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Biosorption of Nickel and Cobalt Heavy Metals using Green Marine Macro algae: A Preliminary Study

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ABSTRACT: This study investigates the biosorption capabilities of the marine macro alga *Ulva lactuca* for the removal of nickel (Ni) and cobalt (Co) ions from aqueous solutions. Experimental parameters, including pH, temperature, initial ion concentration, and contact time, were systematically varied to assess their impact on adsorption. The adsorption process followed pseudo-second-order kinetics, with equilibrium adsorption capacities of 44.84 mg/g for Ni and 43.29 mg/g for Co, highlighting chemisorption as the primary mechanism. Isothermal studies revealed that the Langmuir model provided maximum adsorption capacities of 84.03 mg/g for Ni and 50.00 mg/g for Co, emphasizing the potential of *Ulva lactuca* to achieve monolayer adsorption. Thermodynamic analysis demonstrated an endothermic, spontaneous, and feasible adsorption process, with increased randomness at the solid-liquid interface. These results underscore the effectiveness of *Ulva lactuca* as a biosorbent for heavy metal remediation and offer valuable insights for developing eco-friendly water treatment systems.

1.INTRODUCTION:

Heavy metals are widely acknowledged as among the most insidious contaminants that infiltrate the food chain through improper waste disposal into water bodies and land. Heavy metals are commonly identified as metals possessing a density exceeding 5 g/cm³. Despite their widely acknowledged harmful effects, the utilization of heavy metals continues to expand within various industrial domains (Nithya et al., 2019). Chromium, nickel, arsenic, cadmium, copper, zinc, lead, and mercury constitute a group of heavy metals that, due to their non-biodegradable nature, find their way into water bodies, exerting significant repercussions on both human health and the environment (Nithya et al., 2018). Their persistence in the environment, coupled with their propensity to accumulate within living organisms and their inability to biodegrade, amplifies their potential to enter the food chain and accumulate. While these metals are essential as micronutrients and occur naturally in plants and animals at low concentrations, heightened exposure levels can result in severe health consequences, including toxicity, cancer, and various diseases. Consequently, extensive research was done into the presence of metal ions in aquatic systems and their toxic properties (Zhao et al., 2018).

Long-term exposure to nickel and its compounds can lead to various detrimental effects on human health, including lung fibrosis, kidney problems, cardiovascular diseases, and respiratory tract cancer. Workers exposed to nickel and its compounds have shown a higher incidence of nasal and lung cancer (Genchi et al., 2020). Additionally, nickel negatively affects plant growth, reducing seed germination, root and shoot development, overall biomass, and final crop yield. Furthermore, nickel toxicity in plants causes chlorosis, necrosis, and hinders essential physiological processes like photosynthesis and transpiration, resulting in oxidative damage (Hassan et al., 2019).

Cobalt toxicity can manifest with a wide range of health issues in humans, affecting the hematological, cardiovascular, immunological, gastrointestinal, endocrinological, dermatological, ophthalmological, and neurological systems (Sheikh, 2016). Elevated levels of cobalt in the environment can disrupt various plant functions, primarily by triggering the production of reactive oxygen species (ROS), such as hydroxyl radicals ($\cdot\text{OH}$) and hydrogen peroxide (H_2O_2), leading to increased levels of malondialdehyde (MDA) and proline, and altering the activities of antioxidant enzymes. ROS generation in plants under cobalt stress disrupts photosystem II and interferes with the electron transport chain. Furthermore, heightened cobalt content in the soil reduces the presence of photosynthetic pigments and disrupts nitrogen metabolism in plants. Therefore, there is a pressing need to remediate sites where cobalt has accumulated (Mahey et al., 2020).

Efforts to mitigate heavy metal contamination in wastewater encompass various techniques, including adsorption, sedimentation, electrochemical processes, ion exchange, biological treatments, cementation, coagulation/flocculation, filtration, membrane processes, chemical precipitation, and solvent extraction (Fahim et al., 2006). Nevertheless, conventional methods often prove inadequate when dealing with low concentrations of heavy metals. Hence, there is an urgent need to develop cost-effective and efficient separation methods to reduce heavy metal ion concentrations to levels that meet environmental standards (Panda et al., 2017).

Algae exhibit a broad classification, encompassing macroalgae and microalgae. Macroalgae includes notable categories such as *Phaeophyceae*, represented by brown algae, and *Rhodophyta*, characterized by red algae. On the other hand, microalgae comprise species like *Chlorella* and *Spirulina* (Aniruddha et al., 2022). The diversity within these classifications underscores the ecological significance and commercial potential of algae. Seaweeds are rich in various functional groups such as carboxyl, sulfhydryl, amide, hydroxyl, phosphate, imidazole as well as imine moieties which are proven to be better metal binders (Gardea-Torresdey et al., 2004). The marine weed *Ulva* is a *Chlorophyta* member which is an edible sea weeds with a wide range of health promoting bioactive compounds. This weed is a good dietary product, reduces gastrointestinal disorders and enhances the capacity of reduction of pathogenicity of chronic diseases of gastrointestinal pathway as well as best proven to work as anticancerous (Abirami & Kowsalya, 2011).

Among the array of water treatment techniques available, adsorption emerges as a preferred method for removing heavy metal ions due to its exceptional efficiency, ease of application, the availability of diverse adsorbent materials, and cost-effectiveness. Numerous studies have explored the use of agricultural waste products and microorganisms such as fungi, yeast, cyanobacteria, and algae as biosorbents for heavy metal removal. Research has revealed that various forms of algae, including both micro and macroalgal species, exhibit the ability to bind with industrial pollutants such as heavy metals and dyes to varying degrees (Fu & Wang, 2011). Apart from ability to remove heavy metal ions macro and microalgae have successfully been used to produce biofuel (Sivanesh et al., 2022) as well as in drug delivery systems (Subramanian et al., 2020).

