ADSORPTION OF NICKEL (II) IONS FROM SOLUTION USING SAWDUST AND MODIFIED SAWDUST

BABATOPE OLUFEMI[1*], EMEKA NNANNA[1]

[1]Chemical and Petroleum Engineering Department, University of Lagos, Akoka, Yaba, Lagos, Nigeria

Abstract: By varying adsorbate concentration, temperature, contact time, pH, and adsorbent weight, the capacity of non-modified (NM) and modified (M) sawdust adsorbents to adsorb Ni^{2+} ions were studied in this work. The adsorption of Ni (II) ions rose as the adsorbent weight increased but reduced as the adsorbate concentration increased. Adsorption was greatest at pH 6, with the NM and M adsorbents removing 95.09 and 96.95% of Ni^{2+} ions, respectively. The highly dependent nature of the percent removal on operational variables was established by employing Analysis of Variance (ANOVA) as well as the Bonferroni-Holm Posthoc statistical test relationship significance. It was discovered that the NM and M sawdust are adequate adsorbents in removing Ni^{2+} cations from its solution. Freundlich, Langmuir, Temkin and Dubinin Raduschkevich (DR) isotherms were applied to match the sorption data. The adsorption of the two biosorbents was best characterized by the Freundlich isotherm model. Chemisorption was suspected based on the energy values obtained from the Temkin and DR isotherms. The second order kinetics best fit both the NM and M adsorption activities. The ability to absorb Ni (II) ions is impressive.

Keywords: adsorption, isotherm, nickel, modified, sawdust

1. INTRODUCTION

Efforts to remove hazardous heavy metal ions from wastewater have been intensively explored in recent years due to their toxicity to animal and plant life, as well as other environmental issues. Several methods have been used to extract these metal ions from industrial waste streams and soil compositions over the years. Heavy metals were extracted from contaminated solutions using low-cost adsorbents, among other methods. Despite the fact that modified carbon substrate adsorption appears to be capable of removing a variety of trace elements from wastewater and solutions, the slightly expensive nature of modified carbon for adsorption is a barrier to large-scale implementation [1]. In recent years, effective removal of large volumes of nickel (II) ions from wastewater using low-cost adsorbents has been proposed as a viable solution to some of these challenges and researched [2].

By-product sawdust from the timber industry is usually utilized as a fuel for cooking or packaging material. Šćiban and Klašnja used fir, poplar, oak, willow, and black locust wood sawdust, as well as Kraft lignin and pulp, as adsorbents for the elimination of copper ions, according to a chronological investigative narrative [3]. The Langmuir isotherm accurately describes the system. The adsorbent quantity, initial cation concentration, and solution pH value were the important parameters that influenced Ni^{2+} ion sorption on maple sawdust, according to Shukla et al. [1]. After an hour, the highest percentage of metal was removed, with pH ranges of 2 to 5 indicating the greatest increase in metal ion uptake on sawdust. Shukla and Pai [4] looked at removing Cu(II), Ni(II) and Zn(II) from colored groundnut shells. According to them, the dye-loaded sawdust adsorbent had adsorption values

of 9.87 mg.g^{-1} for Ni(II), 8.07 mg.g^{-1} for Cu(II), and 17.09 mg.g^{-1} for Zn(II), which were significantly higher than the unloaded sawdust adsorbent's adsorption values of 8.05, 4.94, and 10.96 mg.g^{-1}, respectively.

Rao et al. [5] employed a neem (*Azadirachta indica*) sawdust biosorbent treated with hydrochloric acid to remove Cu^{2+} and Ni^{2+} ions from wastewater. The effects of adsorbent weight, initial metal ion concentration, pH, and contact time on the properties were explored. The pH of copper ions was 5.0, while the pH of Ni^{2+} ions was 4.0. After 150 mins, the maximum ion removal was obtained for copper ions, and after 180 mins, the maximum ion removal was achieved for nickel ions. Bulut and Tez [6] studied the biosorption of lead, cadmium and nickel from aqueous solution using walnut sawdust. As observed, Pb(II) > Cd(II) > Ni(II) was the adsorbent's selectivity order, and walnut sawdust was shown to be a commendable adsorbent for metal ion removal from contaminated solutions. Metals Pb(II), Cr(VI), Hg(II), and Cu(II) were adsorbed by treated sawdust according to Meena et al. [7]. The adsorption process was regulated by pH, concentration, contact time, temperature, and adsorbent weight. The biosorption capabilities of the treated sawdust were Pb(II) (52.38 mg.g^{-1}), Cr(VI) (111.61 mg.g^{-1}), Hg(II) (20.62 mg.g^{-1}), and Cu(II) (5.64 mg.g^{-1}). Lim et al. [8] investigated the effectiveness of *Pinus koraiensis* sawdust in removing heavy metals from aqueous solutions. The impact of pH and initial concentration was investigated using isotherms and kinetics models. The adsorption isotherms were found to fit the Freundlich and Langmuir models well, with $Pb^{2+} > Cu^{2+} > Zn^{2+}$ as the order of adsorption capacity. Rafatullah et al. [9] investigated the biosorption of Ni(II), Cu(II), Cr(III), and Pb(II) ions from different synthetic aqueous solutions using meranti sawdust. Meranti sawdust was found to be capable of adsorbing Ni(II), Cu(II), Cr(III), and Pb(II) ions from ionic solutions in the concentration range of 1–200 mg.L^{-1}, with the maximum biosorption achieved at a pH of 6.

