

Evaluating the Potential Effectiveness of *Moringa oleifera* Seeds Biomass as an Adsorbent in the Removal of Copper (Cu) in Water

Victor Uzoma Nwagbara^{1*}, Franklin Obeng Sika², William Azuka Iyama³, Kayini Chigayo⁴, Habauka Majority Kwaambwa⁴

¹Department of Civil and Environmental Engineering, Namibia University of Science and Technology, Windhoek, Namibia ²School of Nursing Bronx, Lehman College, New York, USA

³Institute of Geosciences and Space Technology, River State University, Port Harcourt, Nigeria

⁴Department of Natural and Applied Sciences, Namibia University of Science and Technology, Windhoek, Namibia Email: *vnwagbara@nust.na

How to cite this paper: Nwagbara, V. U., Sika, F. O., Iyama, W. A., Chigayo, K., & Kwaambwa, H. M. (2022). Evaluating the Potential Effectiveness of *Moringa oleifera* Seeds Biomass as an Adsorbent in the Removal of Copper (Cu) in Water. *Journal of Geoscience and Environment Protection*, *10*, 120-143.

https://doi.org/10.4236/gep.2022.103010

Received: November 22, 2022 **Accepted:** March 20, 2022 **Published:** March 23, 2022

Copyright © 2022 by author(s) and Scientific Research Publishing Inc. This work is licensed under the Creative Commons Attribution International License (CC BY 4.0). http://creativecommons.org/licenses/by/4.0/

Abstract

This study was based on the evaluation of the potential effectiveness of Moringa oleifera seeds biomass as a biosorbent in the removal of copper (Cu) in water which was justified by the level of toxicity, environmental unfriendliness and costly nature of chemical coagulants presently used. Fourier transform infrared (FTIR) analysis was used to identify the Moringa oleifera seeds biomass functional groups present in the adsorption of metal ions and found to be the carboxylic acid and amine functional groups (-COOH and -NH). The effects of contact time, adsorbent dosage, metal ion concentration and pH were studied. The maximum adsorption capacity at pH 5, room temperature and 0.8 g dosage was 70% for Cu(II). The adsorption data fitted better to the Langmuir than the Freundlich models as the sorption capacity (q_m) of Moringa oleifera seeds biomass for Cu(II) was 3.64 mg/g. The separation factor (R_I) was within the range of 0 and 1 which showed that the Cu(II) biosorption processes were favourable for Moringa oleifera biosorbent. The results showed that Moringa oleifera seed biomass is an effective adsorbent in the removal of the studied heavy metals in water. The effective pH for the Cu(II) removal was 5.0 as equilibrium was achieved practically in 35 min. The quantitative analysis of defatted Moringa oleifera should be studied in order to have a fair mixing ratio between Moringa oleifera seeds biomass and the adsorbate. There is also the ardent need to work on environmentally friendly disposal of adsorbent after saturation of adsorbent by analyte to avoid secondary pollution.

Keywords

Moringa oleifera, Adsorbate, Adsorbent, Adsorption, Copper (Cu), Langmuir, Freundlich Model, Functional Groups

1. Introduction

Heavy metals also known as trace elements occur naturally in the environment and find their ways into human bodies via drinking water and food. Heavy metals such as copper (Cu) are essential to the maintenance of human metabolic processes but are dangerous to human health at higher concentrations (Dowlatshahi et al., 2014). The defining factor of heavy metals is the density hence, heavy metals are elements that have a specific density that is above 5 g/cm³ (Jarup, 2003). Bioaccumulation of heavy metals in human bodies is very detrimental because they are toxic and cause multiple damages to organs (Tchounwou et al., 2012). Araujo et al. (2013) supported the outcome of the study of Tchounwou et al. (2012) availability of heavy metals like copper even at controlled amounts can lead to organ illnesses such as kidney or liver, skin, bones and teeth. Copper is one of the toxic metals hence said to be a heavy metal according to Koller and Saleh (2018), and its presence in water poses a potential threat to public health. The major remarkable degradation of environmental quality is the emission of pollutants containing toxic metals which is a serious problem threatening human health causing various diseases and disorders (Wuana & Okieimen, 2011). Waste streams such as industrial effluents may contain heavy metals such as Cu, Zn, Ni, Pb, Cd and Cr which are often encountered from chemical and mining industries. Among these heavy metals, contamination by Cu is more of significant concern as this metal is used in many sectors (Gebrehawaria et al., 2014). However, the conventional methods of water treatment which include ion exchange and chemical precipitation have not been successful due to cost and environmental harm.

