

## Harnessing Water Hyacinth (*Eichhornia crassipes*) Plant Powder for Efficient Removal of Cadmium and Nickel from Aqueous Solutions

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Water hyacinth plant powder (WPP) prepared from mature, dried water hyacinth (*Eichhornia crassipes*) plant, found in various water bodies in Assam, India, was investigated to assess its ability as bioadsorbent to remove cadmium and nickel from aqueous solutions using adsorption process. WPP was characterized by Fourier transform infrared (FTIR) spectroscopy and scanning electron microscopy (SEM). The maximum biosorption was found at pH 5.0 and 7.0 for the metal ions Cd(II) and Ni(II), respectively on WPP. In the batch study, 10 synthetic mediums containing 40, 50, 60 70 and 80 mg L<sup>-1</sup> of the two toxic elements, Cd and Ni were treated with WPP. From the batch study, it was found that second-order kinetics is followed by both the metal (Cd and Ni) for the biosorption process and for the explanation of adsorption equilibrium data Langmuir model is suitable for both Cd(II) and Ni(II) biosorption on WPP. In the present study Langmuir monolayer capacity for Cd was observed to be 34.11 mg g<sup>-1</sup> and 0.26 mg g<sup>-1</sup> for Ni. These results indicated that WPP might be an effective adsorbent for treatment of water contaminated with cadmium and nickel.

**Keywords:** Potentially toxic elements, Biosorption, Batch study, Optimum adsorption parameters.

### INTRODUCTION

Cadmium (Cd) and nickel (Ni) are the potentially toxic elements that pose serious environmental and health risks when released into aquatic systems. Industrial activities such as electroplating, mining, smelting, petroleum refining, and metal processing contribute to the discharge of these contaminants into water bodies [1-6]. Their persistence, toxicity, and tendency to accumulate in living organisms make their removal from contaminated water an important environmental concern. Excessive Cd exposure can cause kidney and liver damage, neurological disorders and carcinogenic effects, while prolonged Ni exposure has been associated with respiratory disorders, dermatitis and cancer [7-9]. The presence of these metals in drinking water and wastewater highlights the need for effective and economical treatment methods.

Conventional wastewater treatment techniques, such as chemical precipitation, ion exchange, membrane filtration, reverse osmosis and electrochemical treatment, have been widely investigated for removing potentially toxic elements

[10-15]. Despite their effectiveness, these methods may involve high operating costs, substantial energy consumption, complex treatment procedures and the generation of secondary waste. Activated carbon is another widely used adsorbent, but its production cost and regeneration losses can restrict its application [16-19]. These limitations have encouraged study into economical, efficient and locally available alternative adsorbents for wastewater treatment [20].

Adsorption has received considerable attention due to its operational simplicity, relatively low energy requirements, and potential for effective contaminant removal [7,15,21-23]. Various agricultural residues and plant-derived materials have been investigated as biosorbents for removing metal ions from aqueous solutions. Reported materials include waste tea leaves, sugarcane bagasse, citrus peels, rice husk, peanut shells, walnut shells and other forms of plant biomass [24-32]. Their adsorption performance depends on factors such as solution pH, contact time, initial metal concentration, adsorbent dosage and surface characteristics. Although several materials have achieved substantial removal efficiencies under

laboratory conditions, the identification of inexpensive and readily available biosorbents remains an important research objective.

Water hyacinth (*Eichhornia crassipes*) is an abundant aquatic plant that may serve as a useful raw material for developing low-cost biosorbents. Its biomass contains lignin, cellulose, and hemicellulose, which can contribute to the surface characteristics and functional groups involved in metal-ion adsorption [33,34]. The composition of the plant varies between its roots and stems. Previous studies have reported a higher lignin content in the roots, while the stem contains relatively higher amounts of cellulose and hemicellulose [33]. These structural components make water hyacinth biomass a material of interest for investigating the removal of potentially toxic metals from aqueous solutions.

The use of water hyacinth as an adsorbent may provide a practical approach to utilising plant biomass for environmental remediation. Its suitability depends on its adsorption capacity, removal efficiency and behaviour under different experimental conditions. Investigating the stem powder may help establish whether this readily prepared plant material can effectively remove Cd(II) and Ni(II) ions from contaminated water. The present study investigates the application of water hyacinth stem powder as a bioadsorbent for the removal of Cd(II) and Ni(II) from spiked aqueous solutions. The selection of the stem fraction was guided by its cellulose and hemicellulose content and its potential suitability for adsorption applications [33,34]. The effects of contact time and solution pH were examined, and the point of zero charge ( $\text{pH}_{\text{pzc}}$ ) was evaluated to characterize the adsorbent surface. Adsorption equilibrium data were analysed using the Langmuir and Freundlich isotherm models, while the kinetic behaviour was assessed using pseudo-first-order and pseudo-second-order models. These investigations were undertaken to characterize the adsorption process and assess the effectiveness of water hyacinth stem powder for Cd(II) and Ni(II) removal. The findings may contribute to the development of accessible, plant-based adsorbents for treating metal-contaminated aqueous systems.

## EXPERIMENTAL

Chemicals used in this study were cadmium nitrate (Aldrich 99%), nickel nitrate (Aldrich 99%), methylene blue (Merck), copper bis-ethylenediamine (Kemphasol), sodium hydroxide (FlukaChemika 99%) and HCl. Stock solutions of adsorbates (nitrates of Cd and Ni) were prepared by using de-ionized water (concentrations of Cd and Ni, 1000 mg L<sup>-1</sup>), which were further diluted to required concentrations during the experiments.

**Preparation of biosorbent:** The water hyacinth plant (*E. crassipes*) was cleaned with water to remove dust particles and soluble impurities and then it was dried in the sun at 308-310 K for 4-5 days followed by further drying in an air oven at 323-333 K for 24 to 30 h. A mechanical grinder was used to grinding the dried plant leaves into a fine powder. After sieving and fractionating into 50-100  $\mu\text{m}$  particle fractions the powder was washed with distilled water to remove all the

coloured pigments and then dried for several hours in an air oven at room temperature.

**Characterization:** The synthesized WPP were characterized by a Perkin-Elmer FT-IR spectrometer in the range 4000-400 cm<sup>-1</sup>. The morphology of the synthesized WPP was studied using a JEOL JSM-6390 LV scanning electron microscope operating at accelerating voltage of 15-20 kV.

**pH point zero charge ( $\text{pH}_{\text{pzc}}$ ):** The point of zero charge ( $\text{pH}_{\text{pzc}}$ ) of the water hyacinth adsorbent was determined using the solid addition method [35,36]. A series of 100 mL conical flasks, each containing 25 mL of 0.1 mol dm<sup>-3</sup> KCl solution, were prepared. The initial pH ( $\text{pH}_i$ ) of each solution was adjusted between 1 and 12 using 0.1 mol dm<sup>-3</sup> HCl or NaOH, and the pH was measured using a LABMAN LMPH pH meter. Subsequently, 100 mg of water hyacinth powder was added to each flask. The suspensions were shaken for 24 h, after which the final pH ( $\text{pH}_f$ ) of the supernatant was recorded. The difference between the initial and final pH values ( $\text{pH}_i - \text{pH}_f$ ) was plotted against  $\text{pH}_i$ . The pH at which the curve intersected the  $\text{pH}_i$  axis, corresponding to  $\text{pH}_i - \text{pH}_f = 0$ , was taken as the  $\text{pH}_{\text{pzc}}$ . The results are presented in Table-1.

| Initial pH ( $\text{pH}_i$ ) | Final pH ( $\text{pH}_f$ ) | Difference in pH ( $\Delta\text{pH}$ ) |
|------------------------------|----------------------------|----------------------------------------|
| 2                            | 4.18                       | -2.18                                  |
| 3                            | 5.14                       | -2.14                                  |
| 4                            | 5.24                       | -1.24                                  |
| 5                            | 5.38                       | -0.38                                  |
| 6                            | 6.32                       | -0.32                                  |
| 7                            | 6.53                       | 0.47                                   |
| 8                            | 6.75                       | 1.25                                   |
| 9                            | 6.99                       | 2.01                                   |
| 10                           | 7.11                       | 2.89                                   |
| 11                           | 7.90                       | 3.10                                   |
| 12                           | 8.50                       | 3.50                                   |

**Adsorption experiments:** Batch adsorption experiments were conducted to investigate the removal of Cd(II) and Ni(II) ions from aqueous solutions using water hyacinth plant powder (WPP). A known amount of adsorbent was added to 50 mL of metal-ion solution of a specified concentration in 100 mL Erlenmeyer flasks. The suspensions were agitated at a constant speed in a temperature-controlled water bath shaker (NSW, India) at 303 K for a predetermined period. After agitation, the suspensions were allowed to settle, and a portion of the supernatant was centrifuged. The residual concentrations of Cd(II) and Ni(II) in the supernatant were determined using an atomic absorption spectrophotometer (Perkin-Elmer Analyst 200). Unless otherwise specified, the experiments were performed at the natural pH of the metal-ion solutions.

The effect of pH on metal-ion adsorption was investigated over the range of 2.0-7.0. For these experiments, WPP was added at a dosage of 2 g L<sup>-1</sup> to solutions containing 40 mg L<sup>-1</sup> of Cd(II) or Ni(II). The suspensions were agitated at 303 K for the respective equilibrium times. The initial pH was adjusted using 0.1 mol dm<sup>-3</sup> HCl or NaOH and measured with a Systronics Digital pH Meter 335. The effects of contact time

and adsorbent dosage on metal uptake were examined at 303 K using WPP dosages of 1, 2, 3, 4, and 5 g L<sup>-1</sup>. Samples were collected after contact times of 10, 20, 30, 60, 90, 120, 180, and 240 min to investigate the adsorption kinetics of Cd(II) and Ni(II). Adsorption isotherm experiments were performed using WPP dosages of 1, 2, 3, 4, and 5 g L<sup>-1</sup>. The suspensions were agitated at 303 K for the equilibrium contact times of 60 min for Cd(II) and 90 min for Ni(II). The amount of metal adsorbed per unit mass of WPP at time *t* (*q<sub>t</sub>*) and the percentage adsorption were calculated using eqns. 1 and 2, respectively.

$$q_t (\text{mg g}^{-1}) = \frac{(C_o - C_t)}{m} \quad (1)$$

$$\text{Extent of adsorption (\%)} = \left( \frac{C_o - C_t}{C_o} \right) \times 100 \quad (2)$$

where *C<sub>o</sub>* and *C<sub>t</sub>* are the initial and final liquid-phase concentrations (mg L<sup>-1</sup>) of metal ions at *t* = 0 and *t* = *t* time, respectively and *m* is the mass of the WPP (g).