Muhaisen [10] investigated how sawdust removed nickel ions from simulated wastewater containing 100 mg.L^{-1} nickel concentration. The effects of pH, contact time, sawdust weight, and temperature were explored, and it was discovered that the maximum adsorption uptake was 12.5 mg.g^{-1}. Eletta et al. [11] created a sawdust biosorbent to remove dye from textile effluent as efficiently as possible. At the ideal circumstances of 90 mins, 1.5 g, and 275 rpm for contact time, adsorbent weight, and agitation speed respectively, an upper limit adsorption capacity of 98.5% was attained. Bark and wood sawdust, together with the leaves of *A. auriculiformis*, have previously been proven to be effective sorption materials for Ni^{2+} cations [12]. Oyewo et al. [13] investigated the use of modified sawdust-derived cellulose nanocrystals (CNC) as coagulants for the removal of Cd (II) and Ni (II) ions from water. For nickel and cadmium, the optimal pH for removal was 7.10, with adsorptive removal values of 956.6 mg.g^{-1} and 2207 mg.g^{-1}, respectively. With R^2 statistical coefficients of 0.988, 0.988, and 0.982, respectively, the DR model adequately reflected the isotherms of Ni (II) ion biosorption by wood sawdust, leaves, and crushed bark.

Saleh et al. [14] developed a chemically modified natural sawdust (CMSD) sorbent by refluxing citric acid and sawdust to remove Hg(II) ions from a variety of samples with a metal ion recovery of over 95%. Tiwari et al. [15] examined the potential of *Dalbergia sissoo* sawdust as a natural NM biosorbent of Zn^{2+} and Ni^{2+} cations. The maximum biosorption of Zn^{2+} and Ni^{2+} cations at pH values of 7 and 5 was reported to be 20 and 10 mg.L^{-1} adsorbate concentrations, respectively. For Zn^{2+} and Ni^{2+} cations, agitation rates of 120 and 100 rpm, biosorbent weights of 1.5 and 0.5 g, and adsorption times of 30 and 90 mins were obtained, respectively. The use of $NaNO_2/NaHCO_3$ modified sawdust-based cellulosic nanocrystals (MCNC) materials as an adsorbent and coagulant to remove Fe, Cu, and Pb from cationic solution has been described [16]. According to the study, lead and copper uptake followed the Langmuir isotherm model, with highest adsorption capacities of 2.82 and 111.1 mg.g^{-1}, respectively, and iron uptake had a maximum biosorption capability of 81.96 mg.g^{-1}.

The influence of contact time, pH, adsorbate concentration, temperature, adsorbent weight, and adsorbent modification on the ability of sawdust to extract Ni (II) metal ions from an aqueous solution is explored in this study. The biosorption process was fitted using the Langmuir, Temkin, Freundlich and DR adsorption isotherm models, together with the pseudo 1st and 2nd order models' kinetics.

2. MATERIALS AND METHODS

2.1. Adsorbent preparation
Sawdust (wood particles mixture) as a waste by-product commonly found in the timber industry was collected from Oko-Baba Timber Saw mill in Lagos, South West Nigeria. Preparation of NM sawdust biosorbent included washing with deionized water, followed by drying in the sun. The M sawdust biosorbent was also washed with deionized water several times, followed by decolourization with 1% w/v formaldehyde in the ratio of 1 part sawdust to 5 parts formaldehyde at 50 °C for 4 hrs. The M sawdust was then filtered, rinsed repeatedly with

deionized water to dilute leftover formaldehyde and later modified in a hot air oven for 24 hrs. at 80 ºC. In addition, equal parts of the prepared sawdust were combined with equal parts of concentrated sulphuric acid and baked in an oven for 24 hrs. at 150 ºC. As described by Baral et al. [17], the heated biosorbent material was then rinsed with deionized water and immersed in a 1% sodium bicarbonate solution for 12 hrs. to eliminate any remaining acid. The produced material was then dried for 24 hrs. at 105 °C in an oven before being sieved. The averages of three runs from the technique were used to verify data reproducibility. The experiment started with the NM adsorbents and then moved on to the M adsorbents.

2.2. Preparation of nickel (II) ion solution
A ready solution consisting of 100 mg.L^{-1} of Ni (II) ions was generated by the dissolution of 0.1 g of Ni(NO$_3$)$_2$.6H$_2$O in deionized water. The starting solution pH was changed as needed by mixing 1 M HNO$_3$ with 1 M NaOH, following the approach described by Gloaguen and Morvan [18].

2.3. Apparatus and reagents used
These are United States OHAUS Model P4102 Electronic Mass Balance, England Pyrex beakers (50 – 500 mL), Germany Merck 37% w/w formaldehyde, Germany Merck ≥99.0 % w/w sodium bicarbonate, England Pyrex conical flasks (50 – 500 mL), England Pyrex measuring cylinders (50 – 1000 mL), United States manufactured incubator with shaking platform (FSIM-SPO16, Labcon), England Surgifield Model SM 1002A Muffle electric furnace, Germany Merck KGaA Whatman (Model 1001-125) 125 mm diameter filter paper, England Mesh Sieve (Model BSS 410/43), Germany Merck >90% Nitric acid (HNO$_3$), Stopwatch, Germany Merck ≥99.5 % w/w Nickel (II) nitrate hexahydrate (Ni(NO$_3$)$_2$.6H$_2$O) crystals, Germany Merck 32% w/w Hydrochloric acid (HCl), Germany Merck 99.8% w/w Methanol (CH$_3$OH) solution, Germany Merck >98% w/w Sodium hydroxide (NaOH) pellets, Germany made Merck -10 to 250 ºC Mercury in glass thermometer, England Lemfield Medical Model DHG9053A Heating Drying Oven, United States Hanna Instruments model HI98107 pH meter, spatula, United States The Lab Depot Inc. Model RS232 orbital shaker, Australia RATEK model SWB20D water bath shaker, de-ionized water, United States Buck Scientific 210VGP model Atomic Absorption Spectrophotometer (AAS).