In this context, the primary objective of this study is to investigate the biosorption behavior of *Ulva lactuca*, a type of green macroalga, for the removal of Nickel and Cobalt ions from aqueous solutions. By examining the capacity of *Ulva lactuca* to adsorb these heavy metals, this research seeks to contribute valuable insights into environmentally friendly and sustainable methods for addressing heavy metal pollution in water sources.

2.MATERIAL AND METHODOLOGY:

Marine macro algae samples were collected from Valiazheekal, Kayamkulam. Tamil Nadu. Analytical grade chemicals Cobalt nitrate hexahydrate and Nickel chloride hexahydrate, NaOH/HCl were obtained.

2.1 Preparation of algal powder:

The samples collected were identified as *Ulva lactuca* species through morphological features as shown in Figure 1(a). Then the samples were shade dried after washing with sea water and removal of epiphytes. Then they were ground into fine powder of

particle size 0.25 mm diameter using a motor and pestle as shown in Figure 1(b). Then the powder was used for further biosorption studies.

2.2 Preparation of metal solution:

Cobalt nitrate hexahydrate and Nickel chloride hexahydrate were taken in their salt form and stock solutions of both the metals were prepared in the concentration of 100 mg/L and pH was adjusted to 8 using NaOH/HCl as per the necessity.



Figure 1: a. *Ulva lactuca* sample,



Figure 1:b. *Ulva lactuca* powder

2.3 Biosorption studies:

Biomass of *Ulva lactuca* dosage was taken as 10 mg, 15 mg and 20 mg in test tubes. The heavy metal solution prepared was added in equal quantity in all the test tubes, that is 0.015 L, and the test tubes were kept for incubation at 25°C overnight. After incubation the test tubes are shaken well and centrifuged at 4000 rpm for 30 minutes. Then the centrifuged solution was filtered using Whatman no.1 filter paper.

2.4 Characterization:

Bio adsorption of the heavy metals by the samples was observed with UV-VIS Spectrophotometer at 675 nm. The filtered sample was sent for biosorption of heavy metals using UV-VIS Spectrophotometer at 675 nm.

Fourier Transmission Infrared Spectroscopy (FTIR) data was taken to identify the functional groups which attach to the heavy metals in their vicinity. Samples were prepared using KBr pellets and were analyzed using FTIR for the presence of functional groups.

The analysis of the contaminated biomass involved a comprehensive examination employing Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDX). These advanced techniques were utilized to assess the algae's capacity for adsorbing Cobalt and Nickel ions, shedding light on its performance in environmental remediation. The biomass after the adsorption process was used for the characterization study.

For analyzing the samples using SEM and EDX, the sample was prepared by using a drop of it onto the gold grid and subsequently drying in air before transfer of the mount to microscope which was operated at 15.0 V voltage.

3.RESULTS AND DISCUSSION:

3.1 FTIR:

The samples underwent analysis using FTIR spectra which unveiled the mechanism of heavy metal biosorption onto *Ulva lactuca* through the identification of its functional groups, as illustrated in Figure 4 and 5. FTIR spectral data for nickel biosorption has revealed the adsorption of this heavy metal onto the functional groups. Peaks between 2500 and 2000 cm^{-1} depict C- H stretching from CH_2 groups (Solmon et al., 2012). Peaks from 3500 to 3000 indicate the presence of hydroxyl as well as amino groups which are actual adsorbers of the heavy metal nickel (Sheng et al, 2004).

The FTIR spectrum of cobalt biosorption has revealed that the metal cobalt may be bound to the functional groups present from 3500 to 1500 cm^{-1} as well as 1000 to 500 cm^{-1} as O-H bond shows water molecule presence indicating high intensity for the formation of metal oxygen bonding (Hannichi et al., 2019).

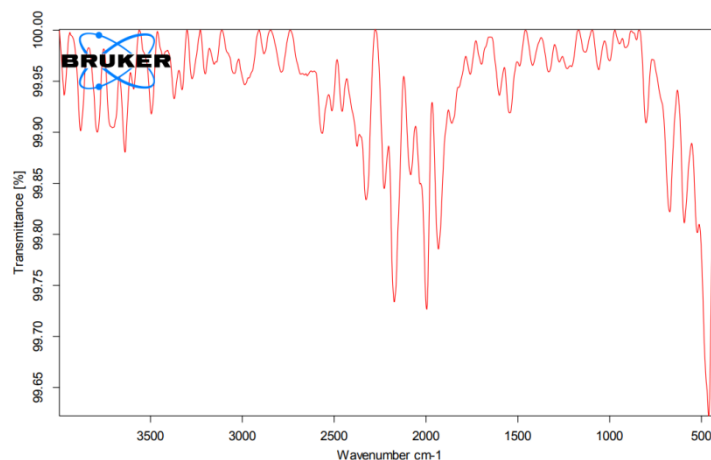


Figure 2: FTIR spectrum of Nickel biosorption by *Ulva lactuca* species

Sharp peaks of alcohols, aliphatic primary amines, aldehydes, carbon dioxide, Alkyne, Ketenimine, Alkene, nitro compound, hydroxyl groups, carboxyl groups, Sulfoxide, Alkene, and Halo compounds were found in the FTIR spectrum of Figure 4.

