leaf powder is a promising, and sustainable biosorbent for effective removal of copper ions from wastewater.

Keywords: adsorption, characterization, modelling, optimization, sustainability, treatment.

INTRODUCTION

Industrial activities have significantly intensified environmental pollution, especially with rapid urbanization and the continuous expansion of manufacturing industries. As a result, large quantities of pollutants are discharged into natural water systems, leading to the degradation of water quality. Wastewater refers to water that has been contaminated through domestic, commercial, or industrial activities [Aghalari et al., 2020]. These effluents are commonly released into rivers, streams, lakes, ponds, estuaries, and oceans, contributing to widespread aquatic pollution [Qasem et al., 2021]. Wastewater treatment involves the removal of contaminants from sewage or industrial effluents before they are discharged into receiving water bodies such as rivers and seas [Aghalari et al., 2020].

The increasing concentration of heavy metals in wastewater is largely attributed to industrial growth and changing human consumption patterns [Razzak et al., 2022]. Although some metals may not be highly toxic in large forms, even trace amounts can pose serious health and environmental risks [Razzak et al., 2022]. Heavy metals are non-biodegradable, allowing them to persist in the environment for long periods. They can accumulate in living organisms and become more concentrated as they move up the food chain [Vidu et al., 2020]. The presence of toxic heavy metals in water and soil is a major environmental issue that threatens both ecosystems and human health [Das and Poater, 2021]. Due to their stability and ability to dissolve and spread easily, these metals can disperse across ecosystems and cause harmful effects even at low concentrations [Qasem et al., 2021].

In response to these concerns, several wastewater treatment methods have been developed, including chemical precipitation, membrane filtration, ion exchange, and adsorption. Among these techniques, adsorption is widely preferred because of its simplicity and high effectiveness in removing trace heavy metals from aqueous solutions [Raji et al., 2023]. Recently, biosorption using low-cost agricultural and plant-based materials has gained attention as a sustainable alternative for heavy metal removal. Plant-derived adsorbents such as leaves, fruit peels, and agricultural waste are commonly studied due to their availability, biodegradability, and surface functional groups that enhance metal adsorption [Elkhaleefa et al., 2021]. Furthermore, chemical modification of these biosorbents can improve their adsorption capacity by increasing surface area and introducing additional active binding sites [Abegunde et al., 2020].

The study aims to evaluate the effectiveness of guava leaves in removing Cu^{2+} from synthetic wastewater. The project aims to create an eco-friendly method for removing heavy metals from wastewater, thereby protecting both the environment and human health.

METHODOLOGY

Materials and reagents

This study investigated the effectiveness of guava leaves as a biosorbent for the removal of Cu^{2+} ions from wastewater. The biosorbent was chemically modified using tartaric acid ($C_4H_6O_6$) to enhance its adsorption properties, followed by treatment with sodium hydroxide (NaOH). In addition, NaOH and hydrochloric acid (HCl) solutions were used for pH adjustment during the preparation and experimental process. The guava leaves were dried using a Daihan Scientific oven and then ground into powder form using a mortar and pestle. The pH of the solutions was measured using a calibrated pH meter. The modified guava leaf powder was characterized to evaluate its properties as a biosorbent. Scanning electron microscopy (SEM) was used to examine surface morphology, Fourier transform infrared spectroscopy (FTIR) was employed to identify functional groups, and the iodine number method was used to estimate surface area.

Preparation of biosorbent

The guava leaves were gathered at Lipa Batangas. The process of the biosorbent used. Only expanded guava leaves to achieve the high quality and homogeneity. To remove supernatant particles, running water was applied to the collected leaves. They were rinsed off with distilled water to eliminate any remaining impurities. In a hot oven, the leaves were dried to approximately 100 °C. Guava leaves powder (GLP) was kept in a desiccator to prevent moisture loss [Gupta et al., 2023].

Alkali modification

GLP was treated to alkali treatment to improve its adsorption efficiency and enhance its interaction with the adsorbent material [Gupta et al., 2023]. This modification increased the availability of alkaline functional groups and altered the surface properties toward a more non-polar character, which can improve the adsorption of certain target molecules [Abegunde et al., 2020]. The treatment also influenced the surface charge behavior of the adsorbent, which may enhance the attraction of oppositely charged species during adsorption. For the preparation process, 8 g of GLP was treated with 200 mL of 0.1 N sodium hydroxide (NaOH) solution [Olawale et al., 2022]. The mixture was stirred for 10 minutes and then left to stand for 24 hours to ensure sufficient chemical interaction. After treatment, the solution was filtered using a funnel to remove excess alkaline solution and residual lignin-containing compounds. The resulting modified guava leaf powder was dried in an oven at 75 °C for 12 hours and then stored in a desiccator to prevent moisture absorption [Gupta et al., 2023].

Acid modification

This modification of the biosorbent increased its surface acidity while reducing the overall mineral content [Rehman et al., 2019]. In addition, it enhanced the presence of oxygen-containing functional groups on the surface, which contributed to the formation of more negatively charged sites. These negatively charged sites improve the adsorption of positively charged species through electrostatic attraction [Rehman et al., 2019]. For the acid treatment process, 2 g of alkali-modified guava leaf powder (GLP) was dispersed in 14 mL of 1.0 M tartaric acid ($C_4H_6O_6$) and allowed to react to achieve further surface modification. After treatment, the sample was thoroughly washed using 250 mL of distilled water to remove any residual acid. The biosorbent was then oven-dried for 12 hours at 75 °C. Finally, the dried GLP was stored in a desiccator to maintain its stability and prevent moisture absorption.

Characterization of biosorbent

Scanning electron microscopy

The surface morphology of the modified guava leaf powder was examined using SEM. Prior to imaging, the samples were sputter-coated with a thin layer of gold–palladium to enhance conductivity. During analysis, the coated specimens were placed inside the SEM chamber and subjected to progressively increasing accelerating voltages to obtain detailed surface images [Raji et al., 2023].

