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**Sustainable and Low-Cost Approach for Effective Remediation of Nickel(II)
Ions Using NaOH-Modified Tea Waste and Its Biochar**

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Abstract

Nickel contamination in natural water bodies has become a major environmental concern, causing undesirable issues in ecosystems, requiring the remediation of Ni(II) from contaminated aqueous systems. Although many approaches have been in practice, biosorption provides a sustainable and low-cost methodology as a viable alternative. In this respect, this study investigates the potential of NaOH-modified tea waste adsorbent (STWA) and NaOH-modified tea waste biochar (STWB) for the remediation of Ni(II) from contaminated aqueous solutions. Application of Fourier transform infrared spectroscopy, X-ray fluorescence spectroscopy, scanning electron microscopy, thermogravimetric analysis and point of zero charge confirms favorable surface characteristics for Ni(II) adsorption. Optimum conditions of 0.60 g and 0.30 g dosages, 20 min shaking time and 10 min settling time lead to the extent of removal of Ni(II) from 10 mg L⁻¹ solution by TW and its biochar at 76% and 65%, respectively, for ambient pH and temperature, which are increased up to 95% and 98%, respectively, by NaOH treatment. Investigation of kinetics confirms efficient and superior biosorption, while the Weber–Morris intra-particle diffusion (IPD) model indicates multi-stage adsorption governed by film diffusion and IPD. Isotherm modeling indicates that STWB follows the Langmuir model, with a maximum adsorption capacity (q_m) of 15.17 mg g⁻¹, whereas the Freundlich model is suitable for STWA, with q_m of 24.64 mg g⁻¹. It is further determined that competing ions reduce adsorption efficiency, with STWB showing better stability. Regeneration is possible with HNO₃, HCl and EDTA with >90% desorption, confirming the sustainable removal of Ni(II).

Keywords: Tea waste, biosorption, biochar, Ni(II) remediation, Optimization

1. Introduction

Effluents released from various industrial fields have been marking their territory, forming polluted environments. Among these, the release of toxic metals and their compounds into water reservoirs has been a major concern recently. Metal ions are non-biodegradable and can be accumulated through bioaccumulation, biomagnification, and bioconcentration in animals, including humans, through food chains (Nnaji et al., 2023). The toxicity of these heavy metals can lead to severe health issues in the human body, such as reduced growth and development, cancer, organ damage, nervous system impairment, and even death when minimum exposure levels are exceeded (Oladimeji et al., 2024). Consequently, several heavy metal removal techniques, such as filtration, electrochemical methods, oxidation/reduction, ion exchange, oxidation/reduction and reverse osmosis, have been implemented (Kotabewatta & Priyantha, 2024). However, their disadvantages such as low removal efficiency and lack of cost-effectiveness confront adsorption as a viable alternative (MALKOC & NUHOGLU, 2005).

Adsorption distinguishes itself among heavy metal physicochemical treatment techniques due to its high adsorption efficiency, cost-effectiveness, and ease of handling. It has thus become a globally popular wastewater treatment technology (Panneerselvam et al., 2011). The adsorption process is typically described using equilibrium, kinetics, and thermodynamic models. Specifically, Langmuir, Freundlich, and Temkin adsorption isotherm models; pseudo first order and pseudo second order kinetics models, and intra particle diffusion model deliver essential data about the adsorption process (Quansah et al., 2024). Activated carbon is broadly implemented as an effective adsorbent in sewage water treatment. However, due to high activation cost, extensive research screening for cost-effective adsorbent has been carried out (Amarasinghe & Williams, 2007).

Over the past five decades, nickel contamination of soil has progressively increased through both human activities and natural processes, particularly through the accumulation of ash remnants from coal combustion, disposal of municipal sewage sludge, nickel alloy industries and their studies, pigment production, tannery wastewater, and the weathering of mafic and ultramafic rocks (El-Naggar et al., 2021; S. Sen Gupta & Bhattacharyya, 2006; Levická & Orliková, 2024). Recent studies have been carried out investigating the suitability of many types of biosorbents, such as agricultural waste, microbial biomass, algae, biochar and modified natural materials, for the remediation of nickel (Aryal & Liakopoulou-Kyriakides, 2015; Fdez-Sanromán et al., 2020; Su et al., 2023). Among these, modified natural materials and biochar show significant efficiency in heavy metal adsorption from polluted water. Table 1 shows an overview of the comparative analysis of nickel removal percentages achieved by various biosorbents under their respective experimental conditions, based on reported studies. Operational parameters are different among these studies, and the values provide general indication about the biosorbent effectiveness towards the nickel adsorption. Along with the removal efficiency, adsorption capacity (q) is widely used to investigate the adsorption performance of adsorbents, providing a fair comparison between biosorbents regardless of dosage. Table 2 indicates the reported equilibrium adsorption capacities of some natural and modified biosorbents for nickel adsorption.

89

90 **Table 1:** Evaluation of nickel adsorption percentage among various biosorbents

Biosorbent	Removal percentage (%)	Reference
Chicken egg shell	94	(Mashangwa et al., 2017)
Raw tea waste	70	(Khair et al., 2025)
Raw orange peel	70	(Salleh et al., 2023)
<i>Lemna minor</i>	82	(Axtell, 2003)
<i>Salvinia sp</i>	74	(UGYA, 2019)
<i>Nymphaea lotus</i>	86	(Charazińska et al., 2022)

91

92 **Table 2:** Evaluation of nickel adsorption capacity among various biosorbents

Biosorbent	q (mg g ⁻¹)	Reference
Natural zeolite containing tripolite	1.79	(Kolmykova et al., 2023)
Sugarcane-based activated carbon	2.99	(Van Tran et al., 2017)
Sugarcane bagasse	12.35	(Ezeonuegbu et al., 2021)
Walnut shell	13.92	(Georgieva et al., 2020)

Orange peel	62.89	(Ferda Gönen, 2012)
DTPA-modified banana	29.24	(F. Wang et al., 2022)
DTPA-modified pomegranate peel	16.61	(F. Wang et al., 2022)

The selection and preparation of the biosorbent hold a vital role in the successful execution of the adsorption strategy (Li et al., 2021). The porosity of the biosorbent, which influences the adsorption proficiency, can be further boosted through surface modification using defined chemicals customized for the intended applications (Li et al., 2021). For example, EDTA, which enhances the chelation, and acid or base treatment, which aids hydrolysis of ester linkages, can be used (Liang et al., 2020). Such modifications are employed not only to enhance available active adsorption sites, but also to improve stability and reusability (Liang et al., 2020).

Previous studies have confirmed that the use of tea waste for the remediation of heavy metals from the contaminated aqueous solution is a low-cost, efficient, and sustainable biosorbent (Datta & Deb, 2025). The tea plant (*Camellia sinensis* (L.)) is a perennial evergreen crop with a high economic value cultivated in tropical and subtropical regions (Datta & Deb, 2025). Tea waste (TW), which is called refused tea, is the byproduct arising from the processing of tea in the factory, and large quantities of waste are produced on an industrial scale. In composition, TW is rich in cellulose, hemicellulose, lignin, proteins, tannins, polyphenols and residual caffeine, along with various functional groups including hydroxyl (–OH), carboxyl (–COOH), and ester groups, giving the favorable surface functionalities for the adsorption of heavy metals (Çakmak et al., 2024).

Raw TW and biochar have been investigated as low-cost and eco-friendly biosorbents for heavy metal remediation. However, fewer studies have been carried out on systematic comparative evaluations that integrate surface chemistry, adsorption mechanisms, and material stability. Specifically, limited studies have simultaneously clarified the relationships among surface functional groups, surface charge characteristics, adsorption isotherms, thermal stability, and competitive ion selectivity for Ni(II) removal. Consequently, the underlying mechanisms governing differential adsorption performance between modified TW and biochar remain poorly understood. To address this knowledge gap, this study concentrates on the characterization of NaOH-modified tea waste adsorbent (STWA) and NaOH-modified tea waste biochar (STWB) as efficient adsorbents. Further, comprehensive investigations were conducted on optimization and evaluation of adsorption performance under controlled experimental conditions, equilibrium and kinetic behaviors, investigation of competitive ion interference, regeneration efficiency using various desorption agent and mechanistic insights into Ni(II) uptake for a sustainable approach for the removal of Ni(II) from aqueous solutions are focused.

2. Materials and Methods:

2.1 Biosorbent preparation

Factory TW was collected from a tea processing factory located in Sabaragamuwa Province of Sri Lanka. TW collected was washed first with tap water to eliminate surface impurities and loosely bonded particles and then with boiled water to remove leachable colored compounds present in the tea waste. This was followed by extensive rinsing with deionized water to remove any residual matter. Thereafter, the cleaned TW was oven-dried at 80 °C overnight. Once dried, the TW was ground and sieved to retain particle sizes from 0.500 mm to 0.710 mm to achieve a consistent particle size for further experiments. To chemically activate the biosorbent, 0.10 mol L⁻¹ NaOH

was employed as the treatment agent (Rathnayaka et al., 2024). To achieve this, 10.0 g of sieved, cleaned TW was mixed with 1.0 L of 0.10 mol L⁻¹ NaOH, and the mixture was stirred for 1.0 h using a magnetic stir at 150 rpm to facilitate proper interaction between the base and the functional groups present in TW. After stirring, the suspension was allowed to settle for an hour. Finally, STWA was washed thoroughly with tap water, followed by deionized water until the washing solution exhibited the neutral pH.

2.2 Biochar preparation

Oven-dried TW was taken for the preparation of tea waste biochar. The pyrolysis process was carried out at 300 °C with a time duration of 1.0 h. To perform chemical modification, 10.0 g of TW biochar was treated with 0.10 mol L⁻¹ NaOH at 150 rpm for 1.0 h and allowed to settle for 1.0 h. STWB was washed with tap water, followed by deionized water until the black color was completely removed and the washing solution became neutral pH. Samples of STWB were oven-dried at 80 °C overnight.

2.3 Characterization of biosorbent

The biosorbent was characterized using Fourier transform infrared (FTIR) spectroscopy (ATR-FTIR: PerkinElmer Spectrum TWO FTIR Spectrophotometer, USA), X-ray fluorescence (XRF) spectroscopy (FISCHERSCOPE XAN 250, Germany), thermal gravimetric analysis (TGA) (PerkinElmer TGA 4000, USA), and scanning electron microscopy (SEM) (ZEISS EVO LS 15, Germany). FTIR spectroscopic analysis was conducted to identify functional groups present in the adsorbent, while the elemental composition due to Ni(II) adsorption was determined using XRF. SEM was utilized to analyze the structural surface morphology of the biosorbent. TGA is helpful

for evaluating the thermal stability of biosorbents by indicating how they behave under different temperatures and assessing the impact of chemical modifications on their heat resistance.

2.4 Point of zero charge (PZC)

The PZC of different types of TW was analyzed using potentiometric titration. Three different concentrations of NaNO₃ solutions (0.1 mol L⁻¹, 0.01 mol L⁻¹, and 0.001 mol L⁻¹) with different ionic strengths were prepared (Priyantha & Kotabewatta, 2019). A fixed amount of the biosorbent was added to 250.0 mL of each NaNO₃ solution in separate 500 mL beakers. Then the suspensions were agitated for 24.0 h at ambient temperature in closed beakers using a magnetic stirrer to reach equilibrium. Following equilibration, the pH of each suspension was adjusted to pH 4.00 using 0.1 mol L⁻¹ HNO₃. Subsequently, the pH was raised to 12.0 by adding 0.05 mL of 0.10 mol L⁻¹ NaOH using a micropipette, and the pH was recorded after each addition. Finally, the specific surface charge (C g⁻¹) was determined and plotted against the pH of the solution for each electrolyte concentration.

2.5 Optimization of experimental parameters

Adsorption experiments were performed under ambient conditions to determine optimum conditions for the maximum removal efficiency of Ni(II). Each experiment was executed in triplicate, and the average values were considered. The total concentration of each Ni(II) solution was determined using atomic absorption spectroscopy (AAS) (Thermo SCIENTIFIC M SERIES, USA), and the removal percentage was calculated using the following Equation 1.

$$\text{Removal percentage(\%)} = \frac{c_i - c_e}{c_i} \times 100\% \quad [1]$$

where C_i is the initial Ni(II) concentration and C_e is the concentration of Ni(II) at adsorption equilibrium (Tijjani et al., 2024).

Dosage optimization: The effect of adsorbent dosage was investigated through the variation of mass of STWA/STWB from 0.10 g to 1.20 g. For this, the adsorbent was added to glass jars, containing 50.0 mL of 10 mg L⁻¹ Ni(II) solutions, and they were shaken at 150 rpm on orbital shaker for 1.0 h, followed by a 1.0 h settling time. Thereafter, 5.0 mL aliquots of the supernatant were withdrawn for AAS analysis to determine the final concentration of Ni(II).

Shaking time optimization: To assess the optimal shaking time, a series of experiments was carried out by changing the shaking time from 10 min to 90 min at 150 rpm with a 1.0 h settling time. For that, an optimized dosage of the biosorbent was used with 50.0 mL of 10 mg L⁻¹ Ni(II) solutions.

Settling time optimization: Using the same solution (50 mL of 10 mg L⁻¹ Ni(II)), optimized dosage, and optimized shaking time, the optimum settling time was determined by varying the time from 5 min to 70 min.

2.6 Investigation of kinetics

The adsorption rate of Ni(II) by STWA was evaluated before reaching equilibrium by withdrawing 5.0 mL aliquots from 10 mg L⁻¹ Ni(II) solution treated with 12.0 g of STWA at ambient conditions. Samples were collected at 1-min intervals during the first 15 min, and subsequently at 5-min intervals up to 60.0 min. The experiment was repeated for a 25 mg L⁻¹ Ni(II) solution with the same conditions, and samples were taken up to two hours. The first hour was the same as the above, and from 1.0 h 10.0 min, periods were used until the end of 2.0 h. The same procedure was used for the 6.0 g of STWB.

Equations (2), (3) and (4) represent pseudo-first-order (PFO), pseudo-second-order (PSO), and the Weber and Morris intra-particle diffusion models, respectively

The pseudo-first order kinetics model is given by,

$$\ln(q_e - q_t) = \ln q_e - kt \quad [2]$$

where q_e is the adsorption capacity at equilibrium (mg g^{-1}), q_t is the amount adsorbed at time t (mg g^{-1}), k is a rate constant (min^{-1}), and t is time of interaction (min) (Dharmarathna & Priyantha, 2024).