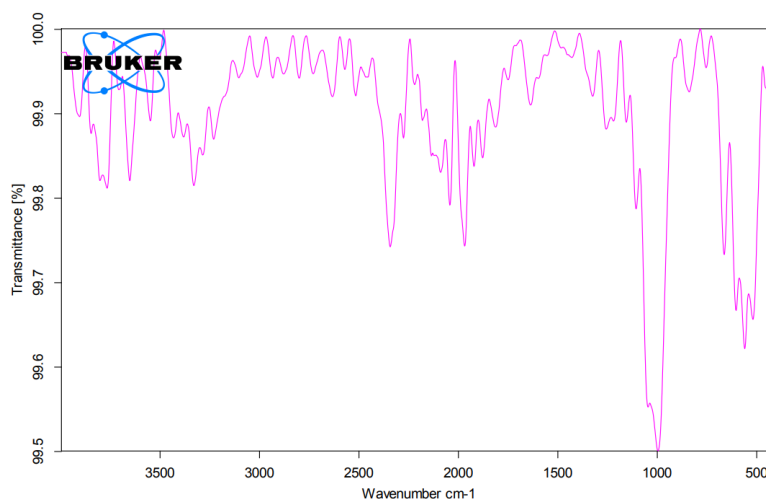


Figure 3: FTIR spectrum of Cobalt biosorption by *Ulva lactuca* species

Sharp peaks of alcohols, aliphatic primary amine, carboxylic acid, alkynes, alkenes aromatic compounds anhydrates, hydroxyl groups, imidazole groups were found in the FTIR spectrum of Figure 5.

3.2. SEM and EDX:

The SEM images serve multiple important purposes in our study. Firstly, they visually authenticate the algae's capacity to adsorb Nickel and Cobalt ions, substantiating the analytical data. Moreover, these images provide valuable insights into the morphological alterations undergone by the algae during the adsorption process, shedding light on the structural changes that occur.

By presenting the SEM images in Figures 6 and 7, we offer a tangible and accessible means for researchers and readers to directly observe the outcomes of the algae's interaction with this heavy metal ions. This visual evidence reinforces the significance of algae as a potential eco-friendly solution for metal ion pollution remediation.

Figure 6 displays the SEM image and EDX capturing the algae following the absorption of Nickel ions, while Figure 7 illustrates the SEM image and EDX portraying the algae post adsorption of Cobalt ions. These compelling visual representations serve as concrete evidence of the algae's remarkable prowess in effectively sequestering these metal ions.

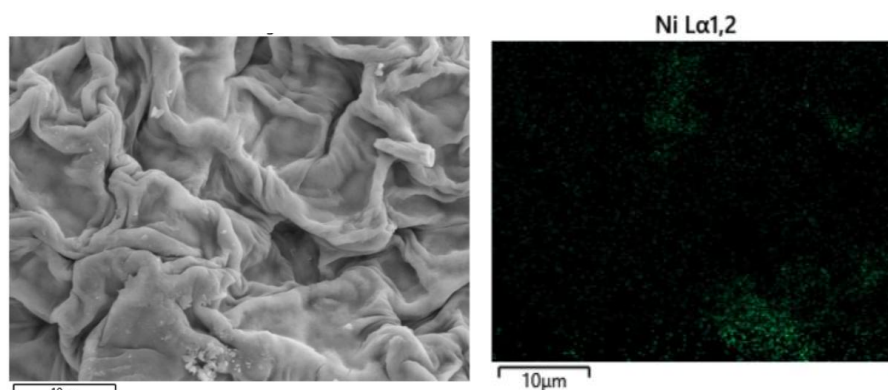


Figure 4 : SEM and EDX image of algae after adsorption of Nickel ions

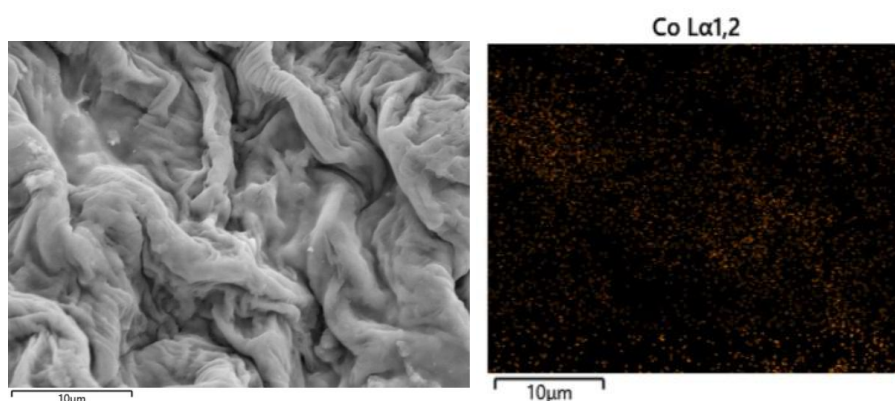


Figure 5: SEM and EDX image of algae after adsorption of Cobalt ions

3.3. Batch Experiments:

3.3.1. Effect of pH:

To investigate the impact of pH on the adsorption of nickel and cobalt by the algae, we examined the adsorption capacity and efficiency under varying pH conditions in the solution. The addition of 0.06 gm of algae to the solution was kept constant, while maintaining a temperature of 60°C and a contact time of 120 minutes. The initial concentration of nickel or cobalt ions in the solution was 50 ppm.