Fourier transform infrared spectroscopy

The modified guava leaves powder was analyzed with its wavelength around 3500 to 1500 cm^{-1}. The modified guava leaves powder was measured by using spectrophotometers to measure the concentration of hydroxyl or carboxylic acid group and other functional groups that contain oxygen [Buenaño et al., 2024].

Iodine number

Samples (0.4, 0.7, and 1.0 g) were transferred into 250 mL flasks and treated with 10 mL of 5% hydrochloric acid (HCl), then gently boiled for 30 seconds. After cooling, 50 mL of 0.100 N iodine solution was added, and the mixture was agitated for 15 minutes [Hoàng and Quyen, 2024]. The solution was then filtered, and a 10 mL aliquot was diluted to 100 mL using distilled water. The diluted sample was titrated using 0.100 N sodium thiosulfate until a pale yellow color was observed. Afterwards, 2 mL of starch indicator was added, and titration was continued until the solution became colorless [Hoàng & Quyen, 2024].

Preparation of synthetic wastewater

A 100 mL beaker, dissolved 1 g of copper (II) sulphate to produce 1000 mg/L. Once the mixture was prepared, it was transferred to a 1 L volumetric flask and diluted [Rukayat et al., 2021].

Experimental layout for optimization

In this study, the selected variables are pH, contact time, and biosorbent dosage, which were taken for optimization. The parameters were established to ensure the effective adsorption of copper (II) in wastewater. The experimental runs (Table 1) evaluates the effects of pH, contact time, and biosorbent dosage on the removal efficiency of Cu^{2+} ions. The experiments are systematically conducted using pH levels of 4, 7, and 10, contact times of 30, 45, and 60 minutes, and biosorbent dosages of 0.4, 0.7, and 1.0 g to determine their influence on the biosorption of copper (II) ions using modified guava leaf powder.

Batch adsorption experiment

The efficacy of the adsorbents on Cu^{2+} removal from synthetic wastewater was assessed from batch experiments [Gupta et al., 2023]. For these experiments, 50 mL of Cu^{2+} at initial concentration of 50 ppm was placed in a 100 mL Erlenmeyer flask. To make sure the removal of Cu^{2+}, batch adsorption was achieved with different doses of guava leaves powder, specifically 0.4 g, 0.7 g, and 1.0 g. The pH of the samples was adjusted to 4, 7, and 10 using 0.1 N sodium hydroxide (NaOH) and 0.1 N hydrochloric acid (HCl). The mixtures were then agitated at different contact times of 30, 45, and 60 minutes at a constant stirring speed of 160 rpm using a magnetic stirrer [Gupta et al., 2023]. The percentage removal of Cu^{2+} ions was determined using an atomic absorption spectrophotometer (AAS).

Determination of metal removal efficiency

The uptake of metals may also be in the form of percentage of metal removal which is obtained as:

Table 1. Experimental runs for Box-Behnken design in copper (II) ion biosorption

Factors	Unit	Levels		
		-1	0	1
pH		4	7	10
Contact time	min	30	45	60
Biosorbent dosage	g	0.4	0.7	1.0

$$Removal\ Efficiency\ (\%) = \left(\frac{Co - Ce}{Co}\right) \times 100 \quad (1)$$

where: Co represents initial concentration (ppm), and Ce represents the equilibrium concentration (ppm) [Shah et al., 2021].

Kinetic studies

To evaluate the adsorption rate of Cu^{2+} ions, the samples were agitated using a mechanical shaker operating at 160 rpm for contact times of 10, 20, 30, 45, and 60 minutes. After, it was filtered. The copper ions was analyzed using AAS [Shah et al., 2021]. The PFO and PSO have been used to investigate the specific contact times. These models were considered qualified for understanding the kinetics of heavy metal adsorption onto guava leaf [Raji et al., 2023].

Isotherm studies

The adsorption isotherm study was carried out using pH, biosorbent dosage, and contact time. Batch adsorption tests were performed with an initial concentration of Cu^{2+} at 50, 70, 90,

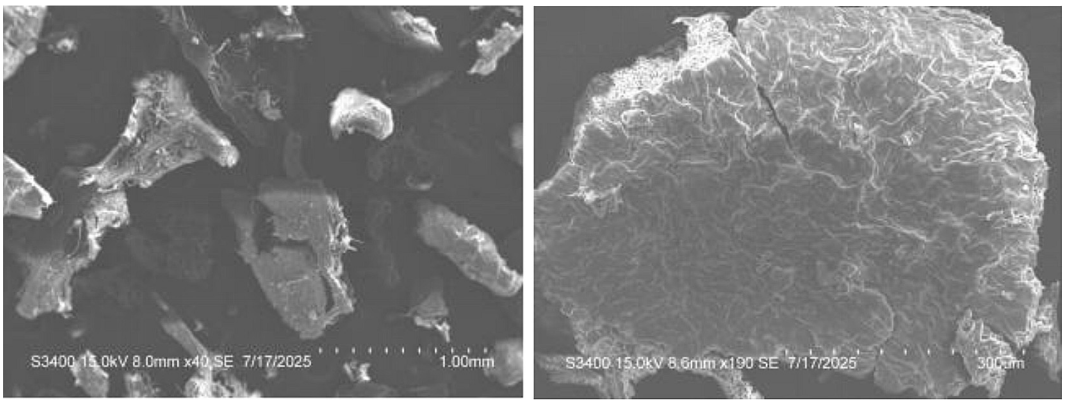
110, and 150 mg/L. All samples were agitated at 160 rpm. All the isotherm experiments were conducted at the ambient temperature (25–30 °C). This temperature was selected as it is similar to ambient temperature that is expected and is also used in most biosorption studies [Smoczyński et al., 2020]. The literature states that adsorption processes may be either endothermic or exothermic and the temperature effect differs according to the biosorbent system and adsorbate system [Smoczyński et al., 2020]. Other studies have discovered that mild heating enhances adsorption by raising the molecular mobility, and opening the binding sites [Smoczyński et al., 2020]. After treatment it was measured using of AAS [Al Ali et al., 2021].

