

## Kinetics and equilibrium studies of copper, zinc, and nickel ions adsorptive removal on to *Archontophoenix alexandrae*: conditions optimization by RSM

Raseed A. Khera<sup>a</sup>, Munawar Iqbal<sup>b,\*</sup>, Aftab Ahmad<sup>c</sup>, Syeda M. Hassan<sup>d</sup>, Arif Nazir<sup>b</sup>, Abida Kausar<sup>e</sup>, Heri S. Kusuma<sup>f</sup>, Jan Niasr<sup>g</sup>, Nasir Masood<sup>h,\*</sup>, Umer Younas<sup>b</sup>, Rab Nawaz<sup>i</sup>, Muhammad I. Khan<sup>j</sup>

<sup>a</sup>Department of Chemistry, University of Agriculture, Faisalabad 38040, Pakistan, email: chem.edu.pk@outlook.com (R.A. Khera)

<sup>b</sup>Department of Chemistry, The University of Lahore, Lahore, Pakistan, emails: munawar.iqbal@chem.uol.edu.pk (M. Iqbal), anmalik77@gmail.com (A. Nazir), umer0608analyst@gmail.com (U. Younas)

<sup>c</sup>Department of Biochemistry/Centre for Advanced Studies in Agriculture and Food Security (USPCASAFS), University of Agriculture, Faisalabad, Pakistan, email: ahmadaftab1862@hotmail.com (A. Ahmad)

<sup>d</sup>Department of Chemistry, Lahore Garrison University, Lahore, Pakistan, email: monahassan185@gmail.com (S.M. Hassan)

<sup>e</sup>Department of Chemistry, Government College Women University Faisalabad, Faisalabad, Pakistan, email: abida.kausar@hotmail.com (A. Kausar)

<sup>f</sup>Analytical Chemistry Research Group, Department of Chemical Education, Faculty of Education and Teachers Training, University of Nusa Cendana, Kupang 85001, Nusa Tenggara Timur, Indonesia, email: heriseptyakusuma@gmail.com (H.S. Kusuma)

<sup>g</sup>National Center of Excellence in Physical Chemistry, University of Peshawar, Peshawar 25120, Pakistan, email: pashkalawati@gmail.com (J. Nisar)

<sup>h</sup>Department of Environmental Sciences, COMSATS University Islamabad, Vehari Campus, email: nasirmasood2004@gmail.com (N. Masood)

<sup>i</sup>Department of Environmental Sciences, The University of Lahore, Lahore 53700, Pakistan, email: rab.nawaz@envs.uol.edu.pk (R. Nawaz)

<sup>j</sup>Department of Physics, The University of Lahore, Lahore, Pakistan, email: muhammad.iftikhar@phys.uol.edu.pk (M.I. Khan)

Received 13 November 2019; Accepted 2 April 2020

---

### ABSTRACT

This study focuses on the investigation of adsorptive behavior of Cu, Ni, and Zn ions by *Archontophoenix alexandrae* in single metal system (SMS), bi-metal system (BMS), and tri-metal system (TMS). This was done through a novel strategy by combining factorial design (FD), response surface methodology (RSM), and mixture design (MD). The adsorption study was carried out as a function of pH, contact time, and biomass dosage and validated through screening design. To improve adsorption capacities of metallic ions, RSM and MD involving central composite design and simplex lattice design were used. The experimental designs demonstrated the maximum adsorption capacity for Cu. The existence of Cu ions suppressed the adsorption of Ni and Zn ions. Langmuir isotherm model and the pseudo-second-order kinetic model best explain the adsorption kinetics of Cu(II), Ni(II), and Zn(II) metal ions on to *A. alexandrae*. The *A. alexandrae* could possibly be used as an efficient biosorbent for the removal of toxic pollutants from industrial effluents.

**Keywords:** Biosorption; King palm; Factorial design; Response surface methodology; Equilibrium modeling

---

\* Corresponding authors.

## 1. Introduction

The heavy metals are being discharged from various chemical industries including mining operations, electro-plating, refrigeration, stoneware, storage batteries, pigment production, and tanning. These metals contaminate the water bodies [1–7]. Ni, Cu, and Zn are the central metals present in industrial wastewater [8,9]. The different techniques that are extensively applied for the elimination of metal ions from polluted reservoirs are ion exchange, complexation, the solvent extraction process, phytoremediation, membrane separation, chemical precipitation, and adsorption. All these methods are expensive and ineffective at the lower concentration of metals in aqueous streams. Biosorption is one of the most viable methods that are generally employed for the elimination of heavy metals from water sources [10–19].

*Archontophoenix alexandrae* is generally known as King Palm, Alexandrae palm, or Alex palm. Enormous quantities of residues obtained from leaves and leaf sheaths are somewhere associated with the king palm production, with some variations according to species. These residues could possibly enlist as natural dietary stuff, however, no information is available regarding chemical composition and application as a food ingredient of this material into the literature. The king palm has a strong environmental association, as it lessens the stress over palmito industry and illicitly extracted species, that is, *Euterpe edulis*. Moreover, it can be easily cultivated. The chemical inspection, antioxidant prospective, and microstructure of *A. alexandrae* flour were documented [20]. The plant has a considerable amount of fiber with low ash content [21–25]. This plant is economical, eco-friendly, and easily accessible adsorbent since no major use is reported in Pakistan, so annually lot of waste is produced, which can be utilized for adsorption. Ni, Cu, and Zn which are commonly present in the industrial effluents are toxic for living organisms even at low concentrations [4,27–29]. The basic purpose of this study to remove these polluted metals from aqueous sources using biomaterials. Three experimental design techniques have been employed, that is, five-factor factorial designs, response surface methodology (RSM) along with MD to recognize the distinctiveness of metal deduction from TMS using biosorption. FD methodology was very helpful for viewing several factors to discover the prominent effects and interactions as well [30–32]. The majority of RSM utilized in poly systems was deliberated for optimization. The RSM method was employed to evaluate the biosorption results under a variety of metal compositions leading toward ideal biosorption potential [33–35].

Moreover, metal-contaminated wastewater may be diluted prior to treatment if the concentration of metal ion is excessively high. Thus, two MDs, standing for high as well as low on the metal dose by the same heavy metal components, were offered in this activity to explore the effect of metal dosage on biosorption. The application of MD helped a lot in finding the interaction of the metal biosorption among three targeted metal ions. Triangular contour figures and three-dimensional surface graphs were created to explain the thrice metal biosorption statistics in MD scheme. By the study of respective designs, the number or quantity of experimental runs was reduced. While, quantitative

explanation and prediction of the metal uptake activity of King palm biosorbent were also effectively clarified using isotherms (Langmuir and Freundlich) and kinetic study.

## 2. Material and methods

The King palm biomass used as a biosorbent material was collected from region around Qadir bakhsh farm, Faisalabad, Pakistan. The leaves were removed from the plant stems, washed with high purity water; oven drying at about 70°C for 72 h, grinded by mechanical grinding mill. The biomass was sieved in order to obtain diverse particle ranges and then stored in air tight container till further use. All the analytical grade chemicals were employed for metal sorption. The stock solutions of 1,000 mg/L of Zn(II), Cu(II), and Ni(II) were formed in de-ionized water [28].

### 2.1. Batch experiments

The plant biomass was added in solutions comprising relevant heavy metals and concentrations were set in accordance with the experimental design method. Every experiment was performed in 150 mL flask having 60 mL heavy metal ion solution. The pH of the solution was maintained by the addition of HCl and NaOH solutions. The metal ions concentration was determined by atomic absorption spectrometer. The percentage removal and quantity of adsorbed metal ions ( $q_e$ ) were evaluated by Eqs. (1) and (2).

$$\text{Removal rate (\%)} = \frac{C_i - C_e}{C_i} \times 100 \quad (1)$$

$$\text{Adsorption amount (mg/g)} q_e = \frac{(C_i - C_e)V}{M} \quad (2)$$

where  $C_i$  stands for initial metal ion concentration and  $C_e$  is the final concentration at equilibrium,  $V$  is the volume, and  $M$  is the mass of biosorbent (g). The concentrations of remaining metal ions were obtained by Hitachi polarized Zeeman atomic absorption spectrophotometer Z-8200.

### 2.2. Experimental design

Three experimental design methodologies, that is, FD, RSM, and MD were used to interpret the characteristics of metals removed from aqueous solution by *A. alexandrae*. All these designs were successfully computed by statistical software Design-Expert 9.0.5.1 (Stat-Ease, Inc., Minneapolis, MN, USA).