The pseudo-second order kinetics model is given by,

$$\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{1}{q_e} t \quad [3]$$

where q_t is the amount adsorbed at time t (mg g^{-1}), k is the rate constant ($\text{g mg}^{-1} \text{min}^{-1}$), q_e is the adsorption capacity at equilibrium (mg g^{-1}), and t is time of interaction (min) (Osman et al., 2024).

The Weber and Morris IPD model is given by,

$$q_t = k_{id} t^{1/2} + C \quad [4]$$

where q_t is the amount adsorbed at time t (mg g^{-1}), k_{id} represents the IPD rate constant (min^{-1}), C (mg g^{-1}) is a constant that characterizes the boundary layer thickness of the linear plot and t is time of interaction (min) (Nnadozie & Ajibade, 2020).

2.7 Investigation of adsorption isotherms

To investigate the equilibrium behavior of Ni(II) adsorption on STWA, a batch isotherm study was performed with different initial concentrations of Ni(II). For that, a concentration series ranging from 10 mg L^{-1} to 500 mg L^{-1} of Ni(II) was prepared. For each concentration, 0.60 g of STWA

was added to 50.0 mL of the Ni(II) solution in glass jars. Then they were shaken at 150 rpm using an orbital shaker for the optimized contact time of 20 min. Suspensions were allowed to settle for 10 min to ensure the separation of biosorbent particles. Finally, the 5.0 mL of aliquots of each solution were withdrawn, diluted accordingly as required, and the equilibrium concentration of Ni(II) was assessed using AAS. Finally, the data were fitted to both the Langmuir and the Freundlich adsorption-isotherms to investigate the adsorption behavior and surface characteristics of the biosorbent. The same procedure was carried out for STWB using the dosage of 0.30 g.

2.8 Interference study

Optimized dosages of the STWA and STWB are treated under previously optimized conditions with solution consisting of 25 mg L⁻¹ of Ni(II) and 25 mg L⁻¹ interference agent. Then 5.0 mL aliquots of the mixture were withdrawn into test tubes and analyzed the final concentration of the Ni(II) using AAS.

2.9 Regeneration study

Initially, the adsorption process of Ni(II) was carried out using STWA and STWB under previously optimized conditions. Then the metal-loaded biosorbent was separated by filtration and oven dried. Dried biosorbents were treated with 50.0 mL of different desorption agents, namely 0.10 mol L⁻¹ HNO₃, 0.10 mol L⁻¹ HCl, 0.10 mol L⁻¹ EDTA and deionized water, and agitated at 150 rpm for 1.0 h shaking time with 10 min of settling time. Thereafter, 5.0 mL of aliquots were withdrawn and analyzed using AAS to determine the extent of desorption according Equation (5),

$$\text{Desorption percentage (\%)} = \frac{c_d}{c_t - c_e} \times 100\% \quad [5]$$

where C_d is desorbed Ni(II) concentration, C_i is the initial Ni(II) concentration before adsorption and C_e is the concentration of Ni(II) at adsorption equilibrium (Boeykens et al., 2018).

3. Results and Discussion

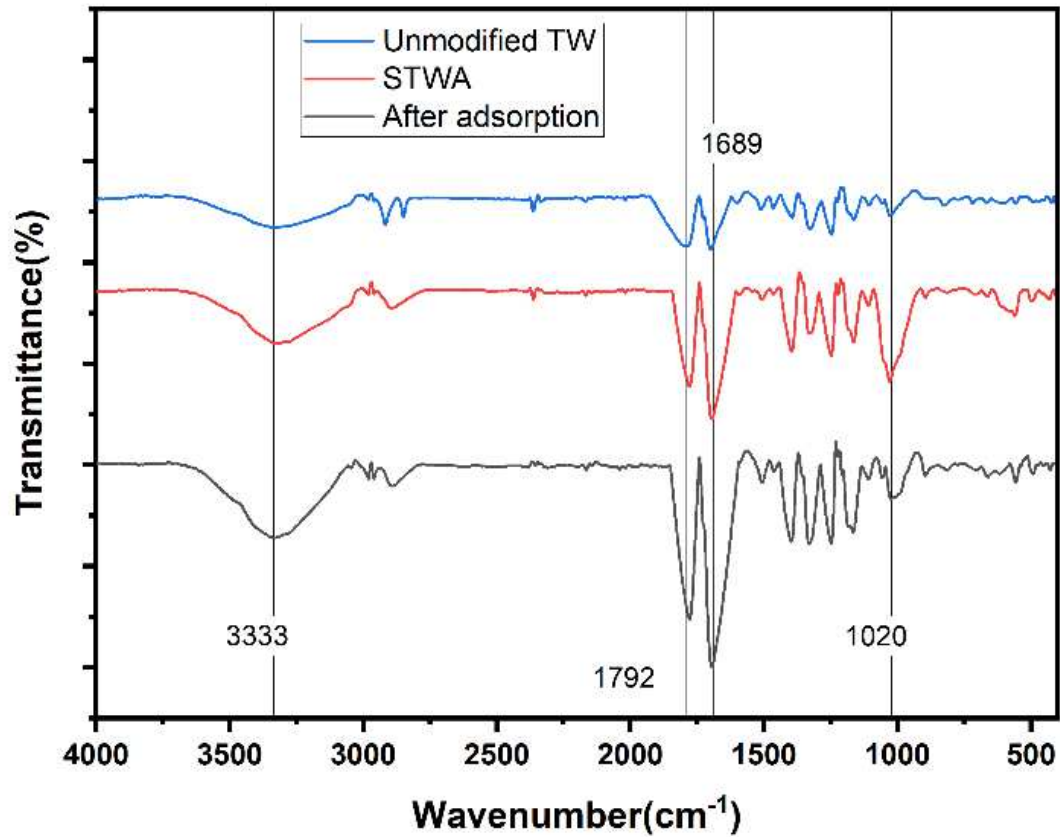
3.1 Characterization of raw TW before and after adsorption of Ni(II)

3.1.1 FTIR analysis

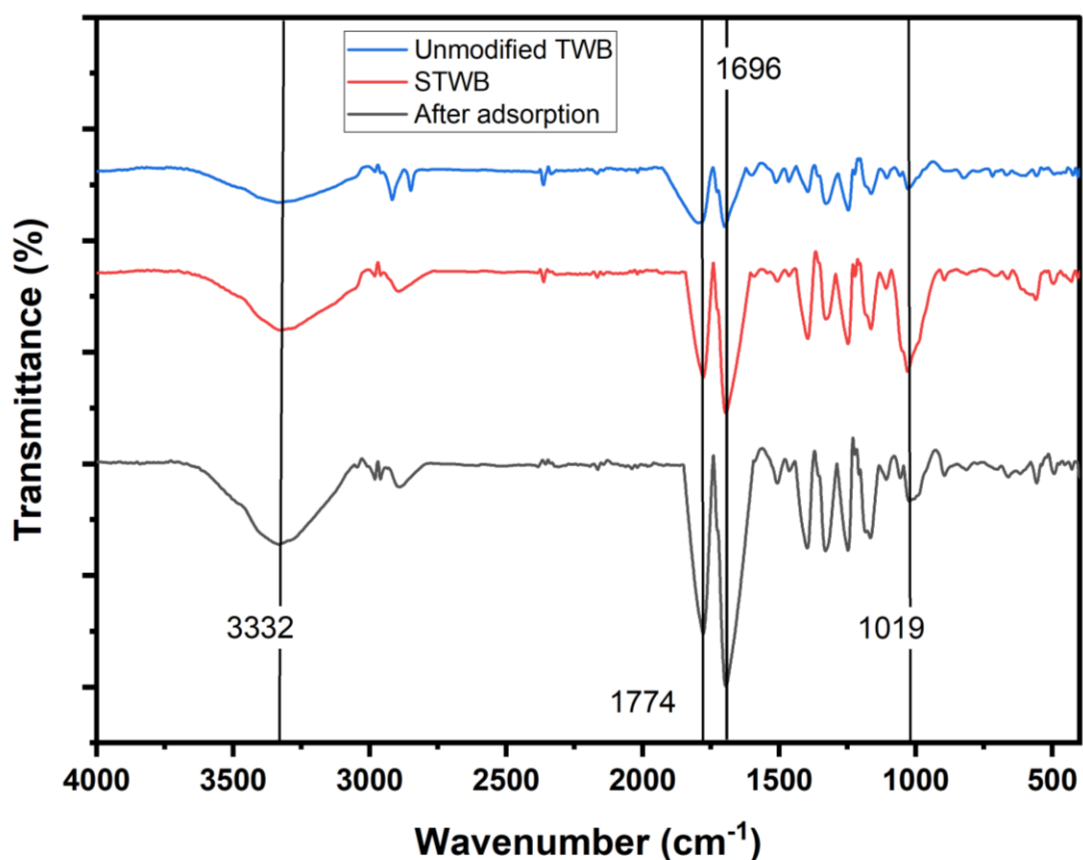
FTIR spectroscopy is a rapid, nondestructive method used to determine the molecular structure and functional groups in organic and inorganic materials. This method uses infrared radiation to pass through the sample with some radiation absorbed by molecular bonds inducing vibrational transitions, and some pass through, producing a characteristic spectrum of wave number vs transmittance that reflect the functional groups. In this study, FTIR spectroscopic analysis confirms the involvement of functional groups such as hydroxyl, carboxylic, and ester groups which would promote adsorption of Ni(II) through complexation (Figure 1). In raw TW, key bands appear at 3334 cm^{-1} (O–H), 1793 cm^{-1} (C=O ester), 1689 cm^{-1} (C=O carboxylic acid), and 1021 cm^{-1} (C–O alcohol) (A. Gupta & Balomajumder, 2017; Liu et al., 2018). In TW biochar, slight changes are observed in band positions (3332 cm^{-1} (O–H), 1774 cm^{-1} (C=O ester), 1697 cm^{-1} (C=O carboxylic acid), and 1019 cm^{-1} (C–O alcohol) due to dehydration, decarboxylation and partial decomposition of cellulose and hemicellulose associated with aromatization during the biochar formation. After NaOH modification (STWA, STWB), band intensities increase and shift slightly, indicating activation and enhanced availability of binding sites. Following Ni(II) adsorption, decrease in intensity and slight shifts in the above bands are observed, suggesting direct involvement in metal binding.

Table 3: Key functional groups present in TW

Wavenumber (cm ⁻¹)	Functional group
3334	–OH (Hydroxyl)
1793	C=O (Ester)
1690	C=O (Carboxylic acid)
1021	C–O (Alcohol)



(a)

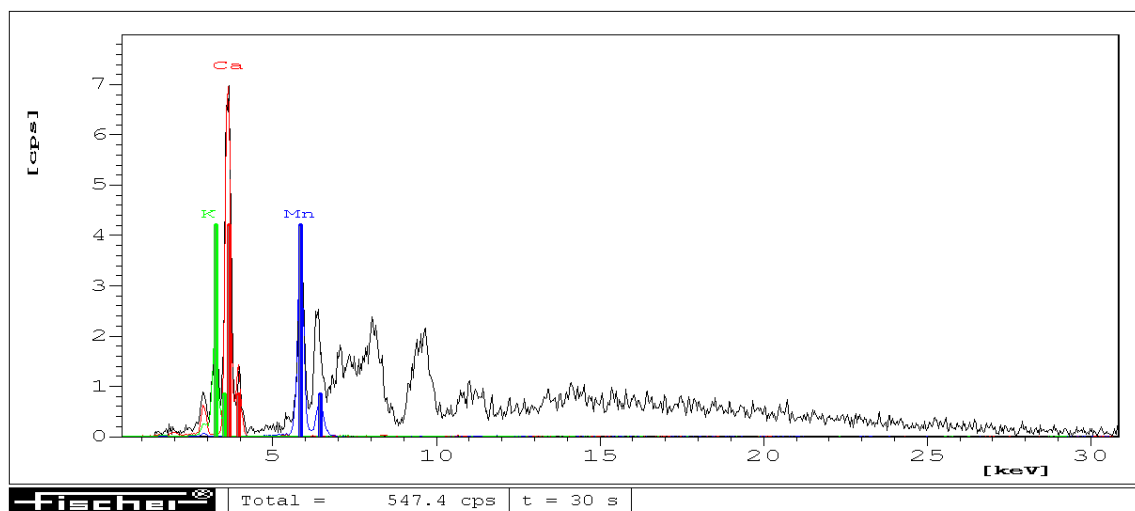


(b)

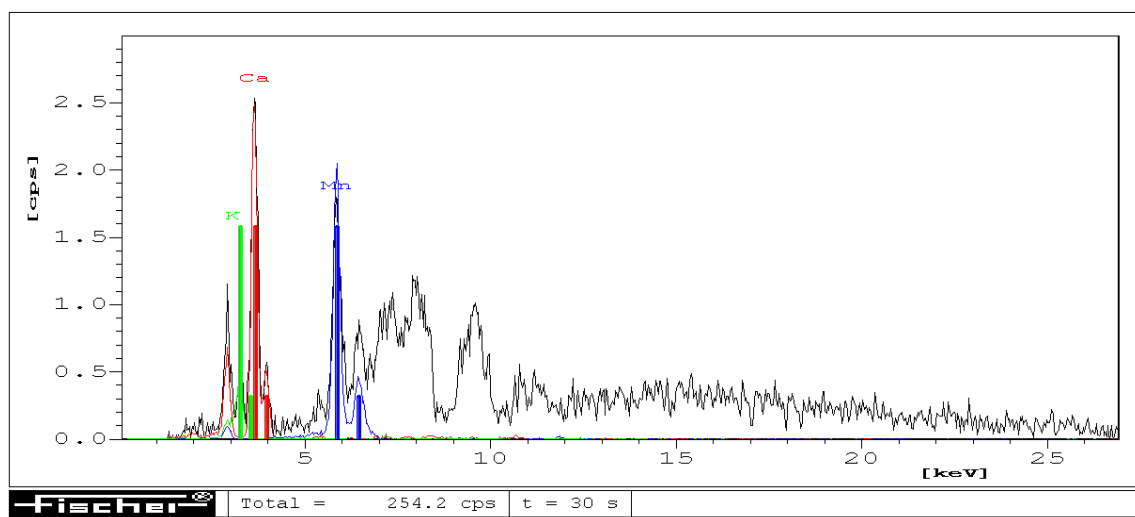
Fig. 1 FTIR spectra of (a) unmodified TW, STWA and STWA after Ni(II) adsorption (b) unmodified TWB, STWB and STWB after adsorption of Ni(II)