Pollution of heavy metals in an aquatic environment is produced by natural and anthropogenic sources which depend on the type of activities that are predominant around the aquatic environment. Toxic metals have been released into the environment as a result of technical and scientific advancements, which end up in these valuable natural resources in many regions of the world. Toxic metals have been released into the environment as a result of technical and scientific advancements, which end up in these valuable natural resources in many parts of the world (Nwagbara & Iyama, 2019). Aquatic ecosystem is the residual collection of pollution and heavy metals generated from either geologic formation or anthropogenic activities such as agriculture and industrial activities (Iyama et al., 2018). Namibia is among the driest countries in sub-Saharan Africa that depend on underground water and surface dams due to low and irregular rainfall (Kullgren & Perdell, 2010). Elements such as Cu exhibit human toxicity at slightly high concentrations (Vijayaraghavan et al., 2011).

In the mining area of Tsumeb which is the focus area of this study, Tsumeb smelter produces about 60,000 tonnes of sulphur per annum which is discharged into the environment in the form of sulphur dioxide (Mapani et al., 2014). Sulphur dioxide gas may combine with heavy metals such as Cu to form complexes that are not biodegradable and are poisonous water contaminants.

Remarkable degradation of environmental quality is the emission of pollutants containing toxic metals, threatening human health and causing various illnesses and disorders (Wuana & Okieimen, 2011). Waste streams may contain Cu often encountered from chemical and mining industries. Among these heavy metals, contamination by Cu is of more significant concern as this metal is often encountered in many sectors (Gebrehawaria et al., 2014).

The adsorption capacity of an adsorbent is determined by numerous factors. It includes adsorbent (species age), type of adsorbate, presence of competing ions, method of biomass preparation and several physico-chemical parameters (temperature, pH, and ionic concentration).

Several techniques have been used in the literature to remove heavy metals from industrial waste or polluted water. Some of the known methods as explained by Ushakumary & Madhu (2014) include chemical precipitation, coagulation and membrane filtration process. However, these techniques are not costeffective, have undesirable environmental health effects, time-consuming and complex. Adsorption technique is regarded as the most efficient technique in removing heavy metals (Mahamadi, 2019), but it is influenced by several parameters such as contact time, initial metal concentration, pH and adsorbent dosage. Therefore, this study is mainly focused on the removal efficiency of Cu from contaminated water using *Moringa oleifera* seed biomass (biosorbent) due to their abundant availability, low cost, high biocompatibility, biodegradability, non-toxic behaviour and ease of chemical modification.

Moringa oleifera is a specie of the family *Moringaceae*. *Moringaceae* belongs to the family of plants that belong to the order, *Brassicales*. It is an angiosperm plant that is represented by fourteen species and a single genus *Moringa*. It is a shrub or small tree that grows up to the height of 12 meters (Araujo et al., 2013). It is usually a single trunk with an open crown trunk and grows mainly in the steppe climates and subtropics zone. According to Kwaambwa et al. (2012), *Moringa oleifera* can be found in sub-Saharan Africa since it tolerates a habitat that is dry sandy and poor soils.

Reddy et al. (2010) explained that *Moringa oleifera* traces its origin to Northern India and is locally grown in many regions like Africa, Arabia, Southeast Asia, the Pacific and Caribbean Islands and South America. The leaves are the parts that are mostly used because it is medicinal, nutritional and has positive economic value. Figures 1-4 show the plants, pods, seeds and kernels of this tree respectively.

Research has been focused on the use of *Moringa oleifera* seeds and fruits as the best-known application in water treatment and purification. Water purification



Figure 1. Moringa oleifera tree (Katima Mulilo).