2.4. Adsorption procedure
The adopted procedure of this work is similar to Gloaguen and Morvan [18] and Baral et al. [17]. The amount of Ni(II) ion adsorbed at equilibrium was calculated using equation (1):

$$q_{e=} \frac{(C_o - C_e)}{m} V \qquad (1)$$

2.5. Effect of varying initial metal ion concentration
Initial Ni^{2+} ion concentrations of 0.5, 1.0, 2.0, 3.0, 4.0, and 5.0 mg.L^{-1} per run were used for batch adsorption. Inside beakers, each of the 25 mL solutions of the various Ni (II) ion concentrations got exactly 0.5 g of NM adsorbent. The resultant mixtures were stirred vigorously, evenly, and continuously in a water bath for 30 mins at a constant temperature of 30 °C using a platform shaker. Each beaker's contents were filtered after that. An AAS was deployed to determine the residual level of Ni^{2+} ions in the filtrates, with the amount of Ni^{2+} ions adsorbed.

2.6. Effect of varying the contact time
The adsorption of Ni ions on NM sawdust adsorbent was studied at varied time intervals ranging from zero to 180 mins. Adsorption was performed with a 25 mL solution containing 0.5 mg.L^{-1} of starting ion concentration. The nickel solutions were measured into beakers with 0.5 g of adsorbent in each. The mixes were consistently mixed for 30 mins at 30 °C. The treatment was then repeated for 60, 90, 120, 150, and 180 mins at different times. The contents were filtered after each duration. An AAS was used to assess the amount of Ni^{2+} ions in the filtrates, and the weight of Ni^{2+} ions adsorbed was computed.

2.7. Effect of temperature variation
The adsorption of Ni^{2+} ions was studied at temperatures ranging from 30 to 70 °C. Each run used 25 mL of Ni^{2+} ions solution consisting of 0.5 mg.L^{-1} at the start. Using 0.5 g of adsorbent, the Ni^{2+} ions solutions were adsorbed. The mixes were consistently mixed for 30 mins at 30 °C. The method was repeated at temperatures of 40, 50, 60, and 70 °C. The contents were filtered at the end of each run, and the residual Ni^{2+} ions concentration in the filtrates was measured using an AAS.

2.8. Effect of pH variation
At pH levels of 2, 4, 6, 8, and 10, the adsorption of Ni^{2+} ions was investigated. This was done with a 25 mL solution containing 0.5 $mg.L^{-1}$ Ni^{2+} ions as the starting concentration. With 0.5 g of adsorbent, the ionic solutions were measured into beakers. At 30 °C, the mixtures were consistently agitated for 30 mins. The content was filtered at the end of each pH test. An AAS was used to determine the remnant of Ni^{2+} ions in the filtrates, and the weight of Ni^{2+} ions removed was computed.

2.9. Effect of adsorbent weight variation
Sixty millilitres of stock divalent nickel solutions were added to deionized water in 100 mL volumetric flasks to make an ionic Ni^{2+} solution with a concentration of 60 $mg.L^{-1}$. Before transferring into 100 mL Erlenmeyer flasks, the pH was corrected to 7.0 using 1M HNO_3 or 1 M NaOH, depending on the situation. The adsorbent's weight was changed from 0.2 to 1.0 g. An AAS was used to assess the amount of Ni^{2+} ion adsorbed after the mixtures were agitated for 30 mins at 30 °C.

2.10. Effect of adsorbent modification on adsorption
The above-mentioned procedures were carried out again using M sawdust biosorbent.

3. RESULTS AND DISCUSSION

3.1. Physical properties of adsorbents
The M adsorbent has higher physical property values than the NM adsorbents as can be seen in Table 1.

Table 1. Physical properties of adsorbents.

Properties	Non-Modified (NM) Sawdust	Modified (M) Sawdust
Moisture content (%)	1.411	1.808
Bulk density ($g.cm^{-1}$)	0.672	0.715
Specific gravity	1.267	1.317
Porosity	0.470	0.774

3.2. Analysis of adsorbents with Fourier transform infrared (FTIR) spectroscopy
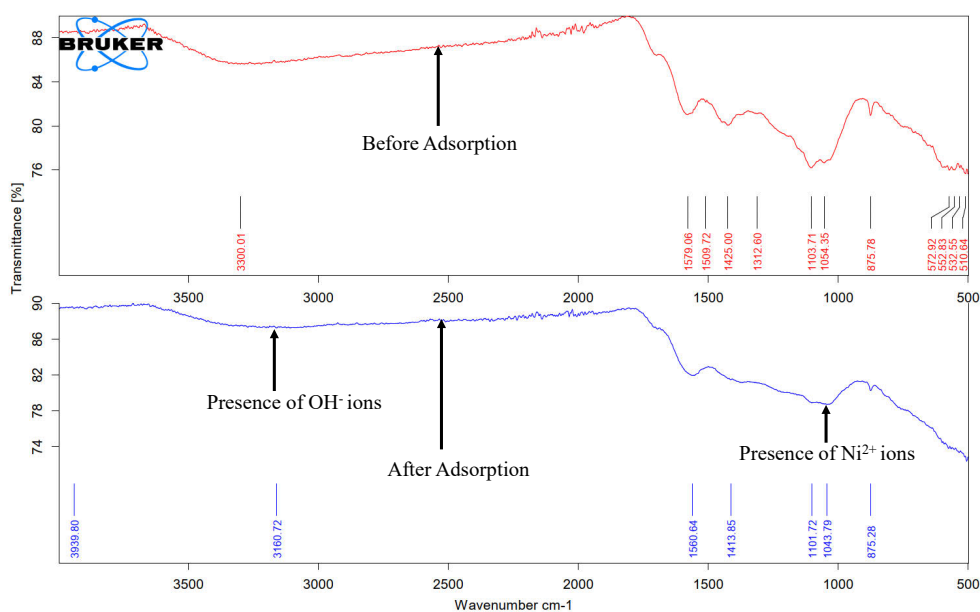Figure 1 depicts the sawdust's FTIR spectroscopy before and after adsorption.