3.1.2 XRF spectroscopic analysis

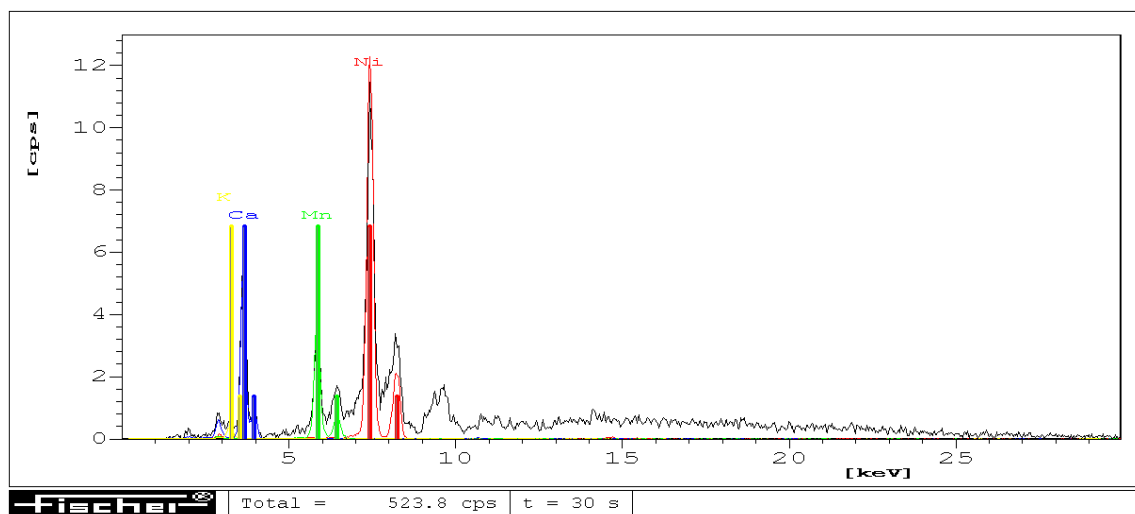
XRF spectroscopy is nondestructive and rapid analytical technique which uses interaction between X-rays and material under investigation for the determination of elemental composition. XRF spectroscopy allows both qualitative and quantitative analysis of a variety of samples including solids, liquid and powders. According to Figure 2(a,b) and Figure 3 (a,b), Ni peak does not appear in the spectra confirming that unmodified TW, STWA, unmodified TW biochar and STWB are free from residual Ni. Moreover, the Ni peak that appears in Figure 2(c) and Figure 3(c) confirms the adsorption of Ni(II) by the STWA and STWB.



(a)

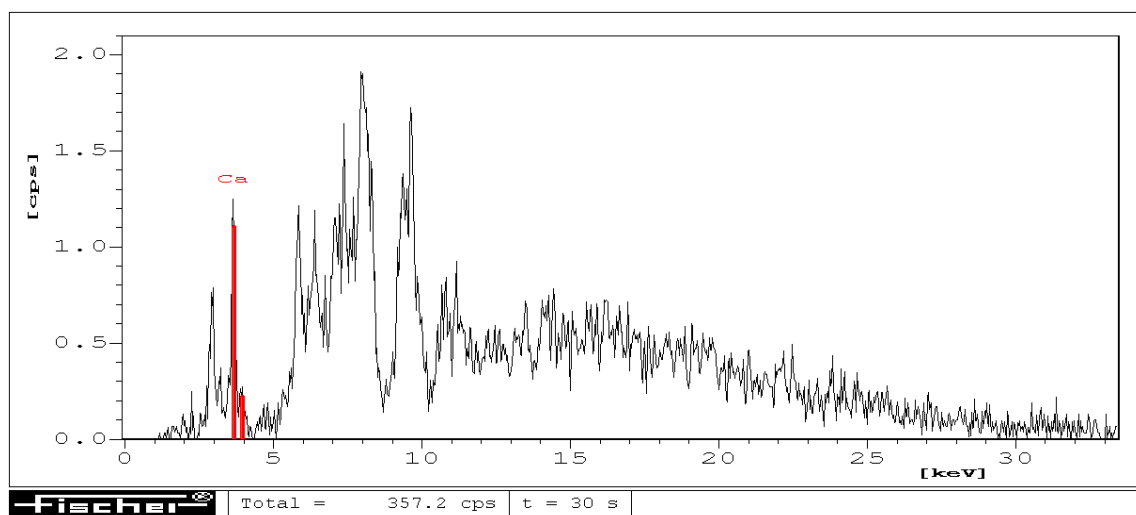


(b)

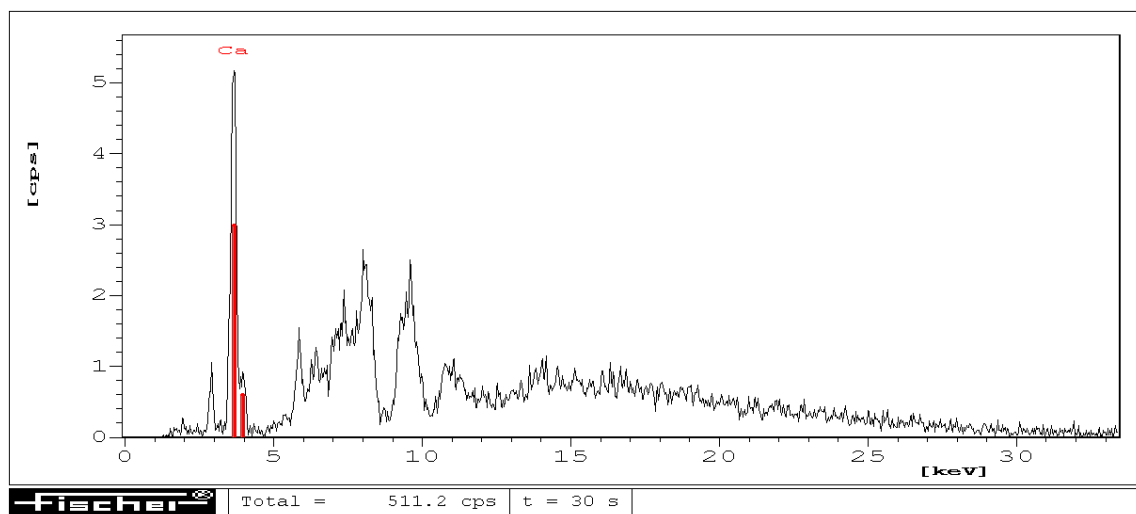


(c)

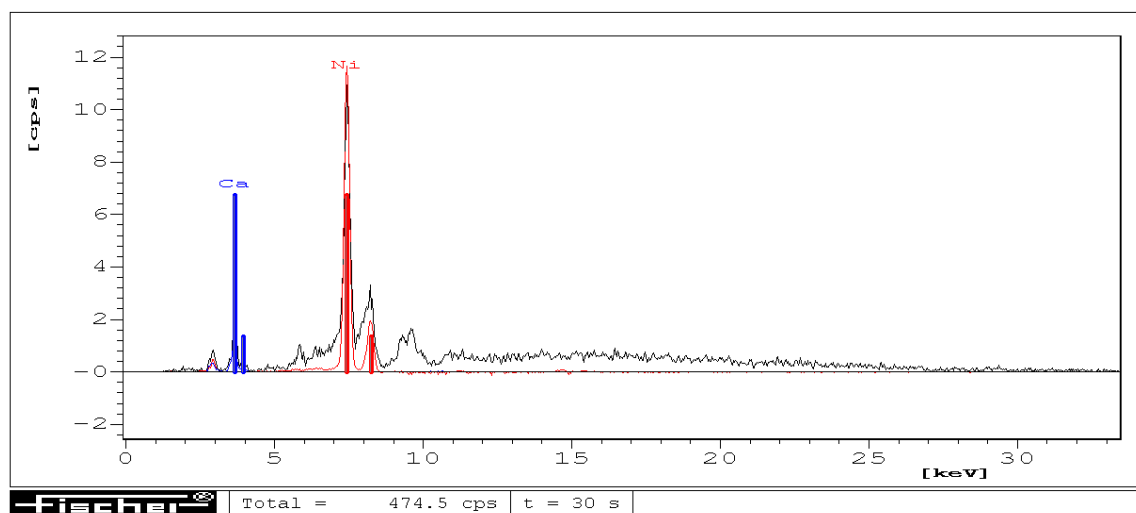
Fig. 2 X-ray fluorescence spectrum of (a) unmodified TW, (b) STWA and (c) STWA
after Ni(II) adsorption



(a)



(b)



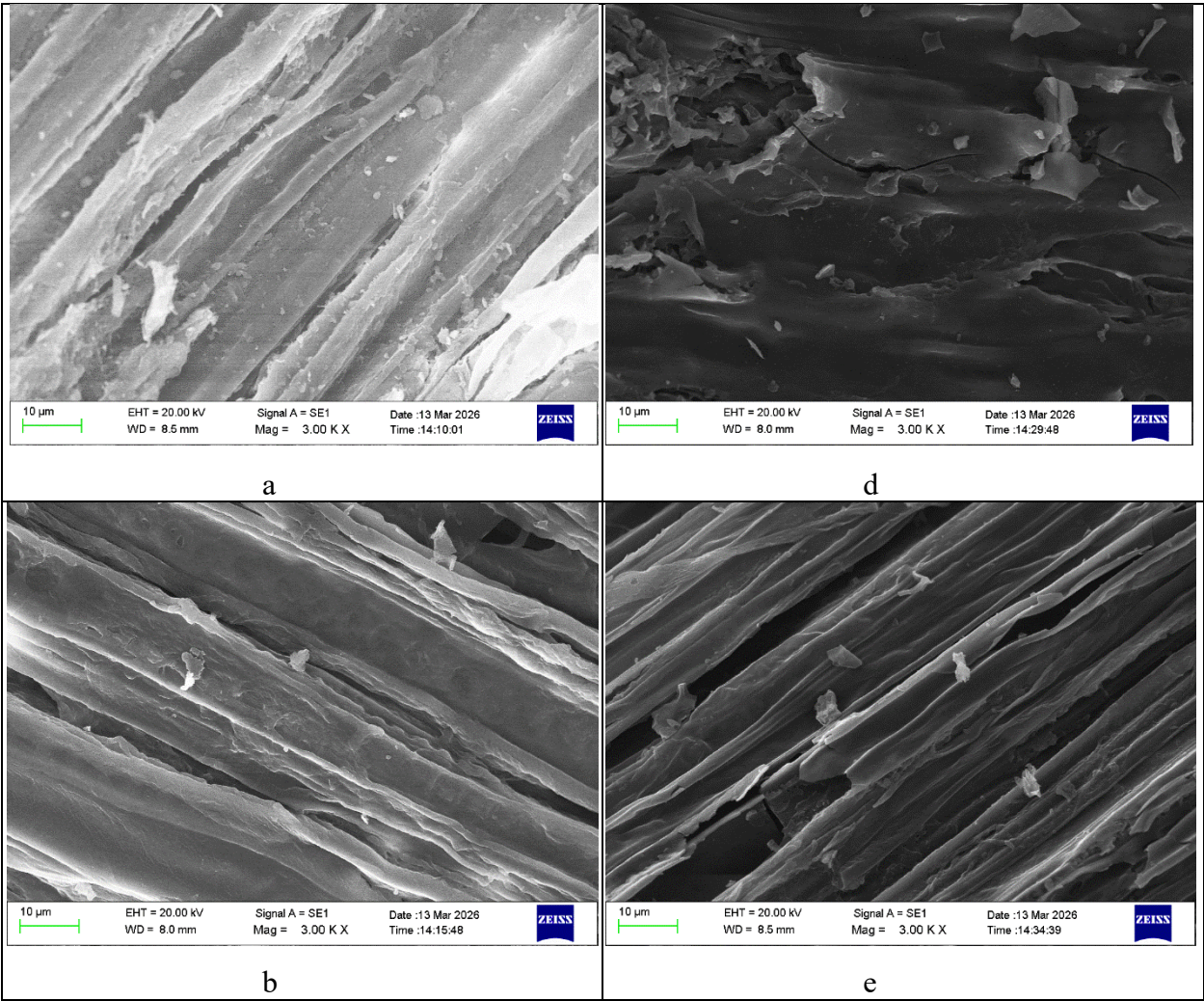
(c)

Fig. 3 X-ray fluorescence spectrum of (a) unmodified TWB, (b) STWB and (c) STWB after Ni(II) adsorption

3.1.3 SEM analysis

SEM analysis is important in adsorption research because it provides high resolution and 3-D images, allowing direct visualization of surface morphology, porosity and structural changes of biosorbents which aids determining the adsorption efficiency. Figure 4 demonstrates the SEM analysis of unmodified TW, STWA, Ni(II) adsorbed STWA, unmodified TWB, STWB and Ni(II) adsorbed STWB. Both unmodified TW and TWB show a smooth, compact and less porous surface compared to STWA and STWB. Among unmodified TW and unmodified TWB, unmodified TWB shows a rougher and more irregular surface with many visible fractures. The compact structure of unmodified biosorbents blocks the accessibility of functional groups, reducing the number of available active adsorption sites for Ni(II), resulting in lower adsorption capacity. After chemical modification, significant surface structural changes are observed in STWA and STWB. The surface has become rougher, more irregular and highly porous with the development of cracks and fissures than unmodified biosorbents. This transformation is due to the removal of lignin in the cell wall, waxes and other extractives, which cover the internal adsorption active sites during

344 NaOH treatment, enhancing surface area and exposing previously inaccessible functional groups.
345 After adsorption of Ni(II), both STWA and STWB show clear morphological changes confirming
346 the adsorption of Ni(II).