**Desorption and regeneration experiments:** The desorption and regeneration studies were conducted using WPP (2.0 g L<sup>-1</sup>) with a particle size of 50–100 μm. The adsorbent was added to 100 mL of Cd(II) or Ni(II) solutions at initial concentrations of 40 and 80 mg L<sup>-1</sup> and equilibrated for 60 min at room temperature. The adsorbent was then recovered, and its adsorption capacity was determined. The used adsorbent was washed three times with distilled water to remove residual metal ions from the surface and dried in an oven at 105 °C to constant mass. A 0.1 mol dm<sup>-3</sup> HCl solution was used as the desorbing agent. The recovered adsorbent was mixed with 40 mL of HCl solution in a 100 mL Erlenmeyer flask and agitated at 120 rpm for 60 min at 30 ± 0.5 °C. After equilibration, the mixture was filtered through Whatman No. 42 filter paper. The concentrations of Cd(II) and Ni(II) in the filtrate were measured using an atomic absorption spectrophotometer (Perkin-Elmer Analyst 200). The desorption efficiency and the amount of metal ions adsorbed per unit mass of adsorbent were calculated using eqns. 3 and 4, respectively [37].

$$\text{Desorption efficiency (\%)} = \left( \frac{C_{de}}{C_{ad}} \right) \times 100 \quad (3)$$

$$\text{and } C_{ad} (\text{mg g}^{-1}) = \frac{(C_o - C_t)}{m} \quad (4)$$

where *C<sub>ad</sub>* denotes the amount of metal ions adsorbed per unit mass of adsorbent and *C<sub>de</sub>* is the concentration of metal ions desorbed, *C<sub>o</sub>* and *C<sub>t</sub>* are the initial and final liquid-phase concentrations (mg L<sup>-1</sup>) of metal ions at *t* = 0 and *t* = *t* time, respectively and *m* is the mass of the WPP (g).

The amount of each metal desorbed from the WPP into the solution per unit mass of adsorbent, *Q<sub>d</sub>* (mg/g) at equilibrium was calculated using eqn. 5 [37]:

$$Q_d = \left( \frac{C_{de}}{m} \right) \times V \quad (5)$$

where *C<sub>de</sub>* (mg/L) is the liquid phase metal concentration detected in the desorbing solution at equilibrium conditions, *m* is mass of adsorbent and *V* (L) is the volume of the desorbing solution.

**Adsorption kinetics:** The adsorption kinetics of Cd(II) and Ni(II) onto WPP were investigated using the pseudo-first-order (Lagergren) and pseudo-second-order kinetic models to examine the adsorption behaviour and gain insight into the possible interactions between the metal ions and the adsorbent. The pseudo-first-order model is commonly used to describe adsorption processes in which the rate is related to the number of unoccupied adsorption sites and may involve diffusion-controlled uptake [38]. Eqn. 6 is the rate equation for the pseudo first order reaction:

$$\log(q_e - q_t) = \log q_e - \left( \frac{k_1}{2.303} \right) t \quad (6)$$

where, *q<sub>t</sub>* is the amount adsorbed at time *t* and *q<sub>e</sub>* is the amount adsorbed at equilibrium, respectively of the pseudo first order adsorption phenomena and *k<sub>1</sub>* (L min<sup>-1</sup>) is the rate constant.

The applicability of the pseudo-first-order kinetic model was assessed by comparing the equilibrium adsorption capacity (*q<sub>e</sub>*) calculated from the Lagergren plot with the experimentally determined value. A close agreement between these values supports the suitability of the model. A substantial deviation suggests that the pseudo-first-order model may not adequately describe the adsorption process, justifying the evaluation using the pseudo-second-order kinetic model [39]. The linear form of second order kinetic equation is given by:

$$\frac{t}{q_t} = \frac{1}{h} + \left( \frac{1}{q_e} \right) t \quad (7)$$

where *h* = *k<sub>2</sub>q<sub>e</sub><sup>2</sup>* is the initial adsorption rate as *t* → 0. The plot of *t/q<sub>t</sub>* vs. *t* gives a linear relationship and *q<sub>e</sub>*, *k<sub>2</sub>* and *h* can be computed directly from the plot. By comparing the '*q<sub>e</sub>*' values obtained from the second order plots with those obtained experimentally, now, the validity of second order kinetics can again be tested.

**Adsorption isotherms:** The adsorption equilibrium data for Cd(II) and Ni(II) onto WPP were analyzed using the Langmuir and Freundlich isotherm models. The Freundlich model describes adsorption on heterogeneous surfaces with non-uniform adsorption energies. Its linear form is expressed as:

$$\log q_e = \left( \frac{1}{n} \right) \log C_e + \log K_f \quad (8)$$

where *q<sub>e</sub>* is the amount of the adsorbate adsorbed per unit mass of the adsorbent, *C<sub>e</sub>* is the concentration in the liquid phase of the adsorbate in equilibrium, respectively and *K<sub>f</sub>* and 1/*n* are Freundlich coefficients.

The values of 1/*n* can be calculated from the slope and *K<sub>f</sub>* can be calculated from the intercept of the straight line obtained by plotting of log *q<sub>e</sub>* vs. log *C<sub>e</sub>*. The constant *K<sub>f</sub>* represents the adsorption capacity and 1/*n* represents the intensity of adsorption. The numerical value of 1/*n* should be less than 1 i.e., 1/*n* < 1 for a favourable adsorption process and for the formation of relatively stronger bond between adsorbate and adsorbent [40].

Langmuir isotherm is valid for single-layer adsorption at specific homogeneous sites of the adsorbent. The linear form of Langmuir isotherm is given as:

$$\frac{1}{q_e} = \left( \frac{1}{a} \right) + \left( \frac{1}{abC_e} \right) \quad (9)$$

where  $C_e$  is the equilibrium concentration of the adsorbate in liquid phase, 'a' is the number of moles of solute adsorbed per unit weight of adsorbent in forming a monolayer on the surface, commonly known as the Langmuir monolayer coverage, b is a constant related to the equilibrium constant of adsorbate-adsorbent equilibrium. Plots of  $1/q_e$  against  $1/C_e$  yield the Langmuir isotherm. Both 'a' and 'b' can be obtained using the slope and the intercept of the plot. For the Langmuir type of adsorption, the separation factor ( $R_L$ ) can be calculated as:

$$R_L = \frac{1}{(1 + bC_o)} \quad (10)$$

where b ( $L \text{ mg}^{-1}$ ) refers to the Langmuir coefficient and  $C_o$  is the adsorbate initial concentration ( $\text{mg L}^{-1}$ ). The values of  $R_L$  between 0 and 1 indicate favourable adsorption for an adsorption system under study [40].

## RESULTS AND DISCUSSION

**Characterization of bioadsorbent:** The specific surface area ( $S_g$ ) of the prepared bioadsorbent (WPP) was determined using the methylene blue adsorption method [41]. The value of  $S_g$  of the prepared WPP bioadsorbent obtained by the method was  $35.23 \text{ m}^2 \text{ g}^{-1}$ . This value was higher than that of a number of plant-based adsorbents [42], e.g. coffee residue ( $2.57 \text{ m}^2 \text{ g}^{-1}$ ), pyrolyzed coffee residue ( $3.91 \text{ m}^2 \text{ g}^{-1}$ ), coffee residue bound on clay ( $6.48 \text{ m}^2 \text{ g}^{-1}$ ). Similar surface area values were reported by Anirudhan & Jalajamony [43] for commercial cellulose powder ( $21.7 \text{ m}^2 \text{ g}^{-1}$ ) and cellulose-based anion exchanger ( $33.2 \text{ m}^2 \text{ g}^{-1}$ ).

The FTIR spectrum of WPP before adsorption (Fig. 1a) exhibited distinct absorption bands at  $3328.10$ ,  $1621.05$ ,  $1365.98$ ,  $1035.18$  and  $517.44 \text{ cm}^{-1}$  [44]. The broad band at  $3328.10 \text{ cm}^{-1}$  was attributed to O–H stretching vibrations of surface hydroxyl groups and adsorbed water [45,46]. The band at  $1621.05 \text{ cm}^{-1}$  was associated with C=O stretching vibrations, while the absorption at  $1365.98 \text{ cm}^{-1}$  was assigned to C–H bending. The band at  $1035.18 \text{ cm}^{-1}$  may be attributed to C–O, C–N and C–C vibrations, whereas the peak at  $517.44 \text{ cm}^{-1}$  was associated with C–X stretching vibrations. Similar functional groups have been reported in previous studies of water hyacinth and other plant-based biosorbents [38,47–50].

After Cd(II) adsorption (Fig. 1b), the spectrum exhibited a broad band between  $3500$  and  $3000 \text{ cm}^{-1}$ , with distinct peaks at  $1736.89$ ,  $1365.89$ ,  $1026.81$  and  $526.26 \text{ cm}^{-1}$ . Following Ni(II) adsorption (Fig. 1c), the characteristic bands appeared at  $3333.77$ ,  $1735.99$ ,  $1615.18$ ,  $1366.17$ ,  $1026.52$  and  $526.88 \text{ cm}^{-1}$ . The observed shifts and changes in band intensity suggest the involvement of surface functional groups in the metal-ion binding through interactions such as surface complexation and ion exchange. The cation exchange capacity of WPP, determined using the copper bis(ethylenediamine) complex method, was  $0.76 \text{ meq g}^{-1}$  [51], supporting its potential to bind metal cations through ion-exchange interactions.

**SEM analysis:** The SEM micrographs of WPP before adsorption (Fig. 2a–b) revealed a heterogeneous surface with numerous pores, small openings and irregular, fractured edges. These structural features may provide accessible binding sites for metal-ion adsorption. After Cd(II) and Ni(II) adsorption (Fig. 2c–f), changes in surface morphology and reduced apparent porosity were observed, suggesting the occupation of surface sites by the adsorbed metal ions. Similar morphological changes have been reported for other plant-based biosorbents following metal-ion uptake [52,53].

**Effects of pH:** Fig. 3 illustrates the effects of solution pH on Cd(II) and Ni(II) adsorption by WPP, respectively. The pH influences both metal-ion speciation in solution and the availability and charge of surface binding sites. The experiments were conducted at  $303 \text{ K}$  using  $40 \text{ mg L}^{-1}$  metal-ion solutions and an adsorbent dose of  $2 \text{ g L}^{-1}$ . The pH was varied from 2 to 7, with contact times of 60 min for Cd(II) and 90 min for Ni(II), corresponding to their respective equilibrium times. The pH range was restricted to 7 to minimize the possibility of metal hydroxide precipitation. Maximum adsorption was observed at pH 5 for Cd(II) and pH 7 for Ni(II).

These findings are consistent with previous studies. Sobhanardakani & Zandipak [4] reported increased Cd(II) and Ni(II) removal with increasing pH, reaching 98.8% and 95.4%, respectively, at pH 7 using functionalised, SDS-coated magnetite nanoparticles. Shafiee *et al.* [54] and Omidi *et al.* [15] also observed enhanced Cd(II) adsorption by biochar as the solution pH increased from 3 to 7, with little further change at pH 8 and 9. Similarly, maximum Ni(II) removal at pH 7 was reported using  $\text{CeO}_2$  nanoparticles supported on  $\text{CuFe}_2\text{O}_4$  nanofibres [7]. The improvement in adsorption with increasing pH can be attributed, in part, to reduced protonation of surface functional groups and an increase in negatively charged binding sites, which favour interactions with positively charged metal ions [4]. However, the optimum pH differs between Cd(II) and Ni(II), indicating that their adsorption by WPP is also influenced by metal-specific interactions with the adsorbent surface.