RESULTS AND DISCUSSION

Characterization of the guava leaves powder

Scanning electron microscopy

Images from the SEM analysis at different magnifications are presented in Figures 1–3. The micrographs show the morphological changes brought about by tartaric acid–NaOH treatment, which improve the surface characteristics of the biosorbent, including increased surface area, better pore accessibility, and a greater number of active binding sites for metal adsorption.



(a) (b)

Figure 1. SEM of guava leaves powder altered with NaOH and tartaric at: (a) x40, (b) x190

The surface in Figure 1a is rough and uneven with visible cracks and peeling, which means that it is structurally damaged because of chemical treatment. This augments surface area, and offers routes of absorption of copper ions. Figure 1b reveals layered and flake like structures that were produced with the help of acid induced removal of hemicellulose and swelling of the alkaline fibers. Such modifications leave more adsorption sites unoccupied making the biosorbent have greater capacity to hold copper.

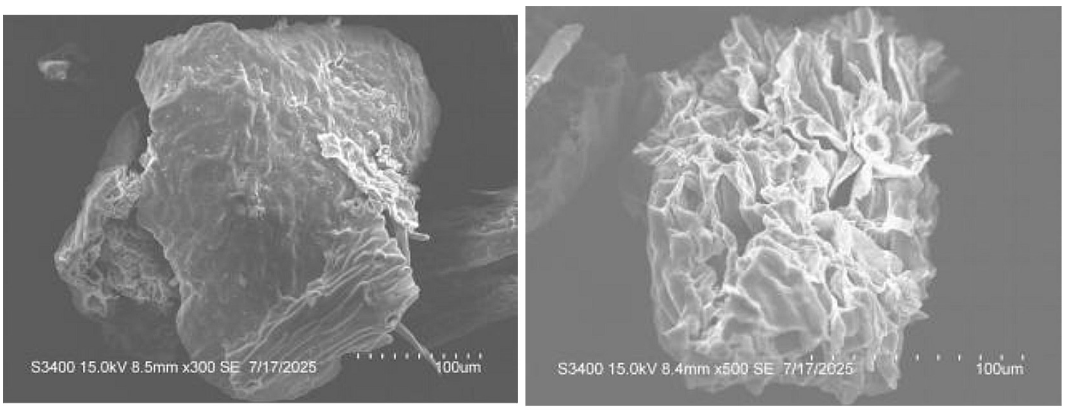
Figure 2a at higher magnification shows a large number of holes, grooves, and fractures on the biosorbent surface implying that the structure has undergone a lot of degradation. These holes open avenues through which copper react with the material through a physical adsorption mechanism or ion exchange mechanism or through a complexation mechanism which enhances adsorption. In Figure 2b, the surface is more fractured with ridges and valleys which are probably the remains of vascular structures that have been chemically treated. The increased roughness and irregularity provide more binding sites, One reason the tartaric acid-NaOH modification was efficient in improving the biosorbent's surface properties is because it showed how well this method improve the capping of copper.

In Figure 3a, a granulated surface is depicted with microcracks and roughness, This is an indication of surface deterioration, which increases the number of adsorption sites and binding sites for copper, as shown by the exposed -OH and -COOH groups. Figure 3b shows porous and discontinuous structure that bears micropores, which increases the transport of ions and surface area. These traits are suggestive of high biosorption efficacy and good chemical activation. The SEM images explicitly illustrate that the tartaric acid-NaOH change made a tremendous impact on the structure of the guava leaves powder creating the roughness of the leaf surfaces, holes, fibre swelling, and fragmentation.

Fourier transform infrared spectroscopy

The GLP NaOH, and GLP Tartaric and GLP NaOH-Tartaric spectra showed broadening of peaks and lower energy, which showed structural change (Figure 4). The huge peaks at 3278, 3307, and 3523 cm -OH stretching, indicating that the number of hydroxyl groups on GLP NaOH-Tartaric increases following alkali modification. These clusters serve as metal binding sites of heavy metal because they form lone pairs and hydrogen bonds [Abegunde et al., 2020]. The -OH and -NH groups that are the subjects of adsorption through complexity, chelation, or hydrogen bonding have the range of 3200–3600 cm^{-1} [Abegunde et al., 2020].

The highest peak at 3008 cm^{-1} is an indication that C-H of lignin or arboreal phenolics, which add to structural specificity and adsorption [Rehman et al., 2019]. The -COOH (C=O stretching) is associated with metal coordination and it appears in the 1714 cm^{-1} band. C=O vibrations indicate that it is conjugated and are confirmed by the presence of C=O vibrations at 1683-1685 cm^{-1} in conjugated systems, which are essential in the binding of metals [Olawale et al., 2022]. Lastly, aromatic C=C bands at 1514–1562 cm^{-1} mean the presence of phenolic structures.



