

Adsorption of Ni (II) ions from wastewater on adsorbents derived from natural materials: Kinetic and Thermodynamic study

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ABSTRACT

The excessive exposure of nickel ions to the environment can lead to severe damage of kidneys, lungs, dermatitis and cancer. Therefore, it is necessary to remove nickel ions from wastewater. So batch mode adsorption experiments of Ni (II) ions on different natural materials were carried out in the present study. The parameters studied includes initial Ni (II) ion concentration, contact time, dose of adsorbents, pH and temperature. All Freundlich, Langmuir and Temkin adsorption isotherm models were found to be best fitted models as per the linear regression coefficient R^2 values. The monolayer (maximum) adsorption capacities (q_m) ranging from 4.608 to 13.514 mg/g for natural adsorbents under study. As $q_{e(ther)}$ values are matched with $q_{e(exp)}$ showed that Lagergen pseudo-second order model fits the kinetics of adsorption of Ni (II) ions on these natural materials. Amount of Ni (II) ions adsorbed on adsorbents was found to be directly proportional with pH and temperature. According to thermodynamic analysis, adsorption of Ni (II) ions on adsorbents was favourable, spontaneous and endothermic physical adsorption. Out of the six adsorbents under study, Mango (*Mangifera indica*) leaf powder was found have greater adsorption capacity and Tamarind (*Tamarindus indica*) fruit shell powder had least adsorption capacity towards Ni (II) ions.

Key words : Ni (II) ions, Adsorbents, Adsorption isotherm, Kinetic and thermodynamic.

Introduction

Many industries such as electroplating, electronic equipment, mining and battery manufacturing processes commonly release Ni(II) ions into water or nickel on surface of earth which is not biodegradable and the accumulation of nickel in ecological system can cause harmful effects to human, animals and plants. Excess nickel concentrations on soils can damage plants and high nickel concentrations in water can cause damage to marine life and also can diminish growth rates of algae and microorganisms. The excessive exposure to nickel leads to severe

damage of lungs and kidneys, skin dermatitis and can also cause cancer (Denkhans *et al.*, 2002). Most common methods used to remove toxic metal such as nickel, copper, chromium, cadmium etc from industrial wastewater includes electro-coagulation, chemical precipitation, ion-exchange, reverse-osmosis and adsorption (Ghodbane *et al.*, 2008). Adsorption on low cost adsorbents/ biosorbents for removal of such toxic metals from wastewater has been reported. These adsorbing materials include, sawdust (Ajmal *et al.*, 1998), Modified soybean hull (Marshall *et al.*, 1999), wild cocoyam biomass (Horsfall *et al.*, 2004), brewery Biomass (Kim *et al.*,

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2005), sugar beet pulp (Aksu *et al.*, 2005).

In the present study, we attempt the use six adsorbents derived from plant materials as biosorbents for the removal of Ni (II) ions from wastewater.

Materials and Methods

Adsorbents

Following adsorbents of ≥ 120 mesh size are used in the present study:

- 1) Mango (*Mangifera indica*) leaf powder (MLP)
- 2) Pineapple (*Ananascomosus*) peel powder (PPP)
- 3) Mangrove (*Sonneratiaapetala*) plant fruit powder (MPFP)
- 4) Tamarind (*Tamarindus indica*) fruit shell powder (TFSP)
- 5) Coconut (*Cocos nucifera*) coir pith (CCP)
- 6) Toor plant (*Pisum sativum*) leaf powder (TPLP)

IR spectral studies of adsorbents were carried out to recognize the mechanism of adsorption.

Adsorbate

Stock solution of concentration 500 mg/l of Ni (II) was prepared by dissolving 2.239 g of Nickel sulphate in 500 ml of water and 5ml of 1:1 HNO₃ was added. The solution was diluted and made up to 1000 ml. Fresh solutions were used during adsorption studies.

Batch Mode Adsorption Studies

Batch mode studies were carried out by shaking 25 ml aqueous solution of Ni (II) ions at 230 rpm agitation speed of varying concentration for different time intervals at nearly 303K temperature and at pH 5. At pre-determined time, adsorbent was removed by centrifugation and residual concentration of supernatant of Ni(II) ions was analyzed spectrophotometrically at λ_{max} .

Variations of dose of adsorbent, agitation speed, pH and temperature were also studied.

Effect of Contact Time

In batch mode adsorption experiments, 25 mg of each adsorbent were shaken with 25 ml of Ni(II) ion solution with an initial concentration of 10 mg/l at nearly 303K on a shaker at 230 rpm for 5, 10, 15, 20, 30, 40, 50 and 60 minutes at pH 5. The optimum contact time was identified by performing these batch mode experiments.