**pH point zero charge ( $\text{pH}_{\text{pzc}}$ ):** At pH values below the  $\text{pH}_{\text{pzc}}$ , the adsorbent surface becomes positively charged due to protonation, favouring the adsorption of negatively charged species. Conversely, at pH values above the  $\text{pH}_{\text{pzc}}$ , surface deprotonation results in a negative charge, which promotes the adsorption of positively charged species. As shown in Fig. 4, the difference between the initial and final pH values is negative when the initial pH is below 6.5, indicating an increase in solution pH. This behaviour suggests that the point of zero charge ( $\text{pH}_{\text{pzc}}$ ) of water hyacinth is approximately 6.5. Similar values have been reported by Nascimento *et al.* [36], who obtained a  $\text{pH}_{\text{pzc}}$  of 6.3 for water hyacinth and by Uddin *et al.* [50], who reported a value of 6.72 for HCl-treated water hyacinth (H-WH). These findings indicate that the  $\text{pH}_{\text{pzc}}$  of water hyacinth-based adsorbents lies close to neutral pH.

**Effect of contact time and initial cadmium concentration:** Fig. 5 illustrates the effect of contact time on Cd(II) adsorption by WPP at  $303 \text{ K}$ . The adsorption capacity ( $q_t$ ) increased with contact time up to 60 min, after which it remained nearly constant, indicating that adsorption equilibrium was reached at approximately 60 min. This rapid uptake

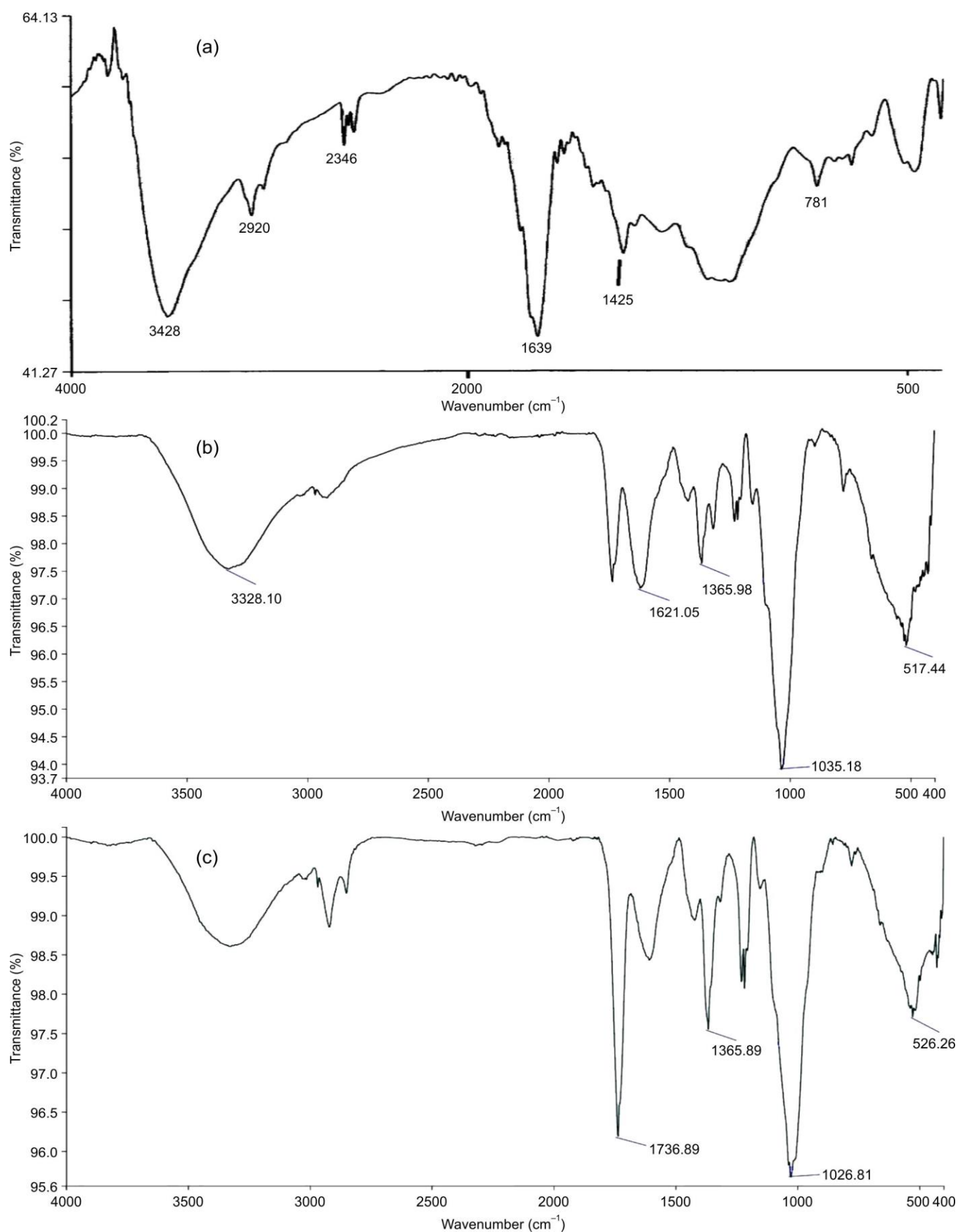


Fig. 1. FTIR spectra of water hyacinth plant powder (WPP) (a) before adsorption, (b) after adsorption with Cd(II) and (c) after adsorption with Ni(II)

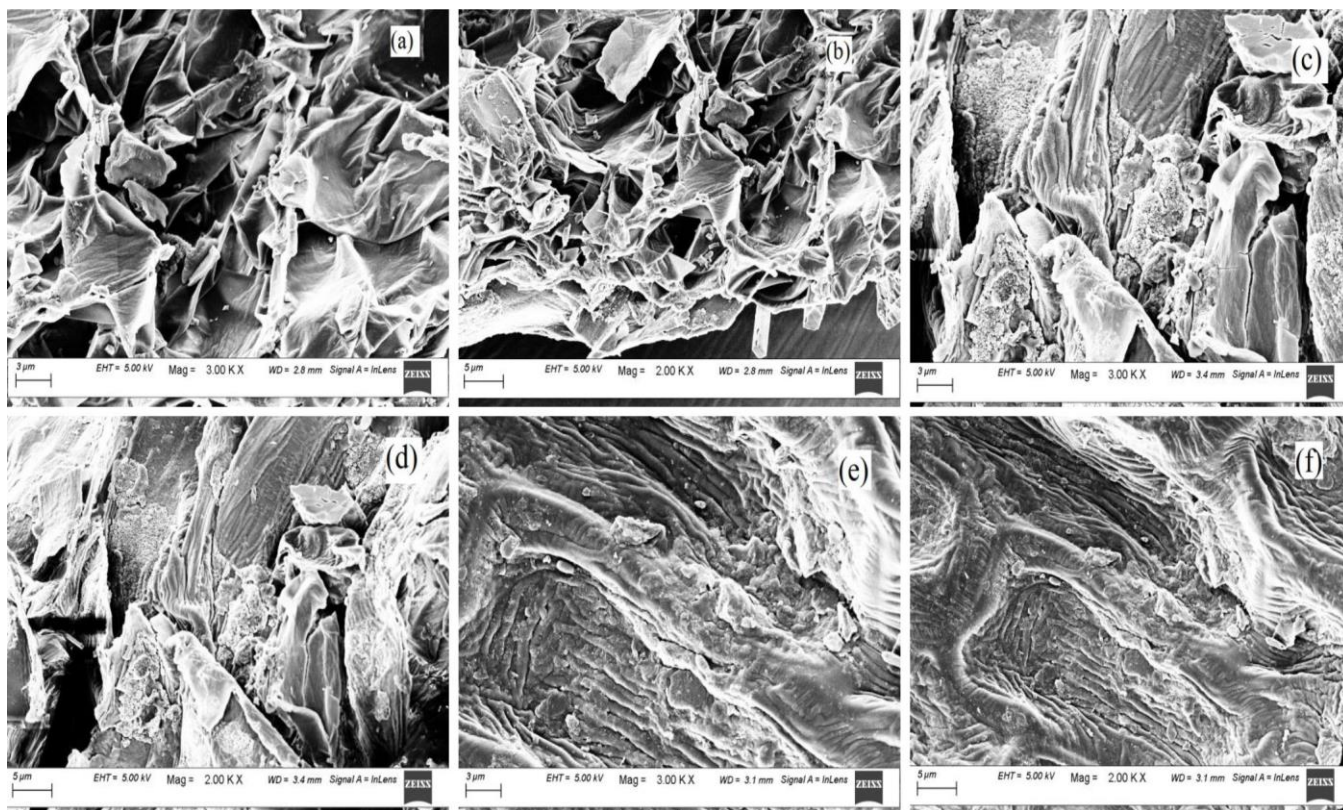


Fig. 2. SEM images of (a) WPP particles (3  $\mu\text{m}$ ), (b) single big WPP particle (5  $\mu\text{m}$ ), (c) WPP particles after Cd adsorption (3  $\mu\text{m}$ ), (d) single big WPP particle after Cd adsorption (5  $\mu\text{m}$ ), (e) WPP particles after Ni adsorption (3  $\mu\text{m}$ ) and (f) single big WPP particle after Ni adsorption (5  $\mu\text{m}$ )

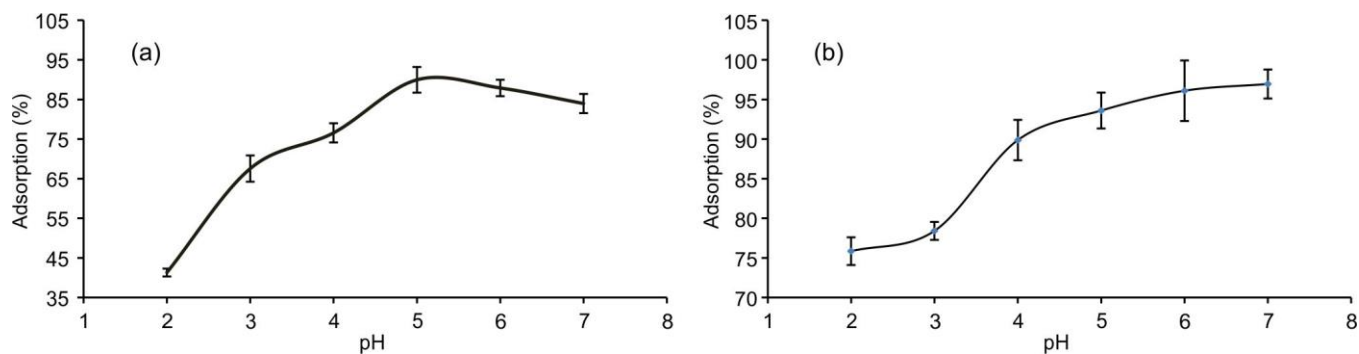


Fig. 3. Effect of pH on the sorption of (a) Cd and (b) Ni by WPP at 303 K

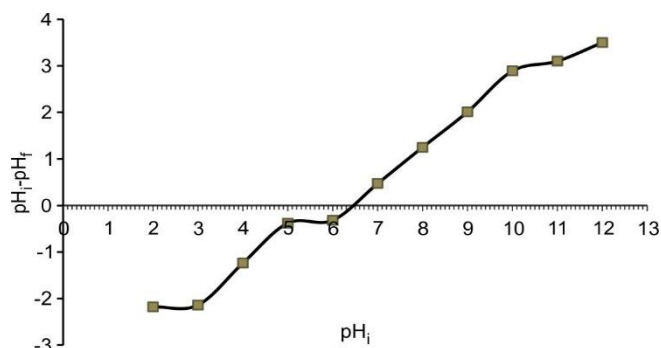


Fig. 4. pH point zero charge ( $\text{pH}_{\text{pzc}}$ ) of water hyacinth plant powder (WPP)

suggests that a substantial number of available adsorption sites were occupied during the initial contact period. Similar

trends were reported by Mahvi *et al.* [55] and Ajmal *et al.* [56]. A contact time of 60 min was also found sufficient to achieve Cd(II) adsorption equilibrium using biochars at different temperatures [15], while Montalvo-Andía *et al.* [57] reported an optimum contact time of 30 min for cadmium removal using chemically modified rice husk.