(a) (b)

Figure 2. Scanning electron microscopy of guava leaves powder modified with NaOH and tartaric: (a) x300, (b) x500 magnification

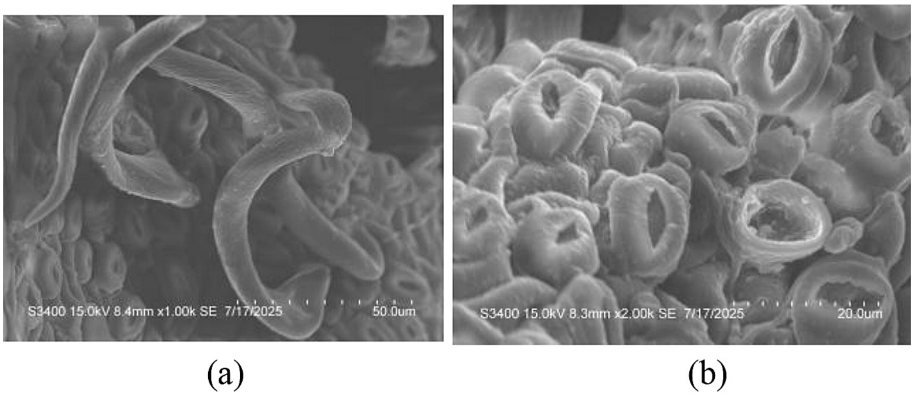


Figure 3. SEM guava leaves powder modified with NaOH and tartaric at: (a) 1000 × magnification, (b) 2000 × magnification

Iodine number

It is calculated by the quantity of iodine absorbed in the solution when adsorbing, which makes it a direct measure of the ability of biosorbent [Foo and Hameed, 2021]. The iodine content of biosorbents commonly ranges between 300 to 600 mg/g (untreated or low-activation), between 600 to 900 mg/g, and between 900 to 1200 mg/g or higher in terms of iodine concentration in extremely porous and chemically modified adsorbents [Foo and Hameed, 2021]. Moreover, effective biosorbents tend to have the residual concentration of iodine between 0.01 and 0.06 N which is the concentration of iodine that still stays in the solution after adsorption. While the amount of iodine inside the solution decreases, the iodine adsorption increases hence this value negatively correlates to the fee of iodine number [Hassan et al., 2020].

Table 2 illustrates the modified guava leaves powder iodine number and iodine remaining following various treatments. Guava leaves modified with NaOH-tartaric contained the greatest amount of average iodine concentration (925.33 mg/g) which reflects the most extensive growth of pore and surface area. It also contained the least residual iodine meaning that it had more uptake capacity. The values of the RSD (1.53–3.74%) are good in terms of precision and reproducibility.

Efficiency of copper (II) removal using modified biosorbent

Table 3 indicates the proportion removal of Cu^{2+} beneath distinct experimental conditions together with pH, contact time, and biosorbent dosage. Run 7 carried out the highest removal efficacy with a removal percentage of 98.87% at pH

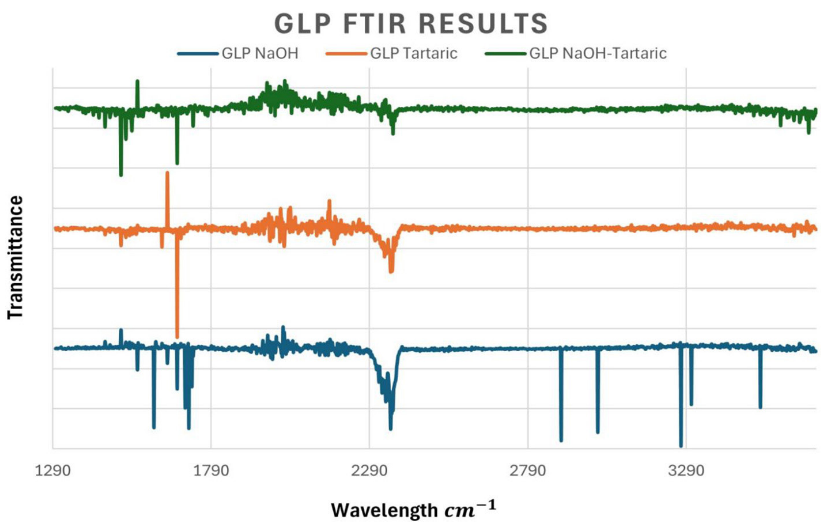


Figure 4. FTIR characterization of modified guava leaves powder

7, 45 minutes, and a biosorbent dosage of 0.7 g, indicating that this mixture is the most effective. A majority of the runs resulted over 94% removal and this is an indication that modified guava leaf powder is a powerful biosorbent. In addition, the lower and upper pH values caused much less efficiency (e.g, Run 14 with 90.6% at pH 10), which means neutral pH is more suitable in biosorption. The consistency of the findings of replicates justifies the reliability of the data.

The most suitable regression model for the biosorption data is quadratic regression model. The quadric model is the most appropriate among all the models that have been analyzed. The model that should be accustomed in the study on the biosorption process in this research is the one that has been indicate because it shows a level of statistical significance and strong predictive capability.

Effect of parameters

Figure 5 indicates a 3D surface plot that highlights how pH (A) and contact time (B) have interaction to the removal efficacy of copper (II) ions (R1). The floor shape, as proven via previous statistical analysis, is curved, which indicates the quadratic version. The graph indicates that growing both contact time and pH accompany to a higher percentage of copper removal. The effectiveness of the elimination is maximum at a rather excessive pH and duration of contact time, which can be at 98.87%. The efficiency is reduced at lower or excessively high pH values, and this is due to reduced metal precipitation or ion exchange. At lower pH levels, such as pH 4, 5, and 6, copper removal is less effective because there are greater hydrogen, which compete with copper for the energetic websites on the biosorbent. Contact time plays a big role in how well the copper is removed. The removal percentage is higher at shorter times, like between 30 to 36 minutes was quite down, which means that there was no equilibrium yet. Nevertheless, the response curve decreased after 50 minutes and this implies that the biosorption process had already reached equilibrium, and no significant growth in copper removal was observed.