Effect of Dose of Adsorbent

25 mg/l initial concentration of Ni(II) ions solution of 25 ml were shaken with 25 mg, 50 mg, 75 mg, 100 mg, 125 mg and 150 mg of adsorbent (i.e, adsorbent dose of 1, 2, 3, 4, 5 and 6 g/l) by keeping other parameters such as contact time, agitation speed, temperature and pH of 40 minutes, 230 rpm, 303K and 5 respectively constant.

Effect of Initial Ni(II) ion Concentration

Initial Ni(II) ion concentration of 4, 6, 8, 10, 12 and 14 mg/l were shaken with 1 g/l of adsorbent. Contact time, agitation speed, temperature and pH of 40 minutes, 230 rpm, 303K and 5 and respectively were kept constant.

Effect of pH

Initial pH of Ni(II) ion solutions for 10 mg/l concentration were adjusted to 2, 3, 4, 5 and 6. Contact time, adsorbent dose and temperature of 30 minutes, 1 g/l and 303K respectively were kept constant.

Effect of Temperature

303K, 313K and 323K temperatures were used in conjunction with 8 mg/l Ni (II) ion concentration. Contact time, adsorbent dose and pH of 40 minutes, 1 g/l and 5 respectively were kept constant.

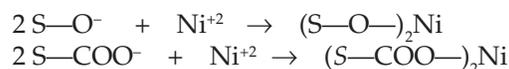
Results and Discussion

Infrared spectroscopic studies

The FTIR spectra of MPFP (Figure 1) and CCP (Figure 2) showed bands for bonded –OH group, C=O group in carboxylic acid (-COOH) or ester (-COO-), secondary amino (-NH-) group, –SO₃, C-O stretching in ether group. The adsorbents with these functional groups are most probably participated in metal binding during adsorption.

Mechanism

Electrostatic attraction between oxyanion (—O⁻) or carboxylate ions (—COO⁻) from adsorbent surface and cationic Ni⁺² ion results into either chemisorptions or electrostatic physical adsorption between two oppositely charged ions..



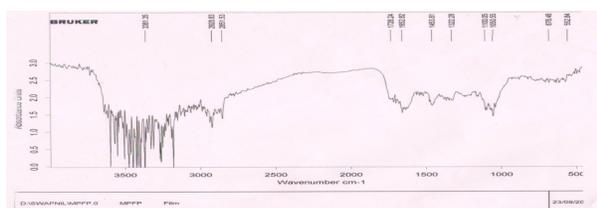


Fig. 1. FTIR Spectra of MPFP

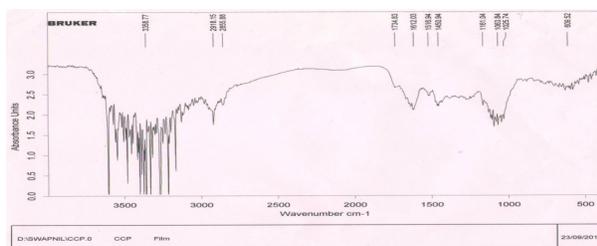
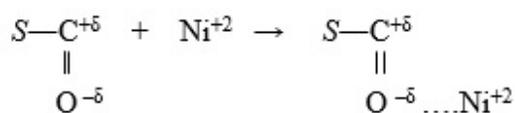
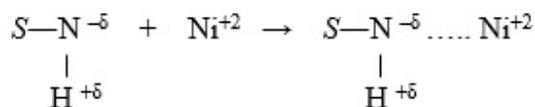
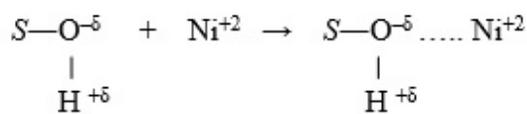
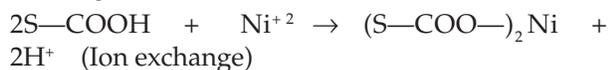
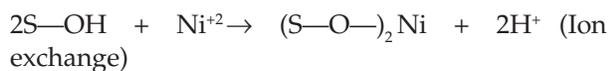


Fig. 2. FTIR Spectra of CCP

Electrostatic physical adsorption due to ion dipolar interaction between Ni⁺² ions and polar groups such as OH, NH and CO groups of adsorbents.



The adsorption of Ni⁺² ions also takes place due to exchange of H⁺ ions of -OH or -COOH groups from the surface of adsorbents and cationic Ni⁺² ions. Thus, protons (H⁺ ions) are released into the solution.



Batch Mode Adsorption Studies

Parameters, which influence the extent of adsorption of Ni (II) ions influenced by parameters such as initial Ni (II) ion concentration, contact time, dose of adsorbent, pH and temperature were investigated

Effect of Contact Time

Effect of contact time on adsorption of Ni (II) from 10 mg/l initial concentration solutions is presented in Figure 3. Adsorption of Ni (II) was faster in first 5 minutes and after 40 minutes amount of Ni (II) ion adsorbed was almost constant. Therefore 40 minutes optimum contact time was used for further studies.