Fig. 1. FTIR spectroscopy of sawdust revealing functional groups before and after adsorption.

In Figure 1, the OH$^-$ ions peak at 3160.72 cm^{-1} wavelength show the presence of water, while the Ni^{2+} ions peak at 1043.79 cm^{-1} wavenumber reveals the presence of nickel metal adsorption.

3.3. Effect of adsorbent weight variation

The metal adsorption capability was modified by the adsorbent weight in the solution. As seen in Figure 2, increasing the adsorbent dose resulted in an increase in adsorbate removal. Adsorption rose dramatically as the adsorbent weight increased for both adsorbents. After adding 1 g of adsorbent, the removal efficiency of both the NM and M adsorbents are at 85.445% and 94.791%, respectively.

3.4. Effect of adsorbate concentration variation

As seen in Figure 3, the percent removal decreased as the initial Ni (II) metal ion molar density increased. The event could have been caused by the increasing concentration exhausting the active sites. Adsorption capacity fell steeply as adsorbate concentrations increased until around 150 mg.L^{-1} for both adsorbents, after which it decreased gradually but more slowly. As the adsorbate dose increased from 40 to 200 mg.L^{-1}, the removal efficiency of the non-modified adsorbent decreased from 95.8% to around 85.01%. As the adsorbate molar density increased from 40 to 200 mg.L^{-1}, the removal of Ni ions using M adsorbents decreased from 96.43% to around 87.07%.
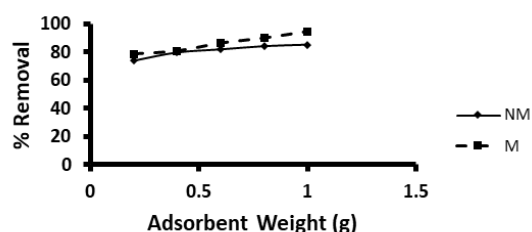

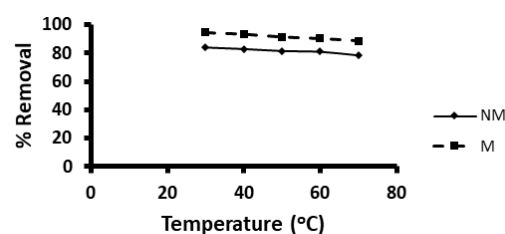Fig. 2. Adsorbent weight effect on adsorption.

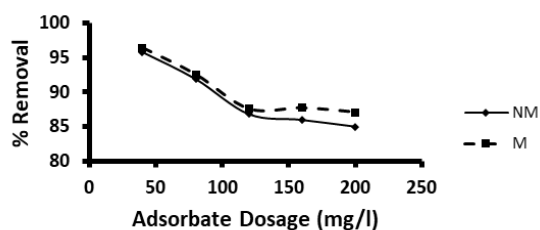Fig. 5. Effect of temperature variation on adsorption.

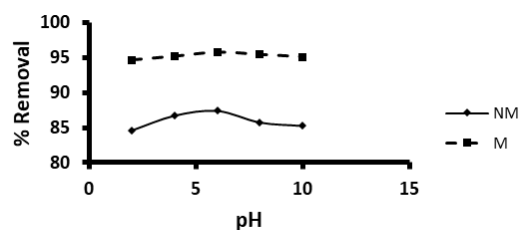Fig. 3. Effect of adsorbate concentration on adsorption.

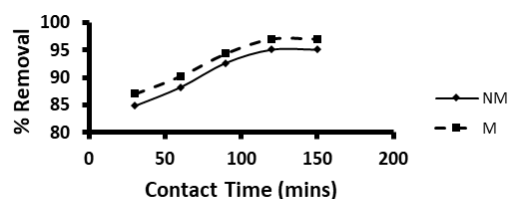

Fig. 6. Adsorption dependence on pH variation.

Fig. 4. Uptake time variation effect on biosorption.

3.5. Contact time variation effect

The importance of uptake time variation stems from the requirement to determine the potential for quick binding, kinetics, and the process of removing metal ions by biosorbents, as well as to determine the best time for complete removal of the desired adsorbate ion. As can be observed from Figure 4, the removal effectiveness of the non-modified adsorbent is consistently lower than that of the modified adsorbent.

3.6. Effect of temperature variation

Temperature influenced the adsorption behavior of the Ni^{2+} ion in solution as shown in Figure 5. The adsorption efficacy decreased as the temperature rose from 30 to 70 °C. Even when the temperature was changed, the M

adsorbent performed better in terms of adsorption. The optimal adsorption temperature was discovered to be 30 °C. This pattern pointed to chemisorption.

3.7. Adsorption effect due to pH variation
The pH of ionic solutions is an important variable that influences cation adsorption operations. The availability of binding sites in metallic ion adsorption is determined by metal chemistry together with the ionization conditions of the sorbent's functional molecular groups in solution. Figure 6 depicts the effect of pH on adsorption efficacy. As can be seen, the adsorption capacity of all adsorbents increased as the system pH increased from around 5.5 to 7.5, after which adsorption capacities decreased as the pH of the system increased. This demonstrates that adsorption is best for the system at pH values of around 5.5–7.5 and was best at pH 6.