This methodology has been used by many researchers for testing and separated major effects in testing variables [30–34,36–38]. A chain of factorial experiments is optimized for assessing main effects as well as interactions of factors. Minimum Run resolution IV screening Design (MRRIVSD) was applied in order to observe the contribution of required factors in removing heavy metal pollutants by King palm. In factorial technique five factors, that is, solution pH, agitation speed, biomass dose, adsorption time, and initial metal ions concentration were selected to check the response of metal removal through biosorption. Every factor was

characterized at two levels, that is, high and low, denoted by +1 and -1, respectively. The details of factors and their levels are recapitulated in Table 1. The two-level five factors FD were performed according to the above experimental conditions. For every factor, two levels were chosen one was low and the other was high.

RSM is typically applied for the optimization of experimental treatments. RSM was employed to determine the collaboration of related heavy metals in the biosorption process. Additionally, the consequences of ternary metal biosorption were also predicted. Usually, there are numerous design techniques can be selected, for instance, face-centered cube design (FCCD), Box–Behnken design plus central composite design (CCD). The FCCD, a modified edition of the CCD, was operated to acquire the experimental information [32–34]. This FCCD comprised of 20 experiments, signifying the six sockets on the six cubic surfaces, eight sockets on the eight vertices, plus six replications at the central point. Table 2 displays conditions for experimental conditions of RSM and MDs. There were total of five factors, that is, pH, time, concentration, agitation speed, and biosorbent dose. The initial concentration was taken from 60 to 120 mg/L containing dose 3 g/L at pH (5.5) and agitation speed of 150 rpm for about 12 h.

In response surface designs, each heavy metal ion concentration is independent from other two metals. Conversely, in MD, each metal ion was dependent upon each other and

the computation of three metals was definite [39]. The investigational factors in MD were the fraction of three metals. Simplex lattice design (SLD) is generally utilized to examine the elemental properties of the mixture. Consecutively, this research implemented amplified SLD through axial points to enhance the internal runs in support of experimental design [31,32]. Two sets of MDs with the overall heavy metal concentrations of 60 and 120 mg/L were performed, respectively. Each set included overall nine experimental runs as well as details of metals solution composition.

### 2.3. Adsorption modeling

The prediction of biosorption capability and investigation of adsorption behavior was further strengthened by Langmuir and Freundlich isotherms. These isotherms helped in estimating the quantity of metal sorbate that a particular adsorbent maintained as well as remained in experimental solution at equilibrium [40,41]. According to Langmuir model, there is monolayer uptake of adsorbed molecules on uniform (homogeneous) layer and this adsorption takes place without any contact among adsorbed molecules. The Langmuir isotherm is represented by Eq. (3):

$$\frac{C_e}{q_e} = \frac{1}{q_{\max} K_c} + \frac{C_e}{q_{\max}} \quad (3)$$

Table 1  
Different factors and levels employed for ternary metal biosorption using *Archontophoenix alexandrae* biosorbent

Factors	Names	Units	Levels and range (coded)	
			-1	+1
A	Contact time	min	30	180
B	Shaking speed	rpm	120	150
C	Initial metal concentration	mg/L	30	135
D	Biosorbent dose	g/L	2	6
E	pH		5	6

Table 2  
Percentage removal of metal ions as a function of process variables using *Archontophoenix alexandrae* biosorbent

No.	Time (min)	Agitation speed (rpm)	Concentration (mg/L)	Biosorbent dose (g/L)	pH	Removal (%)		
						Cu	Ni	Zn
1	30	120	135	2	5	15.9	14.8	15.1
2	180	150	30	6	6	93.6	81.5	84.9
3	180	120	135	2	6	55.8	38.5	47.2
4	180	150	30	2	6	90.1	69.1	84.1
5	30	120	30	6	6	80.2	45.5	70
6	30	150	135	6	6	71.5	48.9	60
7	180	150	135	6	5	66.8	48.6	50
8	30	120	135	6	5	20.5	11	10.9
9	180	120	135	2	5	55.5	32.5	39.1
10	30	150	30	2	6	55	35.5	42.5
11	180	120	30	2	5	50	20.8	37.7
12	30	150	30	6	5	60.5	39.1	40

In the Eq. (3),  $q_{\max}$  and  $q_e$  are maximum adsorption and experimental capabilities (mg/g), while  $C_e$  is concentration at equilibrium (mg/L);  $K_c$  is the equilibrium constant (mg/L). Whereas, the Freundlich model suggests a multilayer adsorption on a heterogeneous layer of bio-sorbent by interaction involving sorbed particles [42–45]. The linear mathematical equation of Freundlich model is expressed by Eq. (4):

$$\ln q_e = \frac{1}{n} \ln C_e + \ln K_f \quad (4)$$

### 3. Results and discussion

#### 3.1. Minimum run resolution IV screening design

The MRRIVSD was applied for the analysis of the contribution of five factors. The observed or experimental responses of Cu(II), Zn(II), and Ni(II) for tested factors are summarized in Table 2 and statistical analysis is shown in Table 3. The predicted  $R^2$  value and adjusted  $R^2$  value of factorial experiments for Cu, Zn, and Ni were in close association. The  $R^2$  value was larger for Cu (0.8983) as compared to Ni (0.8947) and Zn (0.8939). The priority order, in accordance with  $R^2$  values, was (Cu(II) > Zn(II) > Ni(II)). The larger  $F$ -values for all metals and lowest  $P$ -values show the significance for the models. The regression equations obtained by application of MRRIVSD were as follows:

$$\text{Removal (\%)} \text{ of Cu} = +59.62 + 12.36A + 5.69B - 6.49C + 10.02D + 10.69E \quad (5)$$

$$\text{Removal (\%)} \text{ of Ni} = +48.46 + 11.36A + 3.56B - 5.80C + 7.96D + 13.17E \quad (6)$$

$$\text{Removal (\%)} \text{ of Zn} = +40.5 + 10.97A + 6.55B - 2.77C + 8.97D + 9.55E \quad (7)$$

These regression models or equations represented the effect of experimental factors on responses. The terms  $A$ ,  $B$ ,  $C$ ,  $D$ , and  $E$  symbolize adsorption time, revolution speed, metal concentration, biosorbent quantity, and pH value. While, it is evident from the above proposed regression

equations [Eqs. (5)–(7)] time, biosorbent dose, and pH have a considerable effect on the metal removal.

The effects of tested parameters or factors were additionally examined through main effects graphs for uptake of Cu(II), Zn(II), and Ni(II) as given in Figs. 1 and 2. These plots specify the virtual significance of effects of five tested factors. For every investigated metal, five graphs were drawn which demonstrated the effect of factors on the removal of metal ions. Overall, the effect of pH, biomass load, and time were main factors for the three studied metal ion removals. This result is formerly identified from Eqs. (5) to (7) for Cu(II) and Ni(II). The time, pH, and biomass dose had positive influence while initial Cu ion concentration and agitation speed was found unhelpful. On the other hand, in case of Zn(II), pH, shaking speed, biomass amount, and time influenced positively and metal ion concentration affected oppositely. Although, shaking speed and metal ion concentration were as well-involved in metal removals but their effects were less prominent than the remaining three factors as summarized in ANOVA (Table 3). So, there were three out of five factors that enhanced metal removal phenomenon [14,46,47].

#### 3.2. Data analysis from RSM

Based on the results from factorial design, the performance of ternary metal biosorption was investigated in subsequent RSM along with MDs. The optimized conditions from FD were pH 5.5, biomass dose 3 g/L, agitation velocity 150 rpm, and contact time 12 h was utilized for further investigation (Table 4). The statistical importance of RSM was assessed by ANOVA. The results displayed larger  $F$ -values (1,604.34 for Cu, 101.5 for Zn, and 70.31 for Ni) and low probability value. This suggested that three regression models had high significance.

The value of  $R^2$  (0.9993) was additional for Cu(II) but, for Zn(II) as well as Ni(II) was 0.985 and 0.984. For these metals the numerical value of predicted  $R^2$  also adjusted  $R^2$  was in close association. All these parameters have shown that models for regression study were significant statistically.

The prediction of multi metal adsorption was further strengthened by response surface contour plots. These plots for characteristic biosorption of Cu(II), Ni(II), and Zn(II) are

Table 3  
ANOVA for metal ions removal using *Archontophoenix alexandrae* biosorbent

Source	Sum of Squares			F-values			Prob > F			Significant
	Cu	Zn	Ni	Cu	Zn	Ni	Cu	Zn	Ni	
Model	5,648	5,398	4,179	10.6	10.20	10.11	0.0061	0.0078	0.0069	
A	1,628	1,377	1,248	15.28	13.01	15.54	0.0079	0.0113	0.0076	
B	421	336	328	3.95	3.18	5.18	0.0940	0.1249	0.0631	
C	323	133	176	3.04	1.26	0.93	0.1319	0.3048	0.3725	
D	1,070	676	859	10.05	6.39	10.4	0.0193	0.0448	0.0180	
E	1,142	1,735	911	10.72	16.4	11.02	0.0169	0.0067	0.0160	
Residual	639	635	459							
Correlation total	6,287	6,033	4,675							

$R^2 = 0.8983$  (Cu),  $0.8947$  (Zn),  $0.8939$  (Ni),  $A = \text{Time (min)}$ ,  $B = \text{Agitation speed (rpm)}$ ,  $C = \text{Concentration (mg/L)}$ , and  $D = \text{Biosorbent dose (g/L)}$ .