Nearly 10 to 75% for Ni (II) ion uptake appears to have been adsorbed in first 5 minutes duration and at equilibrium it reached up to 25 to 91% for Ni (II) depending upon the adsorption ability of different adsorbents.

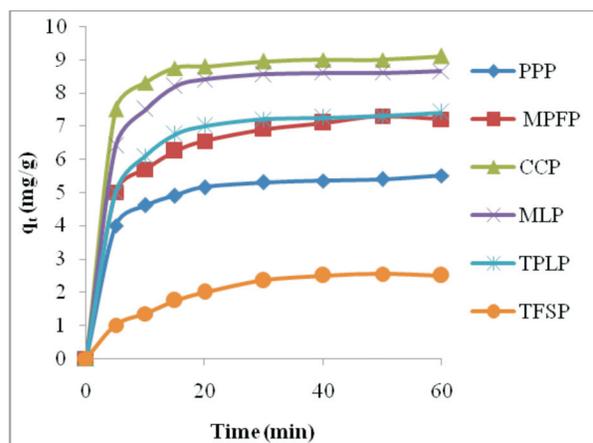


Fig. 3. Effect of contact time on adsorption of Ni (II).

The rapid uptake of Ni (II) ions at initial stage of adsorption was because of more number of active sites on the surface of adsorbent, after that slower adsorption due to intra particle diffusion.

The adsorption capacities of adsorbents found to be of the order CCP > MLP > TPLP > MPFP > PPP > TFSP.

Pseudo - first order, pseudo- second order and intra particle diffusion models (Arivoli *et al.* 2007) were used to investigate the mechanism of adsorption.

Results of Langergen pseudo first order kinetic model are shown in Figure 4, Table 1. The q_{e(exp)} values differ from q_{e(the)} calculated values from the linear plot of log (q_e - q_t) versus t showed that adsorption of Ni (II) ions is not a first order kinetics on these adsorbents.

Results of Langergen pseudo second order kinetic model are shown in Figure 5, Table 1. Highly linear plot of t/q_t versus t showed chemisorption played a significant role in the rate determining step. The correlation coefficient (R²) for second order adsorption

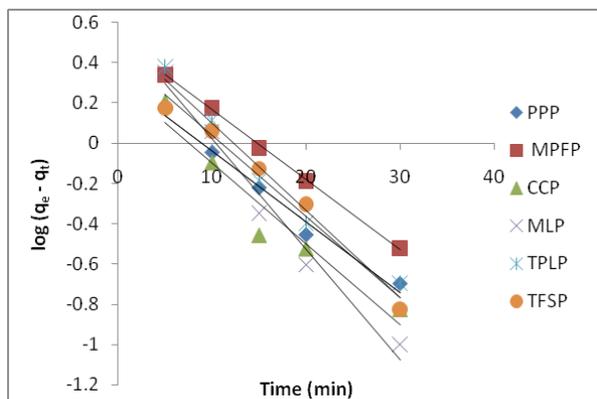


Fig. 4. Pseudo first order plot

model lie between 0.995 to 0.999 and $q_{e(the)}$ values are very close to $q_{e(exp)}$ values showed that Langergen pseudo second order adsorption equation fit well and Nickel ion adsorption process appears to be controlled by chemical adsorption. This shows that the adsorption of the Ni (II) ions on the adsorbents under study is the second order kinetics.

The values of intra particle diffusion rate constant

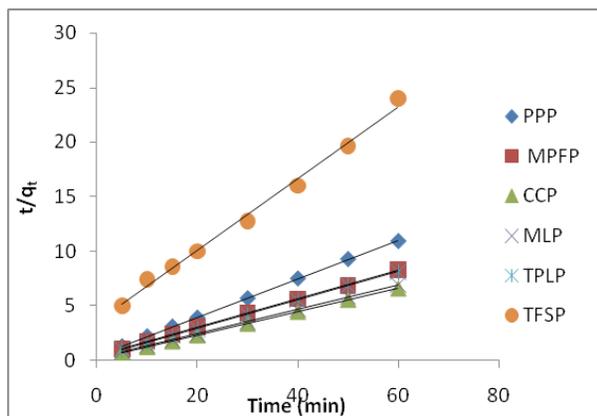


Fig. 5. Pseudo second order plot

K_1 ($\text{mg g}^{-1} \text{min}^{-1/2}$), were determined from the slope of the plot q_t against $t^{1/2}$, Figure 6, Table 2, do not pass through origin but showed linear relationship due boundary layer effect. Higher values of K_1 illustrate an enhancement in the rate of adsorption. Also larger the intercept values greater the contribution of surface sorption in the rate determining step.