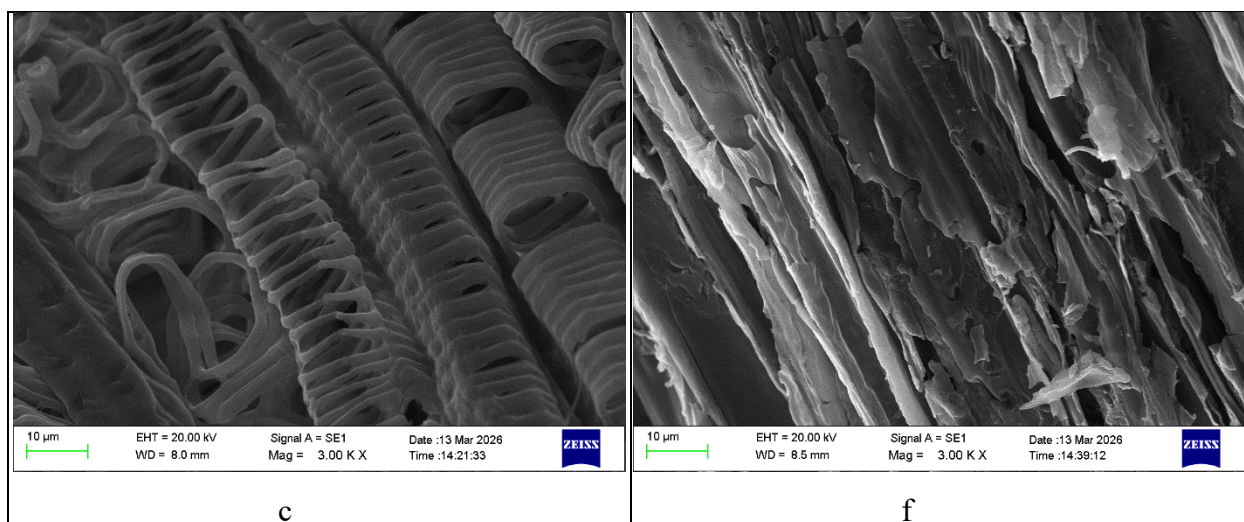


Fig. 4 SEM images of (a) unmodified TW, (b) STW, (c) Ni(II) adsorbed STWA, (d) unmodified TWB (e), STWB and (f) Ni(II) adsorbed STWB

3.1.4 Point of zero charge (PZC)

The PZC is the pH at which the surface of an adsorbent has a neutral charge (Çakmak et al., 2024). If the solution $\text{pH} > \text{PZC}$, the surface will be negatively charged, which is favorable for cation adsorption, and if the $\text{pH} < \text{PZC}$, the surface will be positively charged, which is favorable for anion adsorption. As shown in Figure 5, PZC values were determined by investigating the specific charge as a function of solution pH for NaNO_3 solutions of three concentrations using several adsorbents used in this study. NaNO_3 is used as the background electrolyte in surface charge determination because it does not interact on the adsorbent surface. The results suggest that raw TW adsorbent and unmodified TW biochar have higher PZC values, approximately pH 10.90 and pH 9.25, respectively, revealing a limited number of negatively charged sites at neutral pH (7.0). After NaOH treatment, both STWA and STWB demonstrate a noticeable shift in PZC to lower pH values, approximately to pH 4.50 and 5.50, respectively, which indicates that the increase of negatively charged sites due to deprotonation and exposure of functional groups such as $-\text{OH}$ and

–COO[−]. As a result, the modified adsorbents are more effective in adsorbing positively charged metal ions like Ni(II) at neutral to slightly acidic pH.

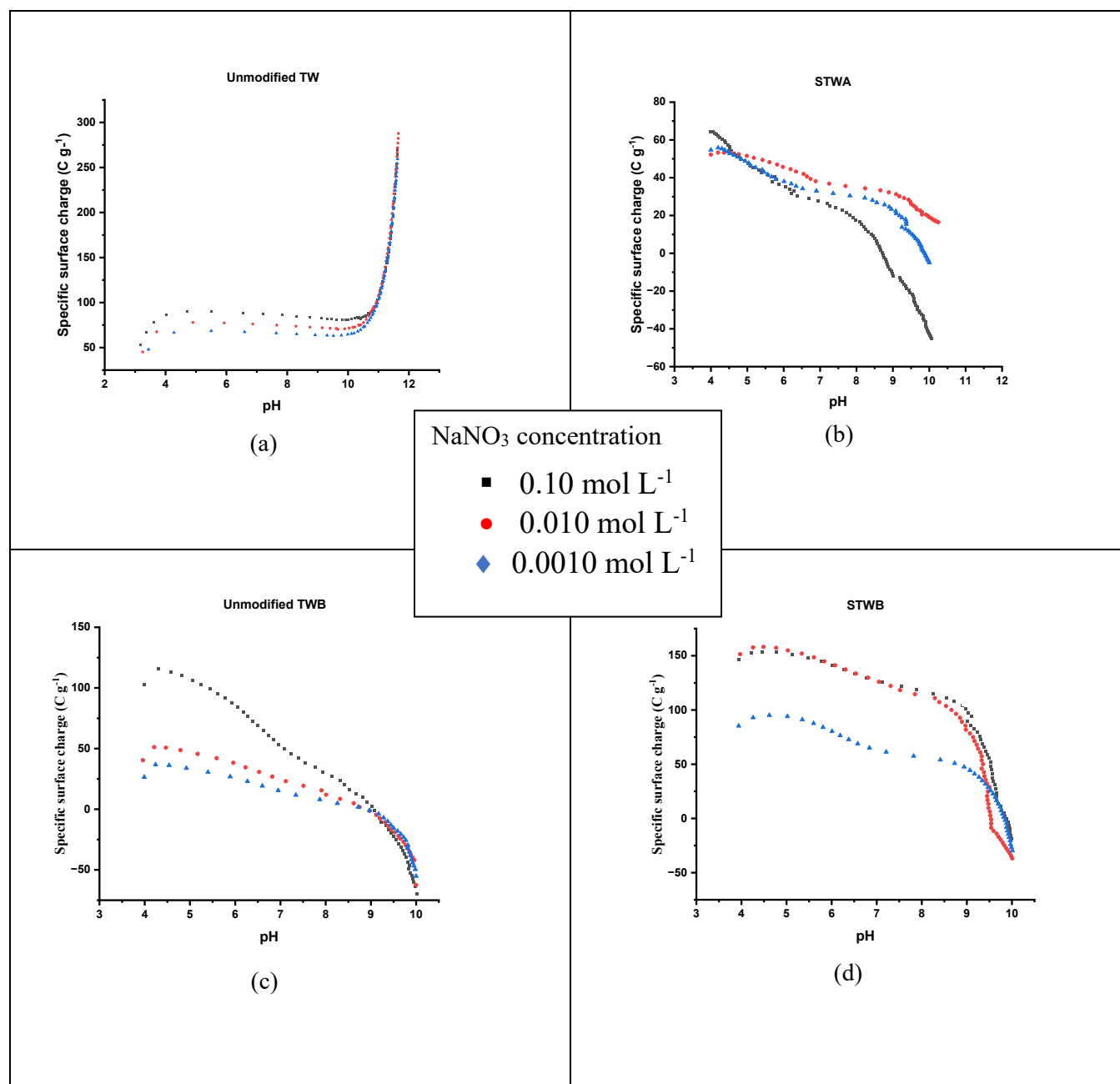


Fig. 5 Point of zero charge (PZC) of (a) unmodified TW, (b) STW, (c) unmodified TWB and (d) STWB

3.1.5 Thermal gravimetric analysis (TGA)

TGA is a technique that measures the mass of the sample over time as the temperature changes, allowing to determine the material composition, thermal stability, decomposition and moisture content of the sample. For the typical lignocellulose biomasses, the decomposition occurs in multiple stages. Initially, intramolecular moisture is removed from ambient temperature to 120 °C, hemicellulose is decomposed from 200 °C to 320 °C, followed by cellulose decomposition from 300 °C to 400 °C. Decomposition of lignin, being a stable polymer, requires a broad temperature range, from 200°C to 800°C (Paredes et al., 2024; P. Wang & Howard, 2017). Figure 6 demonstrates the mass loss curves with increasing temperature for unmodified TW, STWA, unmodified TW biochar and STWB, indicating the thermal behavior that reflects the structural and compositional changes among the adsorbents.

According to Figure 6, the TGA curves of unmodified TW and STWA show similar decomposition patterns, with some differences. The cell walls contain lignin tightly bound to the cellulose and hemicellulose through ester bonds. When TW is treated with NaOH, these ester bonds are hydrolyzed and exposing more hydroxyl groups and carboxylic groups, thereby providing more active functional groups for adsorption of Ni(II). In both samples, an initial mass loss below 120 °C was observed due to the evaporation of physically bound water. It is little higher in STWA because water molecules move inside and bind with internal functional groups during the treatment process due to the absence of lignin and cell walls. That is, STWA does not have water-impermeable cell walls. Another noticeable difference in mass loss of STWA is observed between 200–380 °C with additional mass loss compared to that of TW, because more functional groups introduced during the modification process are decomposed, while broader degradation extending up to 600 °C corresponds to the decomposition of lignin. On the other hand, TW is fully

decomposed indicating lower thermal stability, while STWA leaves a slightly higher residue, reflecting the incorporation of Na-based minerals during the modification process, indicating more thermal stability.

In contrast, TW biochar and STWB demonstrate much higher thermal stability than unmodified TW and STWA because, in the pyrolysis process, the decomposition of cellulose, hemicellulose, and lignin occurs at relatively low temperature, allowing the aromatic ring formation, polymerization, and the cross-linking of carbon chains. These structures are highly stable and resistant to decomposition. Initial mass loss in both TW biochar and STWB is attributed to the moisture loss, similar to that of unmodified TW and STWA. According to Figure 6(d), lignin is not completely decomposed, and it is present in biochar. After treatment with NaOH, lignin is hydrolyzed similar to what is observed in STWA. The small additional mass loss observed in STWB in the range of 200 °C – 400 °C likely corresponds to the decomposition of newly introduced functional groups, which are beneficial for the adsorption process. Overall, TGA results reveal that pyrolysis and modification with NaOH significantly enhance the thermal stability and the functional groups, confirming the superior adsorption capacity of the STWA and STWB.

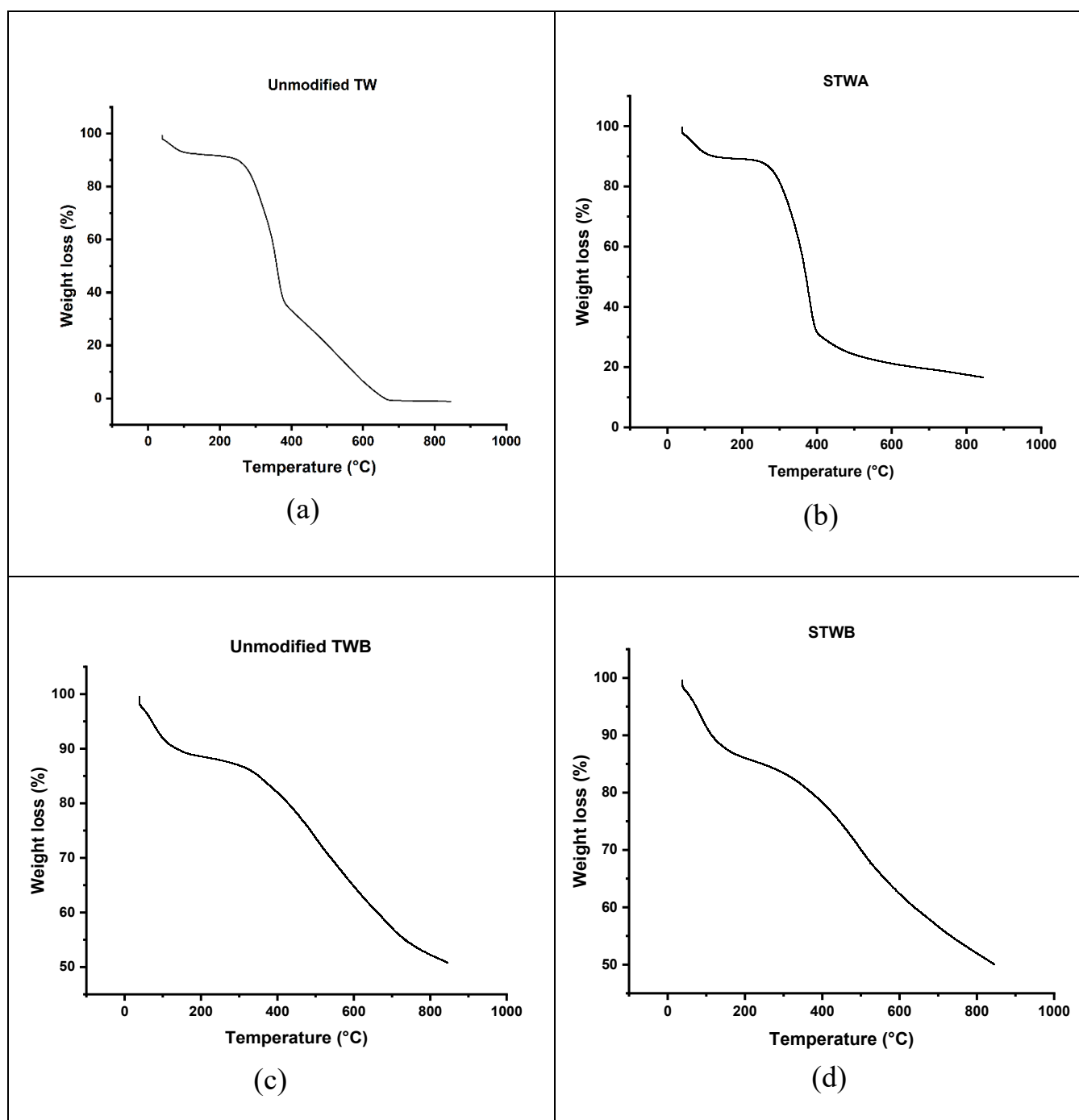


Fig. 6 TGA of (a) unmodified TW, (b) STW, (c) TWB and (d) STWB

3.2 Optimization of parameters

Optimizing experimental parameters is crucial in adsorption to maximize the adsorption efficiency, minimize waste and cost, improve reproducibility, understand system behavior, and support the real-world applicability. In this study, optimization of key parameters such as adsorbent dosage, shaking time, and settling time were performed to investigate their effect on the removal efficiency of Ni(II) STWA and STWB.