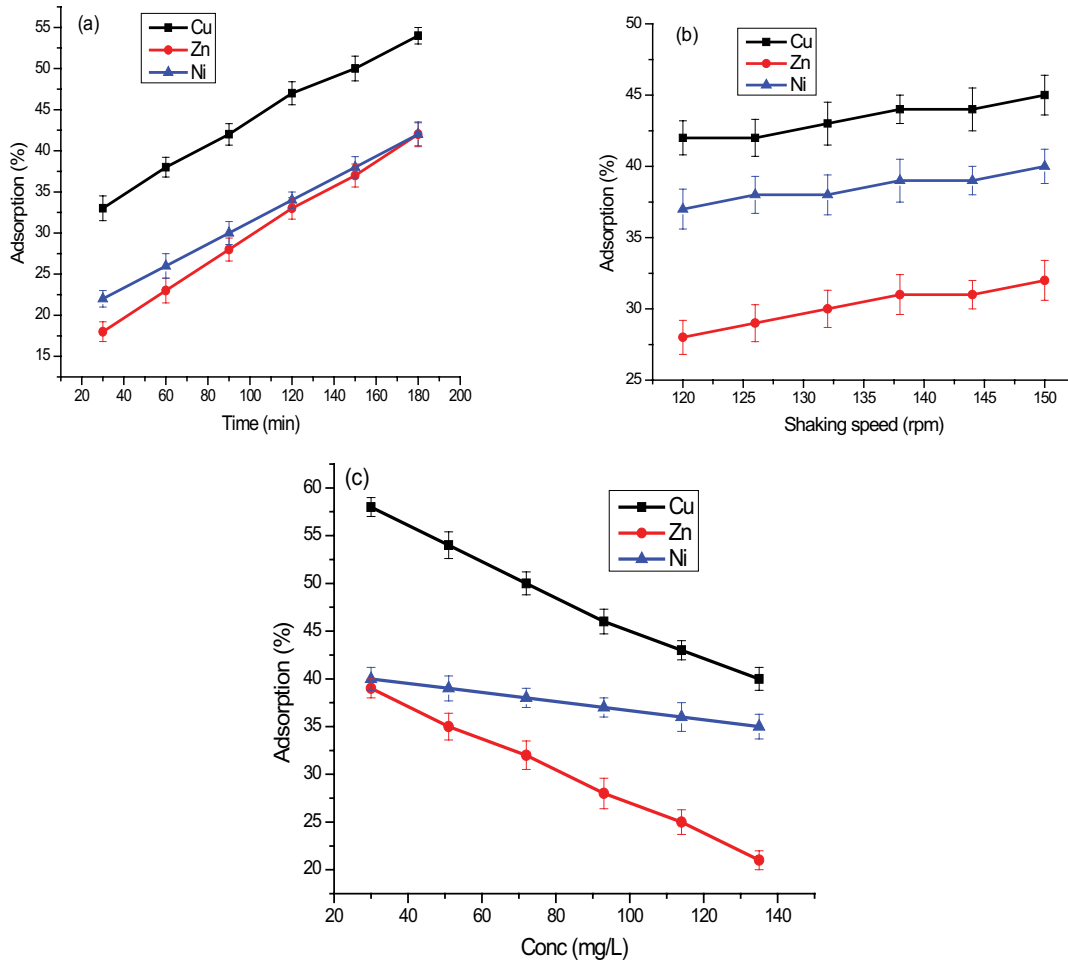


Fig. 1. Metal ions adsorption onto *A. alexandriae* as a function of (a) contact time, (b) shaking speed, and (c) initial concentration.

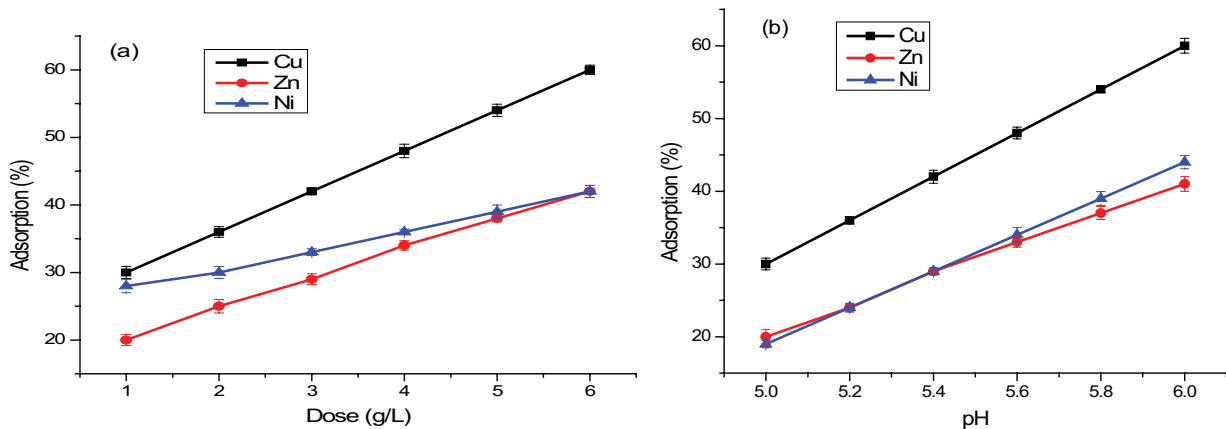


Fig. 2. Metal ions adsorption onto *Archontophoenix alexandriae* as a function of (a) adsorbent dose and (b) pH.

depicted in Fig. 3. Each contour plot showed many mixtures or combinations of two experimented variables while keeping third variable at central levels.

Fig. 3a illustrates that the adsorption of Cu was decreased with an increase in the concentration of Ni and Zn but after some time, Zn concentration did not influence

the Cu adsorption, only Ni was involved in lessening the sorption of Cu(II). While Fig. 3b displays the combined effect of Cu and Zn concentration on the biosorption of Ni. The uptake of Ni was decreased with a rise in the initial concentration of Zn and Cu. So, both metals had a suppressing effect on Ni uptake. Similarly, Fig. 3c explains the

Table 4  
Response surface methodology and two mixture designs for biosorption using *Archontophoenix alexandrae* biosorbent

No.	RSM (face centered) (mg/L)			Mixture design I (60 mg/L)			Mixture design II (120 mg/L)			Adsorption capacity (mg/g)		
	Cu	Ni	Zn	Cu	Ni	Zn	Cu	Ni	Zn	Cu	Ni	Zn
1	0	0	0							0	0	0
2	60	0	0	60	0	0				25.3	0	0
3	30	30	0	30	30	0				15.7	6.5	0
4	30	30	30							16.2	5.6	10
5	30	30	30							16.5	5.2	8.4
6	30	30	30							16	5.4	8.9
7	30	30	30							16.3	5.5	7.9
8	30	30	30							16.1	5.5	7.3
9	30	30	30							16.3	5.8	7.5
10	30	60	30							15.4	13.1	10
11	0	30	30	0	30	30				0	6.5	10.2
12	0	60	0	0	60	0				0	16.1	0
13	60	30	30							24	5	10
14	30	30	60							16.5	6.8	15.4
15	30	0	30	30	0	30				16.1	0	9.1
16	60	60	0				60	60	0	23.5	14.7	0
17	0	0	60	0	0	60				0	0	20.5
18	60	0	60				60	0	60	23.9	0	15
19	0	60	60				0	60	60	0	10.1	19
20	60	60	60							23	13.9	15.89
21				10	10	40				5.2	2.35	14.3
22				40	10	10				18.1	2.1	3.5
23				20	20	20				10.1	4.5	5.2
24				10	40	10				5.3	11.4	3.8
25							0	0	120	0	0	25
26							40	40	40	17	10	9.2
27							20	80	20	9.09	20	5.4
28							120	0	0	45.5	0	0
29							20	20	80	4.53	5.4	20
30							0	120	0	0	30	0
31							80	20	20	34.7	5.1	4.12

synchronized effect of Cu along with Ni, respectively. When the concentration of Cu was raised from 0 to 60 mg/L, the Zn uptake was decreased sharply, but the concentration of Ni influenced the Zn adsorption for a while after this Ni(II) did not influenced the Zn metal uptake. The suppression effect of Cu ion was greater than Ni ion on Zn uptake.