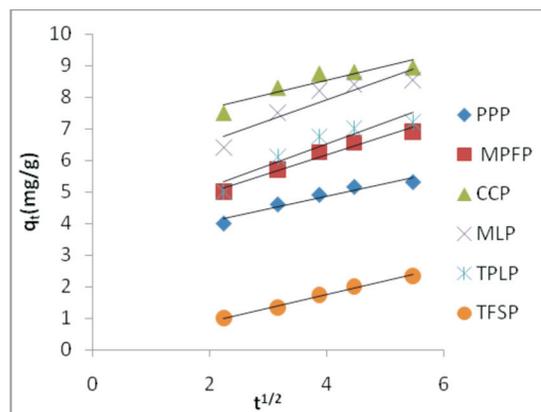


Fig. 6. Intra particle diffusion plot.

Effect of dose of adsorbent

The adsorption of Ni (II) ions was studied by varying the dose of adsorbent. It was found that Percentage removal of Ni (II) ions increased as in Figure 7, but amount of Ni (II) ions adsorbed per unit mass of adsorbent decreased as in Figure 8 with increased in adsorbent dose from 1 to 6 g/l. With increase in amount of adsorbent, number of active sites available for adsorption also increases thus percentage removal of Ni (II) also increases. But with increase in amount of adsorbent, all active sides may not be available during adsorption due to overlapping between these sites and thus amount adsorbed mg/g of adsorbent decreases. Thus, the adsorption of Ni (II) ions increased with the sorbent dosage and

Table 1. Results of Pseudo First and Second order model plot

Adsorbent	Initial Ni (II) ion Conc. (mg/l)	Pseudo -first order model				Pseudo -second order model				
		$q_{e(exp)}$ (mg/g)	K_1 (min^{-1})	$q_{e(the)}$ (mg/g)	R^2	$q_{e(exp)}$ (mg/g)	K_2 (g/mg/min)	$q_{e(the)}$ (mg/g)	h (mg/g.min)	R^2
PPP	10	5.5	0.08061	2.08449	0.983	5.5	0.07822	5.68182	2.52525	0.999
MPFP	10	7.2	0.0783	3.25837	0.999	7.2	0.04152	7.69231	2.457	0.999
CCP	10	9.1	0.09212	2.00447	0.934	9.1	0.10032	9.43396	8.92857	0.999
MLP	10	8.65	0.12436	3.71535	0.978	8.65	0.07168	8.92857	5.71429	0.999
TPLP	10	7.4	0.09903	3.43558	0.974	7.4	0.02102	7.69231	1.24378	0.999
TFSP	10	2.5	0.09212	2.76694	0.978	2.5	0.031	3.04878	0.28818	0.993

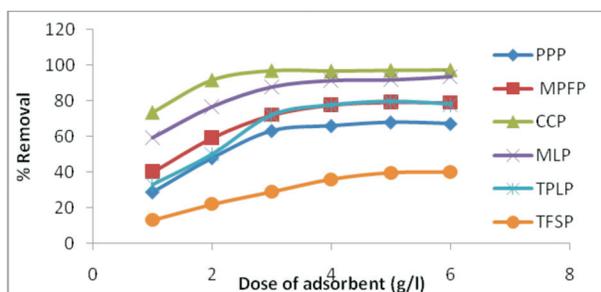


Fig. 7. Effect of adsorbent dosage on percentage Removal of Ni (II).

reached an equilibrium value after certain dose of adsorbent. Adsorbent dose of nearly 4 g/l was required to attend equilibrium for the adsorbents under study. But the amount of Ni (II) ions adsorbed after equilibrium per unit mass of adsorbent is different for different adsorbent.

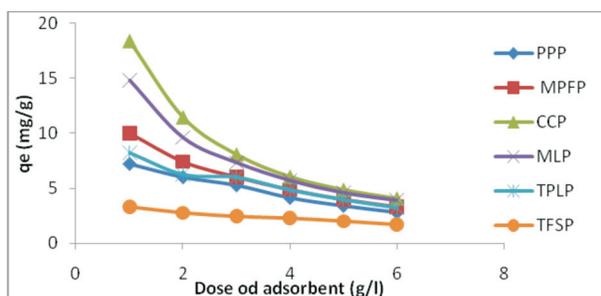


Fig. 8. Effect of adsorbent dosage on amount of Ni (II) adsorbed in mg/g of adsorbent

Effect of Initial Metal Ion Concentration

Amount of metal ions adsorbed per unit mass of adsorbent increased from 3.1 to 6.2 mg/g for PPP, 3.75 to 8.6 mg/g for MPFP, 3.95 to 12 mg/g for CCP, 3.8 to 11.1 mg/g for MLP, 3.6 to 8.7 mg/g for TPLP, 1.25 to 2.75 mg/g for TFSP (Figure 9) but Percentage sorption of Ni(II) ions decreased from 77.5 to 44.29 % for PPP, 93.75 to 61.43 % for MPFP, 98.75 to 85.71

% for CCP, 95 to 79.29 % for MLP, 90 to 62.14 % for TPLP, 31.25 to 19.64 % for TFSP (Figure 10) with increase in initial Ni(II) ion concentration from 4 to 14 mg/l.