Figure 2. Moringa oleifera pods (Katima Mulilo).



Figure 3. Moringa oleifera seeds.



Figure 4. Moringa oleifera seed kernels.

and the treatment of turbid water is the best-known application of this plant. Cationic polyelectrolytes are found in the seeds of all the various species of *Moringa oleifera*, which is the effective constituent in the treatment of water and an alternative for aluminium sulphate. The active proteins act as cationic polyelectrolytes which attach themselves to the particles and create binding between

them, producing flocs in the water (Arnoldsson et al., 2008). According to Rabiee (2011), the cationic polyelectrolytes are made up of positively charged ionic groups that bind with colloidal and suspended impurities or pollutants in water. Continuous stirring and mixing of proteins in contaminated water speed up electrostatic flocculation hence condensing the contaminants as flocs. Compared to the commonly used coagulant chemicals, *Moringa oleifera* has several advantages including low cost, biodegradable sludge production and lower sludge volume, and it does not affect the pH of the water. Another advantage is that the residue obtained as a by-product from the oil extraction of *Moringa oleifeira* seeds can be used as fertilizer and processed animal feeds. Apart from turbidity removal, *Moringa oleifera* seeds also possess antimicrobial properties (Madsen et al., 1987).

2. Materials and Methods

2.1. Instrumental Analysis and Sample Preparation

2.1.1. Atomic Absorption Spectrometer

The AAS (Atomic absorption spectrometer) is used to ascertain the concentration of the metals under investigation in the supernatant. For the measurement of un-adsorbed Cu(II) ions, the AAS is calibrated using standards of known concentration under the same conditions as the unknown.

2.1.2. Jar Test Instrument

Jar test instrument was used in the laboratory to determine the optimum operating conditions for the polluted water such as contact time and optimum coagulant dose on a small scale. In this procedure, the Jar testing apparatus containers were filled with 6 water samples to determine the contact time with a rotation speed per minute of 100 rpm. After 30 min of settling period, the supernatants were drawn from each sample and analysed using AAS.

2.1.3. pH Meter

Before utilizing the pH meter, it was calibrated with standard saline (KCl) solutions (buffer). pH reading was stabilised for at least 2 minutes for accurate reading and once the reading was stabilised, the value of the pH was taken.

2.1.4. Electrical Conductivity Meter

It is designed for water quality applications measuring electrical conductivity, total dissolved solids and dissolved oxygen, the instrument was calibrated using the pH buffer solution for it to give accurate measurement. The electrical conductivity of the water samples was determined by inserting probes into the samples and waiting for the readings to stabilize.

2.1.5. Spectrum Two Fourier Transform Infrared (FTIR) Spectroscopy

FTIR analysis of *Moringa oleifera* seeds biomass was performed using a Fourier transform infrared spectrometer (FTIR-ASTM E1252, New Delhi, India) before sorption of Cu(II) ion.

2.1.6. Moringa oleifera Seeds Biomass Preparation

Moringa oleifera seeds were harvested from a tree in Katima Mulilo, Zambezi region. 200 g of *Moringa oleifera* seeds were dried and dehusked and washed in distilled water (to remove dust and water-soluble impurities) and sun-dried. The white kernels were ground to a fine powder using pestle and mortar. Defatting was done using diethyl ether $[(C_2H_5)_2O]$ by mixing thoroughly in a magnetic stirrer and the powder was then obtained by suction filtration using Büchner flask and dried at room temperature in open air on a bench for 72 h. The powder was crushed again and sieved through the size range of 150 - 250 µm sieves to obtain the *Moringa oleifera* seeds biomass (MOSB) that was used as an adsorbent. The dried sample was stored in airtight bottles at room temperature for the adsorption studies. The process of obtaining MOSB is shown in **Figure 5**.

2.1.7. Stock Solutions Preparation

All the chemical reagents used in these studies were analytical grade that was sourced from Medlab Services in Windhoek. 1000 mg/L stock solutions with metal ion Cu(II) was prepared by dissolving 3.970 g of 99% $CuSO_4 \cdot 5H_2O$ from copper sulphate pentahydrate ($CuSO_4 \cdot 5H_2O$) respectively in 1000 mL of water samples from Ondundu, Tsumeb in 3 different volumetric flask using Equation (1) (Chong, 2016). Diethyl ether [C_2H_5)₂O, was used to defat *Moringa oleifera* seeds biomass and other chemicals such as NaOH and HCl were used for preparing solutions of varying pH.