3.8. Statistical evaluation of % removal with variables
With the Daniel's XL Toolbox Version 7.3.4 software, a statistical analysis of the percent removal with various factors for the NM and M sawdust adsorbents was carried out using Analysis of Variance (ANOVA) and the Bonferroni-Holm Posthoc significance test. The degrees of freedom estimated between the groups (DFB) value was 2, the degrees of freedom estimated within the groups (DFW) value was 12, and the lowest Fisher's ratio (F) statistical value was obtained for variation of percent removal with pH at 12.97876, while the highest Fisher's ratio (F) value was obtained for variation of percent removal with temperature at 48.2842. The F values are desirably high and acceptable, which denotes a satisfying reliable relationship among the variables. The highest and lowest statistical probability factor (P) was 0.000998 and 1.8233×10^{-6} respectively, which were both smaller than the critical probability factor (P_C) with a value of 0.05 confined in the 95% confidence interval, which signified a desired statistical relevance for all the variables. The Bonferroni-Holm Posthoc statistical significance test of the % removal with the variables presented in Table 2 were all significant. This confirmed that the %removal was greatly influenced by the variables considered.

Table 2. Statistical Bonferroni-Holm Posthoc significance test of variables with % removal.

Group 1	Group 2	Critical	P	Significanc
Adsorbent weight (g)	% Removal	0.016667	0.002849	Significant
Adsorbent weight (g)	% Removal	0.025	0.002851	Significant
Adsorbate concentration (mg.L^{-1})	% Removal	0.016667	0.002951	Significant
Adsorbate concentration (mg.L^{-1})	% Removal	0.025	0.002953	Significant
Contact time (min)	% Removal	0.016667	0.002998	Significant
Contact time (min)	% Removal	0.025	0.003002	Significant
Temperature (°C)	% Removal	0.016667	0.000118	Significant
Temperature (°C)	% Removal	0.025	0.000119	Significant
pH	% Removal	0.025	0.006637	Significant
pH	% Removal	0.05	0.0073	Significant

3.9. Adsorption isotherms
The development of an appropriate isotherm model for adsorption is essential for designing and optimizing adsorption operations. The adsorption isotherms parameters of Ni^{2+} metal cations on NM and M sawdust adsorbent are presented in Figures 7 to 14.

3.9.1. Langmuir adsorption isotherm
Figure 7 shows how the non-modified sawdust adsorbent fits best within the Langmuir model. The greatest adsorption capability q_m of non-modified sawdust in Figure 8 was 123.46 mg of nickel (II) ions per 1 g of non-modified sawdust. The Langmuir model's isotherm constant was 0.192 L.mg^{-1}. Its R_L value, on the other hand, is smaller than one, indicating that adsorption was favorable. The greatest adsorption capacity q_m of the modified sawdust was 121.95 mg of nickel (II) ions per 1 g of modified sawdust. The Langmuir model K_L's isotherm constant was 0.232 L.mg^{-1} and its R_L value was 0.00733, which is also less than 1, indicating that adsorption was favorable.
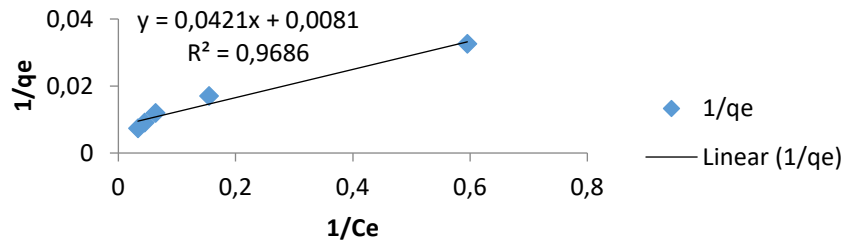
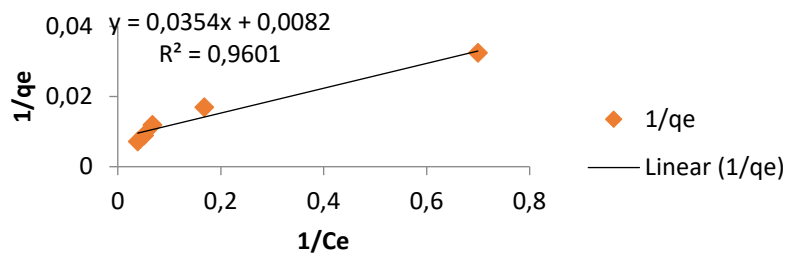Fig. 7. Langmuir isotherm for NM sawdust.

Fig. 8. Langmuir isotherm for M sawdust.