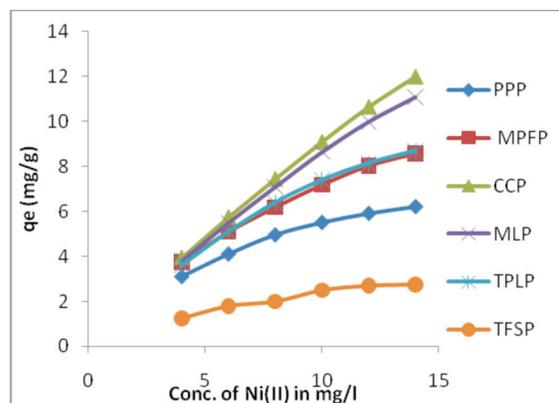


Fig. 9. Effect of initial metal ion concentration on adsorption of Ni (II).

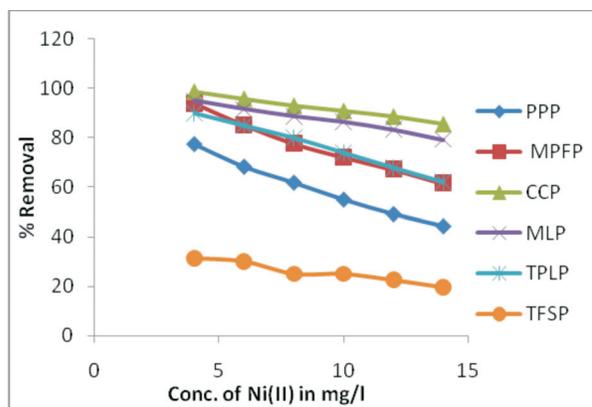


Fig. 10. Effect of initial metal ion concentration on percentage removal of Ni (II).

At any agitation time, increase in initial nickel ion concentration decreased the percent removal and increased the amount of nickel uptake (qe) per unit mass of the adsorbent. Thus it is seen that for the

Table 2. Results of Intra particle diffusion model plot

Adsorbent	Initial Conc. Ni (II) ion (mg/l)	Intra particle diffusion model		
		K_i (mg/g/min ^{1/2})	A (mg/g)	R ²
PPP	10	0.402	3.241	0.933
MPFP	10	0.594	3.794	0.968
CCP	10	0.437	6.777	0.843
MLP	10	0.665	5.251	0.864
TTLP	10	0.678	3.8	0.887
TFSP	10	0.427	0.045	0.993

low initial concentrations, the percent uptake of the Ni (II) ions was high and vice versa.

Freundlich, Langmuir and Temkin isotherm models (Arivoli *et al.*, 2007) were used to test the equilibrium data of adsorption.

The Freundlich adsorption plot of $\log q_e$ against $\log C_e$ showed good linearity with R^2 from 0.957 to 0.997, indicating the adsorption of Ni (II) ions obeys the Freundlich adsorption isotherm (Figure 11). The values of K_f and n are given in the Table 3. From values it is clear that the adsorbent which has greater sorption capacity has higher value of K_f and vice versa. Values of n between 1 to 10 indicate an effective adsorption while higher values of K_f indicate an easy uptake of nickel ions from the solution. Thus, Freundlich adsorption isotherm fit well to these sorption studies.

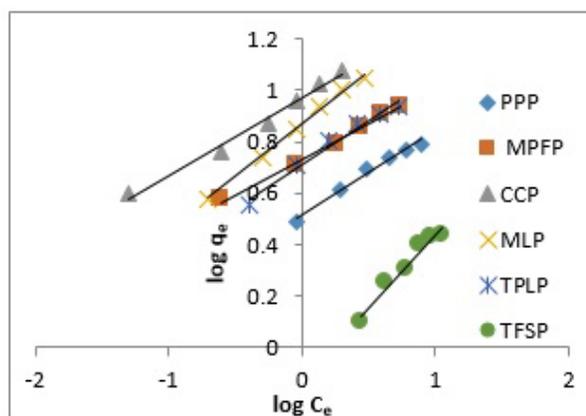


Fig. 11. Freundlich isotherm plot

A linear plot of C_e / q_e against C_e suggests the applicability of the Langmuir isotherm (Figure 12). The values of q_m and b were determined from the slope and intercepts of the plot and are given in Table 3. Monolayer (maximum) adsorption capacities (q_m) obtained from Langmuir plots give the idea of effectiveness of adsorbents towards Ni (II) ion. These

q_m values vary from adsorbent to adsorbent depending upon active sites present on the surface of adsorbent. R_L values are given in Table 4, lying between 0 to 1, indicate favourable adsorption. Correlation coefficient values lie between 0.961 to 0.998, showing very good linearity to almost all adsorbents. Thus, Langmuir adsorption isotherm fits well to these adsorption studies.