The concentrations of the heavy metals in water samples collected from Ondundu Tsumeb were within the permissible limits for drinking water as compared to USEPA standards.

Cu equivalent to 1 g =
$$\frac{\text{Molecular weight of } CuSO_4 \cdot 5H_2O \times 100}{\text{Atomic weight of } Cu \times Purity}$$
(1)





Figure 5. Schematic representation of *M. oleifera* seed biomass preparation (MOSB).

The solutions were then diluted to obtain standard solutions of 10, 20, 30, 40, 50, 60, 70, 80, 90 and 100 mg/L using Equation (2) (Chong, 2016).

$$C_1 V_1 = C_2 V_2 \tag{2}$$

where C_1 is a concentration of stock solution, V_1 is volume of stock solution to be diluted to a volume V_2 to obtain concentration C_2 . Other working solutions were obtained by serial dilution of stock solutions.

2.2. Batch Adsorption Experiments

This study was carried out on adsorption of Cu(II) from aqueous solutions by *Moringa oleifera* seeds biomass. Cu(II) ions uptake by *Moringa oleifera* seeds biomass from aqueous solutions (ranging 10 - 100 mg/L) were studied by a batch technique at room temperature (25°C). A known quantity of *Moringa oleifera* seeds biomass (0.8 g) was added into 100 mL aqueous solutions and stirred continuously for 100 rotations per minute (rpm) with a Jar test apparatus. 35 minutes (min) was selected as the optimum contact time for the aqueous solutions. The supernatants were filtered through a Whatman filter paper (0.45 µm pore size). The concentrations of the un-adsorbed Cu(II) ions in the filtrates were determined using atomic absorption spectroscopy (iCE 3300 AAS, Thermo Fisher Scientific Inc., UK) with air/acetylene flame. Quantification of the metals was based upon calibration curves of standard solutions of Cu(II) ion.

The amount of metal sorbed by biomass expressed as % removal (% RE) was calculated from the difference between the initial metal quantity (C_o) and the metal ions at equilibrium (C_e) using Equation (3), q_e was calculated using the Equation (4) (Cheraghi et al., 2015).

% Removal (% RE) =
$$\frac{C_o - C_e}{C_o} \times 100$$
 (3)

$$q_e \left(\text{mg/g} \right) = \frac{\left(C_o - C_e \right) V}{m} \tag{4}$$

where V is the volume of solution used in litres, and m is the mass of adsorbent (g).

2.3. Adsorption Isotherm

Using Equations (5) and (6), the adsorption data for Cu(II) ions were fitted onto Langmuir and Freundlich adsorption isotherm models, respectively.

$$\frac{1}{q_e} = \frac{1}{q_m b} + \frac{1}{q_m} C_e \tag{5}$$

$$\ln q_e = \ln K_F + \frac{1}{n} \ln C_e \tag{6}$$

where:

 C_e -adsorbate equilibrium concentration (mg/L).

 q_e —quantity of metal ion adsorbed per gram of adsorbent at equilibrium (mg/g).

 q_m —adsorption capacity (mg/g). b—rate of adsorption (L/mg). K_r —adsorption capacity (mg/g). n—heterogeneity of the adsorbent.

2.4. Data Analysis

Each experiment was conducted in triplicate to ensure the reproducibility of results. All the experiments were performed in triplicate to confirm reproducibility; hence, the reported value of Cu(II) metal ion adsorbed is the average of three measurements. Standard deviations were below 5%. Statistical analyses were performed using the statistical functions of Microsoft Excel version Office XP.