In all cases, every metal ion put suppressing effect on the binding of other metal ions, but Cu metal displayed maximum inhibitory action. However, Cu ions present in solution decreased the uptake capacity of Zn and Ni ions significantly. Briefly, the order of adsorption in TMS was establish to be Cu(II) > Zn(II) > Ni(II). The conclusions can be enlightened by the physical and chemical parameters of respective metals. Further investigation would be requisite to give details of the adsorption process since usually metal ions be supposed to fight for characteristic binding places lying on the biosorbent resulting in the reduction of the biosorption trend. Recognition of the mutual effect

of heavy metals on their adsorption might considerably contribute to extensive biosorption function in wastewater management [22,23,48–51].

### 3.3. Mixture design

The experimental outcomes of the uptake capacity of three metals are also given in Table 5. The mixture experiments were performed with similar conditions like RSM. The results were also validated by ANOVA. The ANOVA demonstrated that the bigger  $F$ -values (2,975.4 for Cu, 1,331.4 for Zn, and 932.45 in support of Ni ion. The minimum values of  $P$  recommended more exceptional model. The degree of deviation was estimated by computing  $R^2$  value. The  $R^2$  was greater for Cu (0.9967) and lesser for Zn (0.991) and Ni ions (0.9987), respectively. The values of co-relation coefficient  $R^2$  and adjusted  $R^2$  were near to 1 for three investigated metals, which indicates a close

Table 5  
Comparison of equilibrium isotherms for metals ions adsorption

System	Metal ions	Langmuir isotherm			Freundlich isotherm		
		$q_{max}$ (mg/g)	$K_c$ (L/mg)	$R^2$	$q_{max}$ (mg/g)	$K_c$ (L/mg)	$R^2$
Single metal system	Cu (II)	26.31	1.01	0.973	0.661	0.289	0.964
	Zn (II)	62.5	1	0.993	0.802	0.562	0.995
	Ni (II)	22.72	1	0.956	0.560	0.457	0.940
Ternary metal system	Cu (II)	58.82	1	0.936	0.986	0.484	0.919
	Zn (II)	22.7	1	0.956	0.585	0.416	0.911
	Ni (II)	20.83	1	0.955	0.497	0.526	0.953

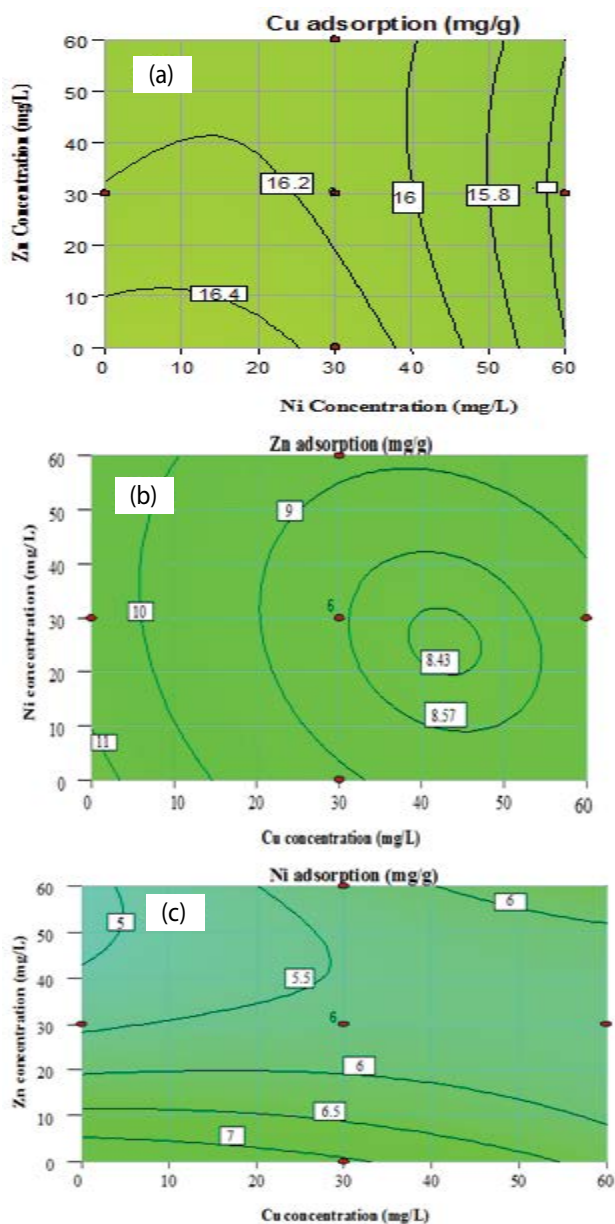


Fig. 3. Surface contour plots for the competitive biosorption of, (a) Cu(II), (b) Zn(II), and (c) Ni(II) onto *A. alexandreae* in ternary system.

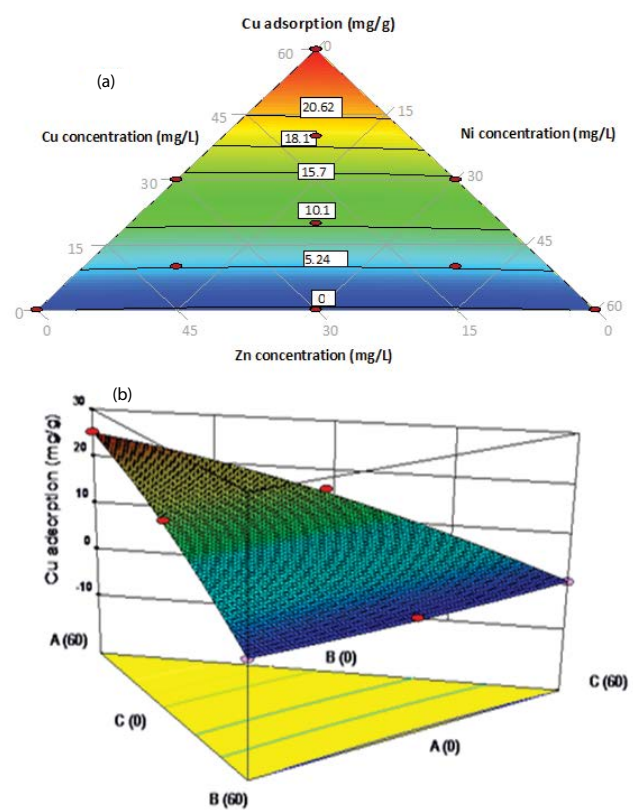


Fig. 4. (a) Contour plot and (b) response surfaces for Cu(II) adsorption onto *A. alexandreae*.

association between experimental and predicted values. The Adjusted  $R^2$  numerical values were 0.9926 in favor of Cu(II), 0.9890 in support of Ni(II) as well as 0.9802 for Zn(II). While the predicted  $R^2$  values were 0.9601 for Cu metal, 0.8371 for Ni ion, and 0.9368 for Zn. Noticeably, both  $R^2$  values (predicted and adjusted) were close to each other. Figs. 4–6 are graphical depictions for adsorption of Cu, Ni, and Zn in ternary metal solution, respectively. Two graphical methodologies were applied to explain the data in two MD, that is, contour plot and 3D triangular plots. In the TCDs (Figs. 4a–6a), evaluation of the metal biosorption profile demonstrates that the level of influence for sorption of an objective metal through *A. alexandreae* was in the array of  $Cu^{2+} > Zn^{2+}$ ,  $Cu^{2+} > Ni^{2+}$ , and  $Zn^{2+} > Ni^{2+}$  for Ni,



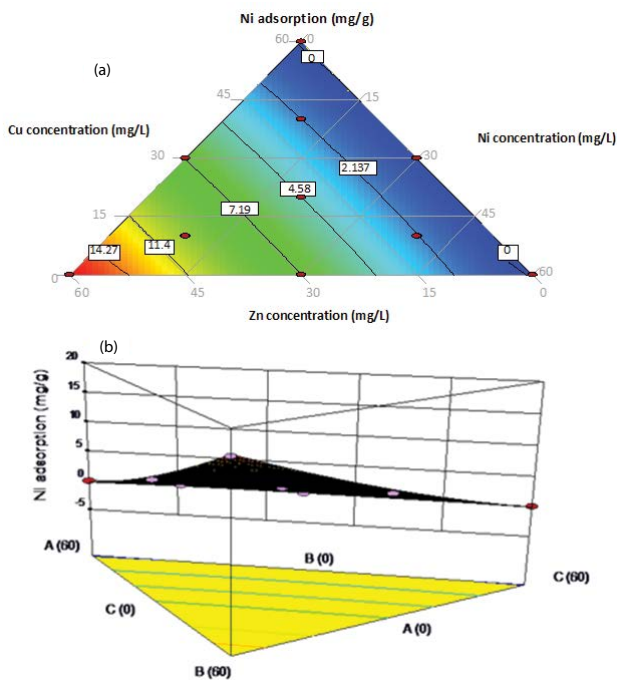


Fig. 5. (a) Contour plot and (b) response surfaces for Ni (II) adsorption onto *A. alexandriae*.