As shown in the Figure 8, the adsorption of nickel ions exhibited a noticeable trend with changing pH values in the aqueous solution. It increased from 40% at pH 1 to 97% at pH 6, and then decreased to 60% as the pH further increased to 8. Similarly, the adsorption capacity demonstrated a similar pattern, rising from 16.67 mg/g at pH 1 to 40.42 mg/g at pH 6, and then decreasing to 25 mg/g.

The increase in Ni (II) adsorption by algae with rising pH is primarily due to the hydrolysis of Ni(II) and the surface properties of the algal biomass. Nickel exists in different forms— Ni^{2+} , $\text{Ni}(\text{OH})^+$, $\text{Ni}(\text{OH})_2^0$, $\text{Ni}(\text{OH})_3^-$, and $\text{Ni}(\text{OH})_4^{2-}$ —depending on the pH. At $\text{pH} < 9$, Ni^{2+} is the dominant species. The lower adsorption of Ni^{2+} at low pH can be attributed to competition between H^+/Na^+ and Ni^{2+} for binding sites on the algal surface. The maximum adsorption of Ni(II) occurs at pH 6, where a significant proportion of binding sites are available for interaction with Ni^{2+} . At higher pH levels, deprotonation of surface functional groups on the algae enhances the availability of negatively charged sites, leading to increased electrostatic attraction between Ni^{2+} and the algal surface. The adsorption process is not dominated by the precipitation of $\text{Ni}(\text{OH})_2$, as its low precipitation constant indicates limited precipitation under these conditions. A slight decline in adsorption at higher pH values is attributed to the formation of soluble hydroxyl complexes (Kurup et al., 2024).

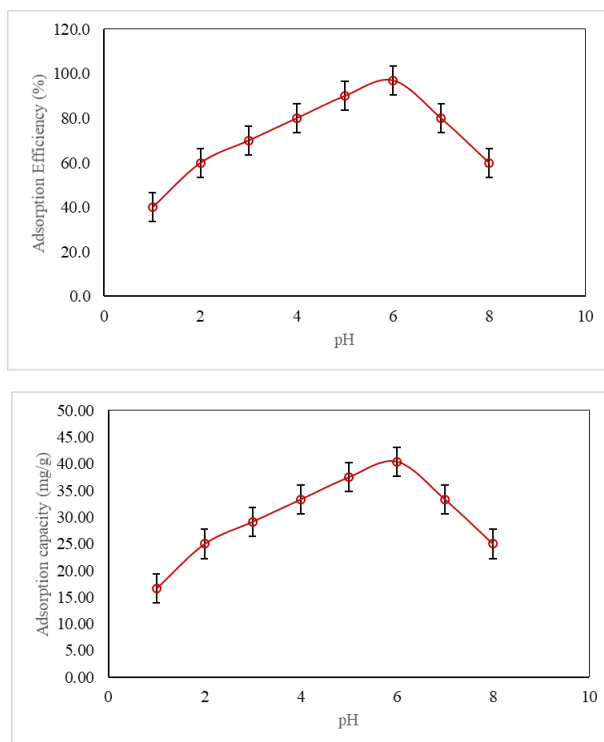


Figure 6 Effect of pH on the adsorption of nickel ions

As shown in Figure 9, the adsorption of cobalt ions demonstrated a clear trend with varying pH levels in the aqueous solution. Adsorption efficiency increased from 34% at pH 1 to 91% at pH 8, while the cobalt ions removed per gram of algae also rose from 14.17 mg/g at pH 1 to 37.92 mg/g at pH 8. This behavior can be attributed to the competition between excess H^+ ions and Co^{2+} for the adsorption sites at low pH, which suppresses cobalt uptake. At higher pH values, the deprotonation of surface functional groups on the algae increases the number of negatively charged sites. This enhances electrostatic attraction, facilitating more effective adsorption of Co^{2+} onto the algal surface (R. Wang et al., 2021).

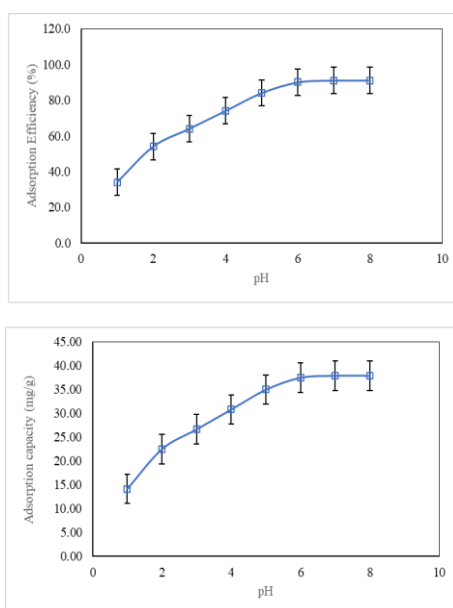


Figure 7 Effect of pH on the adsorption of cobalt ions

3.3.2 Effect of initial concentration and Isothermal Modeling

The initial concentrations were varied from 50 to 500 ppm of nickel and cobalt ions. The testing was conducted at a temperature of 60°C, incorporating 0.06 gm of algae into the solution, with a contact time of 120 minutes.

As portrayed in Figure 10, it is clear that the efficacy of the algae in removing nickel ions decreases, with increase in initial concentration of ions moving from 97% to 24% as the concentration at the beginning, elevates from 50 ppm to 500 ppm. Contrarily, the adsorption capacity increased, initiating at 40.41 mg/g with a starting concentration of 50 ppm nickel ions, and peaking at 100 mg/g with an initial concentration of 500 ppm nickel ions.