#### Effect of contact time and initial nickel concentration:

Fig. 6 showed that the adsorption amount of nickel ions ( $q_t$ ) increased with increase in time (min) up to 30 min for nickel sorption by WPP at 303 K. After 30 min, no more change in the adsorption was observed indicating that for WPP-nickel interactions the time necessary to reach equilibrium was just over 30 min. Similar results was also reported by González-Tavares *et al.* 2023 [58] with an equilibrium time of 30 min for sorption of nickel on treated water hyacinth.

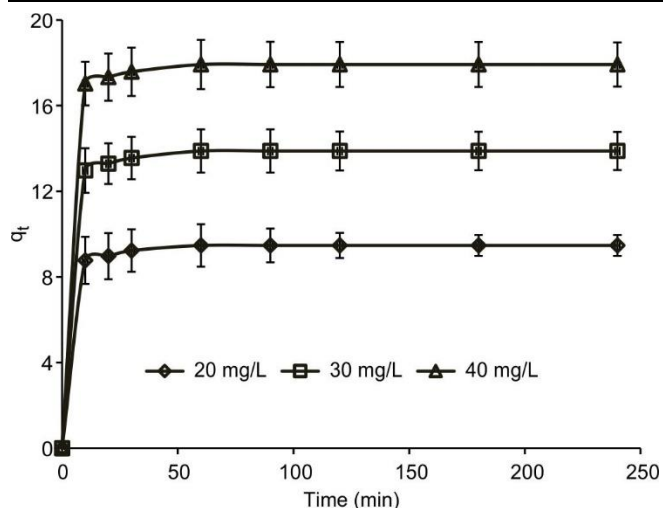


Fig. 5. Effects of contact time on Cd(II) sorption by WPP at 303 K (WPP 2 g L<sup>-1</sup>)

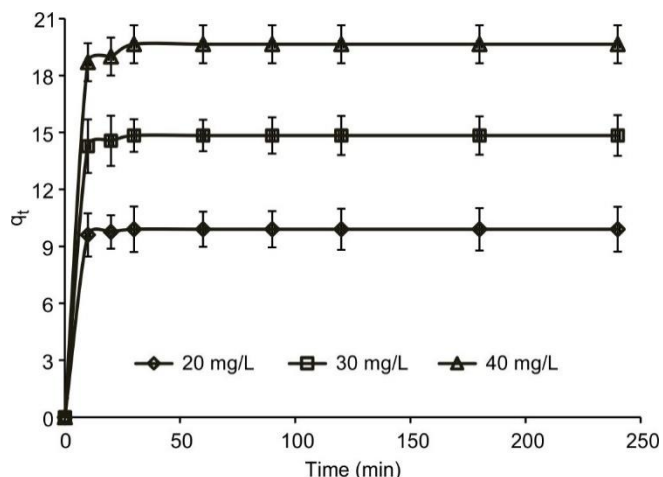


Fig. 6. Effects of contact time on Ni sorption by WPP at 303 K (WPP 2 g L<sup>-1</sup>)

#### Effects of sorbent amount and metal concentration:

The effects of adsorbent dose and initial metal concentration

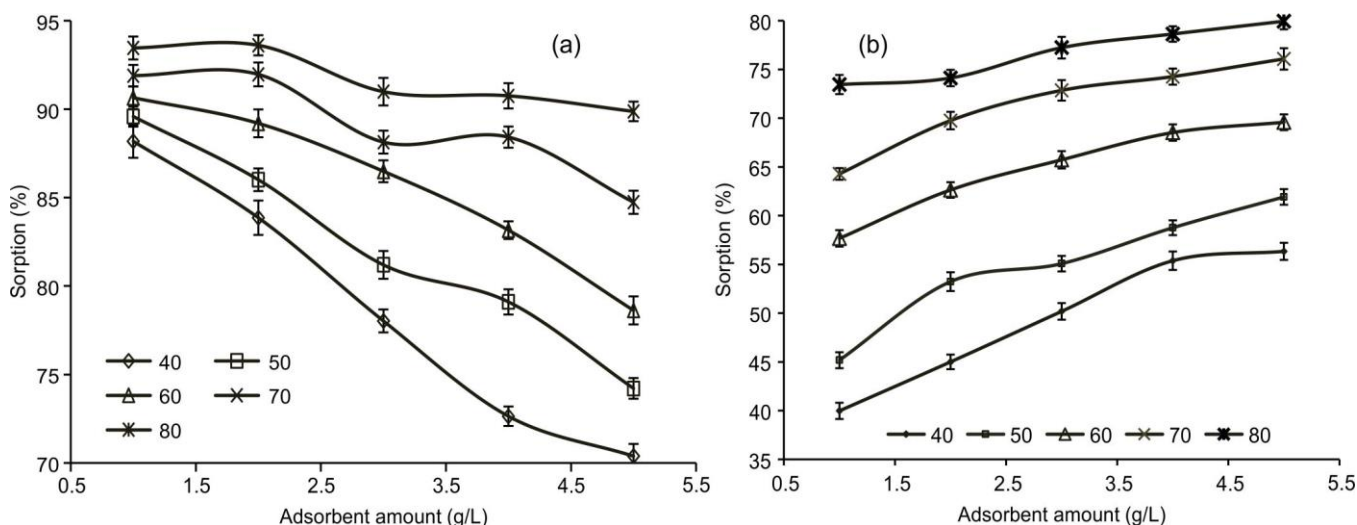


Fig. 7. Effect of sorbent amount on sorption of (a) Cd by WPP at 303 K (metal concentrations, 40-80 mg L<sup>-1</sup>, contact time, 120 min) and (b) Ni by WPP at 303 K (metal concentrations, 40-80 mg L<sup>-1</sup>) contact time, 30 min)

on Cd(II) and Ni(II) adsorption were investigated at 303 K using WPP doses of 1.0-5.0 g L<sup>-1</sup> and initial metal concentrations of 40-80 mg L<sup>-1</sup> (Fig. 7). For both metals, the percentage removal initially increased with increasing adsorbent dose, but became nearly constant beyond a certain dose. This trend can be attributed to the increased availability of surface area and adsorption sites at higher doses; however, once most metal ions have been removed from solution, adding more adsorbent produces little further improvement [59,60]. At a fixed adsorbent dose, the percentage removal decreased as the initial metal concentration increased from 40 to 80 mg L<sup>-1</sup>. This decrease is likely due to the limited number of available adsorption sites, which become progressively saturated at higher metal concentrations [60]. Similar behaviour was reported by Montalvo-Andía *et al.* [57] for Cd(II) removal using chemically treated rice husk.

**Desorption experiments with WPP:** As shown in Tables 2-4, 0.1 M HCl recovered approximately 69.44-77.90% of the adsorbed Cd(II), with the amount desorbed reported as 226.80-515.80 mg g<sup>-1</sup> of adsorbent. For Ni(II), the recovery ranged from 70.12 to 77.67% (Table-3), while the desorbed amount was 242.60-524.40 mg g<sup>-1</sup> (Table-4). These results demonstrate that dilute HCl can release a substantial proportion of the adsorbed metal ions from WPP. Similar findings were reported by Bhran *et al.* [61], who observed approximately 73.94% Cd removal during desorption at an adsorbent dose of 2 g L<sup>-1</sup> and by Sinyeue *et al.* [62], who achieved about 81% Ni<sup>2+</sup> recovery from pine sawdust using 0.1 M HCl.

**Kinetics studies:** The adsorption kinetics of Cd(II) and Ni(II) on WPP were examined using pseudo-first-order and pseudo-second-order models. The Lagergren plots were obtained by plotting  $\log(q_e - q_t)$  against contact time, while the pseudo-second-order plots were constructed using  $t/q_t$  versus  $t$ . The plots for Cd(II) and Ni(II) are shown in Figs. 8 and 9, respectively.

For Cd(II), the Lagergren plots exhibited reasonable linearity, with a mean correlation coefficient ( $r$ ) of 0.92. The equilibrium adsorption capacities calculated from these plots

TABLE-2  
EXTENT OF ADSORPTION OF Cd AND Ni BY WPP

| Mass of the WPP (g) | Liquid-phase concentrations (mg L <sup>-1</sup> ) |    |       |       | Amount adsorbed per unit mass |       | Extent of adsorption (%) |       |
|---------------------|---------------------------------------------------|----|-------|-------|-------------------------------|-------|--------------------------|-------|
|                     | Initial                                           |    | Final |       |                               |       |                          |       |
|                     | Cd                                                | Ni | Cd    | Ni    | Cd                            | Ni    | Cd                       | Ni    |
| 2                   | 40                                                | 40 | 7.57  | 7.22  | 16.22                         | 16.39 | 81.075                   | 81.95 |
| 2                   | 80                                                | 80 | 12.49 | 13.79 | 33.76                         | 33.11 | 84.39                    | 82.76 |
| 2                   | 40                                                | 40 | 6.49  | 7.34  | 16.76                         | 16.33 | 83.78                    | 81.65 |
| 2                   | 80                                                | 80 | 11.73 | 14.24 | 34.14                         | 32.88 | 85.34                    | 82.20 |