3.2.1 Dosage optimization

Figure 7 illustrates the effect of varying the dosage of unmodified TW, STWA, and STWB on the extent of removal of Ni(II) from a 10 mg L⁻¹ solution, under constant shaking time (1.0 h) and settling time (1.0 h). According to the figure, the extent of Ni(II) removal increases from 55% to 80% with unmodified TW, 69% to 95% with STWA, and 85% to 98% with STWB, as the adsorbent dosage increases from 0.1 g to 1.2 g. This enhancement is due to the greater availability of active adsorption sites at higher dosages, leading to a higher probability of Ni(II)–adsorbent collisions, which facilitate the removal. However, once the saturation limit is reached, further increases in dosage does not affect the removal efficiency. As shown in Figure 7, unmodified TW shows a lower removal percentage (75%) compared to STWA (95%) and STWB (98%). Therefore, modified forms of biosorbents were selected for further studies with dosage of 0.60 g (for STWA) and 0.30 g (for STWB) as the optimum for subsequent experiments.

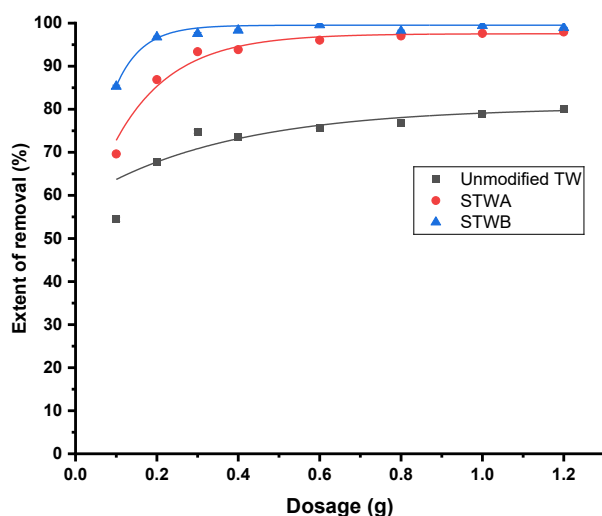


Fig. 7 Effect of dosage on removal of Ni(II) by unmodified TW, STWA and STWB

3.2.2 Shaking time optimization

The effect of shaking time on the extent of removal of Ni(II) ions using STWA and STWB as adsorbents was extensively analyzed to determine the optimal contact time for maximum Ni(II) removal. For that, a series of experiments was carried out by varying the shaking time from 10 min to 90 min with optimized dosages of 0.60 g (for STWA) and 0.30 g (for STWB) by maintaining the initial Ni(II) concentration at 10 mg L⁻¹. All experiments were conducted under controlled conditions with constant agitation to ensure uniform mixing. Shaking promotes better contact between the adsorbent and the adsorbate. Additionally, continuous motion leads to a decrease of the thickness of the boundary layer, facilitating the adsorption efficiency. As shown in Figure 8, the removal percentage of Ni(II) is increased to more than 90% within the first 10 min with both adsorbents. As the shaking time increases, eventually, the removal percentage reaches a steady state, and within 20 min, the adsorption reaches 95% (for STWA) and 98% (for STWB), after which no considerable enhancement is observed with further agitation. Such behavior implies that the active sites on the biosorbent surface have gradually filled up with Ni(II) ions, resulting in

saturation. At this moment, the available sites for Ni(II) ions become diminished. Once equilibrium is reached, the rate of adsorption equals the rate of desorption. According to the observed data, 20 min was selected as the optimal shaking time for both biosorbents in this study.

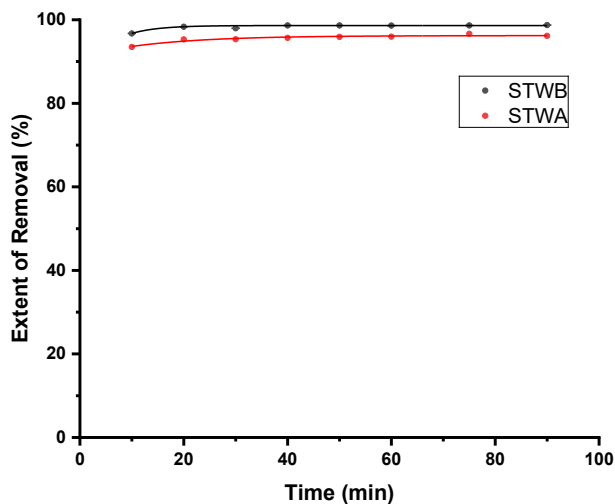


Fig. 8 Effect of shaking time on removal of Ni(II) by STWA and STWB with optimum dosages of 0.60 g (for STWA) and 0.30 g (for STWB)

3.2.3 Settling time optimization

As shown in Figure 9, there is no impact of settling time on Ni(II) adsorption. The results confirm that the majority of adsorption occurs predominantly during the shaking phase. However, a short settling period is still required to ensure proper separation between the solid biosorbent and the aqueous phase. Moreover, shaking induces collisions among molecules, which may lead to a slight increase in temperature. To avoid the impact of temperature variation on adsorption equilibrium, the solution was allowed to cool to room temperature. Therefore, 10 min was chosen as the optimal settling time for further experiments.

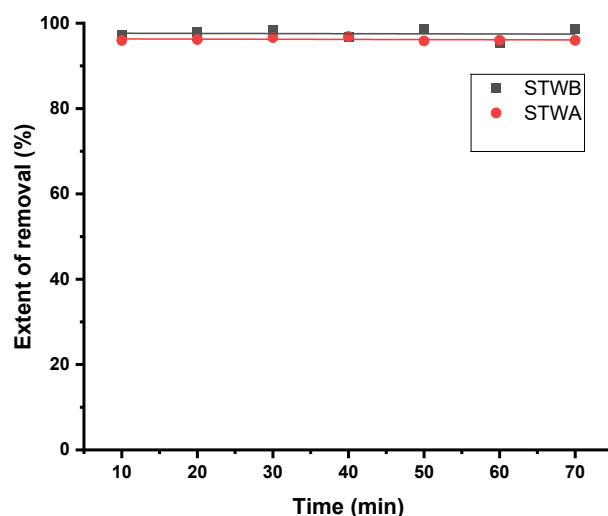


Fig. 9 Effect of settling time on removal of Ni(II) by STWA and STWB at optimum dosages of 0.60 g (for STWA) and 0.30 g (for STWB) and at 20 min shaking time for both adsorbents

3.3 Investigation of kinetics

The Ni(II)–STWA and the Ni(II)–STWB systems demonstrate an exceptionally rapid adsorption behavior, reaching equilibrium very fast. This indicates that the Ni(II) ions have a high affinity towards both STWA and STWB, likely driven by surface interactions with minimal diffusion resistance. This rapid equilibrium limits the conducting of a detailed kinetic study under typical time intervals and standard Ni(II) concentrations. Raising the initial Ni(II) concentration from 10.0 mg L⁻¹ to 25.0 mg L⁻¹ did not change the time taken to achieve equilibrium. Although the kinetics is so fast that it is not possible to investigate under normal circumstances, even at a higher concentration of Ni(II), it is confirmed that STWA and STWB adsorbents are extremely efficient for the rapid removal of Ni(II) from aqueous solutions.

The IPD model is used to identify the rate limiting step in an adsorption process and evaluate the adsorption mechanism. There are three main stages in a diffusion process corresponding to film

diffusion, IPD and adsorption onto internal active sites, which is an equilibrium step (Zhong et al., 2021). According to Figure 10, both diffusion plots of STWA and STWB have tri-linear stages confirming that adsorption occurs through multiple stages. All lines are deviated from the origin ($C \neq 0$), indicating that IPD is not the rate-limiting step (Lach & Okoniewska, 2024). The first linear region of both STWA and STWB shows relatively high k_{id} values of $1.296 \text{ mg g}^{-1} \text{ min}^{-1/2}$ and $1.193 \text{ mg g}^{-1} \text{ min}^{-1/2}$, respectively, indicating fast mass transfer of Ni(II) from bulk solution to the surface of the biosorbent via complexation with functional groups on the biosorbent surface. Notably, lower k_{id} values were observed for STWA ($0.221 \text{ mg g}^{-1} \text{ min}^{-1/2}$) and STWB ($0.329 \text{ mg g}^{-1} \text{ min}^{-1/2}$) in the second stage controlled by IPD of Ni(II) into internal pores of the biosorbents. This is due to decrease in availability of active adsorption sites, decrease in concentration gradient and increase in mass transfer resistance due to active sites of the surface being previously occupied in first stage (Sangoremi, 2025). These factors collectively increase the adsorption resistance and slow down the adsorption rate at the last stage. Overall, these multi-stage IPD plots confirm that adsorption onto both STWA and STWB is governed by a mixed mechanism involving film diffusion and IPD.

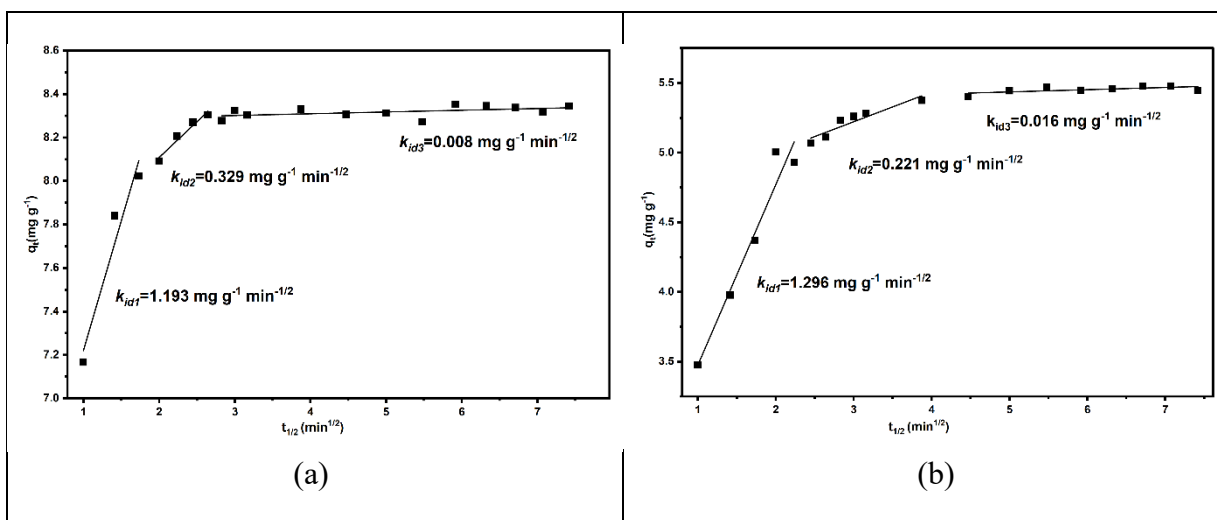


Fig. 10 Adsorption kinetics using weber and Morris intra-particle diffusion model for Ni(II) adsorption by (a) STWA and (b) STWB

3.4 Investigation of adsorption isotherms

Adsorption isotherm analysis contributes to determining the adsorption mechanism between the adsorbate and the adsorbent surface. Langmuir, Freundlich, Temkin, Dubinin–Radushkevich, and Redlich–Peterson models are commonly used in adsorption studies. Among these, Langmuir, Freundlich, and Temkin are frequently used to investigate the adsorption mechanism of natural biosorbents.

The Langmuir isotherm model assumes monolayer adsorption onto a homogeneous surface with a finite number of identical and energetically equivalent adsorption sites. After adsorption, there are no interactions between adsorbed molecules. The linearized Langmuir isotherm model is expressed as follows,

$$\frac{C_e}{q_e} = \frac{1}{q_{max}K_L} + \frac{C_e}{q_{max}} \quad [6]$$

where C_e is equilibrium concentration of adsorbate (mg L^{-1}), q_e is equilibrium adsorption capacity of adsorbent (mg g^{-1}), $q_{\max}$ is maximum adsorption capacity of biosorbent (mg g^{-1}), and K_L is the isotherm constant (L mg^{-1}) (Nadheesha et al., 2021).

Alternatively, the Freundlich isotherm model assumes multilayer adsorption onto a heterogeneous surface of the adsorbent. The adsorption sites are not energetically equivalent, and the energy of the adsorption sites depends on whether the adjacent sites are occupied or not. The linearized Freundlich isotherm model is expressed as follows,

$$\log q_e = \log K_f + \frac{1}{n} \log C_e \quad [7]$$

where q_e is equilibrium adsorption capacity of the adsorbent (mg g^{-1}), K_f is isotherm constant (L mg^{-1}), C_e is equilibrium concentration of adsorbate (mg L^{-1}), and $1/n$ is the adsorption intensity ($0 < 1/n < 1$ implies favorable adsorption) (Tobbi et al., 2024).

On the other hand, the Temkin isotherm model supposes that the heat of the adsorption process decreases linearly with increasing surface coverage due to interactions between the adsorbent and adsorbate. Additionally, it assumes a chemical interactive adsorption process. The linearized Temkin isotherm model is expressed as follows,

$$q_e = B \ln C_e + B \ln K_m \quad [8]$$

where q_e is equilibrium adsorption capacity of the adsorbent (mg g^{-1}), K_f is isotherm constant (L mg^{-1}), C_e is equilibrium concentration of adsorbate (mg L^{-1}), and B is Temkin constant related to sorption heat (J mol^{-1}) (Rauf et al., 2020).

Figure 11 shows the linearized fit of the Freundlich, Langmuir, and the Temkin isotherm models for STWA, and Figure 12 for STWB with the Ni(II) concentration range of 10 mg L⁻¹ to 700 mg L⁻¹. R^2 of the different concentrations is shown in Table 4.