Table 2. The amount of Iodine and the final concentration

Biosorbent treatment	Average iodine number (mg/g)	Average residual iodine concentration (N)	Relative standard deviation (%)
NaOH–Tartaric Modified GLP	925.33 ± 34.72	0.05016 ± 0.00459	3.75 %
NaOH Modified GLP	761.24 ± 13.32	0.07228 ± 0.00336	1.75 %

Table 3. Removal of Cu (II) in percentage with modified guava leaves powder

Run	pH	Contact time (min)	Biosorbent dosage (g)	% Removal of copper (II)
1	4	60	0.7	94.2%
2	4	45	1	95.04%
3	4	45	0.4	94.94%
4	7	30	0.4	96.44%
5	10	30	0.7	96.04%
6	7	45	0.7	97.48%
7	7	45	0.7	98.87%
8	7	45	0.7	95.04%
9	10	60	0.7	94.98%
10	10	45	1	93.12%
11	4	30	0.7	94.56%
12	7	30	1	96.6%
13	7	60	0.4	96.78%
14	10	45	0.4	90.6%
15	7	60	1	94.5%
16	7	45	0.7	94.26%
17	7	45	0.7	93.12%

Figure 6 of the 3D plot response surface display the percentage removal of Cu^{2+} when considering pH and biosorbent dose, using modified guava leaves powder. The effectiveness of copper removal is proportional to the pH and dosage of biosorbent to an optimal point. Out of the studied conditions, pH 7 and biosorbent dosage of 0.7 g gave the highest removal percent, which showed that these are the most favorable conditions to absorb copper. The effect of pH followed a trend similar to the earlier observations, where lower pH levels (4, 5, and 6) resulted in reduced copper removal efficiency. This behavior can be attributed to the competition between hydrogen ions and copper ions for the available adsorption sites present on the surface of the biosorbent. As the pH increased, the adsorption performance gradually improved, with the highest removal efficiency of up to 96% being observed under near-neutral conditions at pH 7.

Once the pH was increased (8, 9 and 10) the removal efficiency did not increase significantly, which may be a result of coproduction of copper hydroxides in place of additional sorption. The dosage of biosorbent was also critical to copper (II) removal because lower dosages (0.4–0.5 g) led to lower elimination efficacy due to fewer active sites where the adsorption can occur. The adsorption capacity increased with increased dosage of the biosorbent to 0.7–0.9 g because of the increased surface area and binding sites which gave copper removals with efficiency of over 97% at 0.9 g, however, efficacy was lower and no significant increase in clearance was observed with further dosage increase. This may be because as the dose increases, particles start to overlap and clump together, which reduces the actual surface area available for absorption.

Figure 7 display how well copper (II) ions are removed base on the amount of biosorbent used and how long it's in contact with the solution. The shape of the graph is curved, which suggests that the two factors have a strong connection and influence on the percentage of copper removed. The higher the dosage of the biosorbent used and the contact time, the better the removal efficiency, but at approximately 0.7 g dosage and 45 minutes contact time it levels off. Beyond a certain point, the increase in removal efficacy either stops or only increases slightly. This might be because the adsorption process reaches a balance, or because the active sites on the biosorbent become fully occupied. When the contact time was shortened to approximately 30–36 minutes, the percentage of copper ion removal decreased, indicating that the adsorption process had insufficient time to fully occur between the copper ions and the available binding regions of the biosorbent.

As the contact time increased within the range of 45–54 minutes, the removal efficiency improved considerably, reaching values greater than 96%. Beyond 54 minutes, a decline in adsorption

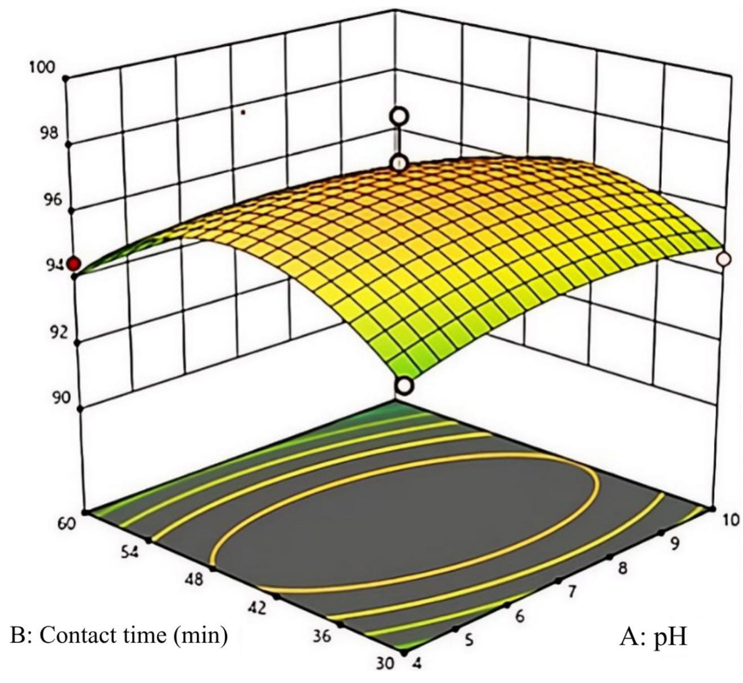


Figure 5. Surface plot of 3D with respect to pH and the duration of contact

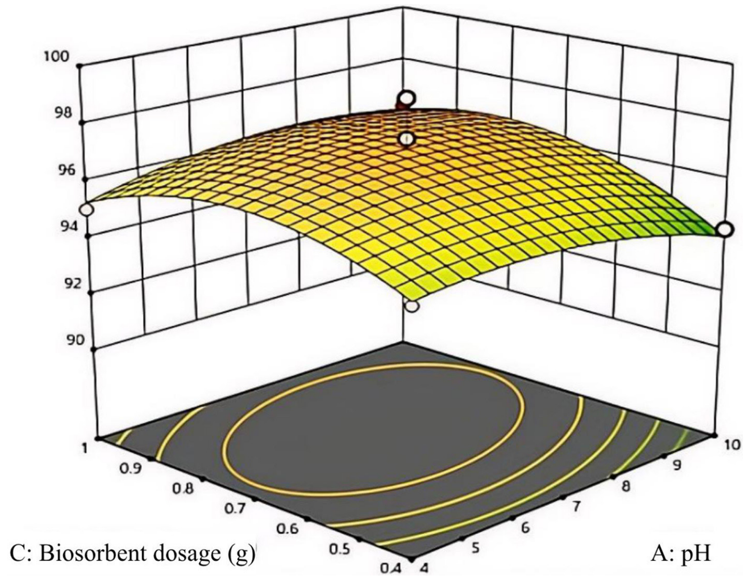


Figure 6. A 3D response surface plot display how pH and the amount of biosorbent affect the removal of Cu^{2+}