3.9.2. Freundlich adsorption isotherm

The Freundlich adsorption model accurately depicts adsorption; nevertheless, it is best suited to modeling adsorption using modified sawdust, as shown in Figures 9 and 10. The modified and non-modified adsorbents from sawdust have adsorption capabilities of 24.9257 mg.g^{-1} and 23.148 mg.g^{-1}, respectively. Non-modified and modified adsorbents have n values of 2.002 and 2.006, respectively, suggesting good adsorption.
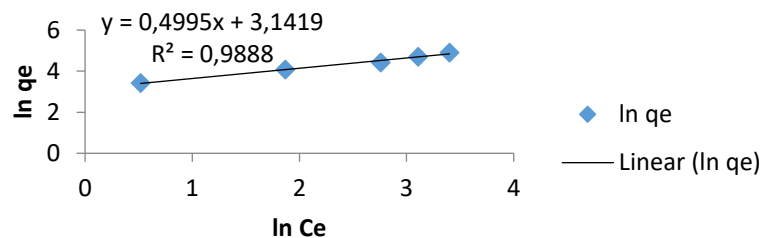
Fig. 9. Freundlich isotherm for NM sawdust.
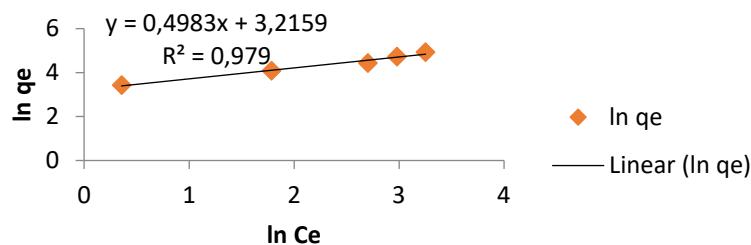
Fig. 10. Freundlich isotherm for M sawdust.

3.9.3. Temkin adsorption isotherm

As shown in Figures 11 and 12 for the Temkin isotherm models, the trend of adsorption was that the NM least-fitted than the M sawdust adsorbent. As observed, the Temkin isotherm revealed how the adsorption heat reduced with higher surface area or uptake of the metallic ion on the biosorbent. The non-modified fitted the Temkin isotherm best at R^2 value of 0.9073, and this could be the reason for the seemingly low values of the heat of sorption constant of 33.854 and 34.038 J.mol^{-1} for NM and M sawdust adsorbents respectively.
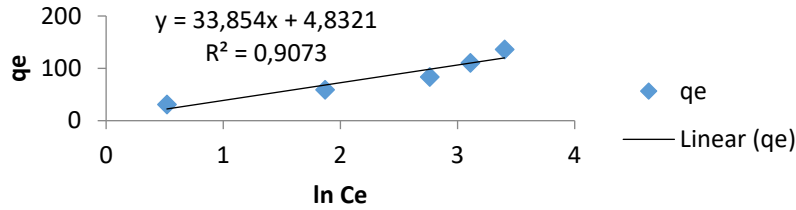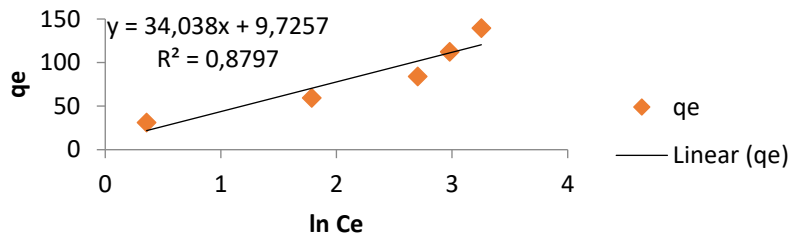
Fig. 11. Temkin isotherm for NM sawdust.

Fig. 12. Temkin isotherm for M sawdust.

3.9.4. Dubinin-Raduschkevich adsorption isotherm

The DR isotherm, as shown in Figures 13 and 14, provides insight into the mean free energy of adsorption (E). The quantity for the M and NM adsorbents were estimated to be 420 and 288.4 kJ.mol^{-1}, respectively, which are larger than 20 kJ.mol^{-1}, indicating chemisorption. Amin et al. [19], explained these findings as well.
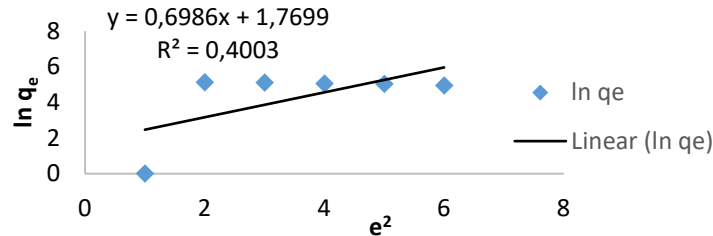
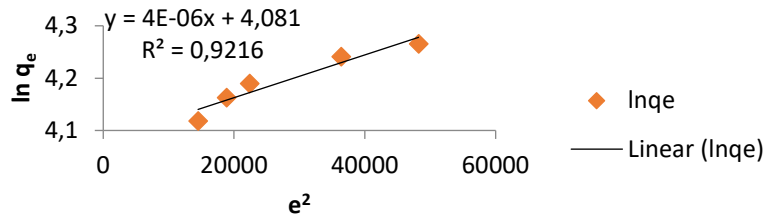

Fig. 13. DR isotherm for NM sawdust.

Fig. 14. DR isotherm for M sawdust.

3.10. Adsorption Kinetics

Equations (2) and (3), which were adapted from Olufemi and Damola-Okesiji [20], explain the pseudo-first and pseudo-second order kinetic models, respectively, where q_t (mg.g^{-1}) depicts the quantity adsorbed at time t, while k_1 and k_2 are kinetic parameters.

$$\log(q_e - q_t) = \log q_e - (k_1/2.303)\, t \tag{2}$$

$$t/q_t = (1/k_2 q_e^2) + t/q_e \tag{3}$$

Figures 15 to 18 show the kinetic plots, and the second order kinetics best described the biosorption process due to the fact that the correlation coefficient R for the NM and M sawdust adsorbent has a value of 0.9996, which is better than that of the first order kinetic model.
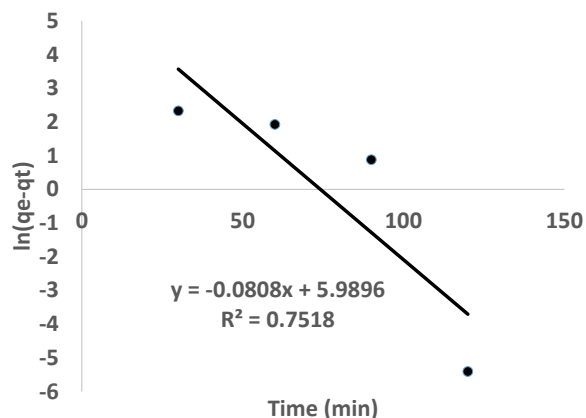