Table 4: R^2 values at different ranges of concentrations of Ni(II) for STWA and STWB

	STWA			STWB		
	All concentrati ons	High Concentrati ons	Low Concentrati ons	All concentrati ons	High Concentrati ons	Low Concentrati ons
Freundlich	0.9772	0.5706	0.9887	0.9690	0.4477	0.9839
Langmuir	0.9126	0.6462	0.9760	0.9951	0.9853	0.9690
Temkin	0.8259	0.5010	0.9344	0.9249	0.4146	0.8427

According to the R^2 values listed in Table 3, all three adsorption models show a better fit at low concentrations of Ni(II) on STWA. Among these three models, the Freundlich adsorption isotherm, with the R^2 value of 0.9887, has become more dominant at low concentrations, indicating that the amount of Ni(II) lost from the solution phase is more than what is required for a monolayer. Therefore, Ni(II), once adsorbed to the surface of the adsorbent would contribute to other means of mass transfer, such as transfer to mesopores and macropores, inter-particle diffusion and intra-particle diffusion. Adsorption at the high Ni(II) concentration is not well explained by any of these three models. According to the R^2 values for the range of all concentrations, Freundlich isotherm is the best fit with an R^2 value of 0.9772.

In parallel, STWB shows the highest R^2 value of 0.9951 for the Langmuir adsorption model with a range of all concentrations of Ni(II), suggesting monolayer coverage on a more homogeneous

surface as compared to STWA. However, at low Ni(II) concentration, Freundlich isotherm becomes more dominant with R^2 of 0.9839, indicating a similar behavior as described earlier for STWA. However, at high Ni(II) concentration, again Langmuir isotherm shows a better fit with R^2 of 0.9853.

Interestingly, the Temkin model shows improved correlation at low Ni(II) concentration for STWA ($R^2 = 0.9344$), suggesting that at lower concentrations, the heat of adsorption decreases linearly with increasing surface coverage due to adsorbate–adsorbent interactions becoming more significant. The Temkin model for STWB exhibits a moderate fit within the entire concentration range ($R^2 = 0.9249$), but with clear limitations at high concentrations ($R^2 = 0.4146$), suggesting that heat of adsorption decreases with coverage, but is less predictable at higher metal ion concentrations.

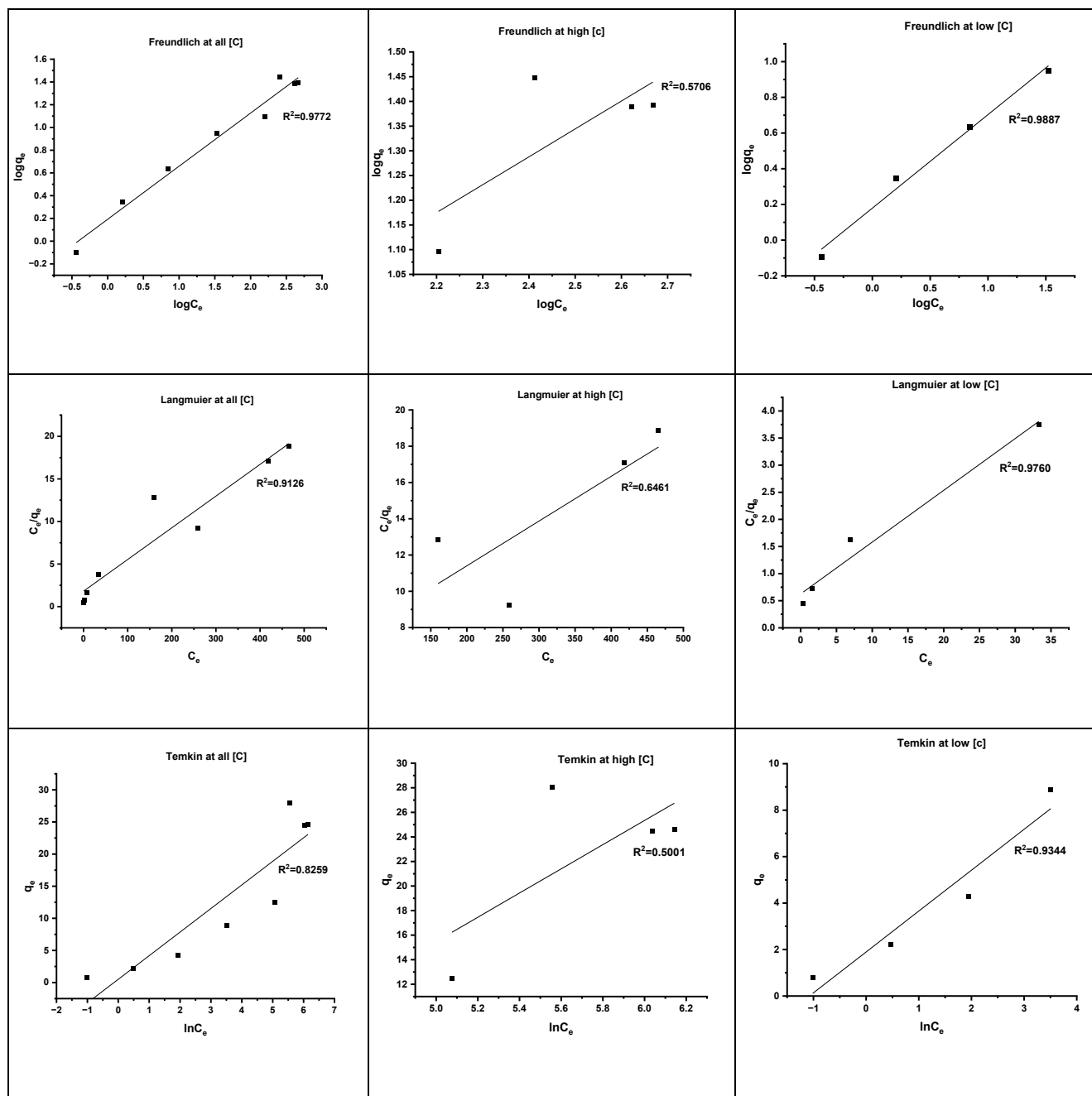


Fig. 11 Adsorption isotherms for Ni(II) adsorbate by STWA adsorbent at equilibrium; Freundlich (top), Langmuir (middle) and Temkin (bottom)

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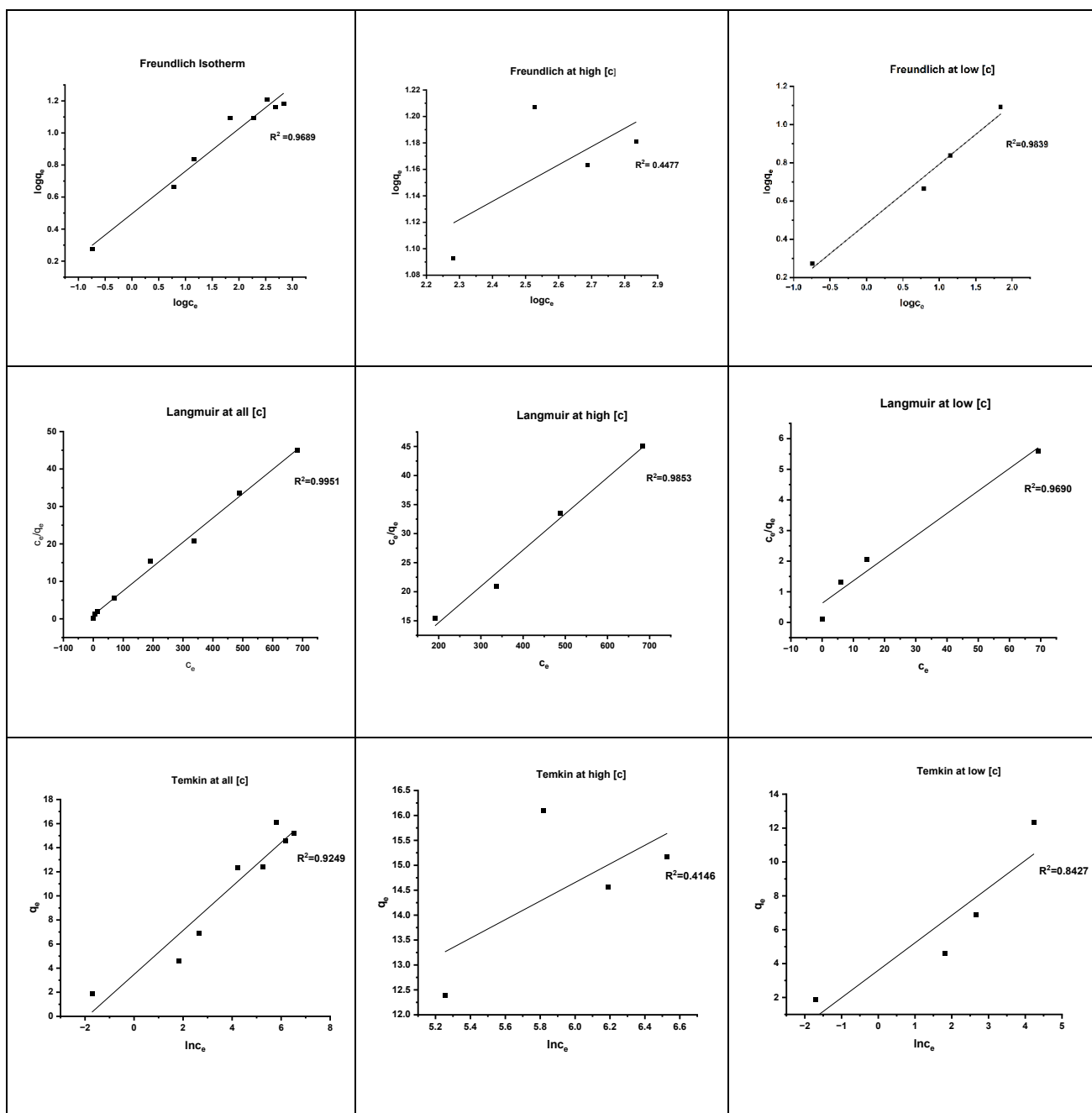


Fig. 12 Adsorption isotherms for Ni(II) adsorbate by STWB adsorbent at equilibrium; Freundlich (top), Langmuir (middle) and Temkin (bottom)

3.5 Interference study

Figure 13 evaluates the extent of removal of Ni(II) by the STWA and STWB in the presence of various interference agent: EDTA, NaCl, Co(II), Al(III), Fe(III), Cr(III), Pb(II), and Cu(II). Trivalent cations such as Al(III), Fe(III), and Cr(III) cause the significant reductions in Ni(II) removal than the divalent cation. Charge density and the affinity for the active adsorption sites of these trivalent cations are higher than the divalent cations. Therefore, Ni(II) removal is significantly lower in the presence of these trivalent cations than the divalent cations. In the presence of NaCl, the removal efficiency is reduced, possibly due to increased ionic strength, which reduces the thickness of the electrical double layer. In all cases, STWB maintained higher Ni(II) removal than STWA, indicating that pyrolysis and modification enhanced surface area, porosity, and functional group stability, confirming resistance to interference.

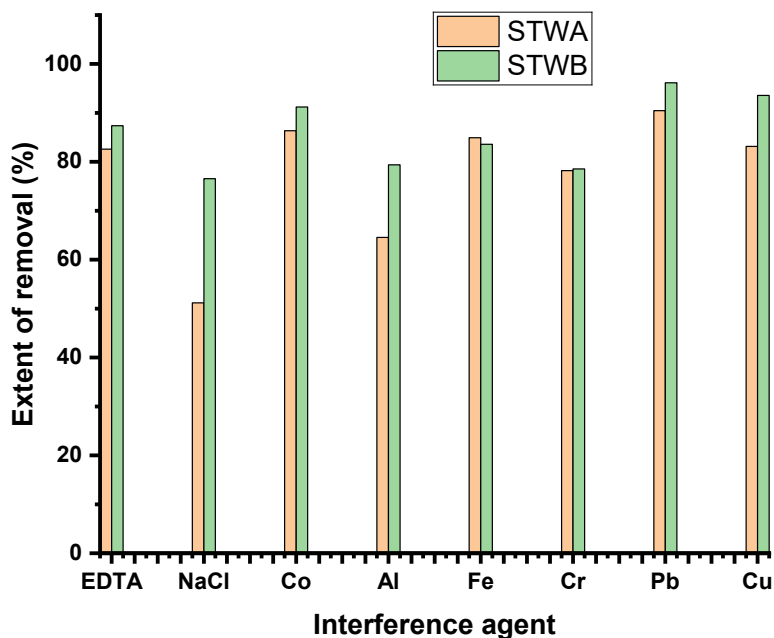


Fig. 13 Effect on Ni(II) removal by STWA and STWB in the presence of interfering agents

3.6 Regeneration study

Among adsorption studies, the principal focus is on adsorption performance, while the post treatment management of spent adsorbents receives comparatively limited attention, although the it is an important aspect. Regeneration provides several advantages including reduction of secondary waste, recovery of adsorbate molecules, reuse of adsorbent material and improve the economic and environmental sustainability of adsorption treatment processes (Zhang et al., 2020). Chemical, thermal, microbial, electrochemical, ultrasound and micro-wave assisted techniques are widely used in regeneration studies (Renu & Sithole, 2024). In this study chemical reagents, namely, HNO_3 , HCl and EDTA and deionized water, were used to detach the Ni(II) from the surface and pores of STWA and STWB. Figure 14 shows the adsorption and desorption performance after treatment with four different desorption agents (HNO_3 , HCl and EDTA and deionized water). Both STWA and STWB exhibit superior desorption efficiency with HNO_3 and HCl achieving values above 95%. During adsorption process Ni(II) ions interact with negatively charged surface functional groups such as COO^- , OH through complexation. Treatment with acids causes the higher H^+ concentrations and effectively replace the Ni(II) from these active sites resulting efficient desorption. EDTA also shows desorption value above 90% for both STWA and STWB which is slightly lower compared to the acidic reagents. The desorption mechanism is governed by the chelation where EDTA forms stable Ni-EDTA complex facilitating the Ni(II) removal from the adsorbent surface (Velempini et al., 2023). In contrast, negligible desorption is observed for the deionized water with the value of 4%. This indicates that Ni(II) is strongly bound to the functional group of the adsorbent surface through chemisorption. After the desorption of Ni(II) , STWA and STWB can be reused and exhausted adsorbents can be safely disposed in landfills or burned in incinerator according to the environmental standards.