TABLE-3  
DESORPTION EFFICIENCY OF WPP FOR Cd AND Ni

| Mass of the WPP (g) | Amount desorbed per unit mass |       | Amount adsorbed per unit mass |       | Desorption efficiency (%) |       |
|---------------------|-------------------------------|-------|-------------------------------|-------|---------------------------|-------|
|                     | Cd                            | Ni    | Cd                            | Ni    | Cd                        | Ni    |
| 2                   | 12.02                         | 12.47 | 16.39                         | 16.22 | 73.34                     | 76.88 |
| 2                   | 25.79                         | 26.22 | 33.11                         | 33.76 | 77.90                     | 77.67 |
| 2                   | 11.34                         | 12.13 | 16.33                         | 16.76 | 69.44                     | 72.37 |
| 2                   | 24.24                         | 23.94 | 32.88                         | 34.14 | 73.72                     | 70.12 |

TABLE-4  
AMOUNT OF Cd AND Ni DESORBED FROM WPP INTO THE SOLUTION PER UNIT MASS OF ADSORBENT, Q<sub>d</sub> (mg/g)

| Mass of adsorbent (g) | Volume of the desorbing solution |    | Liquid phase concentration |       | Amount of desorbed (mg/g) |        |
|-----------------------|----------------------------------|----|----------------------------|-------|---------------------------|--------|
|                       | Cd                               | Ni | Cd                         | Ni    | Cd                        | Ni     |
| 2                     | 40                               | 40 | 12.02                      | 12.47 | 240.40                    | 249.40 |
| 2                     | 40                               | 40 | 25.79                      | 26.22 | 515.80                    | 524.40 |
| 2                     | 40                               | 40 | 11.34                      | 12.13 | 226.80                    | 242.60 |
| 2                     | 40                               | 40 | 24.24                      | 23.94 | 484.80                    | 478.80 |

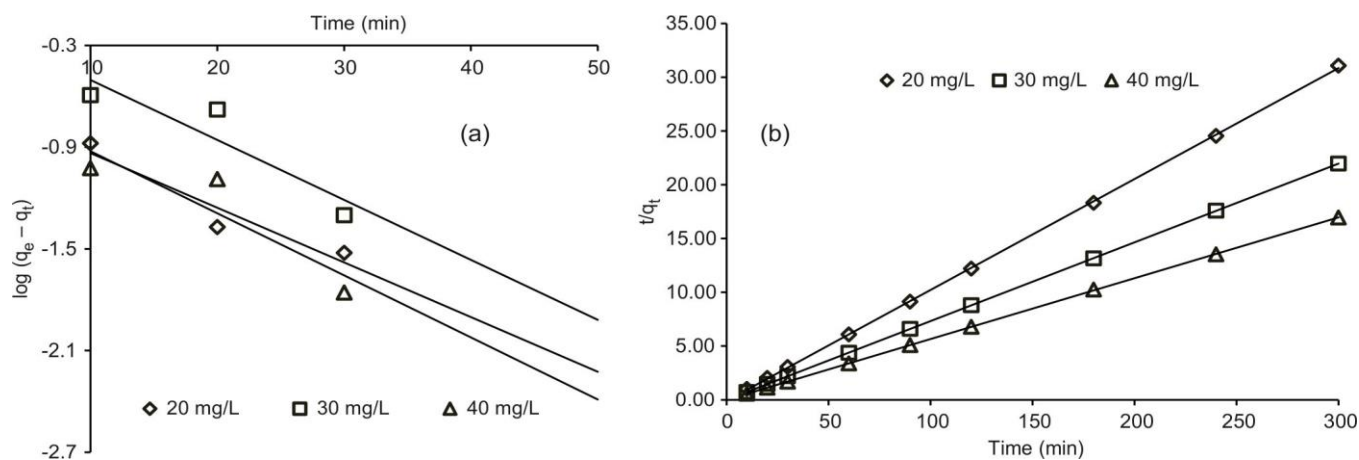


Fig. 8. (a) Pseudo first-order kinetic plots for adsorption of Cd on WPP at 303 K (WPP 2 g L<sup>-1</sup>, Cd concentrations, 20.0-40.0 mg L<sup>-1</sup>) and (b) second-order kinetic plots for adsorption of Cd on WPP at 303 K (WPP 2 g L<sup>-1</sup>, Cd concentrations, 20.0-40.0 mg L<sup>-1</sup>)

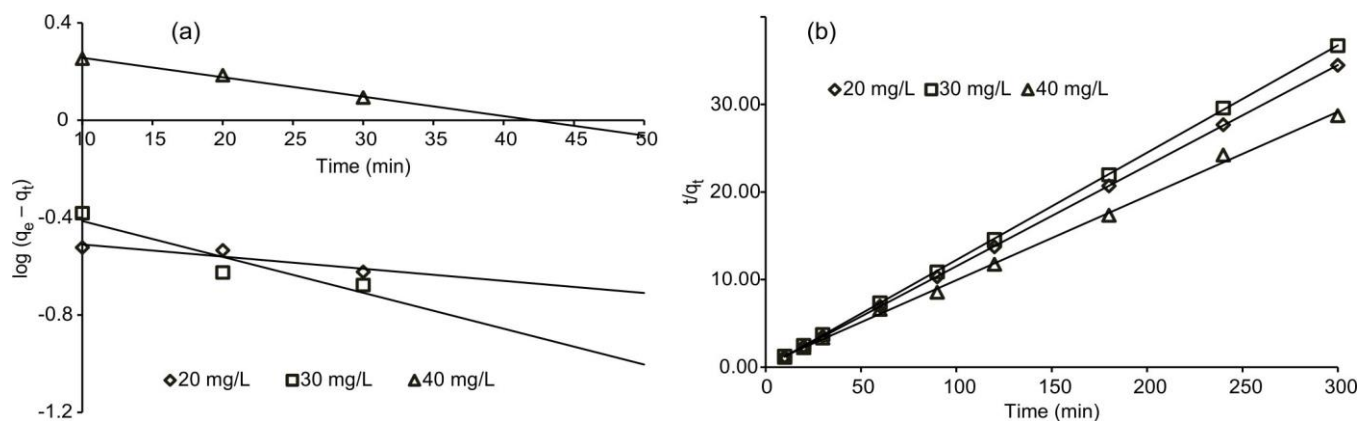


Fig. 9. (a) Pseudo first-order kinetic plots for adsorption of Ni on WPP at 303 K (WPP 2 g L<sup>-1</sup>, Ni concentrations, 20.0-40.0 mg L<sup>-1</sup>) and (b) second-order kinetic plots for adsorption of Ni on WPP at 303 K (WPP 2 g L<sup>-1</sup>, Ni concentrations, 20.0-40.0 mg L<sup>-1</sup>)

$[q_e \text{ (plot)}]$ , though, differed from the experimental values  $[q_e \text{ (exp)}]$ , showing that the pseudo-first-order model did not adequately describe the adsorption kinetics (Table-5). The pseudo-second-order model gave much closer agreement between the calculated and experimental  $q_e$  values. Its rate coefficient ( $k_2$ ) ranged from  $0.12 \times 10^{-1}$  to  $1.05 \times 10^{-1} \text{ g mg}^{-1} \text{ min}^{-1}$ , with a mean of  $0.64 \times 10^{-1} \text{ g mg}^{-1} \text{ min}^{-1}$ , consistent with reasonably rapid Cd(II) uptake over the studied concentration range of 20–40 mg L<sup>-1</sup>.

Adsorption of Ni(II) followed a comparable pattern. The pseudo-first-order equation did not adequately describe the kinetic data (Table-5), whereas the pseudo-second-order model gave close agreement between calculated and experimental  $q_e$  values. The corresponding  $k_2$  values ranged from  $0.03 \times 10^{-1}$  to  $1.86 \times 10^{-1} \text{ g mg}^{-1} \text{ min}^{-1}$ , with a mean of  $0.73 \times 10^{-1} \text{ g mg}^{-1} \text{ min}^{-1}$ , for Ni(II) concentrations of 20–40 mg L<sup>-1</sup>. Comparable pseudo-second-order behaviour has been reported for Cd(II) adsorption on barley straw ash [63], dead and immobilised archaeal cells [64], and live and dead biosorbents of *Sphingomonas* sp. GX\_15 [65]. This kinetic model has likewise been applied to Ni(II) adsorption on peat [66], waste tea (*Camellia sinensis*) materials [67] and barley straw ash [63].

The kinetic data for both metals is better described by the pseudo-second-order model than by the pseudo-first-order model. This fit is consistent with adsorption involving

interactions between the metal ions and functional groups on the WPP surface. The kinetic model alone, though, is insufficient to confirm chemisorption as the rate-limiting mechanism.

**Adsorption isotherms studies:** The adsorption isotherms of Cd(II) and Ni(II) on WPP were evaluated using the Freundlich and Langmuir models at 303 K, with adsorbent doses ranging from 1.0 to 5.0 g L<sup>-1</sup>. The Freundlich plots were constructed by plotting  $\log q_e$  against  $\log C_e$ , while the Langmuir plots were obtained using  $1/q_e$  versus  $1/C_e$ . The Cd(II) isotherms are shown in Fig. 10, and those for Ni(II) are shown in Fig. 11. The calculated isotherm parameters are listed in Tables 6 and 7.

For Cd(II), the Freundlich plots exhibited good linearity, with a mean regression coefficient ( $r$ ) of 0.99. The Freundlich exponent,  $1/n$ , ranged from 0.27 to 0.53, with a mean value of 0.38. These values satisfy the condition  $0 < 1/n < 1$ , which is associated with favourable adsorption. The Freundlich coefficient ( $K_f$ ), ranged from  $22.8 \times 10^{-4}$  to  $23.6 \times 10^{-4} \text{ L mg}^{-1}$  and increased with increasing WPP dose, reflecting a rise in the apparent adsorption capacity.