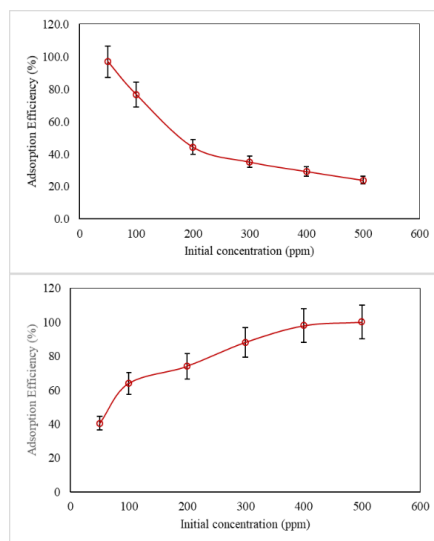


Figure 8 Effect of initial concentration on the adsorption of nickel ions

As shown in Figure 11, the efficiency of algae in removing cobalt ions decreases with increasing initial ion concentration, dropping from 91% at 50 ppm to 23.4% at 500 ppm. However, the adsorption capacity follows an opposite trend, rising from 37.92 mg/g at an initial concentration of 50 ppm to a maximum of 97.5 mg/g at 500 ppm.

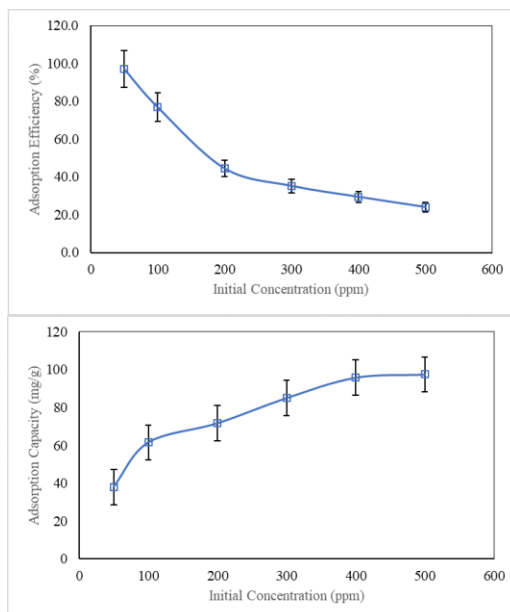


Figure 9 Effect of initial concentration on the adsorption of cobalt ions

The reduction in the adsorption efficiency is because, at lower concentrations of nickel and cobalt ions, there are sufficient active sites on the algal surface to facilitate adsorption. However, at higher concentrations, the fixed active sites on the algae become saturated, leaving some nickel or cobalt ions unadsorbed. A solution with a concentration of 50 ppm of nickel ions was used for subsequent experiments (Kayalvizhi et al., 2022).

The enhanced adsorption capacity can be attributed to an increased mass transfer rate driven by a higher concentration gradient. At lower initial concentrations of nickel and cobalt ions, the adsorption primarily occurs at external surface sites of the algae. However, as the concentration increases, the concentration gradient intensifies, promoting the migration of metal ions to internal binding sites within the algal structure. This process utilizes additional adsorption sites, which corresponds to the increased availability of adsorbent in response to the higher initial concentration (Nie et al., 2024).

To better understand the adsorption mechanism of heavy metal ions onto algae, the equilibrium adsorption data were analyzed using the Langmuir, Freundlich, Temkin, and Dubinin-Radushkevich isotherm models and the results are shown in Table 1.

	nickel	cobalt
Langmuir	$Q_{\max} = 84.03 \text{ mg/g}$ $K_L = 0.61 \text{ L/mg}$	$Q_{\max} = 50.00 \text{ mg/g}$ $K_L = 0.44 \text{ L/mg}$
Freundlich	$n = 2.77$ $K_f = 12.79 \text{ (mg/g)}$ $(\text{L/mg})^{1/n}$	$n = 2.49$ $K_f = 11.21 \text{ (mg/g)}$ $(\text{L/mg})^{1/n}$
Temkin	$B = 10.583$ $K_T = 22.82 \text{ L/g}$ $b_T = 261.6 \text{ J/mol}$	$B = 6.37$ $K_T = 7.40 \text{ L/g}$ $b_T = 0.397 \text{ J/mol}$
Dubinin-Radushkevich	$K = 0.365 \text{ mol}^2/\text{kJ}^2$ $q_m = 83.72 \text{ mg/g}$ $E = 1.17 \text{ kJ/mol}$	$K = 0.11 \text{ mol}^2/\text{kJ}^2$ $q_m = 34.06 \text{ mg/g}$ $E = 2.16 \text{ kJ/mol}$

Table 1: Isotherm constants for various models

Freundlich isotherm showed a better fit for the adsorption of nickel and cobalt ions. The Freundlich model describes the adsorption condition at which the equilibrium coverage fraction is about 50% (J. Wang & Guo, 2020). The Temkin isotherm values suggests that the adsorption process took place through chemisorption. The bonding energy, which was greater than 8 kJ mol^{-1} , further supports the conclusion that the mechanism involved in adsorption is chemical in nature. In chemisorption, the adsorbates attach to the adsorbent through strong interactions, leading to relatively high adsorption energies in this process (Araujo et al., 2018). Also, the higher value of B_T suggests strong adsorption of the ions onto the active algae sites (Anwar et al., 2018).