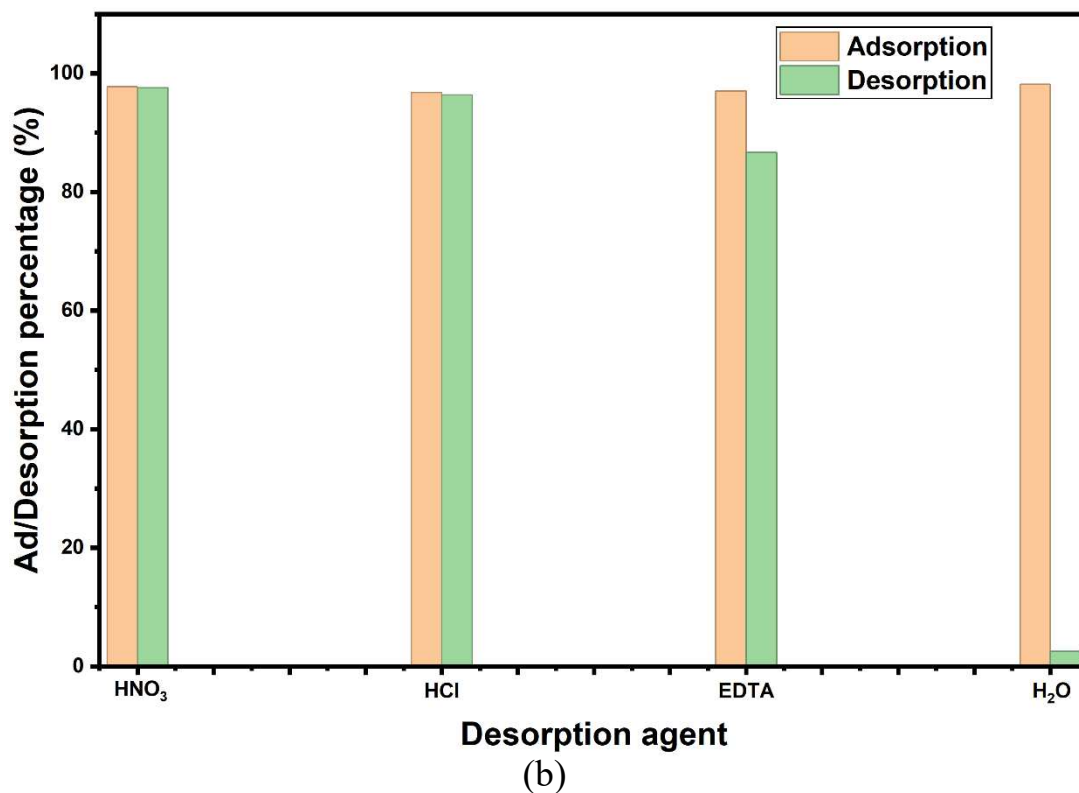
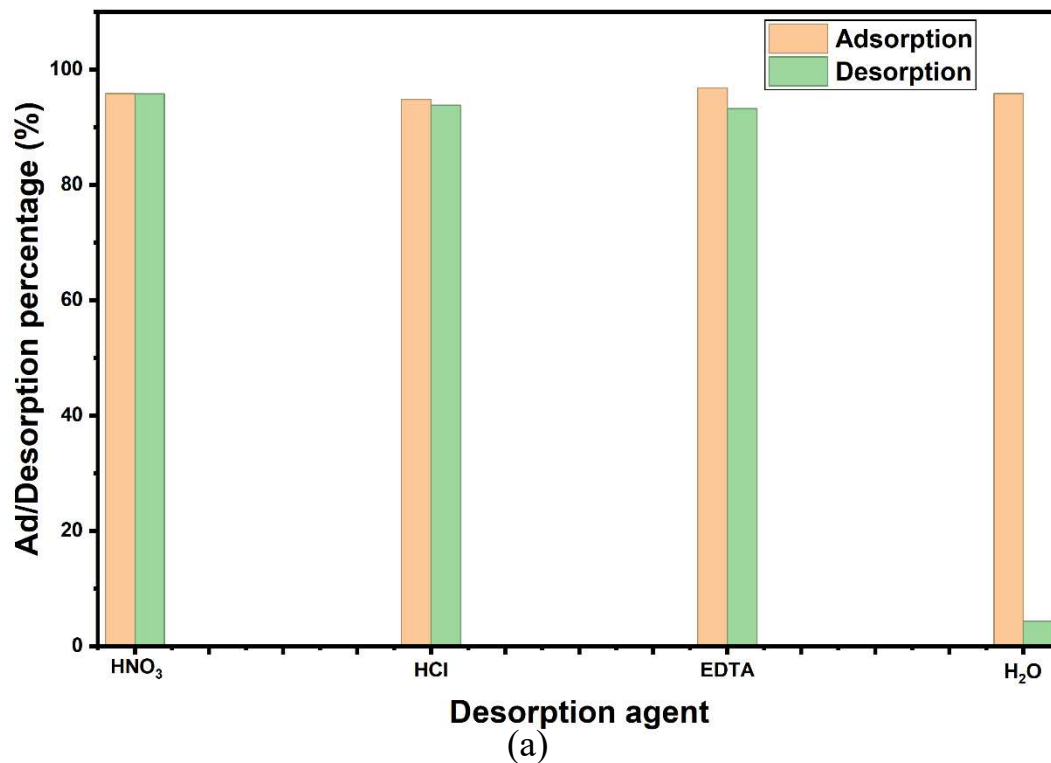


Fig. 14 Regeneration study of STWA (a) and STWB (b) with different desorption agents (HNO₃, HCl, EDTA and deionized water)

4. Mechanism of adsorption

Adsorption of Ni(II) on STWB and STWA occurs through a combination of complexation, physicochemical interactions with surface functional groups, and IPD. In lignocellulosic biomass, lignin is tightly bound with hemicellulose within the cell wall through ester linkages. NaOH treatment breaks these ester bonds, leading to partial removal of lignin from the biosorbent cell wall, thereby exposing more functional groups of the underlying cellulose and hemicellulose layers and generating additional surface-active adsorption sites. Consequently, more hydroxyl, ester and carboxyl groups become available as active sites for Ni(II) binding. This structural modification increases surface accessibility and enhances the adsorption performance of STWA and STWB compared to unmodified TW and TWB.

FTIR analysis confirms the presence of oxygen-containing functional groups, such as hydroxyl, ester and carboxyl groups, which play an important role in Ni(II) adsorption. In addition, XRF analysis reveals the presence of inorganic metal ions such as Mn(II), Ca(II) and K(I) that contribute to the development of surface charges and PZC results clarify the effect of surface charge on adsorption behavior. At suitable pH conditions which is pH higher than the PZC, deprotonation of surface functional groups generates negatively charged sites which favorable for attracting positively charged Ni(II). Further TGA results exhibit the typical thermal degradation pattern of lignocellulosic biomass for unmodified TW and indicate structural changes for unmodified TWB and STWA and STWB supporting the proposed mechanism. Figure 15 shows schematic illustrate of the proposed mechanism of the Ni(II) adsorption onto STWA and STWB.

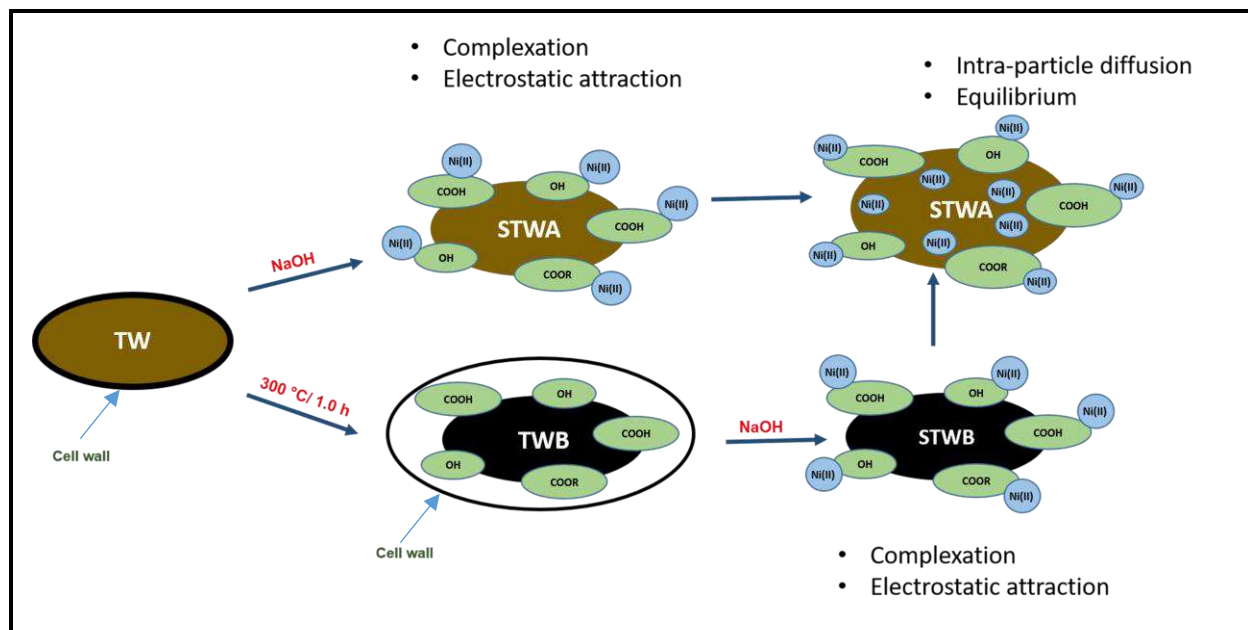


Fig. 15 Schematic illustration of the proposed mechanism of the adsorption of Ni(II) onto STW and STWB

5. Conclusion

The outcome of this study highlights the fact that STWA and STWB are efficient biosorbents for the removal of Ni(II) from aqueous solutions. Ester groups present in unmodified TW would undergo hydrolysis during the treatment with NaOH forming anionic moieties. Further, -OH and -COOH groups would also be converted to corresponding anionic forms during the NaOH treatment. Both these processes are thus favorable for Ni(II) adsorption. SEM analysis reveals that NaOH treatment of TW and TWB significantly enhances the surface morphology, developing pores, cracks and roughened surfaces with the exposure of more functional groups which directly involve in Ni(II) adsorption. Ni(II) adsorbed sample shows evidence of deposition and pore filling supporting the proposed complexation-driven mechanism. Further, the pH at the point zero charge shifts to low values during modification, creating a negatively charged surface at ambient pH, which is also favorable for Ni(II) adsorption. Parameter optimization studies reveal that the

maximum extent of removal can be achieved with a dosage of 0.60 g (for STWA) and 0.30 g (for STWB) with 20 min shaking time and 10 min of settling time for both STWA and STWB. The kinetics study confirms the rapid adsorption of Ni(II) on both adsorbent types, promising their high adsorption capacity to remove Ni(II) from solution. Multi-stage mechanism occurs in the adsorption of Ni(II) onto STWA and STWB, as evidenced by the tri-linear Weber–Morris IPD plots. High k_{id} value of the first stage of each plot reflects rapid mass transfer from the bulk solution to the biosorbent surface via complexation with surface functional groups, while the subsequent IPD stage shows lower k_{id} indicating lower diffusion rate. Overall, Ni(II) adsorption onto STWA and STWB is governed by a mixed mechanism involving both film diffusion and IPD. Adsorption of Ni(II) on STWB obeys the Langmuir isotherm model, indicating the monolayer adsorption onto the homogeneous surface, while the STWA obeys the Freundlich isotherm model. Interference study demonstrates that trivalent cation significantly reduces the Ni(II) removal than divalent cations, and more importantly, STWB shows higher resistance to interference. Biosorbent upon treatment with Ni(II) can easily be regenerated with HCl, HNO₃ and EDTA, demonstrating the sustainability of the use of the biosorbents in this study. In summary, this study emphasizes that the pyrolyzed and NaOH-modified tea waste has high potential for Ni(II) removal as a sustainable, low-cost and highly efficient biosorbent.

6. Statements and Declarations

Competing interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

7. References

- Amarasinghe, B. M. W. P. K., & Williams, R. A. (2007). Tea waste as a low cost adsorbent for the removal of Cu and Pb from wastewater. *Chemical Engineering Journal*, 132(1–3), 299–309. <https://doi.org/10.1016/j.cej.2007.01.016>
- Aryal, M., & Liakopoulou-Kyriakides, M. (2015). Bioremoval of heavy metals by bacterial biomass. *Environmental Monitoring and Assessment*, 187(1), 4173. <https://doi.org/10.1007/s10661-014-4173-z>
- Axtell, N. (2003). Lead and nickel removal using *Microspora* and *Lemna minor*. *Bioresource Technology*, 89(1), 41–48. [https://doi.org/10.1016/S0960-8524\(03\)00034-8](https://doi.org/10.1016/S0960-8524(03)00034-8)
- Boeykens, S. P., Saralegui, A., Caracciolo, N., & Piol, M. N. (2018). Agroindustrial Waste for Lead and Chromium Biosorption. *Journal of Sustainable Development of Energy, Water and Environment Systems*, 6(2), 341–350. <https://doi.org/10.13044/j.sdewes.d5.0184>
- Çakmak, T. G., Saricaoglu, B., Ozkan, G., Tomas, M., & Capanoglu, E. (2024). Valorization of tea waste: Composition, bioactivity, extraction methods, and utilization. *Food Science & Nutrition*, 12(5), 3112–3124. <https://doi.org/10.1002/fsn3.4011>
- Charazińska, S., Burszta-Adamiak, E., & Lochyński, P. (2022). Recent trends in Ni(II) sorption from aqueous solutions using natural materials. *Reviews in Environmental Science and Bio/Technology*, 21(1), 105–138. <https://doi.org/10.1007/s11157-021-09599-5>
- Datta, J., & Deb, S. (2025). Tea factory waste as a cost-effective and sustainable Cadmium(II) adsorbent: Investigating adsorption isotherms, kinetics, and thermodynamics. *Physics and Chemistry of the Earth, Parts A/B/C*, 140, 104042. <https://doi.org/10.1016/j.pce.2025.104042>
- Dharmarathna, S. P., & Priyantha, N. (2024). Investigation of boundary layer effect of intra-

particle diffusion on methylene blue adsorption on activated carbon. *Energy Nexus*, 14, 100294. <https://doi.org/10.1016/j.nexus.2024.100294>