The Langmuir model gave similarly good linear fits for Cd(II), with a mean  $r$  value of 0.99. The monolayer adsorption capacity ( $a$ ) ranged from 22.73 to 62.50 mg g<sup>-1</sup>, with a mean of 34.11 mg g<sup>-1</sup>. The Langmuir equilibrium parameter ( $b$ ) varied from  $0.20 \times 10^{-2}$  to  $0.28 \times 10^{-2} \text{ L g}^{-1}$ , with a mean

TABLE-5  
KINETIC PARAMETERS FOR SORPTION OF Cd AND Ni ON WPP AT 303 K

| Kinetics     | Parameters                                             | Concentration (mg L <sup>-1</sup> ) |      |       |      |       |       | Mean  |      |
|--------------|--------------------------------------------------------|-------------------------------------|------|-------|------|-------|-------|-------|------|
|              |                                                        | 20                                  |      | 30    |      | 40    |       |       |      |
|              |                                                        | Cd                                  | Ni   | Cd    | Ni   | Cd    | Ni    | Cd    | Ni   |
| First order  | k <sub>1</sub> × 10 <sup>-1</sup> (min <sup>-1</sup> ) | 0.74                                | 0.18 | 0.81  | 0.32 | 0.83  | 0.12  | 0.79  | 0.21 |
|              | r <sup>2</sup>                                         | 0.91                                | 0.99 | 0.84  | 0.88 | 0.82  | 0.84  | 0.86  | 0.90 |
|              | r                                                      | 0.96                                | 1.00 | 0.92  | 0.94 | 0.90  | 0.91  | 0.92  | 0.95 |
|              | q <sub>e</sub> (exp) (mg/g)                            | 9.87                                | 8.74 | 13.69 | 8.27 | 17.71 | 10.52 | 13.76 | 9.18 |
|              | q <sub>e</sub> (plot) (mg/g)                           | 0.24                                | 2.17 | 0.71  | 0.59 | 0.28  | 0.35  | 0.41  | 1.04 |
|              | RMSE                                                   | 1.85                                | 1.06 | 2.06  | 0.62 | 2.12  | 0.55  | 2.01  | 0.74 |
| Second order | k <sub>1</sub> × 10 <sup>-1</sup> (min <sup>-1</sup> ) | 0.12                                | 0.30 | 0.76  | 1.86 | 1.05  | 0.03  | 0.64  | 0.73 |
|              | r <sup>2</sup>                                         | 1.00                                | 0.99 | 1.00  | 0.88 | 1.00  | 0.84  | 1.00  | 0.90 |
|              | r                                                      | 1.00                                | 1.00 | 1.00  | 0.94 | 1.00  | 0.91  | 1.00  | 0.95 |
|              | q <sub>e</sub> (exp) (mg/g)                            | 9.87                                | 8.74 | 13.69 | 8.27 | 17.71 | 10.52 | 13.76 | 9.18 |
|              | q <sub>e</sub> (plot) (mg/g)                           | 9.71                                | 8.77 | 13.70 | 8.20 | 17.86 | 10.42 | 13.75 | 9.13 |
|              | RMSE                                                   | 0.11                                | 0.14 | 0.04  | 0.12 | 0.09  | 0.37  | 0.08  | 0.21 |

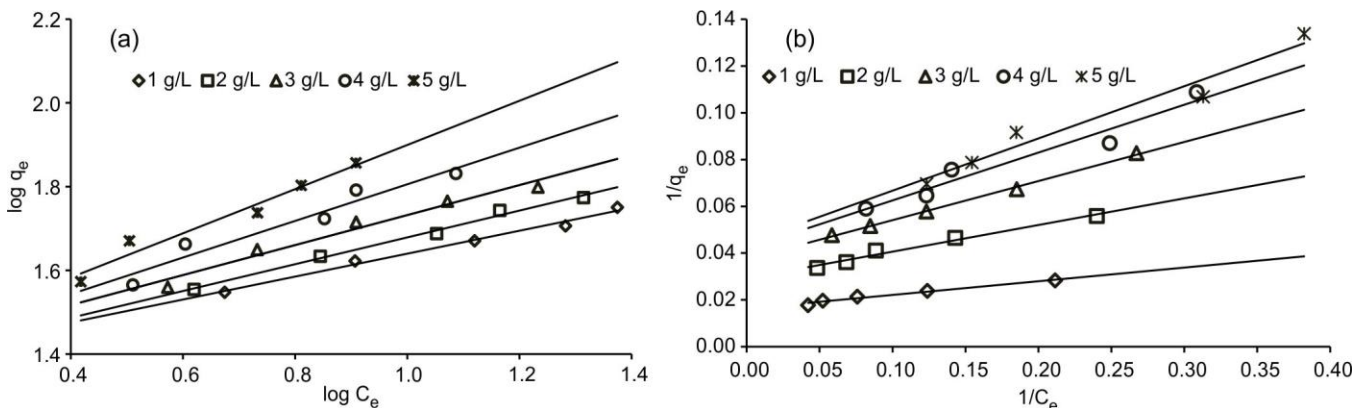


Fig. 10. (a) Freundlich and (b) Langmuir plots for adsorption of Cd(II) on WPP at 303 K [Cd(II) concentration of 40–80 mg L<sup>-1</sup>, WPP, 1–5 g L<sup>-1</sup>, agitation time 120 min]

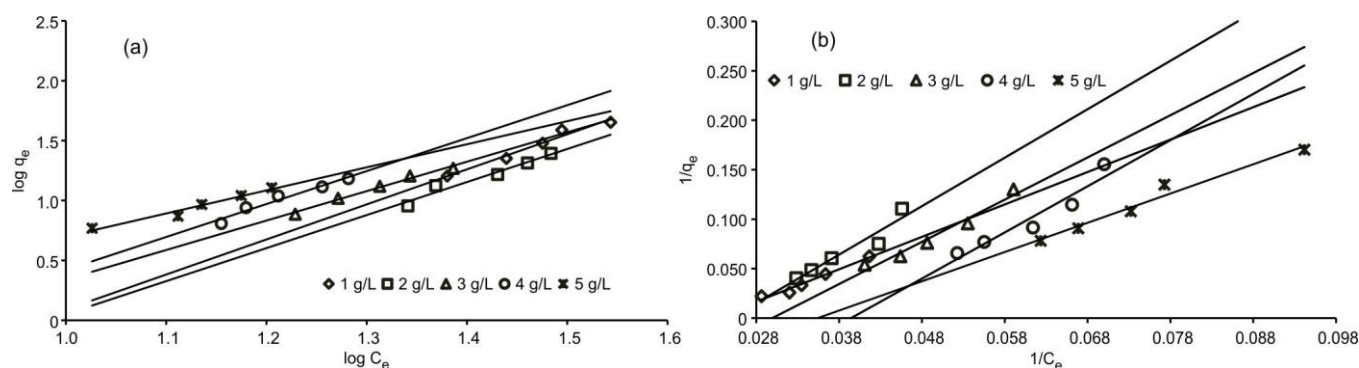


Fig. 11. (a) Freundlich and (b) Langmuir plots for adsorption of Ni(II) on WPP at 303 K [Ni(II) concentration of 40–80 mg L<sup>-1</sup>, WPP, 1–5 g L<sup>-1</sup>, agitation time 30 min]

TABLE-6  
LANGMUIR AND FREUNDLICH ISOTHERM COEFFICIENTS FOR Cd SORPTION ON WPP AT 303 K

| Isotherm   | Parameters                                            | WPP amount (g L <sup>-1</sup> ) |       |       |       |       | Mean  |
|------------|-------------------------------------------------------|---------------------------------|-------|-------|-------|-------|-------|
|            |                                                       | 1                               | 2     | 3     | 4     | 5     |       |
| Langmuir   | r <sup>2</sup>                                        | 0.97                            | 0.98  | 1.00  | 0.95  | 0.96  | 0.97  |
|            | r                                                     | 0.99                            | 0.99  | 1.00  | 0.97  | 0.98  | 0.99  |
|            | a (mg/g)                                              | 62.50                           | 34.48 | 27.03 | 23.81 | 22.73 | 34.11 |
|            | b (Lg <sup>-1</sup> ) × 10 <sup>-2</sup>              | 0.28                            | 0.25  | 0.22  | 0.21  | 0.20  | 0.23  |
|            | R <sub>L</sub>                                        | 0.083                           | 0.073 | 0.070 | 0.065 | 0.060 | 0.070 |
|            | RMSE                                                  | 0.001                           | 0.011 | 0.001 | 0.004 | 0.005 | 0.004 |
| Freundlich | r <sup>2</sup>                                        | 0.99                            | 0.99  | 0.97  | 0.94  | 0.96  | 0.97  |
|            | r                                                     | 0.99                            | 1.00  | 0.98  | 0.97  | 0.98  | 0.98  |
|            | K <sub>f</sub> (Lg <sup>-1</sup> ) × 10 <sup>-4</sup> | 23.17                           | 22.80 | 23.60 | 23.33 | 23.50 | 23.28 |
|            | 1/n                                                   | 0.27                            | 0.32  | 0.36  | 0.44  | 0.53  | 0.38  |
|            | RMSE                                                  | 0.008                           | 0.007 | 0.015 | 0.023 | 0.020 | 0.015 |

TABLE-7  
LANGMUIR AND FREUNDLICH ISOTHERM COEFFICIENTS FOR Ni SORPTION ON WPP AT 303 K

| Isotherm   | Parameters                                            | WPP amount (g L <sup>-1</sup> ) |        |        |        |        | Mean   |
|------------|-------------------------------------------------------|---------------------------------|--------|--------|--------|--------|--------|
|            |                                                       | 1                               | 2      | 3      | 4      | 5      |        |
| Langmuir   | r <sup>2</sup>                                        | 0.98                            | 0.92   | 0.97   | 0.92   | 0.97   | 0.95   |
|            | r                                                     | 0.99                            | 0.96   | 0.98   | 0.96   | 0.98   | 0.97   |
|            | a (mg/g)                                              | 0.31                            | 0.20   | 0.23   | 0.21   | 0.34   | 0.26   |
|            | b (Lg <sup>-1</sup> ) × 10 <sup>-2</sup>              | 43.68                           | 40.48  | 33.59  | 25.36  | 28.42  | 34.31  |
|            | R <sub>L</sub>                                        | 0.0004                          | 0.0004 | 0.0005 | 0.0007 | 0.0006 | 0.0005 |
|            | RMSE                                                  | 0.0025                          | 0.1704 | 0.0050 | 0.0092 | 0.0056 | 0.0386 |
| Freundlich | r <sup>2</sup>                                        | 0.97                            | 0.96   | 0.99   | 0.96   | 0.96   | 0.97   |
|            | r                                                     | 0.98                            | 0.98   | 0.99   | 0.98   | 0.98   | 0.98   |
|            | K <sub>f</sub> (Lg <sup>-1</sup> ) × 10 <sup>-4</sup> | 0.001                           | 0.001  | 0.009  | 0.001  | 0.059  | 0.014  |
|            | 1/n                                                   | 0.34                            | 0.36   | 0.41   | 0.36   | 0.52   | 0.40   |
|            | RMSE                                                  | 0.028                           | 0.031  | 0.016  | 0.027  | 0.023  | 0.025  |

of  $0.23 \times 10^{-2}$  L g<sup>-1</sup>. The mean monolayer capacity points to the potential of WPP for Cd(II) removal. The dimensionless separation factor,  $R_L$ , ranged from 0.060 to 0.083, with a mean of 0.070. Values between 0 and 1 are consistent with favourable adsorption under the conditions studied.

The Cd(II) adsorption capacity obtained for WPP (34.11 mg g<sup>-1</sup>) was higher than the reported value for pomelo peel (21.83 mg g<sup>-1</sup>) [68], but lower than those reported for brown algae (195 mg g<sup>-1</sup>) [69] and seaweed (181.48 mg g<sup>-1</sup>) [60]. Davis *et al.* [70] reported a Cd adsorption capacity of 74.18 mg g<sup>-1</sup> for Sargassum seaweed. Biochars prepared from water hyacinth were reported to have maximum Cd<sup>2+</sup> adsorption capacities of 77.20 mg g<sup>-1</sup> for RBC and 87.20 mg g<sup>-1</sup> for SBC [71].