3.3.3 Effect of Contact Time and Kinetic Studies:

The effect of contact time on the adsorption dynamics was examined over a duration ranging from 0 to 120 minutes, with measurements taken at 10 minute intervals. The adsorbent dosage was maintained at 0.06 g, and the experimental temperature was held constant at 60°C . A nickel ion solution with a pH of 6 and cobalt ion with a pH of 8 and an initial concentration of 50 ppm was used for the study.

The data, as depicted in Figure 12, reveals a steady increase in adsorption efficiency with prolonged contact time, reaching equilibrium within 120 minutes. Adsorption efficiency rose from an initial 40% at 10 minutes to a maximum of 97% at 120 minutes. Concurrently, the adsorption capacity increased from 16.67 mg/g at the start to 40.42 mg/g at equilibrium, showcasing the significant impact of contact time on the adsorption process.

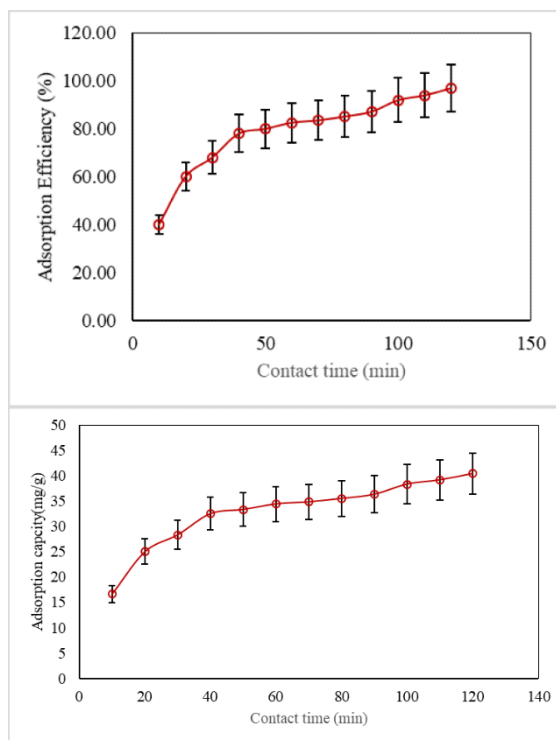


Figure 10 Effect of contact time on the adsorption of nickel ions

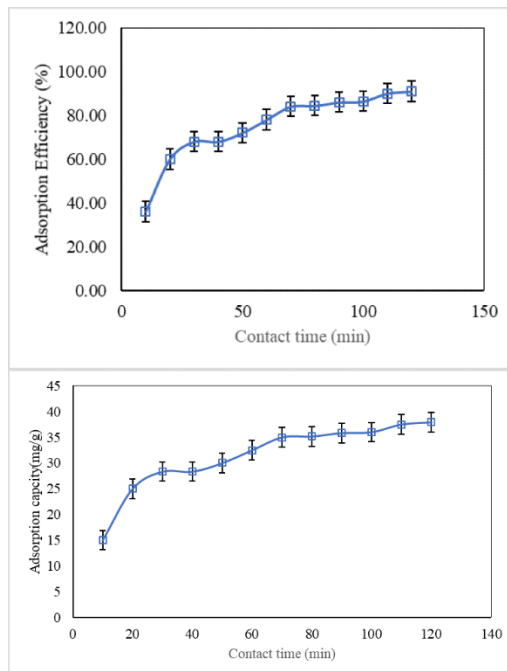


Figure 14 Effect of contact time on the adsorption of cobalt ions

Figure 13 illustrates a consistent increase in adsorption efficiency with extended contact time, reaching equilibrium at 120 minutes. The adsorption efficiency improved from 36% at 10 minutes to a peak of 91% at 120 minutes. Simultaneously, the adsorption capacity rose from 15 mg/g initially to 37.92 mg/g at equilibrium, highlighting the crucial role of contact time in enhancing the adsorption process.

The adsorption process for nickel and cobalt ions onto algae occurs in three distinct stages: an initial phase of rapid adsorption, followed by a gradual adsorption phase, ultimately reaching equilibrium. During the initial phase, the significant concentration gradient of heavy metal ions at the solid-liquid interface drives the rapid transfer of nickel ions from the solution to the algal surface. Simultaneously, the abundance of available adsorption sites on the algae facilitates a swift increase in the amount of ions adsorbed. In the second stage of adsorption, the number of available surface adsorption sites on the algae begins to diminish. This reduction leads to a decreased concentration gradient of ions at the solid-liquid interface, accompanied by increased repulsive interactions. As a result, the rate of adsorption slows, and the adsorption capacity increases at a more gradual pace. By the end of the 120-minute adsorption process, the available adsorption sites on the algae approach saturation. At this stage, further increases in adsorption capacity become challenging, and the system reaches equilibrium (Anulekshmi et al., 2024).

In our examination of the kinetics of adsorption for cobalt, we investigated four distinct kinetic models, Pseudo-first-order and Pseudo-second-order.

	Nickel	Cobalt
Pseudo first order	q_e (mg/g) = 28.352 k_1 (min ⁻¹) = 0.0278 R^2 = 0.9107	q_e (mg/g) = 29.4 k_1 (min ⁻¹) = 0.02818 R^2 = 0.9188
Pseudo second order	q_e (mg/g) = 44.84 k_2 (g/mg min) = 0.00117 R^2 = 0.9956	q_e (mg/g) = 43.29 k_2 (g/mg min) = 0.00127 R^2 = 0.9963

Table 2: Results of kinetic modelling

A correlation coefficient (R^2) of 0.9107 was obtained for the pseudo-first-order kinetic model for nickel ions, with a calculated q_e value of 28.35 mg/g. Similarly, for cobalt ions, the pseudo-first-order model gave an R^2 of 0.9188 and a q_e value of 29.4 mg/g. In both cases, the calculated q_e values did not align well with the experimentally determined adsorption capacities, indicating that the pseudo-first-order model is not suitable for describing the adsorption kinetics of nickel and cobalt ions onto algae.