El-Naggar, A., Ahmed, N., Mosa, A., Niazi, N. K., Yousaf, B., Sharma, A., Sarkar, B., Cai, Y., & Chang, S. X. (2021). Nickel in soil and water: Sources, biogeochemistry, and remediation using biochar. *Journal of Hazardous Materials*, 419, 126421. <https://doi.org/10.1016/j.jhazmat.2021.126421>

Ezeonuegbu, B. A., Machido, D. A., Whong, C. M. Z., Japhet, W. S., Alexiou, A., Elazab, S. T., Qusty, N., Yaro, C. A., & Batiha, G. E.-S. (2021). Agricultural waste of sugarcane bagasse as efficient adsorbent for lead and nickel removal from untreated wastewater: Biosorption, equilibrium isotherms, kinetics and desorption studies. *Biotechnology Reports*, 30, e00614. <https://doi.org/10.1016/j.btre.2021.e00614>

Fdez-Sanromán, A., Pazos, M., Rosales, E., & Sanromán, M. A. (2020). Unravelling the Environmental Application of Biochar as Low-Cost Biosorbent: A Review. *Applied Sciences*, 10(21), 7810. <https://doi.org/10.3390/app10217810>

Ferda Gönen. (2012). Adsorption study on orange peel: Removal of Ni(II) ions from aqueous solution. *AFRICAN JOURNAL OF BIOTECHNOLOGY*, 11(5). <https://doi.org/10.5897/AJB11.1753>

Georgieva, V. G., Gonsalvesh, L., & Tavlieva, M. P. (2020). Thermodynamics and kinetics of the removal of nickel (II) ions from aqueous solutions by biochar adsorbent made from agro-waste walnut shells. *Journal of Molecular Liquids*, 312, 112788. <https://doi.org/10.1016/j.molliq.2020.112788>

Gupta, A., & Balomajumder, C. (2017). Statistical optimization of process parameters for the simultaneous adsorption of Cr(VI) and phenol onto Fe-treated tea waste biomass. *Applied*

729 *Water Science*, 7(8), 4361–4374. <https://doi.org/10.1007/s13201-017-0582-9>

730 Gupta, S. Sen, & Bhattacharyya, K. G. (2006). Adsorption of Ni(II) on clays. *Journal of Colloid*
 731 *and Interface Science*, 295(1), 21–32. <https://doi.org/10.1016/j.jcis.2005.07.073>

732 Khir, N. H. M., Ghafar, N. A., Shukri, N. M., Hapani, M., & Salleh, N. F. M. (2025). *Tea waste:*
 733 *Efficient biosorbent for nickel (II) and chromium (VI) ions removal in aqueous solution.*
 734 050007. <https://doi.org/10.1063/5.0258636>

735 Kolmykova, L. I., Nikashina, V. A., & Korobova, E. M. (2023). Experimental study of the sorption
 736 properties of natural zeolite-containing tripolite and their ability to purify aqueous solutions
 737 contaminated with Ni and Zn. *Environmental Geochemistry and Health*, 45(2), 267–274.
 738 <https://doi.org/10.1007/s10653-022-01346-1>

739 Kotabewatta, P. A., & Priyantha, N. (2024). *Biosorption of Cd 2+ ions onto peel of Artocarpus*
 740 *nobilis Fruit: intra-particle diffusion and isotherm studies.* [https://doi.org/10.21203/rs.3.rs-](https://doi.org/10.21203/rs.3.rs-4400981/v1)
 741 4400981/v1

742 Lach, J., & Okoniewska, E. (2024). Equilibrium, Kinetic, and Diffusion Mechanism of lead(II)
 743 and cadmium(II) Adsorption onto Commercial Activated Carbons. *Molecules*, 29(11), 2418.
 744 <https://doi.org/10.3390/molecules29112418>

745 Levická, J., & Orliková, M. (2024). The Toxic Legacy of Nickel Production and Its Impact on
 746 Environmental Health: A Case Study. *International Journal of Environmental Research and*
 747 *Public Health*, 21(12), 1641. <https://doi.org/10.3390/ijerph21121641>

748 Li, B., Huang, Y., Wang, Z., Li, J., Liu, Z., & Fan, S. (2021). Enhanced adsorption capacity of
 749 tetracycline on tea waste biochar with KHCO₃ activation from aqueous solution.
 750 *Environmental Science and Pollution Research*, 28(32), 44140–44151.

751 <https://doi.org/10.1007/s11356-021-13817-6>

752 Liang, S., Cao, S., Liu, C., Zeb, S., Cui, Y., & Sun, G. (2020). Heavy metal adsorption using
 753 structurally preorganized adsorbent. *RSC Advances*, 10(12), 7259–7264.
 754 <https://doi.org/10.1039/D0RA00125B>

755 Liu, L., Fan, S., & Li, Y. (2018). Removal Behavior of Methylene Blue from Aqueous Solution
 756 by Tea Waste: Kinetics, Isotherms and Mechanism. *International Journal of Environmental*
 757 *Research and Public Health*, 15(7), 1321. <https://doi.org/10.3390/ijerph15071321>

758 MALKOC, E., & NUHOGLU, Y. (2005). Investigations of nickel(II) removal from aqueous
 759 solutions using tea factory waste. *Journal of Hazardous Materials*, 127(1–3), 120–128.
 760 <https://doi.org/10.1016/j.jhazmat.2005.06.030>

761 Mashangwa, T. D., Tekere, M., & Sibanda, T. (2017). Determination of the Efficacy of Eggshell
 762 as a Low-Cost Adsorbent for the Treatment of Metal Laden Effluents. *International Journal*
 763 *of Environmental Research*, 11(2), 175–188. <https://doi.org/10.1007/s41742-017-0017-3>

764 Nadheesha, M. K. F., Mohotti, A. J., & Priyantha, N. (2021). Sorption Isotherm Analysis of Trace
 765 Metals on a Sandy Textured Coconut Growing Soil. *Tropical Agricultural Research*, 32(3),
 766 349. <https://doi.org/10.4038/tar.v32i3.8498>

767 Nnadozie, E. C., & Ajibade, P. A. (2020). Adsorption, kinetic and mechanistic studies of Pb(II)
 768 and Cr(VI) ions using APTES functionalized magnetic biochar. *Microporous and*
 769 *Mesoporous Materials*, 309, 110573. <https://doi.org/10.1016/j.micromeso.2020.110573>

770 Nnaji, N. D., Onyeaka, H., Miri, T., & Ugwa, C. (2023). Bioaccumulation for heavy metal
 771 removal: a review. *SN Applied Sciences*, 5(5), 125. [https://doi.org/10.1007/s42452-023-](https://doi.org/10.1007/s42452-023-05351-6)
 772 [05351-6](https://doi.org/10.1007/s42452-023-05351-6)

773 Oladimeji, T. E., Oyedemi, M., Emetere, M. E., Agboola, O., Adeoye, J. B., & Odunlami, O. A.
 774 (2024). Review on the impact of heavy metals from industrial wastewater effluent and
 775 removal technologies. *Heliyon*, 10(23), e40370.
 776 <https://doi.org/10.1016/j.heliyon.2024.e40370>
 777 Osman, H., Uğurlu, M., Vaizoğullar, A. İ., Atasoy, M., & Chaudhary, A. J. (2024). Statistical
 778 modeling and optimization of heavy metals (Pb and Cd) adsorption from aqueous solution by
 779 synthesis of Fe₃O₄/SiO₂/PAM: isotherm, kinetics, and thermodynamic. *Polymer Bulletin*,
 780 81(16), 14513–14545. <https://doi.org/10.1007/s00289-024-05404-9>
 781 Panneerselvam, P., Morad, N., & Tan, K. A. (2011). Magnetic nanoparticle (Fe₃O₄) impregnated
 782 onto tea waste for the removal of nickel(II) from aqueous solution. *Journal of Hazardous*
 783 *Materials*, 186(1), 160–168. <https://doi.org/10.1016/j.jhazmat.2010.10.102>
 784 Paredes, R., Castells, B., & Tascón, A. (2024). Thermogravimetric Assessment of Biomass:
 785 Unravelling Kinetic, Chemical Composition and Combustion Profiles. *Fire*, 7(11), 396.
 786 <https://doi.org/10.3390/fire7110396>
 787 Priyantha, N., & Kotabewatta, P. A. (2019). Biosorption of heavy metal ions on peel of *Artocarpus*
 788 *nobilis* fruit: 1—Ni(II) sorption under static and dynamic conditions. *Applied Water Science*,
 789 9(2), 37. <https://doi.org/10.1007/s13201-019-0911-2>
 790 Quansah, J. O., Obiri-Nyarko, F., & Karikari, A. Y. (2024). Adsorptive removal of dissolved Iron
 791 from groundwater by brown coal – A low-cost adsorbent. *Journal of Contaminant Hydrology*,
 792 260, 104283. <https://doi.org/10.1016/j.jconhyd.2023.104283>
 793 Rathnayaka, R. M. H., Priyantha, N., & Gunathilake, W. S. S. (2024). Removal of trivalent and
 794 hexavalent chromium from aqueous solution using fiber of *Agave americana* plant and its
 795 modified forms. *Colloids and Surfaces C: Environmental Aspects*, 2, 100029.

796 <https://doi.org/10.1016/j.colsuc.2024.100029>

797 Rauf, N., Liu, G., Cai, Y., & Tahir, S. S. (2020). Sorption studies for the removal of arsenite onto
798 *Pinus roxburghii* cone: pH, isothermal, kinetics and thermodynamic studies. *Desalination and*
799 *Water Treatment*, 185, 196–208. <https://doi.org/10.5004/dwt.2020.25403>

800 Renu, & Sithole, T. (2024). A review on regeneration of adsorbent and recovery of metals:
801 Adsorbent disposal and regeneration mechanism. *South African Journal of Chemical*
802 *Engineering*, 50, 39–50. <https://doi.org/10.1016/j.sajce.2024.07.006>

803 Salleh, N. F., Syamsurizal, M., Ghafar, N. A., Shukri, N. M., & Hapani, M. (2023). ORANGE
804 PEEL WASTES AS LOW-COST ADSORBENT FOR REMOVAL OF NICKEL AND
805 CHROMIUM IN AQUEOUS SOLUTION. *Malaysian Journal of Catalysis*, 7(1), 20–25.
806 <https://doi.org/10.11113/mjcat.v7n1.170>

807 Sangoremi, A. A. (2025). Adsorption Kinetic Models and Their Applications: A Critical Review.
808 *International Journal of Research and Scientific Innovation*, XII(V), 245–258.
809 <https://doi.org/10.51244/IJRSI.2025.120500019>

810 Su, M., Zhou, S., Li, H., Long, J., & Gao, X. (2023). Biosorption for Nickel Removal with
811 Microbial and Plant-Derived Biomasses: A Review Study. *Journal of Biochemical*
812 *Technology*, 14(3), 79–83. <https://doi.org/10.51847/b34UIYrOPc>

813 Tijjani, B., Yaumi, A. L., Mohammed, H. D., Umar, H., Yakubu, E., & Highina, B. K. (2024).
814 Adsorption of Lead, Arsenic and Mercury from Industrial Effluent Using Low-Cost Agro-
815 Waste. *International Journal of Environment*, 13(1), 21–47.
816 <https://doi.org/10.3126/ije.v13i1.70629>

817 Tobbi, O., Hattab, Z., Boutefnouchet, H., Benouis, B., Benamia, F., & Djellabi, R. (2024). Cost-

effective walnut shell biosorbent for efficient Cr(VI) removal from water: Batch adsorption and optimization using RSM-BBD. *Desalination and Water Treatment*, 320, 100783. <https://doi.org/10.1016/j.dwt.2024.100783>

UGYA, A. Y. (2019). EFFICACY OF EICHHORNIA CRASSIPES, PISTIA STRATIOTES AND NYMPHAEA LOTUS IN THE BIOSORPTION OF NICKEL FROM REFINERY WASTEWATER. *Applied Ecology and Environmental Research*, 17(6). https://doi.org/10.15666/aeer/1706_1307513087

Van Tran, T., Bui, Q. T. P., Nguyen, T. D., Le, N. T. H., & Bach, L. G. (2017). A comparative study on the removal efficiency of metal ions (Cu^{2+} , Ni^{2+} , and Pb^{2+}) using sugarcane bagasse-derived ZnCl_2 -activated carbon by the response surface methodology. *Adsorption Science & Technology*, 35(1–2), 72–85. <https://doi.org/10.1177/0263617416669152>

Velempini, T., Ahamed, M., & Pillay, K. (2023). Heavy-metal spent adsorbents reuse in catalytic, energy and forensic applications- a new approach in reducing secondary pollution associated with adsorption. *Results in Chemistry*, 5, 100901. <https://doi.org/10.1016/j.rechem.2023.100901>

Wang, F., Wu, P., Shu, L., Guo, Q., Huang, D., & Liu, H. (2022). Isotherm, kinetics, and adsorption mechanism studies of diethylenetriaminepentaacetic acid—modified banana/pomegranate peels as efficient adsorbents for removing Cd(II) and Ni(II) from aqueous solution. *Environmental Science and Pollution Research*, 29(2), 3051–3061. <https://doi.org/10.1007/s11356-021-15766-6>

Wang, P., & Howard, B. (2017). Impact of Thermal Pretreatment Temperatures on Woody Biomass Chemical Composition, Physical Properties and Microstructure. *Energies*, 11(1), 25. <https://doi.org/10.3390/en11010025>

841 Zhang, X., Chen, J., & Li, J. (2020). The removal of microplastics in the wastewater treatment
842 process and their potential impact on anaerobic digestion due to pollutants association.
843 *Chemosphere*, 251, 126360. <https://doi.org/10.1016/j.chemosphere.2020.126360>
844 Zhong, C., Deng, R., Gao, M., Cao, Y., Weiliang, P., Gu, L., & He, Q. (2021). Enhanced bromate
845 adsorption by using a-FeOOH pillared bentonite. *Desalination and Water Treatment*, 213,
846 248–258. <https://doi.org/10.5004/dwt.2021.26677>
847

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