For Ni(II), both isotherm models yielded linear plots. The Freundlich model gave a mean regression coefficient of 0.98, while 1/n ranged from 0.34 to 0.52, with a mean of 0.40. These values fall within the range associated with favourable adsorption. The reported  $K_f$  values ranged from  $0.001 \times 10^{-4}$  to  $0.059 \times 10^{-4}$  L g<sup>-1</sup> and increased with increasing WPP dose. The Langmuir plots had a mean correlation coefficient of 0.97, supporting the model's applicability to the WPP–Ni(II) system. The monolayer adsorption capacity (a) ranged from 0.20 to 0.34 mg g<sup>-1</sup>, with a mean of 0.26 mg g<sup>-1</sup>, while the equilibrium parameter (b) ranged from  $25.36 \times 10^{-2}$  to  $43.68 \times 10^{-2}$  L mg<sup>-1</sup>. The  $R_L$  values were between 0.0004 and 0.0007, consistent with favourable Ni(II) adsorption under the experimental conditions.

TABLE-8  
COMPARISON OF THE LANGMUIR CAPACITY OF THE PRESENT STUDY WITH PREVIOUSLY REPORTED VALUES

| Metal | Kinetics     | q <sub>e</sub> (exp) (mg/g) | q <sub>e</sub> (plot) (mg/g) | R <sup>2</sup> | Best model   | Ref.         |
|-------|--------------|-----------------------------|------------------------------|----------------|--------------|--------------|
| Cd    | First order  | 13.76                       | 0.41                         | 0.860          | Second order | Present work |
|       | Second order | 13.76                       | 13.75                        | 1.000          |              |              |
| Cd    | First order  | 0.97                        | –                            | 0.938          | Second order | [63]         |
|       | Second order | 1.08                        | –                            | 0.978          |              |              |
| Cd    | First order  | –                           | –                            | 0.165          | Second order | [64]         |
|       | Second order | –                           | –                            | 0.997          |              |              |
| Cd    | First order  | –                           | –                            |                | Second order | [65]         |
|       | Second order | –                           | –                            |                |              |              |
| Ni    | First order  | 9.18                        | 1.04                         | 0.900          | Second order | Present work |
|       | Second order | 9.18                        | 9.13                         | 0.900          |              |              |
| Ni    | First order  | 6.21                        | –                            | 0.986          | Second order | [63]         |
|       | Second order | 6.29                        | –                            | 0.999          |              |              |
| Ni    | First order  | –                           | –                            | 0.872          | Second order | [67]         |
|       | Second order | –                           | –                            | 0.994          |              |              |

TABLE-9  
COMPARISON OF THE OBSERVED PSEUDO-SECOND-ORDER REACTION RATES WITH PREVIOUSLY REPORTED VALUES

| Metal | Adsorbent                                         | Second order rate coefficient, k <sub>2</sub>    |                                                 | Observation (rate of pseudo-second order reaction) | Ref.         |
|-------|---------------------------------------------------|--------------------------------------------------|-------------------------------------------------|----------------------------------------------------|--------------|
|       |                                                   | Range<br>(g mg <sup>-1</sup> min <sup>-1</sup> ) | Mean<br>(g mg <sup>-1</sup> min <sup>-1</sup> ) |                                                    |              |
| Cd    | Water hyacinth plant powder                       | 0.012-0.105                                      | 0.064                                           | Rapid sorption of Cd ions                          | Present work |
|       | Barley straw ash                                  | –                                                | 0.927                                           | Rapid sorption of Cd ions                          | [63]         |
|       | Dead and immobilized archaeal cells               | –                                                | –                                               | Rapid sorption of Cd ions                          | [64]         |
|       | Dead biosorbents of <i>Sphingomonas</i> sp. GX_15 | –                                                | –                                               | Rapid sorption of Cd ions                          | [65]         |
| Ni    | Water hyacinth plant powder                       | 0.003-0.186                                      | 0.073                                           | Rapid sorption of Ni ions                          | Present work |
|       | Barley straw ash                                  | –                                                | 0.159                                           | Rapid sorption of Ni ions                          | [63]         |
|       | Waste tea ( <i>Camellacinensis</i> )              | –                                                | 0.994                                           | Rapid sorption of Ni ions                          | [67]         |

The reported Langmuir capacities for Ni(II) were lower than those cited for *Polyporus squamosus* beads (24.7 mg g<sup>-1</sup>) [72] and the brown alga *Sargassum fluitans* (44.03 mg g<sup>-1</sup>) [73]. The comparative Langmuir capacities and pseudo-second-order kinetic results are presented in Tables 8 and 9, respectively. The Freundlich and Langmuir models both described the experimental data for Cd(II), while both were applicable to Ni(II) adsorption on WPP. The favourable R<sub>L</sub> and 1/n values support favourable uptake of both metal ions. The Langmuir fits are consistent with monolayer adsorption, although fit quality alone does not establish that adsorption occurs exclusively through a monolayer mechanism.

## Conclusion

It can be concluded that the water hyacinth (*Eichhornia crassipes*) plant powder (WPP) is an effective, low-cost biosorbent for removing Cd(II) and Ni(II) ions from aqueous solutions. The Langmuir–Freundlich model provided the best fit to the equilibrium data for the heterogeneous adsorbent surface. The mean Langmuir monolayer adsorption capacities at the natural pH of the solution were 34.11 mg g<sup>-1</sup> for Cd(II) and 0.26 mg g<sup>-1</sup> for Ni(II). Kinetic studies indicated that the adsorption process followed pseudo-second-order kinetics, suggesting the involvement of chemisorption. The adsorption process was favourable and the equilibrium data also showed good agreement with the Langmuir and Freundlich models. These findings demonstrate the potential of WPP as an eco-

nomical biosorbent for treating water contaminated with toxic metal ions, particularly Cd(II) and Ni(II).

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## CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this article.

## DECLARATION OF AI-ASSISTED TECHNOLOGIES

During the preparation of this manuscript, the authors used an AI-assisted tool(s) to improve the language and no data, results or scientific conclusions were generated by AI. All analyses, interpretations and conclusions are the authors' own. The authors reviewed and edited the content and take full responsibility for the published work.