In contrast, the pseudo-second-order kinetic model provided a much better fit. For nickel ions, the model exhibited an excellent correlation coefficient (R^2 = 0.9956) and a calculated q_e value of 44.84 mg/g, closely matching experimental results. Similarly, for cobalt ions, the pseudo-second-order model showed an R^2 of 0.9963 and a q_e value of 43.29 mg/g, also closely aligning with experimental data.

These results highlight the superiority of the pseudo-second-order model, suggesting that the adsorption of nickel and cobalt ions is governed by chemisorption. This involves specific interactions, such as electron sharing or exchange, between the metal ions and the active sites on the algal surface, indicating a more intricate adsorption mechanism (Robati, 2013).

3.3.4 Thermodynamic studies and Van't Hoff plot

The solution temperature is a relevant operating parameter that affects the transport and kinetic processes of heavy metal ion adsorption. Hence the effect of temperature on adsorption was studied by varying the temperature as 30°C, 40°C, 50°C and 60°C. The initial concentration of heavy metal ions remained at 50 ppm, while the adsorbent dosage was 0.06 g with contact time of 120 minutes.

The ability of the adsorbent to effectively remove nickel ions increases from 64% to 97% when the temperature of the solution was raised. The adsorption capacity of the algae also showed a similar trend having a value of 26.66 mg/g at 30°C to 40.41 mg/g at 60 °C as shown in Figure 14.

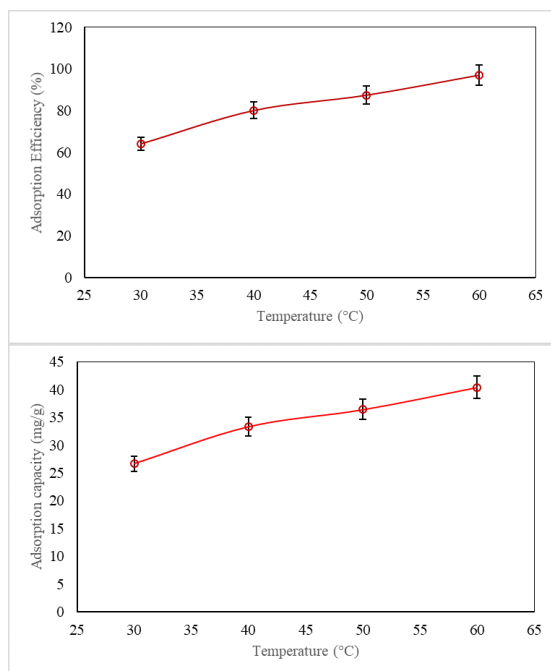


Figure 12 Effect of temperature on the adsorption of nickel ions

The adsorbent's efficiency in removing cobalt ions improved significantly, rising from 54% to 91% as the solution temperature increased. Similarly, the adsorption capacity of the algae followed this trend, increasing from 22.5 mg/g at 30°C to 37.91 mg/g at 60°C, as illustrated in Figure 15.

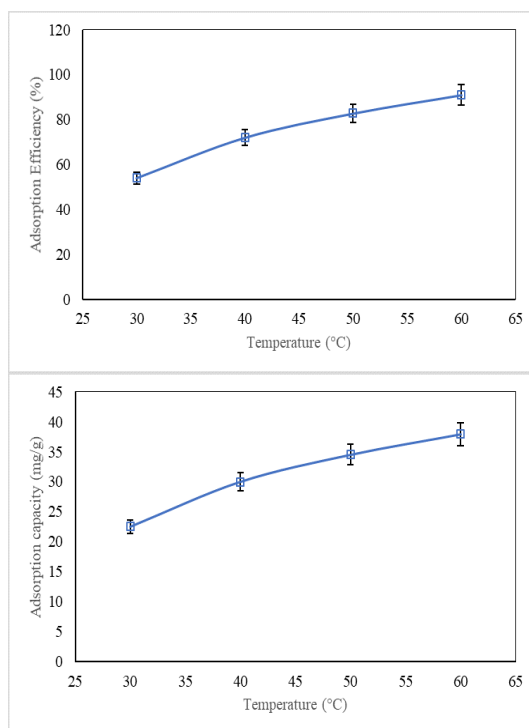


Figure 13 Effect of temperature on the adsorption of cobalt ions

The determination of these thermodynamic parameters from the experimental data was carried out using the following equations:

$$\ln K_c = \frac{\Delta S^\circ}{R} - \frac{\Delta H^\circ}{RT}$$

$$\Delta G^\circ = -RT \ln K_c$$

$$\Delta G^\circ = \Delta H^\circ - T\Delta S^\circ$$

The equilibrium constant K_c was determined, with the standard enthalpy change (ΔH°) in kilojoules per mole (kJ/mol) derived from the slope, and the standard entropy change (ΔS°) in kilojoules per mole per Kelvin (kJ/mol·K) calculated from the intercept of the plot of the natural logarithm of K_c versus the reciprocal of temperature, as shown in Figures 16 and 17 (Priya et al., 2022). The thermodynamic parameters for the adsorption of nickel and cobalt are summarized in Table 3.