Cu, and Zn ions adsorption, respectively. Consequently, biosorption inclination of *A. alexandriae* emerged to lessen in the array of  $\text{Cu}^{2+} > \text{Zn}^{2+} > \text{Ni}^{2+}$ . Whereas, in the triangular 3D adsorption surfaces (Figs. 4b–6b), the separation among the 3D diagrams created by Simplex-lattice model along with the actual experimental records (in solid dots) are noticeably exposed. The expected surfaces effectively harmonized the corresponding experimental data, signifying that the SLD could explain the actions of multi-metal biosorption fairly well. In order to improve the feasibility for practical purposes, multi-metal biosorption experimentation was performed at a higher total concentration of 120 mg/L with a mixture experimental design. The consequences for  $\text{Cu}^{2+}$ ,  $\text{Ni}^{2+}$ , and  $\text{Zn}^{2+}$  biosorption are revealed in Figs. 7–9, respectively. The tendency of viable biosorption ( $\text{Cu}^{2+} > \text{Zn}^{2+} > \text{Ni}^{2+}$ ) was analogous to that examined in the MD experiments with an overall metal concentration of 60 mg/L. Hence, the expected surface from SLD simulation well-coordinated with the experimental data. Comparing Figs. 4–6 with 7–9, the contour of the triangular 3D surface was relatively the same for the runs with two unlike overall metal concentrations (60 and of 120 mg/L). All these findings recommend that the interaction of the objective metal ion with its contemporary metal ions throughout biosorption was like in spite of entire metal concentration. Conversely, with rise in metal concentrations in experimental runs, the amount of adsorption capacities (mg/g) were increased in that respective runs. This proposes that the overall metal concentration of 60 mg/L had not entirely saturated the binding sites on *A. alexandriae*. In this activity, in relation to the outcomes of RSM along with two MDs, highest metal uptake powers of King palm were set up as 45.5 mg/g for  $\text{Cu}^{2+}$ , 30 mg/g for  $\text{Zn}^{2+}$ , and 25 mg/g for  $\text{Ni}^{2+}$ , respectively.

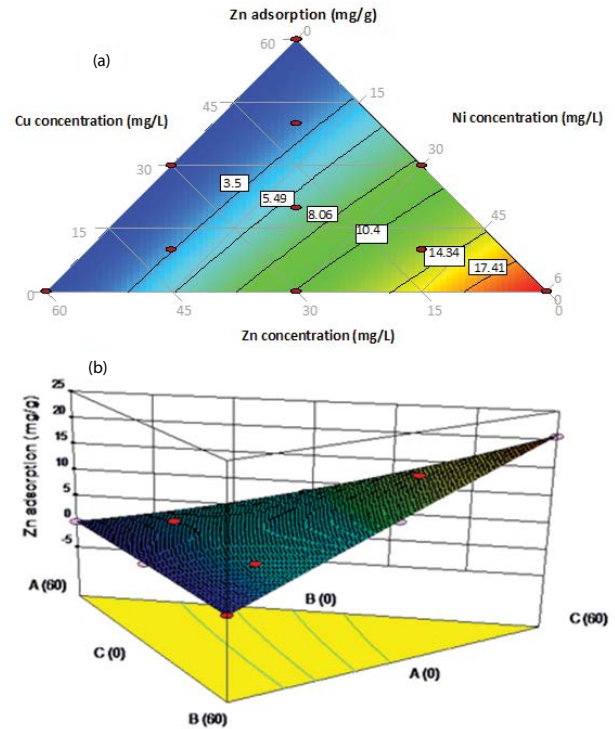


Fig. 6. (a) Contour plot and (b) response surfaces for Zn(II) adsorption onto *A. alexandriae*.

Kaduková and Horváthová [52] investigated that biosorption profile of intended metals, that is, Cu(II), Ni(II), and Zn(II) reduced in the order:  $\text{Cu} > \text{Zn} > \text{Ni}$ .

### 3.4. Equilibrium study of biosorption

The biosorption isotherm experiments were performed at the concentration vary 10–60 mg/L for 8 h, while keeping other investigational constraints or factors identical to RSM and MDs. The data is shown in Table 5. The adsorption data was better fitted with Langmuir isotherm due to the high value of co-relation coefficient and Langmuir constant [40]. In case of SMS, the order of priority was;  $\text{Zn} > \text{Cu} > \text{Ni}$ , owing to high value of  $R^2$ . In reference to the high values of the  $K_c$  and  $R^2$ , the reliable conclusions concerning the order of adsorption was achieved to exist  $\text{Cu(II)} > \text{Zu(II)} > \text{Ni(II)}$  in ternary systems [53–59]. On the other hand, in Freundlich isotherm the numerical values  $R^2$  and  $K_f$  were smaller. The smaller values of  $1/n$ ,  $R^2$ , and  $K_f$  have shown that the adsorption trend of three metals onto King Palm was not good at premeditated conditions. This designates that Cu(II) ions were simply sorbed from aqueous metal solution on top of the biomass with elevated adsorption capacity [60–66]. The priority of biosorbent for many types of heavy metal adsorbate perhaps inter-related to the solution chemistry, specific features of the binding sites [43–45,54,67–73] and salient physicochemical features of the adsorbate. Briefly, there are feasible interaction effects among unlike species in solution in addition to potential interactions going on the surface of biomass maintained by the biosorption mechanism [53,60,64,76–77].



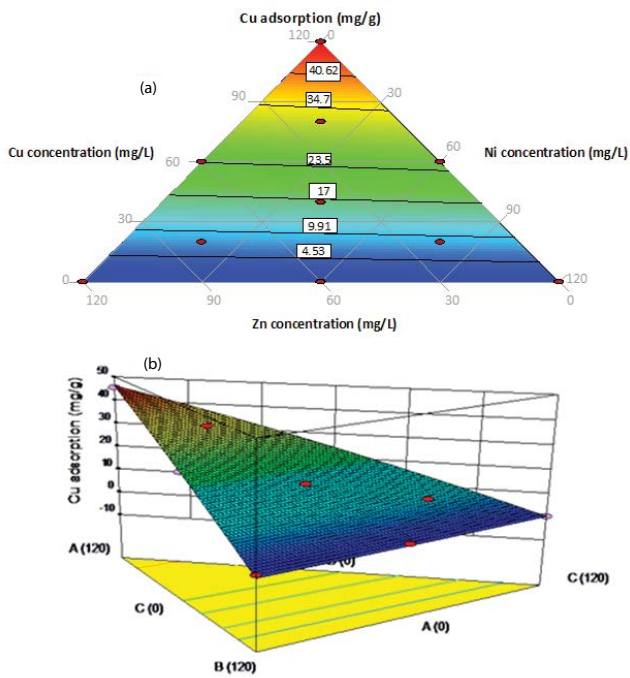


Fig. 7. (a) Contour plot and (b) response surfaces for Cu(II) adsorption onto *A. alexandreae*.

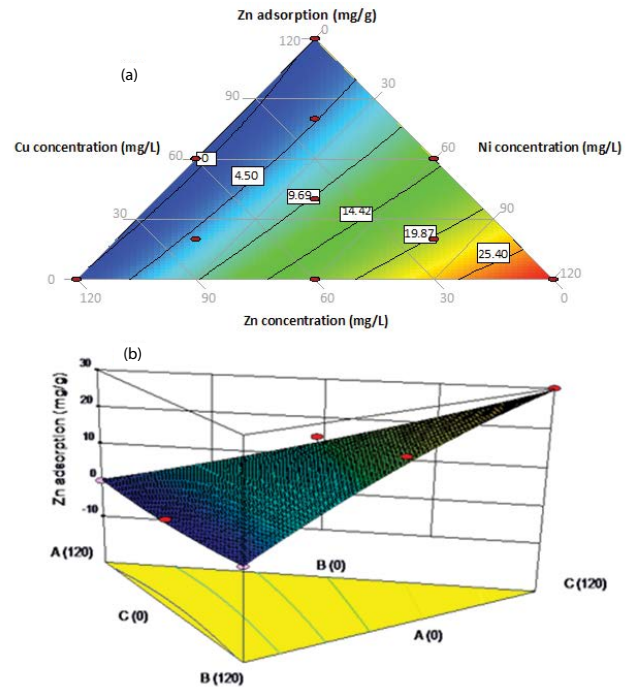


Fig. 9. (a) Contour plot and (b) response surfaces plot for the adsorption of Zn(II) onto *A. alexandreae*.