3. Results and Discussion

3.1. Characterisation of Moringa oleifera Seeds Biomass

The *Moringa oleifera* seeds biomass was characterised by FTIR spectroscopy for possible functional groups responsible for metal uptake whose FTIR spectra for *Moringa oleifera* seeds biomass powder are shown in **Figure 6**. The seeds of *Moringa oleifera* are classified as lignocellulose adsorbents which consist of cellulose, hemicellulose and lignin. These have functional groups which can absorb metal ions through ion-exchange or complexation process (Araujo et al., 2013).

The spectra showed a broad band at 3897 cm^{-1} assigned to the stretching vibration of hydroxyl groups (O-H) on the surface of the *Moringa oleifera* seeds biomass. The presence of the high content of protein in *Moringa oleifera* seeds biomass makes it have a high content of N-H stretching of amide groups (Araujo et al., 2013). The peaks of 2924 cm⁻¹ and 2854.8 cm⁻¹ are the symmetrical and asymmetrical stretching of C-H₃ and CH₂ groups respectively present in





fatty acids (Araujo et al., 2013). The peaks 1745.2 cm⁻¹ and 1659 cm⁻¹ are assigned to C=O bond stretching of Ketone. The band at 1659 cm⁻¹ could be attributed to stretching vibration of CO from carboxylic acid in the presence of intermolecular hydrogen bonding (Han et al., 2010). The peak of 1464 cm⁻¹ is a characteristic of the scissoring vibrations of $-CH_2$ functional groups in lipids (Harder et al., 1998). The band at 1362.8 cm⁻¹ is ascribed to $-CH_2$ stretching vibration in cellulose and hemicelluloses (Ferrer et al., 2016). The band at 1164.1 cm⁻¹ can be ascribed to the vibration of C-O-C in polysaccharides such as cellulose and hemicelluloses (Pandey & Pitman, 2004). The band at 1164.9 cm⁻¹ can be ascribed to the vibration of C-O-C in polysaccharides like cellulose and hemicelluloses (Smidt & Meissl, 2007). The band at 1092.9 cm⁻¹ can be indicative of O-H associated with cellulose and hemicelluloses (Özgenç et al., 2013). The peak at 1036.7 cm⁻¹ presented the C-O stretching vibration in the lignin structure (Cheraghi et al., 2015).

3.2. Point of Zero Charge (pzc)

Biological adsorbents are materials with an amphoteric character; thus, depending on the pH of the solution, their surfaces can be positively or negatively charged depending on point of zero charge (pzc) (Araujo et al., 2013). Point of zero charge (pzc) describes the condition when the electrical charge density on the surface of an adsorbent is zero or neutral. At pH values greater than the point of zero charge (pzc), the biomass surface becomes negatively charged, which favours cationic species (Araujo et al., 2013). The biomass surface becomes positive, when the pH values are less than the point of zero charge which favours anions. Invariably, when the surface of the adsorbent is neutral, then pH is equal to the point of zero charge of the biomass (Khan & Sarwar, 2007). This shows that the surface of *Moringa oleifera* has acidic characteristics for it to be able to adsorb cations (heavy metal ions).

3.3. Effect of Contact Time on Cu Sorption

The equilibrium time required for the adsorption of Cu(II) for *Moringa oleifera* with 20 mg/L of Cu(II) initial concentrations at varying time from 5, 10, 20, 25, 30, 35, 40, 45, 50 and 60 min, and percentage removal of these metal ions were calculated. The experimental conditions used were pH of 5, rotation speed of 100 rotations per minute (rpm), temperature of 25°C and adsorbent dosage of 0.8 g/100mL of *Moringa oleifera* seeds biomass. The results of the effect of the contact time on adsorption of Cu(II) ions are summarised in Figure 7 which showed that Cu(II) removal percentage increases sharply with contact time (5 - 35 min), after 35 min, the Cu(II) removal curves became almost constant, which showed that the point of equilibrium is reached (Table 1). Figure 7 showed that the removal of Cu(II) increased with increase in contact time, hence the optimum sorption time was 35 min for Cu metal ion used for this study in which 71.55% of Cu(II) was removed at the equilibrium time. The increasing contact



Figure 7. Effect of contact time on the sorption of Cu(II) by *Moringa oleifera* seeds biomass.