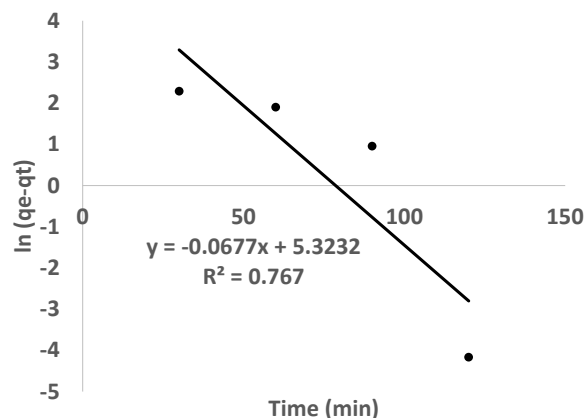Fig. 15. NM sawdust first order kinetics.
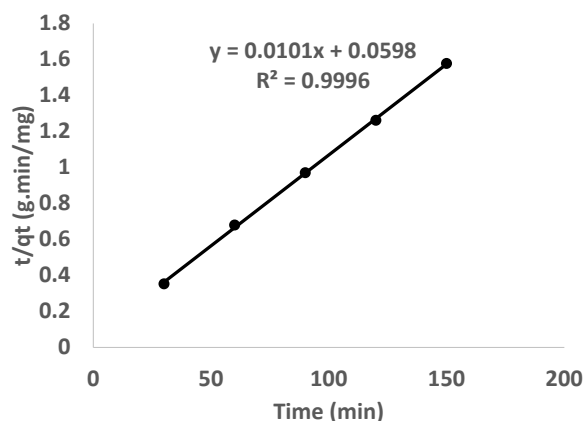

Fig. 16. M sawdust first order kinetics.

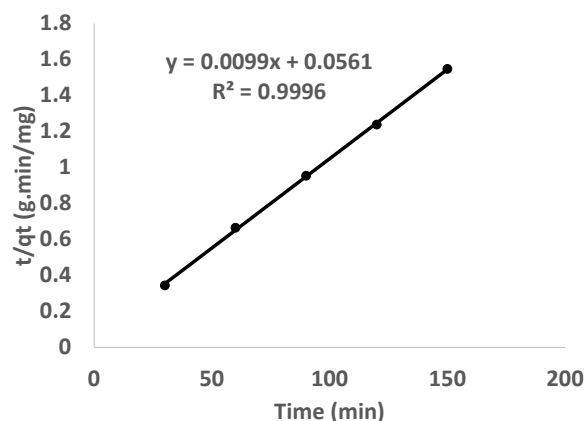Fig. 17. NM sawdust second order kinetics.

Fig. 18. M sawdust second order kinetics.

CONCLUSION

For the non-modified and modified adsorbents used, the biosorption of nickel (II) ions increased with higher adsorbent weight, but reduced with increasing adsorbate dose. Adsorption was optimal at a pH of 6. The statistical evaluation of the biosorption operation with ANOVA and Bonferroni-Holm Posthoc significant test revealed the highly dependent nature of the percentage of nickel ion removal with the controlling variables. The sorption data were evaluated with the Freundlich, Langmuir, Temkin, and DR isotherms. The Freundlich adsorption isotherm described the adsorption of the NM and M biosorbents best. The adsorption energy values of the Temkin and DR isotherms suggested that chemisorption occurred with the adsorbents. The biosorption process was best described with the pseudo-second order kinetics for the NM and M sawdust adsorbents. The sawdust biosorbent performed well enough to merit further investigation in pollution management applications in the environment.

SYMBOLS AND ABBREVIATION

A_T = Binding equilibrium constant of the Temkin isotherm (L.g^{-1})
B = Constant related to heat of sorption (J.mol^{-1})
b_T = Temkin isotherm constant
B_{DR} = isotherm constant
C_o = initial concentration of Ni^{2+} (mg.L^{-1})
C_e = equilibrium nickel concentration (mg.L^{-1})
D_{FB} = degrees of freedom between the groups

D_{FW} = degrees of freedom within the groups
e = Dubinin–Radushkevich isotherm constant
F = Fisher's ratio
h = initial sorption rate (mg/gmin)
K_1= Pseudo-first-order biosorption rate constant (min^{-1})
K_2 = Pseudo-second-order rate constant ($g.mg^{-1}.min^{-1}$)
K_{ad} = Isotherm constant for Dubinin–Radushkevich ($mols^2/kJ^2$)
K_f = Freundlich constant, which represents relative adsorption
K_l= Langmuir isotherm constant related to adsorption free energy ($L.mg^{-1}$)
K_o = Equilibrium Constant
m = Adsorbent's mass (g)
n = Freundlich constant, which indicates the degree of adsorption
P = Probability factor
P_c = Critical Probability factor
q_e = The equilibrium amount of metal adsorbed ($mg. g^{-1}$)
q_s = Isotherms' theoretical capability for saturation ($mg. g^{-1}$)
q_m = Maximum adsorption capacity ($mol.mg^{-1}$)
q_t = Metal uptake rate ($mg.g^{-1}$)
R = Ideal gas constant ($8.31445 \ J.mol^{-1}.K^{-1}$), Correlation Coefficient
t = Time (min)
T = Temperature (K)
V = Aqueous solution volume (L).