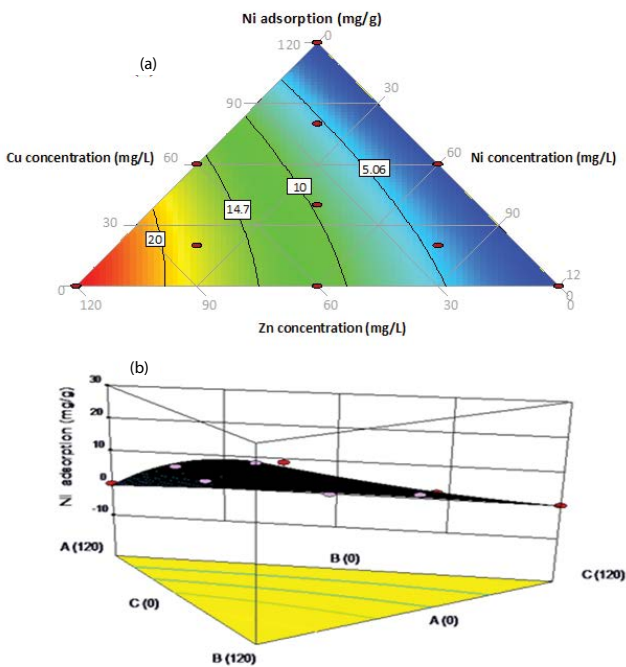


Fig. 8. (a) Contour plot and (b) response surfaces for Ni(II) adsorption onto *A. alexandreae*.

The findings revealed that adsorption efficiency of *A. alexandreae* was promising for Cu, Ni, and Zn ions from the mixture, that is, single metal, bi-metal (BMSs), and tri-metal systems (TMSs), hence, it could be employed

for the sequestration of metals ion from industrial effluents because effluents have diverse types of pollutants [18,46,78–84] including metal ions.

#### 4. Conclusions

Following conclusions have been drawn, findings confirmed that the application of innovative experimental design methodologies presented an efficient way to predict the performance of practicable biosorption processes in single, BMSs and TMSs using *A. alexandreae* as adsorbent. The experimental model was used at notably less numbers of experimental runs, providing the possibility to observe the special effects of important affecting factors on the system. A series of factorial experiments has been optimized for evaluation of main effects as well as interactions among the factors. The time, pH, and biomass dose had positive influence while initial Cu ion concentration and agitation speed was found unhelpful. On the other hand, in case of Zn(II), pH, shaking speed, biomass amount, and time influenced positively and metal ion concentration affected oppositely. The uptake of Ni was decreased with rise in initial concentration of Zn and Cu. So, both metals had suppressing effect on Ni uptake. The order of adsorption in TMS was established as Cu(II) > Zn(II) > Ni(II). The outcomes of RSM along with two MDs, highest metal uptake of adsorbent was 45.5 mg/g for Cu<sup>2+</sup>, 30 mg/g for Zn<sup>2+</sup>, and 25 mg/g for Ni<sup>2+</sup>. The adsorption data was better fitted with Langmuir isotherm due to high value of co-relation coefficient. It is concluded that it is the specific features of binding site and solution chemistry that describes the priority for adsorbents.

## References

- [1] S. Tural, T. Tarhan, B. Tural, Removal of hazardous azo dye Metanil Yellow from aqueous solution by cross-linked magnetic biosorbent; equilibrium and kinetic studies, *Desal. Water Treat.*, 57 (2016) 13347–13356.
- [2] Z. Ullah, S. Hussain, S. Gul, S. Khan, F. Bangash, Use of HCl-modified bentonite clay for the adsorption of Acid Blue 129 from aqueous solutions, *Desal. Water Treat.*, 57 (2016) 8894–8903.
- [3] G. Abbas, I. Javed, M. Iqbal, R. Haider, F. Hussain, N. Qureshi, Adsorption of non-steroidal anti-inflammatory drugs (diclofenac and ibuprofen) from aqueous medium onto activated onion skin, *Desal. Water Treat.*, 95 (2017) 274–285.
- [4] A.M. Awwad, N.M. Salem, M.M. Aqarbeh, F.M. Abdulaziz, Green synthesis, characterization of silver sulfide nanoparticles and antibacterial activity evaluation, *Chem. Int.*, 6 (2020) 42–48.
- [5] A. Sasmaz, M. Yaman, Determination of uranium and thorium in soil and plant parts around abandoned lead–zinc–copper mining area, *Commun. Soil Sci. Plant Anal.*, 39 (2008) 2568–2583.
- [6] A. Sasmaz, E. Obek, The accumulation of arsenic, uranium, and boron in *Lemna gibba* L. exposed to secondary effluents, *Ecol. Eng.*, 35 (2009) 1564–1567.
- [7] E. Obek, A. Sasmaz, Bioaccumulation of aluminum by *Lemna gibba* L. from secondary treated municipal wastewater effluents, *Bull. Environ. Contam. Toxicol.*, 86 (2011) 217–220.
- [8] P.R. Gogate, A.B. Pandit, A review of imperative technologies for wastewater treatment II: hybrid methods, *Adv. Environ. Res.*, 8 (2004) 553–597.
- [9] C. Bar, R. Patil, J. Doshi, M.J. Kulkarni, W. Gade, Characterization of the proteins of bacterial strain isolated from contaminated site involved in heavy metal resistance—a proteomic approach, *J. Biotechnol.*, 128 (2007) 444–451.
- [10] Q. Manzoor, R. Nadeem, M. Iqbal, R. Saeed, T.M. Ansari, Organic acids pretreatment effect on *Rosa bourbonia* phyto-biomass for removal of Pb(II) and Cu(II) from aqueous media, *Bioresour. Technol.*, 132 (2013) 446–452.
- [11] I. Ullah, R. Nadeem, M. Iqbal, Q. Manzoor, Biosorption of chromium onto native and immobilized sugarcane bagasse waste biomass, *Ecol. Eng.*, 60 (2013) 99–107.
- [12] A.E.C. Botero, M.L. Torem, L.M.S. de Mesquita, Surface chemistry fundamentals of biosorption of *Rhodococcus opacus* and its effect in calcite and magnesite flotation, *Miner. Eng.*, 21 (2008) 83–92.
- [13] Y. Göksungur, S. Üren, U. Güvenç, Biosorption of cadmium and lead ions by ethanol treated waste baker's yeast biomass, *Bioresour. Technol.*, 96 (2005) 103–109.
- [14] V. Padmasubashini, B. Sunilkumar, M. Krishnakumar, S.B. Singh, Method validation and uncertainty for the determination of rare earth elements, yttrium, thorium and phosphorus in monazite samples by ICP-OES, *Chem. Int.*, 6 (2020) 98–109.
- [15] A. Mekonnen, Y. Degu, R. Carlson, Appraisal of solvent system effect on bioactivity profiling of *Cordia africana* stem bark extracts, *Chem. Int.*, 6 (2020) 1–10.
- [16] A. Hamilton-Amachree, N.B. Iroha, Corrosion inhibition of API 5L X80 pipeline steel in acidic environment using aqueous extract of *Thevetia peruviana*, *Chem. Int.*, 6 (2020) 110–121.
- [17] A.M. Awwad, M.W. Amer, N.M. Salem, A.O. Abdeen, Green synthesis of zinc oxide nanoparticles (ZnO-NPs) using *Ailanthus altissima* fruit extracts and antibacterial activity, *Chem. Int.*, 6 (2020) 151–159.
- [18] A.M. Alkherraz, A.K. Ali, K.M. Elsherif, Removal of Pb(II), Zn(II), Cu(II) and Cd(II) from aqueous solutions by adsorption onto olive branches activated carbon: equilibrium and thermodynamic studies, *Chem. Int.*, 6 (2020) 11–20.
- [19] I. Ali, M. Suhail, A. Basheer, Advanced spiral periodic classification of the elements, *Chem. Int.*, 3 (2017) 220–224.
- [20] K.N. de Simas, L.d.N. Vieira, R. Podestá, M.A. Vieira, I.I. Rockenbach, C.L. Petkowicz, J. de Deus Medeiros, A. de Francisco, E.R. Amante, R.D. Amboni, Microstructure, nutrient composition and antioxidant capacity of king palm flour: a new potential source of dietary fibre, *Bioresour. Technol.*, 101 (2010) 5701–5707.
- [21] K.C. Tramonte, J.G. Provesi, A.E. Silva, I.M. Dutra, A.N.N. Murakami, M. Maraschin, R.D. De Mello Castanho Amboni, E.R. Amante, Juice from king palm (*Archontophoenix alexandrae*) leaf sheathes: chemical characterisation and use in soft drink formulation, *Int. J. Food Sci. Technol.*, 46 (2011) 1871–1877.
- [22] L. Abate, Bioactivity profiling of four traditional medicinal plants leave extracts native to Alemsaga Forest, Ethiopia, *Chem. Int.*, 5 (2019) 281–290.
- [23] U.P. Chinaza, O.A. Omotayo, A.F. Banji, A.A. Ololade, J.D. Olaoluwa, O.A. Adewale, S. Oluwatosin, Nutritional investigation of three commonly consumed fast foods in two major fast food restaurants in Lagos State, Nigeria, *Chem. Int.*, 5 (2019) 81–86.
- [24] I. Shadrach, A. Banji, O. Adebayo, Nutraceutical potential of ripe and unripe plantain peels: a comparative study, *Chem. Int.*, 6 (2020) 83–90.
- [25] B. Tegegne, A. Belay, T. Gashaw, Nutritional potential and mineral profiling of selected rice variety available in Ethiopia, *Chem. Int.*, 6 (2020) 21–29.
- [26] H.A. Shindy, Novel styryl and aza-styryl cyanine dyes: synthesis and spectral sensitization evaluation, *Chem. Int.*, 5 (2019) 117–125.
- [27] N. Oussama, H. Bouabdesselam, N. Ghaffour, L. Abdelkader, Characterization of seawater reverse osmosis fouled membranes from large scale commercial desalination plant, *Chem. Int.*, 5 (2019) 158–167.
- [28] M. Alasadi, F.I. Khaili, A.M. Awwad, Adsorption of Cu(II), Ni(II) and Zn(II) ions by nano kaolinite: thermodynamics and kinetics studies, *Chem. Int.*, 5 (2019) 258–268.
- [29] E.C. Jennifer, O.P. Ifedi, Modification of natural bentonite clay using cetyl trimethyl-ammonium bromide and its adsorption capability on some petrochemical wastes, *Chem. Int.*, 5 (2019) 269–273.
- [30] M. Iqbal, Z. Ali, M.A. Qamar, A. Ali, F. Hussain, M. Abbas, J. Nisar, Nickel adsorption onto polyurethane ethylene and vinyl acetate sorbents, *Water Sci. Technol.*, 76 (2017) 219–235.
- [31] M. Iqbal, I.A. Bhatti, Gamma radiation/H<sub>2</sub>O<sub>2</sub> treatment of a nonylphenol ethoxylates: degradation, cytotoxicity, and mutagenicity evaluation, *J. Hazard. Mater.*, 299 (2015) 351–360.
- [32] M. Iqbal, N. Iqbal, I.A. Bhatti, N. Ahmad, M. Zahid, Response surface methodology application in optimization of cadmium adsorption by shoe waste: a good option of waste mitigation by waste, *Ecol. Eng.*, 88 (2016) 265–275.
- [33] M.Z. Ahamd, S. Ehtisham-ul-Haque, N. Nisar, K. Qureshi, A. Ghaffar, M. Abbas, J. Nisar, M. Iqbal, Detoxification of photo-catalytically treated 2-chlorophenol: optimization through response surface methodology, *Water Sci. Technol.*, 76 (2017) 323–336.
- [34] M.Z. Ahmad, I.A. Bhatti, K. Qureshi, N. Ahmad, J. Nisar, M. Zuber, A. Ashar, M.I. Khan, M. Iqbal, Graphene oxide supported Fe<sub>2</sub>(MoO<sub>4</sub>)<sub>3</sub> nano rods assembled round-ball fabrication via hydrothermal route and photocatalytic degradation of nonsteroidal anti-inflammatory drug, *J. Mol. Liq.*, 301 (2020) 112343.
- [35] K. Qureshi, M.Z. Ahmad, I.A. Bhatti, M. Zahid, J. Nisar, M. Iqbal, Graphene oxide decorated ZnWO<sub>4</sub> architecture synthesis, characterization and photocatalytic activity evaluation, *J. Mol. Liq.*, 285 (2019) 778–789.
- [36] M.Z. Ahmad, K. Qureshi, I.A. Bhatti, M. Zahid, J. Nisar, M. Iqbal, M. Abbas, Hydrothermal synthesis of molybdenum trioxide, characterization and photocatalytic activity, *Mater. Res. Bull.*, 100 (2018) 120–130.
- [37] M. Iqbal, M. Abbas, M. Arshad, T. Hussain, A.U. Khan, N. Masood, M.A. Tahir, S.M. Hussain, T.H. Bokhari, R.A. Khera, Gamma radiation treatment for reducing cytotoxicity and mutagenicity in industrial wastewater, *Pol. J. Environ. Stud.*, 24 (2015) 2745–2750.
- [38] M. Iqbal, J. Nisar, M. Adil, M. Abbas, M. Riaz, M.A. Tahir, M. Younus, M. Shahid, Mutagenicity and cytotoxicity evaluation of photo-catalytically treated petroleum refinery wastewater using an array of bioassays, *Chemosphere*, 168 (2017) 590–598.