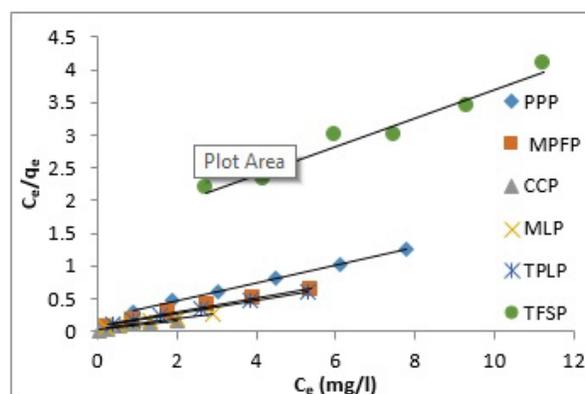


Fig. 12. Langmuir isotherm plot

q_m values were found to be in the order MLP > CCP > TPLP > MPFP > PPP > TFSP.

A linear plot of q_e against $\ln C_e$ of the Temkin isotherms ($R^2 = 0.971$ to 0.999) except CCP ($R^2 = 0.93$), (Figure 13) enables the determination of the constants B and A from the slope and intercept. The results of the plots are given in Table 2. Temkin constant A (equilibrium binding constant) and B related to heat of adsorption showed good results according to the adsorption capacity of a particular adsorbent. Heat of adsorption values are greater for the adsorbent which has greater adsorption capacity, indicating endothermic adsorption. Thus, Temkin adsorption isotherm also fits well to these adsorption studies.

In Table 5, Langmuir adsorption capacities (q_m) of the adsorbents under study are compared with the

Table 3. Effect of initial metal ion concentration on adsorption of Ni (II) ions

Adsorbent	Freundlich isotherm parameters			Langmuir isotherm parameters			Temkin isotherm parameters		
	K_f	n	R^2	q_m	b	R^2	A	B	R^2
PPP	3.2961	3.08642	0.986	7.24638	0.74194	0.998	9.15531	1.465	0.997
MPFP	5.3827	3.62319	0.995	9.52381	1.43836	0.988	33.5417	1.603	0.969
CCP	9.39723	3.26797	0.986	13.3333	3.40909	0.973	84.2815	2.172	0.93
MLP	7.39605	2.43309	0.996	13.5135	1.48	0.989	16.4834	2.803	0.981
TPLP	5.16416	2.91545	0.983	10	1.21951	0.998	14.7963	2.009	0.998
TFSP	0.74473	1.75747	0.96	4.60829	0.1422	0.961	1.1416	1.11	0.971

previous adsorption studies for Ni (II) adsorption, It is found that adsorbents used in the present study has good adsorption capacities as compared to most of the adsorbents used in previous studies.

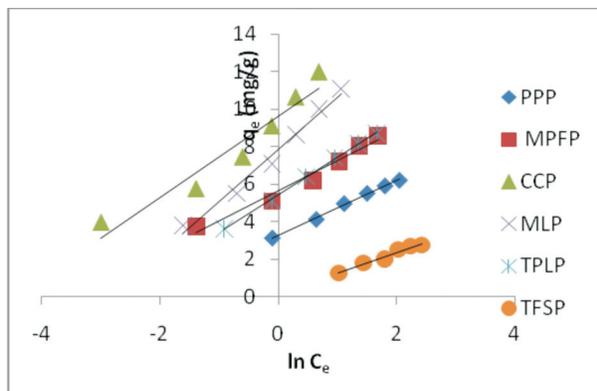


Fig. 13. Temkin isotherm plot

Effect of pH

pH is an important parameter in controlling the adsorption of Ni (II) ions on adsorbent. The adsorption of Ni (II) from 5 mg/l concentration on different adsorbents was studied by varying the pH from 2 to 6. The percentage removal of nickel ions increased

with increase in pH, Figure 14. It was found that adsorption of Ni (II) ions was found to be maximum at pH 5. Thus, batch mode adsorption studies were carried out at pH 5 for Ni (II).

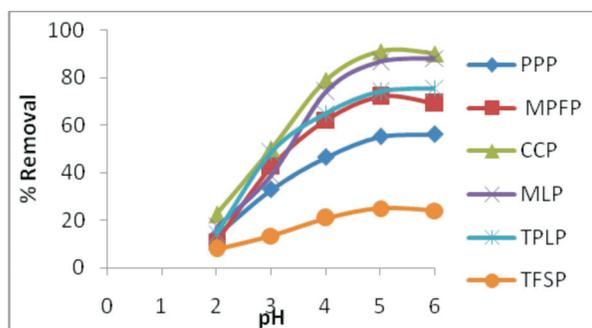


Fig. 14. Effect of pH on adsorption of Ni (II) from initial concentration of 5 mg/l.