capacity was observed, suggesting that equilibrium had already been attained and that no substantial increase in copper removal could take place afterward. The effect of biosorbent dosage revealed that lower amounts of adsorbent (0.4–0.5 g) resulted in reduced adsorption efficiency due to the limited number of available adsorption sites. Increasing the dosage to 0.7–0.9 g significantly enhanced the removal performance, achieving efficiencies above 97%. This improvement may be attributed to the greater surface area and increased availability of functional groups responsible for adsorption. However, further increases beyond 0.9 g produced little to no noticeable improvement in removal efficiency, possibly because of particle aggregation and the overlapping of adsorption sites, which lowered the effective surface area available for adsorption.

Kinetic models

The graph of log (q_e – q_t) against time presented in Figure 8 produced a relatively low R^2 value of 0.5607. This result indicates that the pseudo-first-order (PFO) kinetic model does not adequately describe the adsorption behavior of

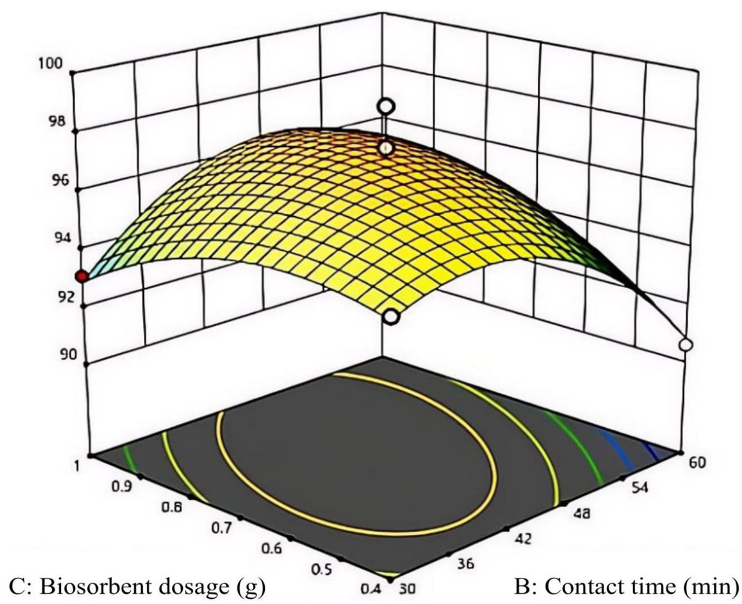


Figure 7. Response surface plot 3D of biosorbent dosage and contact time

Cu^{2+} ions onto the modified guava leaf powder biosorbent. The poor linear correlation suggests that the adsorption process is not primarily governed by physical adsorption or simple diffusion mechanisms. Instead, the results imply the occurrence of chemisorption, where copper ions interact more strongly with the active binding sites and functional groups located on the surface of the biosorbent.

The plot of t/qt versus time (Figure 9) shows a strong linear relationship with a very high R^2 value of 0.9998, indicating that the experimental data closely follows the pseudo-second-order (PSO) kinetic model. This relationship suggests that the adsorption process is mainly governed by chemisorption, involving chemical interactions through electron exchange or electron sharing between the copper ions and the active functional groups present on the biosorbent surface. The nearly perfect linear trend further indicates that the availability of active binding sites strongly influences the adsorption rate, supporting the suitability of the PSO model in describing the kinetic behavior of copper adsorption in this experiment.

Isotherm models

The Langmuir isotherm plot in Figure 10 of 1/qe versus 2/Ce shows no linearity, indicated by the low coefficient of determination (R^2 = 0.4462). Such a low strength of interaction implies that adsorption of Cu^{2+} ions on this biosorbent cannot be well represented in the Langmuir. In the Langmuir, the adsorption procedure is assumed to take place on essentially 'monolithic' surface with infinite active sites and adsorbed species without interaction. These presumptions are not entirely correct for the existing system, as plotted curvature and scatter demonstrate.

The Freundlich plot in Figure 11 (log qe vs log Ce) indicates a moderate linear relationship with 0.5864 as derived from calculating. Adsorption of Cu^{2+} ions onto leaves as biosorbent by guava leaves is described more accurately in the Freundlich isotherm, with an R^2 value greater than that of the Langmuir model. The qe inside the plot rises with an increment in equilibrium attention (Ce), indicating that Cu^{2+} has