- [39] R.A. Khera, M. Iqbal, S. Jabeen, M. Abbas, A. Nazir, J. Nisar, A. Ghaffar, G.A. Shar, M.A. Tahir, Adsorption efficiency of Pitpapa biomass under single and binary metal systems, *Surf. Interfaces*, 14 (2019) 138–145.
- [40] I. Langmuir, The adsorption of gases on plane surfaces of glass, mica and platinum, *J. Am. Chem. Soc.*, 40 (1918) 1361–1403.
- [41] H. Freundlich, Over the adsorption in solution, *J. Phys. Chem.*, 57 (1906) 1100–1107.
- [42] Z. ul Haq, Y. Jamil, S. Irum, M.A. Randhawa, M. Iqbal, N. Amin, Enhancement in the germination, seedling growth and yield of radish (*Raphanus sativus*) using seed pre-sowing magnetic field treatment, *Pol. J. Environ. Stud.*, 21 (2012) 369–374.
- [43] F. Ishtiaq, H.N. Bhatti, A. Khan, M. Iqbal, A. Kausar, Polypyrrole, polyaniline and sodium alginate biocomposites and adsorption-desorption efficiency for imidacloprid insecticide, *Int. J. Biol. Macromol.*, 147 (2020) 217–232.
- [44] A. Kausar, R. Shahzad, J. Iqbal, N. Muhammad, S.M. Ibrahim, M. Iqbal, Development of new organic-inorganic, hybrid bionanocomposite from cellulose and clay for enhanced removal of Drimarine Yellow HF-3GL, *Int. J. Biol. Macromol.*, 149 (2020) 1059–1071.
- [45] S. Noreen, H.N. Bhatti, M. Iqbal, F. Hussain, F.M. Sarim, Chitosan, starch, polyaniline and polypyrrole biocomposite with sugarcane bagasse for the efficient removal of Acid Black dye, *Int. J. Biol. Macromol.*, 147 (2020) 439–452.
- [46] G.N. Iwuoha, A. Akinseye, Toxicological symptoms and leachates quality in Eledunwo, Rivers State, Nigeria, *Chem. Int.*, 5 (2019) 198–205.
- [47] E.B. Hassen, A.M. Asmare, Predictive performance modeling of Habesha brewery wastewater treatment plant using artificial neural networks, *Chem. Int.*, 5 (2019) 87–96.
- [48] M. Gebrekidan, M. Redi-Abshiro, B.S. Chandravanshi, E. Ele, A.M. Mohammed, H. Mamo, Influence of altitudes of coffee plants on the alkaloids contents of green coffee beans, *Chem. Int.*, 5 (2019) 247–257.
- [49] F. Deeba, N. Abbas, M.T. Butt, M. Irfan, Ground water quality of selected areas of Punjab and Sind Provinces, Pakistan: chemical and microbiological aspects, *Chem. Int.*, 5 (2019) 241–246.
- [50] O. Igwe, F. Nwamezie, Green synthesis of iron nanoparticles using flower extract of *Piliostigma thomningii* and antibacterial activity evaluation, *Chem. Int.*, 4 (2018) 60–66.
- [51] N.E. Ibsi, C.A. Asoluka, Use of agro-waste (*Musa paradisiaca* peels) as a sustainable biosorbent for toxic metal ions removal from contaminated water, *Chem. Int.*, 4 (2018) 52–59.
- [52] J. Kaduková, H. Horváthová, Biosorption of copper, zinc and nickel from multi-ion solutions, *Nova Biotechnol. Chim.*, 11 (2012) 125–132.
- [53] S. Yasmin, S. Nouren, N. Bhatti Haq, N. Iqbal Dure, S. Iftikhar, J. Majeed, R. Mustafa, N. Nisar, J. Nisar, A. Nazir, M. Iqbal, H. Rizvi, Green synthesis, characterization and photocatalytic applications of silver nanoparticles using *Diospyros lotus*, *Green Process. Synth.*, 9 (2020) 87–96.
- [54] I. Sohail, I.A. Bhatti, A. Ashar, F.M. Sarim, M. Mohsin, R. Naveed, M. Yasir, M. Iqbal, A. Nazir, Polyamidoamine (PAMAM) dendrimers synthesis, characterization and adsorptive removal of nickel ions from aqueous solution, *J. Mater. Res. Technol.*, 9 (2020) 498–506.
- [55] J. Nisar, S. Hassan, I. Khan Muhammad, M. Iqbal, A. Nazir, A. Sharif, E. Ahmed, Hetero-structured iron molybdate nanoparticles: synthesis, characterization and photocatalytic application, *Int. J. Chem. Reactor Eng.*, 18 (2020), doi: 10.1515/ijcre-2019-0123.
- [56] A. Jamil, T.H. Bokhari, T. Javed, R. Mustafa, M. Sajid, S. Noreen, M. Zuber, A. Nazir, M. Iqbal, M.I. Jilani, Photocatalytic degradation of disperse dye Violet-26 using TiO<sub>2</sub> and ZnO nanomaterials and process variable optimization, *J. Mater. Res. Technol.*, 9 (2020) 1119–1128.
- [57] M. Iqbal, M. Fatima, T. Javed, A. Anam, A. Nazir, Q. Kanwal, Z. Shehzadi, M.I. Khan, J. Nisar, M. Abbas, S. Naz, Microwave assisted synthesis of zinc vanadate nanoparticles and photocatalytic application, *Mater. Res. Express*, 7 (2020) 1–9, doi: 10.1088/2053-1591/ab692e.
- [58] D.N. Iqbal, M. Tariq, S.M. Khan, N. Gull, S. Sagar Iqbal, A. Aziz, A. Nazir, M. Iqbal, Synthesis and characterization of chitosan and guar gum based ternary blends with polyvinyl alcohol, *Int. J. Biol. Macromol.*, 143 (2020) 546–554.
- [59] H. Chaudhry, N. Nisar, S. Mehmood, M. Iqbal, A. Nazir, M. Yasir, Indian mustard *Brassica juncea* efficiency for the accumulation, tolerance and translocation of zinc from metal contaminated soil, *Biocatal. Agric. Biotechnol.*, 23 (2020) 1–6.
- [60] T.N. Chikwe, R.E. Ekpo, I. Okoye, Competitive adsorption of organic solvents using modified and unmodified calcium bentonite clay mineral, *Chem. Int.*, 4 (2018) 230–239.
- [61] N.A. Ayofe, P.O. Oladoye, D.O. Jegede, Extraction and quantification of phthalates in plastic coca-cola soft drinks using high performance liquid chromatography (HPLC), *Chem. Int.*, 4 (2018) 85–90.
- [62] A. Abourriche, H. Hannache, M. Oumam, Elaboration of novel adsorbent from Moroccan oil shale using Plackett–Burman design, *Chem. Int.*, 4 (2018) 7–14.
- [63] K. Legrouri, E. Khouya, H. Hannache, M. El Hartti, M. Ezzine, R. Naslain, Activated carbon from molasses efficiency for Cr(VI), Pb(II) and Cu(II) adsorption: a mechanistic study, *Chem. Int.*, 3 (2017) 301–310.
- [64] S. Jafarinejad, Recent developments in the application of sequencing batch reactor (SBR) technology for the petroleum industry wastewater treatment, *Chem. Int.*, 3 (2017) 241–250.
- [65] S. Jafarinejad, Activated sludge combined with powdered activated carbon (PACT process) for the petroleum industry wastewater treatment: a review, *Chem. Int.*, 3 (2017) 368–374.
- [66] K. Djehaf, A.Z. Bouyakoub, R. Ouhib, H. Benmansour, A. Bentouaf, A. Mahdad, N. Moulay, D. Bensaid, M. Ameri, Textile wastewater in Tlemcen (Western Algeria): impact, treatment by combined process, *Chem. Int.*, 3 (2017) 414–419.
- [67] A. Babarinde, K. Ogundipe, K.T. Sangosanya, B.D. Akintola, A.-O. Elizabeth Hassan, Comparative study on the biosorption of Pb(II), Cd(II) and Zn(II) using Lemon grass (*Cymbopogon citratus*): kinetics, isotherms and thermodynamics, *Chem. Int.*, 2 (2016) 89–102.
- [68] A. Babarinde, G.O. Onyiaocha, Equilibrium sorption of divalent metal ions onto groundnut (*Arachis hypogaea*) shell: kinetics, isotherm and thermodynamics, *Chem. Int.*, 2 (2016) 37–46.
- [69] N.K. Benabdallah, D. Harrache, A. Mir, M. de la Guardia, F.-Z. Benhachem, Bioaccumulation of trace metals by red alga *Corallina elongata* in the coast of Beni Saf, west coast, Algeria, *Chem. Int.*, 3 (2017) 220–231.
- [70] M. Laissaoui, Y. Elbatal, I. Vioque, G. Manjon, Adsorption of methylene blue on bituminous schists from Tarfaya-Boujdour, *Chem. Int.*, 3 (2017) 442–451.
- [71] K. Legrouri, E. Khouya, H. Hannache, M. El Hartti, M. Ezzine, R. Naslain, Activated carbon from molasses efficiency for Cr(VI), Pb(II) and Cu(II) adsorption: a mechanistic study, *Chem. Int.*, 3 (2017) 301–310.
- [72] F. Minas, B.S. Chandravanshi, S. Leta, Chemical precipitation method for chromium removal and its recovery from tannery wastewater in Ethiopia, *Chem. Int.*, 3 (2017) 291–305.
- [73] K.D. Ogundipe, A. Babarinde, Comparative study on batch equilibrium biosorption of Cd(II), Pb(II) and Zn(II) using plantain (*Musa paradisiaca*) flower: kinetics, isotherm, and thermodynamics, *Chem. Int.*, 3 (2017) 135–149.
- [74] A. Chham, E. Khouya, M. Oumam, A.K. Abourriche, S. Gmouh, M. larzek, S. Mansouri, N. Elhammoudi, N. Hanafi, H. Hannache, The use of insoluble mater of Moroccan oil shale for removal of dyes from aqueous solution, *Chem. Int.*, 4 (2018) 67–76.
- [75] O. Chidi, R. Kelvin, Surface interaction of sweet potato peels (*Ipomoea batata*) with Cd(II) and Pb(II) ions in aqueous medium, *Chem. Int.*, 4 (2018) 221–229.
- [76] M. Fazal-ur-Rehman, Methodological trends in preparation of activated carbon from local sources and their impacts on production: a review, *Chem. Int.*, 4 (2018) 109–119.
- [77] S. Ghezali, A. Mahdad-Benzerdjeb, M. Ameri, A.Z. Bouyakoub, Adsorption of 2,4,6-trichlorophenol on bentonite modified with benzyldimethyltetradecylammonium chloride, *Chem. Int.*, 4 (2018) 24–32.