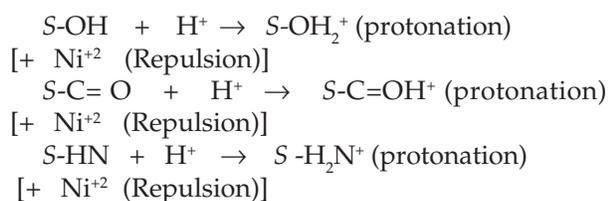
At low pH i.e. high H⁺ ion concentration, the H⁺ ions compete with cationic nickel ions for the exchange sites in the system thereby partially releasing the Ni (II) ions (Ajmal *et al.*, 1998). At low pH, the functional groups of the biosorbent are protonated to form hydronium ions and repulsive forces limit the approach of the Ni (II) ions.

Table 4. Dimensionless separation factor (R_L) calculated from Langmuir constant (b)

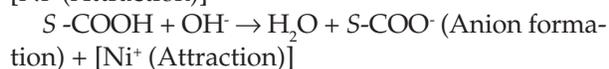
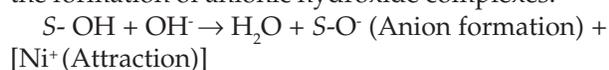
Initial Ni (II) ion Conc. (mg/l)	PPP	MPFP	CCP	MLP	TTLP	TFSP
4	0.25203	0.14807	0.06832	0.14451	0.17012	0.63743
6	0.18343	0.10384	0.04661	0.10121	0.12023	0.53961
8	0.14419	0.07996	0.03537	0.07788	0.09297	0.46781
10	0.11877	0.065	0.0285	0.06329	0.07579	0.41288
12	0.10098	0.05476	0.02386	0.0533	0.06396	0.36949
14	0.08782	0.04731	0.02052	0.04604	0.05533	0.33436

Table 5. Comparison of Langmuir sorption capacities (q_m) of adsorbents with previous studies.

Sorbent	q_m (mg/g)	References
PPP	7.24638	Present study
MPFP	9.52381	Present study
CCP	13.3333	Present study
MLP	13.5135	Present study
TTLP	10	Present study
TFSP	4.60829	Present study
Sawdust of deciduous trees	4.600	Bozicet <i>al.</i> 2009
Activated carbon from <i>Hevea brasiliensis</i>	16.892	Kalavathy <i>et al.</i> 2010
Black carrot (<i>Daucus carota L.</i>) residues	5.745	Guzet <i>et al.</i> 2008
Chitosan/clinoptilolite composite	7.940	Dinuet <i>al.</i> 2010
Red mud	10.95	Lopez <i>et al.</i> 1998
Cercis siliquastrum leaves	4.68	Salehi <i>et al.</i> 2008
Activated sludge	4.06	Addalla <i>et al.</i> 2009



With increasing pH i.e. decreasing H^+ ion concentration, more functional groups such as amino and carbonyl groups, would be exposed leading to attraction between these negative charges and the Nickel ions and hence increases in sorption on the surface of biosorbent (Aksu *et al.*, 2005). The lower uptake of Ni (II) ions at higher pH is may be due to the formation of anionic hydroxide complexes.



All the adsorption experiments of Nickel ions are carried below pH 6 to avoid precipitation of Ni (II) ions as their hydroxides.

Effect of Temperature

Temperature also has important effects on adsorption process. Adsorption of Ni (II) at three different temperatures (303K, 313K and 323K) onto different biosorbents was studied for 8 mg/l initial Ni (II) ion

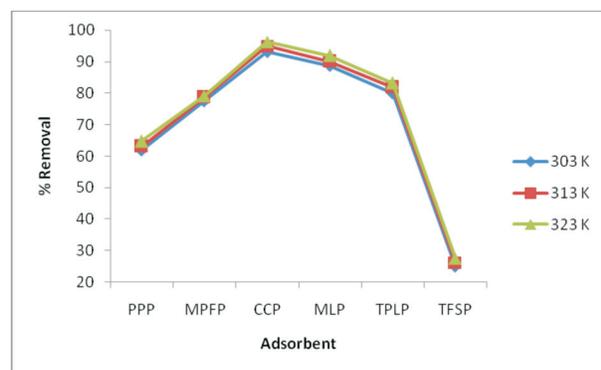


Fig. 15. Effect of temperature on adsorption of Ni (II)

concentration. The results of variations in temperatures on nickel ion adsorption are shown in Figure 15. It is observed that as the experimental temperature increases from 303K to 323K, the nickel ion adsorption also increases. This may be due to the fact that at higher temperature, there is enlargement of the pore sizes of the adsorbent particle which can be beneficial towards the Nickel ion sorption. Also adsorption increased with temperature is due to the increase of intra particle diffusion rate of the nickel into the interior sites of the adsorbent since diffusion is an endothermic process.