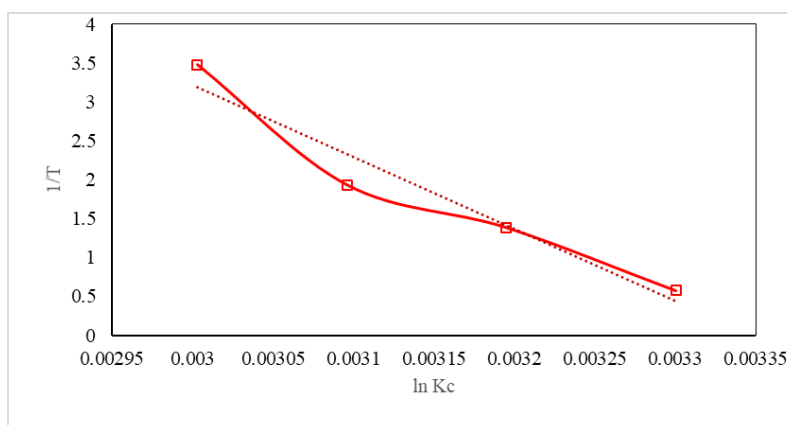


Figure 14 Van't Hoff Plot for adsorption of nickel ions

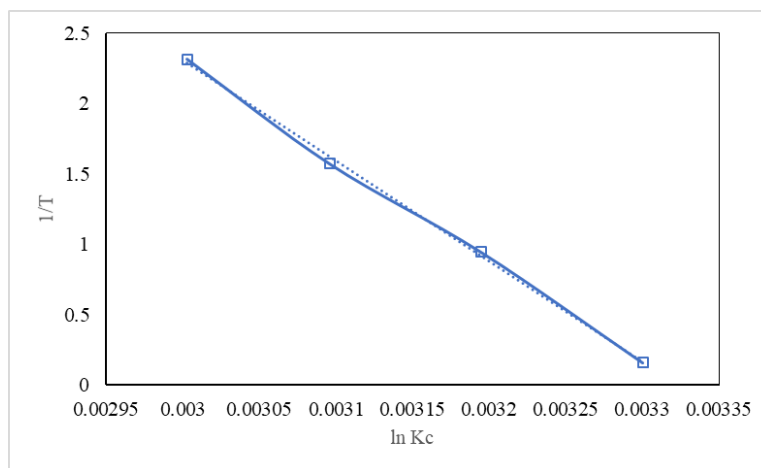


Figure 15 Van't Hoff Plot for adsorption of nickel ions

		nickel	Cobalt
ΔH°		77.168 kJ / mol	59.438 kJ/mol
ΔS°		0.258 kJ / mol. K	0.197 kJ / mol. K
ΔG°	303 K	-1.45 kJ/mol	-0.403 kJ/mol
	313 K	-3.61 kJ/mol	-2.457 kJ/mol

	323 K	-5.19 kJ/mol	-4.220 kJ/mol
	333 K	-9.62 kJ/mol	-6.405 kJ/mol

Table 3 Thermodynamic parameters

In the adsorption of both cobalt and nickel ions by the adsorbent, a positive change in enthalpy was observed, indicating that the process is endothermic. This endothermic nature explains the increased adsorption capacity and efficiency with rising temperature, as higher thermal energy enhances the interaction between the metal ions and the active sites of the adsorbent. The increase in temperature likely promotes the breaking of hydration shells surrounding the metal ions, allowing better access to the adsorption sites. The negative Gibbs free energy values confirm that the adsorption process is both thermodynamically feasible and spontaneous under the experimental conditions. This spontaneity highlights the favorable energetics driving the interaction between cobalt and nickel ions with the adsorbent. Moreover, the positive entropy change suggests an increase in randomness at the solid-liquid interface during adsorption. This increased disorder can be attributed to the displacement of water molecules from the adsorbent surface and their replacement by metal ions, leading to greater system entropy. Together, these thermodynamic parameters provide valuable insights, emphasizing the strong and favorable binding interactions between cobalt and nickel ions and the adsorbent (Ghasemi & Asadpour, 2007).

CONCLUSION:

The study establishes *Ulva lactuca* as a highly effective biosorbent for the removal of nickel and cobalt ions from aqueous solutions, driven by its high adsorption capacity and favorable adsorption dynamics. The Langmuir isotherm analysis revealed maximum adsorption capacities of 84.03 mg/g for Ni and 50.00 mg/g for Co, demonstrating the potential of *Ulva lactuca* to achieve efficient monolayer adsorption on its surface. Experimental data showed equilibrium adsorption capacities of 44.84 mg/g for Ni and 43.29 mg/g for Co, aligning closely with the pseudo-second-order kinetic model, which confirmed chemisorption as the dominant mechanism.

The adsorption efficiency increased with temperature, indicating an endothermic process, as validated by positive enthalpy values of 77.168 kJ/mol for Ni and 59.438 kJ/mol for Co. Negative Gibbs free energy values across studied temperatures confirmed the spontaneity of the process, while positive entropy changes suggested enhanced randomness at the solid-liquid interface. These thermodynamic insights underline the robustness and sustainability of the biosorption process.

The study highlights the potential of *Ulva lactuca* as a cost-effective and environmentally friendly solution for heavy metal remediation. Future research should focus on scaling the process for industrial applications, exploring its performance in multi-metal systems, and evaluating its viability in real-world wastewater treatment scenarios.

Future research also can be focused on multi dimensional exploration of *Ulva lactuca* generated nanoparticles such as in treating Autism (Avni et al., 2026) and as Anticancer drugs (Chen et al., 2026). These lines opens new frontiers in clinical applications of bionanoparticles which is a promising field.

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