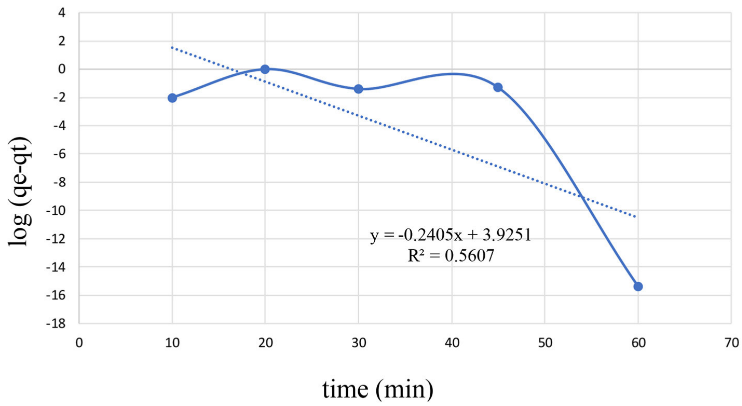


Figure 8. Pseudo-first-order

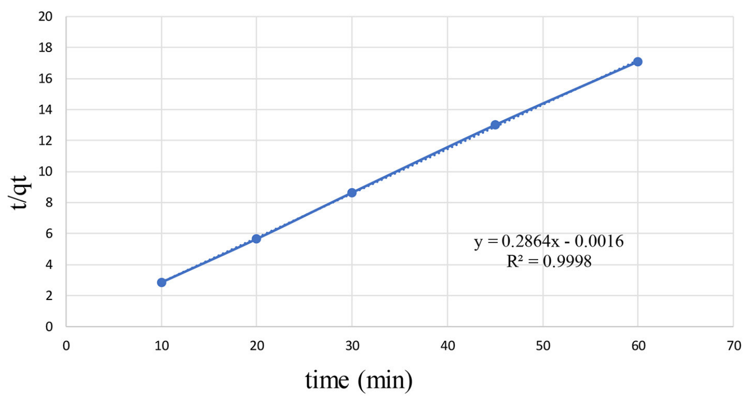


Figure 9. Pseudo-second-order

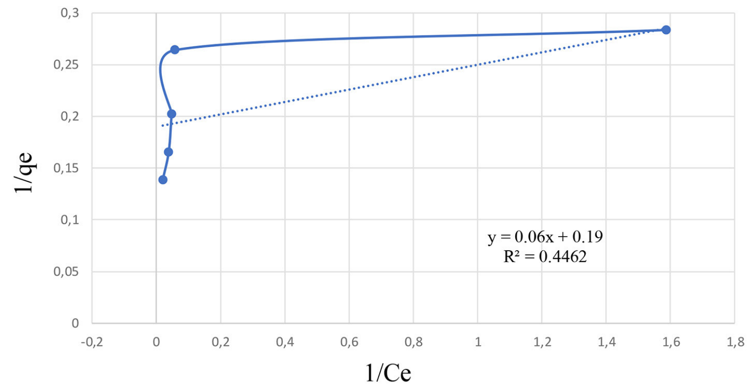


Figure 10. Copper (II) adsorption Langmuir isotherm plot

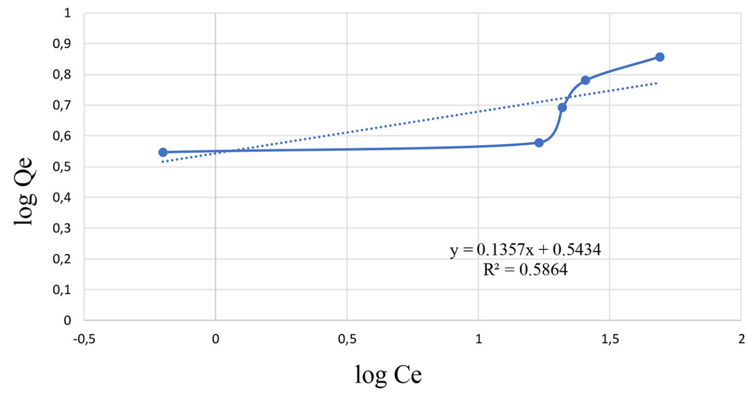


Figure 11. The biosorption of Cu^{2+} ions by Freundlich

better favorable for absorbing. The guava leaf biosorbent has a variety of functional groups, as well as varying affinities for Cu^{2+} ions, as indicated by the moderate R^2 value. The consistent contribution of multilayer adsorption and variable binding strengths to these theories can be attributed to these functional groups.

CONCLUSIONS

The findings of this research demonstrated that modified guava (*Psidium guajava* L.) leaves can serve as an effective and environmentally friendly biosorbent for removing Cu^{2+} ions from synthetic wastewater. Results revealed that pH, contact time, and biosorbent dosage significantly influenced the biosorption performance, with the optimized conditions achieving a maximum removal efficiency of 98.87%. ANOVA results confirmed the significance of the developed model, while the high R^2 value reflected strong predictive capability. Among the isotherm models evaluated, the Freundlich isotherm provided the best fit for the equilibrium data, suggesting adsorption occurred on a heterogeneous surface with varying adsorption energies. Kinetic analysis further indicated that the pseudo-second-order (PSO) model most accurately described the biosorption process, implying that chemisorption was the dominant rate-controlling mechanism. Surface characterization using SEM and FTIR verified structural and functional group changes in the biosorbent after copper adsorption, supporting the experimental observations. Overall, the results highlight the potential of chemically modified guava leaves as an economical and eco-friendly material for copper removal in wastewater treatment applications.

Acknowledgements

We sincerely express our deepest gratitude to our research adviser, Engr. Jenilie G. Velasco, for her dedication, insightful guidance, and unwavering commitment throughout the completion of this study. Her continuous encouragement and confidence in our capabilities inspired us to persevere and give our best in every stage of the research process. We are also grateful to our panel members, Dr. Emmanuel L. Ferrer, Prof. Cristopher B. Parmis, and Mr. Mark Joseph Ferranco, whose constructive suggestions and helpful insights contributed greatly to the refinement and improvement of this study. Our heartfelt appreciation is extended to our families for their endless sacrifices, understanding, and steadfast encouragement. Their love and support served as our source of strength and motivation throughout this journey. Lastly, we would like to thank our friends and fellow researchers for the encouragement, cooperation, and inspiration they shared with us. This achievement would not have been possible without the collective support and meaningful contributions of everyone who became part of this endeavor.