Thermodynamic analysis

Thermodynamic parameters such as ΔG (J/mole), ΔH (J/mole) and ΔS (J/K/mole) were determined (Arivoli *et al.* 2007).

ΔG values were obtained by using equation $\Delta G = -RT \ln K_o$,

ΔH and ΔS values obtained from the slope and intercept of plot $\ln K_o$ against $1/T$, Figure 16, Table 6. Negative ΔG values, low positive ΔH (< 40 KJ/mole) values and positive ΔS values are obtained for these adsorbent – Nickel systems indicates favourable, spontaneous, endothermic physical ad-

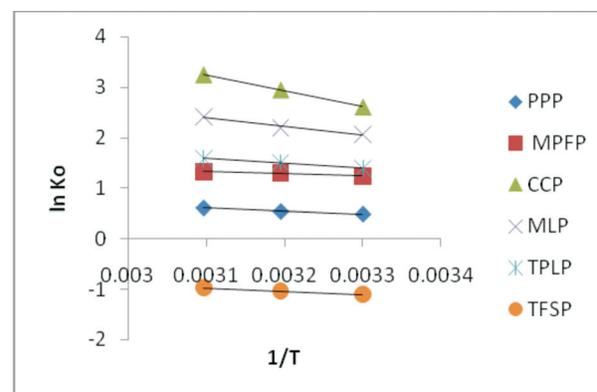


Fig. 16. Von't Hoff plot of effect of temperature on adsorption of Ni (II).

Table 6. Equilibrium constants and thermodynamic parameters

Adsorbent	Ko			ΔG (J/mole)			ΔH (J/mole)	ΔS (J/K/mole)
	303K	313K	323K	303K	313K	323K		
PPP	1.623	1.7119	1.8369	-1219.9	-1398.9	-1632.9	5028.31	20.5855
MPFP	3.4444	3.7059	3.7904	-3115.6	-3408.8	-3578.3	3914.23	23.2626
CCP	13.546	19	25.667	-6565	-7662.3	-8714.7	26006.2	107.5
MLP	7.8889	9	11.308	-5203.2	-5717.8	-6513.4	14599.4	65.2067
TPLP	4	4.5172	4.9259	-3492.3	-3924	-4281.9	8480.28	39.558
TFSP	0.3333	0.356	0.3793	2767.56	2688.2	2603.25	5255.28	8.20592

sorption. Only TFSP showed positive values of ΔG indicates poor adsorption.

Conclusion

Batch mode studies of adsorption of Ni (II) ions on biosorbents were carried out as a function of process parameters includes initial Ni (II) ion concentration, adsorbent dosage, contact time, pH, and temperature.

Adsorption of Ni (II) ions on adsorbent increased with increase of initial nickel ion concentration. Adsorption was found to be faster in first 5 minutes and took about 40 minutes to attend the equilibrium.

Langmuir, Freundlich as well as Temkin isotherm models were found to be the best fitting models. Freundlich constants, Langmuir constants and also Temkin constants values proved that adsorption of Ni (II) ions on to natural materials are favourable. Monolayer maximum adsorption capacities (q_m) of some of the adsorbents under study towards the nickel ions were found have greater than the adsorbents used in the previous studies showed the relevance of these natural adsorbents. Monolayer adsorption capacities values for the adsorbents under study were found to be order of MLP > CCP > TPLP > MPFP > PPP > TFSP.

Lagergen pseudo -second order model fits well to the kinetics of adsorption as linear regression coefficient values $R^2 \approx 1$ and $q_{e(\text{the})} \approx q_{e(\text{exp})}$ showing possibility of chemical adsorption. Intra particle diffusion model plot showed boundary layer effect and larger intercepts indicating maximum contribution of surface adsorption in rate determining step. Adsorption of Nickel ions on the adsorbents was found to increase on increasing pH and temperature. Functional groups like $-\text{COOH}$, $-\text{OH}$, $-\text{NH}_2$, $=\text{CO}$ from the adsorbent surface are major active sites for adsorption of cationic nickel ions. These active sites decreases with decrease in pH due to protonation and therefore adsorption of Ni (II) ions also decreases.

Thermodynamic analysis showed adsorption was favourable, spontaneous, endothermic physisorption with increased disorder and randomness at the solid- solution interface of Ni (II) ion with the adsorbents.

Overall the aim of this adsorption work was to explorer the potential use of adsorbents derived from plant materials for the removal of Ni (II) ions from aqueous solutions. Bio sorption technology,

using such natural materials to remove toxic metal ions from aqueous solutions gives an efficient and cheap alternative compared to traditional physical and chemical remediation techniques.

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