- [78] M. Palutoglu, B. Akgul, V. Suyarko, M. Yakovenko, N. Kryuchenko, A. Sasmaz, Phytoremediation of cadmium by native plants grown on mining soil, *Bull. Environ. Contam. Toxicol.*, 100 (2018) 293–297.
- [79] M. Sasmaz, E. Obek, A. Sasmaz, The accumulation of La, Ce and Y by *Lemna minor* and *Lemna gibba* in the Keban gallery water, Elazig Turkey, *Water Environ. J.*, 32 (2018) 75–83.
- [80] R.D. El Bouzaidi, A. El Gridani, Study of the vibronic coupling in the ground state of Methylthio radical, *Chem. Int.*, 2 (2016) 70–79.
- [81] I.A. Adetutu, G.N. Iwuoha, H. Michael Jnr, Carcinogenicity of dioxin-like polychlorinated biphenyls in transformer soil in vicinity of University of Port Harcourt, Choba, Nigeria, *Chem. Int.*, 6 (2020) 144–150.
- [82] M. Sasmaz, E. Öbek, A. Sasmaz, Bioaccumulation of cadmium and thallium in Pb-Zn tailing waste water by *Lemna minor* and *Lemna gibba*, *Appl. Geochem.*, 100 (2019) 287–292.
- [83] M.M. Alaqarbeh, M.W. Shammout, A.M. Awwad, Nano platelets kaolinite for the adsorption of toxic metal ions in the environment, *Chem. Int.*, 6 (2020) 49–55.
- [84] A. Sasmaz, N. Kryuchenko, E. Zhovinsky, V. Suyarko, N. Konakci, B. Akgul, Major, trace and rare earth element (REE) geochemistry of different colored fluorites in the Bobrynets region, Ukraine, *Ore Geol. Rev.*, 102 (2018) 338–350.