REFERENCES

[1] Shukla, S.S., Li, J.Y., Dorris, K. L., Shukla, A., Removal of Nickel from aqueous solutions by sawdust, Journal of Hazardous Materials, vol. 121, no. 1-3, 2005, p. 243-246.
[2] Yu, B., Zhang, Y., Shukla, A., Shukla, S.S., Dorris, K.L., The removal of heavy metals from aqueous solutions by sawdust adsorption — removal of lead and comparison of its adsorption with copper, Journal of Hazardous Materials, vol. 84, no. 1, 2001, p. 83-94.
[3] Šćiban, M., Klašnja, M., Wood sawdust and wood originate materials as adsorbents for heavy metal ions, Holz als Roh- und Werkstoff, vol. 62, no. 1, 2004, p. 69-73.
[4] Shukla, S.R., Pai, R.S., Adsorption of Cu(II), Ni(II) and Zn(II) on modified jute fibres, Bioresource Technology, vol. 96, no.13, 2005, p.1430-1438.
[5] Rao, P.S., Reddy, K.V.N.S., Kalyani, S., Krishnaiah, A., Comparative sorption of copper and nickel from aqueous solutions by natural neem (*Azadirachta indica*) sawdust and acid treated sawdust, Wood Science and Technology, vol. 41, no. 5, 2007, p. 427-442.
[6] Bulut, Y., Tez, Z., Removal of heavy metals from aqueous solution by sawdust adsorption, Journal of Environmental Sciences, vol. 19, no. 2, 2007, p.160-166.
[7] Meena, A.K., Kadirvelu, K., Mishra, G.K., Rajagopal, C., Nagar, P.N., Adsorptive removal of heavy metals from aqueous solution by treated sawdust (*Acacia arabica*), Journal of Hazardous Materials, vol. 150, no. 3, 2008, p. 604-611.
[8] Lim, J.H., Kang, H.M., Kim, L.H., Ko, S.O., Removal of heavy metals by sawdust adsorption: equilibrium and kinetic studies, Environmental Engineering Research, vol. 13, no. 2, 2008, p. 79-84.
[9] Rafatullah, M., Sulaiman, O., Hashim, R., Ahmad, A., Adsorption of copper (II), chromium (III), nickel (II) and lead (II) ions from aqueous solutions by meranti sawdust, Journal of Hazardous Materials, vol. 170, no. 2–3, 2009, p. 969-977.
[10] Muhaisen, L., F., Nickel ions removal from aqueous solutions using sawdust as adsorbent: equilibrium, kinetic and thermodynamic studies, Journal of Engineering and Sustainable Development, vol. 21, no. 3, 2017, p. 60-71.
[11] Eletta, O.A.A., Mustapha, S.I., Ajayi, O.A., Ahmed, A.T., Optimization of dye removal from textile wastewater using activated carbon from sawdust, Nigerian Journal of Technological Development, vol. 15, no. 1, 2018, p. 26-32.
[12] Denisova, T.R., Sippel, I.Ya., Nguyen, K.T.T., Galimova, R.Z., Shaikhiev, I.G., Investigation of nickel ions adsorption by *Acacia auriculiformis* components, International Journal of Green Pharmacy, vol. 12, no. 4, 2018, p. 895-899.
[13] Oyewo, O.A., Mutesse, B., Leswifi, T.Y., Onyango, M.S., Highly efficient removal of nickel and cadmium from water using sawdust-derived cellulose nanocrystals, Journal of Environmental Chemical Engineering, vol. 7, no. 4, 2019, p. 103251.

[14] Saleh, M., O., Hashem, M.A., Akl, M., Removal of Hg (II) metal ions from environmental water samples using chemically modified natural sawdust, Egyptian Journal of Chemistry, vol. 64, no. 2, 2021, p. 1027-1034.

[15] Tiwari, S., Aachhera, S., Garg, H., Rojra, M., Nagar, N., Gahan, C.S., Comparative biosorption kinetics study of Ni and Zn metal ions from the aqueous phase in sulfate medium by the wooden biomass of *Dalbergia sissoo*, Environmental Quality Management, 2021, p. 1-11.

[16] Oyewo, O.A., Ramaila, S., Mavuru, L., Leswifi, T., Onyango, M.S., Adsorptive and coagulative removal of trace metals from water using surface modified sawdust-based cellulose nanocrystals, Multidisciplinary Scientific Journal, vol. 4, no. 2, 2021, p. 193-205.

[17] Baral, S.S., Das, S.N., Rath, P., Hexavalent chromium removal from aqueous solution by adsorption on treated sawdust, Biochemical Engineering Journal, vol. 31, no. 1, 2006, p. 216-222.

[18] Gloaguen, V., Morvan, H., Removal of heavy metal ions from aqueous solution by modified barks, Journal of Environmental Science and Health. Part A: Environmental Science and Engineering and Toxicology, vol. 32, no. 4, 1997, p. 901-912.

[19] Amin, M.T., Alazba, A.A., Shafiq, M., Removal of copper and lead using banana biochar in batch adsorption systems: isotherms and kinetic studies, Arabian Journal for Science and Engineering, vol. 43, 2018, p. 5711-5722.

[20] Olufemi, B.A., Damola-Okesiji, A.T., Optimal adsorptive bleaching of palm oil with activated beans husks, NUST Journal of Engineering Sciences, vol. 13, nr. 2, 2020.