REFERENCES

1. Abegunde, S. M., Idowu, K. S., Adejuwon, O. M., Adeyemi-Adejolu, T. (2020). A review on the influence of chemical modification on the performance of adsorbents. *Resources, Environment and Sustainability*, *1*, 100001. https://doi.org/10.1016/j.resenv.2020.100001
2. Aghalari, Z., Dahms, H.-U., Sillanpää, M., Sosa-Hernandez, J. E. (2020). Effectiveness of wastewater treatment systems in removing microbial agents: A systematic review. *Globalization and Health*, *16*, 13. https://doi.org/10.1186/s12992-020-0546-y
3. Al Ali, A., Ouda, M., Naddeo, V., Puig, S., Hasan, S. W. (2021). Integrated electrochemical-adsorption process for the removal of trace heavy metals from wastewater. *Case Studies in Chemical and Environmental Engineering*, *4*, 100147. https://doi.org/10.1016/j.cscee.2021.100147
4. Buenaño, L., Ali, E., Jafer, A., Zaki, S. H., Hammady, F. J., Khayoun Alsaadi, S. B., Karim, M. M., Ramadan, M. F., Omran, A. A., Alawadi, A., Alsalamy, A., Kazemi, A. (2024). Optimization by Box–Behnken design for environmental contaminants removal using magnetic nanocomposite. *Scientific Reports*, *14*, 57616. https://doi.org/10.1038/s41598-024-57616-8
5. Das, T. K., Poater, A. (2021). Review on the use of heavy metal deposits from water treatment waste towards catalytic chemical syntheses. *International Journal of Molecular Sciences, 22*(24), 13383. https://doi.org/10.3390/ijms222413383
6. Elkhaleefa, A., Ali, I. H., Brima, E. I., Shigidi, I., Elhag, A. B., Karama, B. (2021). Evaluation of the adsorption efficiency on the removal of lead (II) ions from aqueous solutions using Azadirachta indica leaves as an adsorbent. *Processes, 9*(3), 559. https://doi.org/10.3390/pr9030559
7. Foo, K. Y., Hameed, B. H. (2021). Insights into the modeling of adsorption isotherm systems. *Chemical Engineering Journal*, *413*, 127524. https://doi.org/10.1016/j.cej.2020.127524
8. Ghani, Z. A., Yusoff, M. S., Zaman, N. Q., Zamri, M. F. M. A., Andas, J. (2017). Optimization of preparation conditions for activated carbon from banana pseudo-stem using response surface methodology on removal of color and COD from landfill leachate. *Waste Management*, *62*, 177–187. https://doi.org/10.1016/j.wasman.2017.02.026
9. Gupta, R., Gupta, S. K., Gehlot, C. L., Bahadur, I. (2023). Chemically modified jackfruit leaves as a low-cost agro-waste adsorbent for Pb(II) removal from synthetic wastewater. *Journal of Hazardous Materials Advances*, *10*, 100292. https://doi.org/10.1016/j.hazadv.2023.100292
10. Hassan, M., et al. (2020). Critical review of magnetic biosorbents: Their preparation, application, and regeneration for wastewater treatment. *Science of the Total Environment*, *702*, 134893. https://doi.org/10.1016/j.scitotenv.2019.134893
11. Loan, H. T., Quyen, N. T. (2024). An investigation of the adsorption capacity of activated carbon made from rice husks using the iodine number method. *Journal of Applied Science and Technology*, *41*, 78–83. https://jst.utehy.edu.vn/index.php/jst/article/view/677
12. Olawale, S. A., Bonilla-Petriciolet, A., Mendoza-Castillo, D. I., Okafor, C. C., Sellaoui, L., Badawi, M. (2022). Thermodynamics and mechanism of the adsorption of heavy metal ions on keratin biomasses for wastewater detoxification. *Adsorption Science & Technology*, *2022*, 7384924. https://doi.org/10.1155/2022/7384924
13. Qasem, N. A. A., Mohammed, R. H., Lawal, D. U. (2021). Removal of heavy metal ions from wastewater: A comprehensive and critical review. *npj Clean Water*, *4*, 36. https://doi.org/10.1038/s41545-021-00127-0
14. Raji, Z., Karim, A., Karam, A., Khalloufi, S. (2023). Adsorption of heavy metals: Mechanisms, kinetics, and applications of various adsorbents in wastewater remediation—A review. *Waste*, *1*(3), 775–805. https://doi.org/10.3390/waste1030046
15. Razzak, S. A., Faruque, M. O., Alsheikh, Z., Alsheikhmohamad, L., Alkuroud, D., Alfayez, A., Hossain, S. M. Z., Hossain, M. M. (2022). A comprehensive review on conventional and biological-driven heavy metals removal from industrial wastewater. *Environmental Advances, 7*, 100168. https://doi.org/10.1016/j.envadv.2022.100168

16. Rehman, A., Park, M., Park, S. J. (2019). Current progress on the surface chemical modification of carbonaceous materials. *Coatings*, *9*(2), 103. https://doi.org/10.3390/coatings9020103
17. Rukayat, O. O., Usman, M. F., Elizabeth, O. M., Abosede, O. O., Faith, I. U. (2021). Kinetic adsorption of heavy metal (copper) on rubber (*Hevea brasiliensis*) leaf powder. *South African Journal of Chemical Engineering*, *37*, 100–106. https://doi.org/10.1016/j.sajce.2021.04.004
18. Shah, I. H., Farooqi, I. H., Bhatti, H. N., Khan, M. I. (2021). Application of atomic absorption spectroscopy for heavy metal determination in wastewater samples. *Journal of Environmental Chemical Engineering*, *9*(6), 106734. https://doi.org/10.1016/j.jece.2021.106734
19. Smoczyński, L., Pierożyński, B., Mikołajczyk, T. (2020). The effect of temperature on the biosorption of dyes from aqueous solutions. *Processes*, *8*(6), 636. https://doi.org/10.3390/pr8060636
20. Vidu, R., Matei, E., Predescu, A. M., Alhalaili, B., Pantilimon, C., Tarcea, C., Predescu, C. (2020). Removal of heavy metals from wastewaters: A challenge from current treatment methods to nanotechnology applications. *Toxics*, *8*(4), 101. https://doi.org/10.3390/toxics8040101