Table 1. Effect of contact time on the adsorption of Cu(II) by *Moringa oleifera* seeds biomass (pH = 5, initial conc. = 20 mg/L, dosage = 0.8 g/100mL, room tempt = 25°C and stirring speed = 100 rpm).

Cu(II)							
Time (min)	Initial concentration (C _o) (mg/L)	C_e (mg/L)	% Removal				
5	20	14.77	26.15				
10	20	13.79	31.05				
15	20	12.49	37.55				
20	20	11.14	44.30				
25	20	9.31	53.45				
30	20	7.01	64.95				
35	20	5.69	71.55				
40	20	5.69	71.55				
45	20	5.69	71.55				
50	20	5.69	71.55				
55	20	5.69	71.55				
60	20	5.69	71.55				

time increased the Cu(II) adsorption on *Moringa oleifera* seeds biomass and it remained constant after equilibrium was reached in 35 min, as the binding sites became exhausted, the uptake rate slowed due to competition for decreasing availability of actives sites by *Moringa oleifera* seeds biomass. The behaviour suggests that at the initial stage, sorption takes place rapidly on external surface of *Moringa oleifera* seeds biomass.

Similar study done by Bhatti et al. (2007) on removal of Zn(II) from aqueous solution using *Moringa oleifera* Lam biomass showed that over 90% removal was

achieved within 40 minutes of contact. In similar study done by Aziz et al. (2016) showed the highest percentage removal of 97% for Cd(II) ions was realised at 30 min respectively using *Moringa oleifera* seeds and *Musa cavendish*.

3.4. Effect of pH on Cu Adsorption

The pH of the metal solution plays an important role in the whole adsorption process and particularly on the adsorption capacity by influencing the surface charge of adsorbent, the degree of ionization and speciation of adsorbate (Yao et al., 2010). The pH of the solution plays a vital role in the adsorption capacity of the adsorbent by the way of modifying the functional group of biomass (Begum et al., 2015). The effect of pH on adsorption of Cu(II) ion was done in the pH range of 1.0, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0 and 9.0 Therefore, studying the effect of pH on the removal efficiency of Cu(II) ion was performed by using 0.8 g of *Moringa oleifera* seeds biomass adsorbent with 100 mL of 20 mg/L concentration of Cu(II) ion solution for 35 min at 25°C and the sample was stirred using a Jar test apparatus at rotation speed per minute of 100 rpm. The result of the effect of pH on the adsorption of Cu(II) ion by *Moringa oleifera* seeds biomass is shown in Table 2. There was precipitation at pH beyond 9.0 due to formation of insoluble metal hydroxide and this hinders the adsorption Cu(II); hence the study did not go beyod pH 9.0.

The effect of solution pH on Cu(II) ion adsorption is shown in **Figure 8**. An increase in the solution pH from 1.0 to 5.0 has increased the amount of Cu(II) ion adsorbed as the percentage adsorbance of Cu(II) ion by *Moringa oleifera* seeds biomass increased from 88% and 90.4%. From **Figure 8**, the maximum adsorption of Cu(II) ion onto *Moringa oleifera* seeds biomass was found at pH 5.0. Many adsorption studies report 5.0 as the optimum pH for Cu(II) ion by

Table 2. Effect of pH on the adsorption of Cu(II) by *Moringa oleifera* seeds biomass (pH = 5, initial conc. = 20 mg/L, dosage = 0.8 g/100mL, room tempt = 25°C and stirring speed = 100 rpm).

Cu(II)							
pН	Initial concentration (C_o) (mg/L)	$C_e (\mathrm{mg/L})$	% Removal				
1	20	15.91	20.45				
2	20	13.05	34.75				
3	20	10.22	48.90				
4	20	7.29	63.55				
5	20	5.59	72.05				
6	20	6.99	65.05				
7	20	8.98	55.10				
8	20	10.94	45.30				
9	20	13.18	34.10				



Figure 8. Effect of pH on the adsorption of Cu(II) ion by Moringa oleifera seeds biomass.

Moringa oleifera pod adsorbent and *Phaseolus aureus* hulls (Adelaja et al., 2011; Rao et al., 2009).