## REFERENCES

- M. Ceglowski and G. Schroeder, *Chem. Eng. J.*, **263**, 402 (2015); <https://doi.org/10.1016/j.cej.2014.11.047>
- H.K. Boparai, M. Joseph and D.M. O'Carroll, *J. Hazard. Mater.*, **186**, 458 (2011); <https://doi.org/10.1016/j.jhazmat.2010.11.029>
- Y. Sun, Q. Yue, B. Gao, Y. Gao, X. Xu, Q. Li and Y. Wang, *J. Taiwan Inst. Chem. Eng.*, **45**, 681 (2014); <https://doi.org/10.1016/j.jtice.2013.05.013>
- S. Sobhanardakani and R. Zandipak, *Environ. Monit. Assess.*, **187**, 412 (2015); <https://doi.org/10.1007/s10661-015-4635-y>
- X. Huang and M. Pan, *J. Mol. Liq.*, **215**, 410 (2016); <https://doi.org/10.1016/j.molliq.2015.12.061>
- B.A. Fil, R. Boncukcuoglu, A.E. Yilmaz and S. Bayar, *Korean J. Chem. Eng.*, **29**, 1232 (2012b); <https://doi.org/10.1007/s11814-012-0012-5>
- F. Talebzadeh, R. Zandipak and S. Sobhanardakani, *Desalination Water Treat.*, **57**, 28363 (2016); <https://doi.org/10.1080/19443994.2016.1188733>
- Y. Meng, D. Chen, Y. Sun, D. Jiao, D. Zeng and Z. Liu, *Appl. Surf. Sci.*, **324**, 745 (2015); <https://doi.org/10.1016/j.apsusc.2014.11.028>
- L. Jiang, P. Liu and S. Zhao, *Colloids Surf. A Physicochem. Eng. Asp.*, **470**, 31 (2015); <https://doi.org/10.1016/j.colsurfa.2015.01.078>
- N.A.A. Qasem, R.H. Mohammed and D.U. Lawal, *npj Clean Water*, **4**, 36 (2021); <https://doi.org/10.1038/s41545-021-00127-0>
- S. Nekouei, F. Nekouei, I. Tyagi, S. Agarwal and V. K. Gupta, *Process Saf. Environ. Prot.*, **99**, 175 (2016); <https://doi.org/10.1016/j.psep.2015.11.005>
- Y. Zhu, J. Hu and J. Wang, *J. Hazard. Mater.*, **221-222**, 155 (2012); <https://doi.org/10.1016/j.jhazmat.2012.04.026>
- S. Zhang, Y. Zhang, J. Liu, Q. Xu, H. Xiao, X. Wang, H. Xu and J. Zhou, *Chem. Eng. J.*, **226**, 30 (2013); <https://doi.org/10.1016/j.cej.2013.04.060>
- S. Sobhanardakani, A. Jafari, R. Zandipak and A. Meidanchi, *Process Saf. Environ. Prot.*, **120**, 348 (2018); <https://doi.org/10.1016/j.psep.2018.10.002>
- A.H. Omid, M. Cheraghi, B. Lorestani, S. Sobhanardakani and A. Jafari, *SN Appl. Sci.*, **2**, 1163 (2020); <https://doi.org/10.1007/s42452-020-2954-2>
- Y. Bulut and Z. Tez, *J. Environ. Sci. (China)*, **19**, 160 (2007); [https://doi.org/10.1016/S1001-0742\(07\)60026-6](https://doi.org/10.1016/S1001-0742(07)60026-6)
- S.W. Liao, C.I. Lin and W.H. Wang, *J. Taiwan Inst. Chem. Eng.*, **42**, 166 (2011); <https://doi.org/10.1016/j.jtice.2010.04.009>
- X.S. Li, S.L. Liu, Z.Y. Na, D.N. Lu and Z. Liu, *Ecol. Eng.*, **60**, 160 (2013); <https://doi.org/10.1016/j.ecoleng.2013.07.039>
- M. Petrovic, T. Sostaric, M. Stojanovic, J. Petrovic, M. Mihajlovic, A. Cosovic and S. Stankovic, *Ecol. Eng.*, **99**, 83 (2017); <https://doi.org/10.1016/j.ecoleng.2016.11.057>
- S. Zafar, M.I. Khan, M.H. Lashari, M. Khraisheh, F. Almomani, M.L. Mirza and N. Khalid, *Emergent Mater.*, **3**, 857 (2020); <https://doi.org/10.1007/s42247-020-00126-w>
- E. Kaprara, P. Seridou, V. Tsiamili, M. Mitrakas, I. Tsiaoussis, G. Vourlias, G. Kaimakamis, E. Pavlidou, N. Andritsos and K. Simeonidis, *J. Hazard. Mater.*, **262**, 606 (2013); <https://doi.org/10.1016/j.jhazmat.2013.09.039>
- S. Sobhanardakani, R. Zandipak and R. Sahraei, *Toxicol. Environ. Chem.*, **95**, 909 (2013); <https://doi.org/10.1080/02772248.2013.840379>
- J. Hong, Z. Zhu, H. Lu and Y. Qiu, *Chem. Eng. J.*, **252**, 267 (2014); <https://doi.org/10.1016/j.cej.2014.05.019>
- M. Sciban, M. Klasnja and B. Skrbic, *Wood Sci. Technol.*, **40**, 217 (2006); <https://doi.org/10.1007/s00226-005-0061-6>
- U.K. Garg, M.P. Kaur, V.K. Garg and D. Sud, *J. Hazard. Mater.*, **140**, 60 (2007); <https://doi.org/10.1016/j.jhazmat.2006.06.056>
- M.A. Hanif, R. Nadeem, H.N. Bhatti, N.R. Ahmad and T.M. Ansari, *J. Hazard. Mater.*, **139**, 345 (2007); <https://doi.org/10.1016/j.jhazmat.2006.06.040>
- H.P. Chao and C.C. Chang, *Adsorption*, **18**, 395 (2012); <https://doi.org/10.1007/s10450-012-9418-y>
- F.A. Pavan, I.S. Lima, É.C. Lima, C. Airolidi and Y. Gushikem, *J. Hazard. Mater.*, **137**, 527 (2012); <https://doi.org/10.1016/j.jhazmat.2006.02.025>
- R. Ukey, S. Fatema, M. Farooqui and S. Abed, *Int. J. Sci. Res. Sci. Technol.*, **12**, 1054 (2025); <https://doi.org/10.32628/IJSRST251387>
- S. Kainth, P. Sharma and O.P. Pandey, *Appl. Surf. Sci. Adv.*, **19**, 100562 (2024); <https://doi.org/10.1016/j.apsadv.2023.100562>
- G. Zeng, Y. He, D. Liang, F. Wang, Y. Luo, H. Yang, Q. Wang, J. Wang, P. Gao, X. Wen, C. Yu and D. Sun, *Int. J. Environ. Res. Public Health*, **19**, 13867 (2022); <https://doi.org/10.3390/ijerph192113867>
- F. Batool, R. Qadir, F. Adeeb, S. Kanwal, E.A. Abdelrahman, S. Noreen, B.F.A. Albalawi, M. Mustaqeem, M. Imtiaz, A. Ditta and H.Y. Gondal, *ACS Omega*, **8**, 40128 (2023); <https://doi.org/10.1021/acsomega.3c02986>
- S. Bordoloi, A. Garg, S. Sreedeeep, P. Lin and G. Mei, *Bioresour. Technol.*, **263**, 665 (2018); <https://doi.org/10.1016/j.biortech.2018.05.011>
- W.J. Liu, W.W. Li, H. Jiang and H.Q. Yu, *Chem. Rev.*, **117**, 6367 (2017); <https://doi.org/10.1021/acs.chemrev.6b00647>
- S.A.A. Santana, A.P. Vieira, E.C. da Silva Filho, J.C.P. Melo and C. Airolidi, *J. Hazard. Mater.*, **174**, 714 (2010); <https://doi.org/10.1016/j.jhazmat.2009.09.109>
- R.F. do Nascimento, C.W.B. Bezerra, H.A.S. Silva, M.S. Schultz and S.A.A. Santana, *Cad. Pesqui. (São Luís)*, **20**, 73 (2013); <https://doi.org/10.18764/2178-2229.v20n3p73-80>
- Katsou E, Malamis S, Tzanoudaki M, Haralambous KJ, Loizidou M., *J. Hazard. Mater.*, **189**, 773 (2011); <https://doi.org/10.1016/j.jhazmat.2010.12.061>
- Y.S. Ho and G. McKay, *Process Saf. Environ. Prot.*, **76**, 332 (1998); <https://doi.org/10.1205/095758298529696>
- Y.S. Ho and G. McKay, *Process Biochem.*, **34**, 451 (1999); [https://doi.org/10.1016/S0032-9592\(98\)00112-5](https://doi.org/10.1016/S0032-9592(98)00112-5)
- F. Haghsereht and G. Lu, *Energy Fuels*, **12**, 1100 (1998); <https://doi.org/10.1021/ef9801165>
- P.T. Hang and G.W. Brindley, *Clay Miner.*, **18**, 203 (1970); <https://doi.org/10.1346/CCMN.1970.0180404>
- V. Boonamnuayvitaya, C. Chaiya, W. Tanthapanichakoon and S. Jarudilokkul, *Sep. Purif. Technol.*, **35**, 11 (2004); [https://doi.org/10.1016/S1383-5866\(03\)00110-2](https://doi.org/10.1016/S1383-5866(03)00110-2)
- T.S. Anirudhan and S. Jalajamony, *J. Environ. Manage.*, **91**, 2201 (2010); <https://doi.org/10.1016/j.jenvman.2010.05.019>
- L. Hazarika, K.K. Shah, G. Baruah and R.K. Bharali, *Vietnam J. Chem.*, **61**, 238 (2023); <https://doi.org/10.1002/vjch.202200138>
- Y. Hanumantharao, M. Kishore and K. Ravindhranath, *J. Anal. Sci. Technol.*, **3**, 167 (2012); <https://doi.org/10.5355/JAST.2012.167>
- N.J. Khound and R.K. Bharali, *J. Environ. Chem. Eng.*, **6**, 1726 (2018); <https://doi.org/10.1016/j.jece.2018.02.010>
- J.M. Munene, J.O. Onyatta and A.O. Yusuf, *Asian J. Appl. Chem. Res.*, **6**, 47 (2020); <https://doi.org/10.9734/ajacr/2020/v6i130151>
- M. Ibrahim, R. Mahani, O. Osman and T. Scheytt, *Open Spectrosc. J.*, **4**, 32 (2010); <https://doi.org/10.2174/1874383801004010032>
- S. Das, A. Bhattacharya, S. Halder, A. Ganguly, S. Gu, Y.P. Ting and P.K. Chatterjee, *Sustain. Mater. Technol.*, **3**, 17 (2015); <https://doi.org/10.1016/j.susmat.2015.01.001>
- M.N. Uddin, M.T. Islam and S. Das, *Int. J. Chem. Eng.*, **2014**, 819536 (2014); <https://doi.org/10.1155/2014/819536>
- F. Bergaya and M. Vayer, *Appl. Clay Sci.*, **12**, 275 (1997); [https://doi.org/10.1016/S0169-1317\(97\)00012-4](https://doi.org/10.1016/S0169-1317(97)00012-4)
- S. Madadgar, F. Doulati Ardejani, Z. Boroumand, H. Sadeghpour, R. Taherdangkoo and C. Butscher, *Minerals*, **13**, 106 (2023); <https://doi.org/10.3390/min13010106>
- N.K. Mondal, S. Bhaumik, A. Banerjee, J.K. Datta and T. Baur, *Int. J. Environ. Sci.*, **2**, 1643 (2012).

54. M. Shafiee, R. Foroutan, K. Fouladi, M. Ahmadlouydarab, B. Ramavandi and S. Sahebi, *Adv. Powder Technol.*, **30**, 544 (2019); <https://doi.org/10.1016/j.appt.2018.12.006>
55. A.H. Mahvi, F. Gholami and S. Nazmara, *Eur. J. Sci. Res.*, **23**, 197 (2008).
56. M. Ajmal, R. Ali Khan Rao, S. Anwar, J. Ahmad and R. Ahmad, *Bioresour. Technol.*, **86**, 147 (2003); [https://doi.org/10.1016/S0960-8524\(02\)00159-1](https://doi.org/10.1016/S0960-8524(02)00159-1)
57. J. Montalvo-Andía, W. Reátegui-Romero, A.D. Peña-Contreras, W.F. Zaldivar-Alvarez, M.E. King-Santos, V. Fernández-Guzmán, J.L. Guerrero-Guevara and J.E. Puris-Naupay, *Adsorpt. Sci. Technol.*, **2022**, 3688155 (2022); <https://doi.org/10.1155/2022/3688155>
58. C. González-Tavares, M. Salazar-Hernández, A. Talavera-López, J.M. Salgado-Román, R. Hernández-Soto and J.A. Hernández, *Separations*, **10**, 289 (2023); <https://doi.org/10.3390/separations10050289>
59. K.G. Bhattacharyya and A. Sharma, *J. Hazard. Mater.*, **113**, 97 (2004); <https://doi.org/10.1016/j.jhazmat.2004.05.034>
60. L. Semerjian, *J. Hazard. Mater.*, **173**, 236 (2010); <https://doi.org/10.1016/j.jhazmat.2009.08.074>
61. A.A. Bhran, S. Tadepalli, K.S. Murthy and A.A. AlGhamdi, *Processes*, **13**, 1972 (2025); <https://doi.org/10.3390/pr13071972>
62. C. Sinyeue, T. Garioud, M. Lemestre, M. Meyer, F. Brégier, V. Chaleix, V. Sol and N. Lebouvier, *Heliyon*, **8**, e08842 (2022); <https://doi.org/10.1016/j.heliyon.2022.e08842>
63. M. Arshadi, M.J. Amiri and S. Mousavi, *Water Resour. Ind.*, **6**, 1 (2014); <https://doi.org/10.1016/j.wri.2014.06.001>
64. G.E. Hegazy, N.A. Soliman, M.E. Ossman, Y.R. Abdel-Fattah and M.N. Moawad, *Sci. Rep.*, **13**, 2550 (2023); <https://doi.org/10.1038/s41598-023-29456-5>
65. X. Li, L. Li, Z. Zhao, X. Zhang, J. Kong, L. Liu and R. Li, *Mater. Chem. Phys.*, **305**, 127940 (2023); <https://doi.org/10.1016/j.matchemphys.2023.127940>
66. Y.S. Ho, D.A. John Wase and C.F. Forster, *Water Res.*, **29**, 1327 (1995); [https://doi.org/10.1016/0043-1354\(94\)00236-Z](https://doi.org/10.1016/0043-1354(94)00236-Z)
67. P.E. Aikpokpodion, R.R. Ipinmoroti and S.M. Omotoso, *Am.-Eurasian J. Toxicol. Sci.*, **2**, 72 (2010).
68. W. Saikaew and P. Kaewsarn, *Songklanakarin J. Sci. Technol.*, **31**, 547 (2009).
69. Z.R. Holan, B. Volesky and I. Prasetyo, *Biotechnol. Bioeng.*, **41**, 819 (1993); <https://doi.org/10.1002/bit.260410808>
70. T.A. Davis, B. Volesky and R.H.S.F. Vieira, *Water Res.*, **34**, 4270 (2000); [https://doi.org/10.1016/S0043-1354\(00\)00177-9](https://doi.org/10.1016/S0043-1354(00)00177-9)
71. X. Wang, X. Guo, T. Li, J. Zhu, J. Pang, J. Xu, J. Wang, X. Huang, J. Gao and L. Wang, *Pol. J. Environ. Stud.*, **31**, 2301 (2022); <https://doi.org/10.15244/pjoes/141045>
72. P.A. Wuyep, A.G. Chuma, S. Awodi and A.J. Nok, *Sci. Res. Essays*, **2**, 217 (2007).
73. N.S.E. Mohd Yasim, Z.S. Ismail, S. Mohd Zaki and M.F. Abd Azis, *Malays. J. Anal. Sci.*, **20**, 187 (2016); <https://doi.org/10.17576/mjas-2016-2001-20>