At low pH (1.0 - 4.0), more H⁺ ions were available to compete with Cu(II) ion for the adsorption sites of *Moringa oleifera* seeds biomass (Gurgel & Gil, 2009). In addition, at low pH most of the functional groups of *Moringa oleifera* seeds biomass are positively charged due to protonation which is obvious at low pH values due to the presence of high concentration of H⁺ ions in the solution (Putra et al., 2014). Thereafter, electrostatic repulsion between the positively charged adsorbent surface and the metal ions in solution is engendered and the adsorption of Cu(II) ion becomes more unfavorable (El-Araby et al., 2017). It is an ion-exchange mechanism that involves an electrostatic interaction between positively charged groups in *Moringa oleifera* seeds biomass cell walls and Cu(II) ion (Horsfall & Spiff, 2004).

3.5. Effect of Initial Cu(II) Ion Concentrations

The experiment was carried out with variable initial Cu(II) ion concentrations (10, 20, 30, 40, 50, 50, 60, 70, 80, 90 and 100 mg/L) at room temperature (25° C), pH (5.0), contact time (35 min), adsorbent dosage (0.8 g/100mL) and shaking speed (100 rpm). The results of the experiments are shown in Figure 8 (Table 3). The percentage of Cu(II) ion uptake at 10 mg/L was 70% and the percentage of Cu(II) ion uptake at 100 mg/L was 24.67% as there was decline in percentage removal of Cu(II) ion as initial concentration increases as shown in Figure 9.

This is because, at low concentration, the sorbent has enough active sites which could be easily occupied by Cu(II) ion since the ratio of available adsorption binding sites to the initial number of Cu(II) ion are large. Whereas at higher concentration, there are no more active sites to be occupied and the ratio of available adsorption active sites become fewer. That is the reason for Cu(II) ion left un-adsorbed in solution and the percentage removal which depends upon the initial concentration, decreasing (Yu et al., 2003). This result is compared to recent studies where the percent of metal adsorption decreases with increasing concentration of adsorbate (Bhatti et al., 2007; Azouaou et al., 2010; Yao et al., 2016; Nwagbara & Iyama, 2021).



Figure 9. Effect of initial Cu ion concentrations on adsorption by *Moringa oleifera* seeds biomass.

Table 3. Effect of initial metal ion concentrations [Cu(II)] on adsorption by *Moringa oleifera* seeds biomass (pH = 5, dosage = 0.8 g/100mL, contact time = 35 min, room tempt = 25° C and stirring speed = 100 rpm).

Initial concentration (<i>C</i> _o) (mg/L)	<i>C</i> _e (mg/L)	% Removal	<i>q.</i> (mg/g)	1/ <i>C_e</i> (L/mg)	1/ <i>q</i> e (g/mg)	ln <i>C</i> , (mg/L)	ln <i>q</i> , (mg/g)
10	2.9917	70.0830	0.8760	0.3343	1.1415	1.0958	-0.1321
20	6.3729	68.1355	1.7034	0.1569	0.5871	1.8521	0.5326
30	11.4404	61.8653	2.3200	0.0874	0.4310	2.4372	0.8415
40	17.6438	55.8905	2.7945	0.0567	0.3578	2.8708	1.0277
50	25.7629	48.4742	3.0296	0.0388	0.3300	3.2489	1.1084
60	34.9538	41.7437	3.1308	0.0286	0.3194	3.5540	1.1413
70	44.1421	36.9399	3.2323	0.0227	0.3093	3.7874	1.1732
80	51.8731	35.1586	3.5159	0.0193	0.2844	3.9488	1.2573
90	62.9236	30.0849	3.3846	0.0159	0.2955	4.1419	1.2192
100	75.3273	24.6727	3.0841	0.0133	0.3243	4.3218	1.1263

However, as seen in **Figure 10**, the adsorbed amount of metal ions per unit mass of adsorbent (q_e) increases as. the initial concentration of the adsorbate solution increases until it reaches maximum then reached a plateau which represents the maximum adsorption capacity of *Moringa oleifera* seeds biomass. The adsorption capacities were increased from 0.88 mg/g at Cu(II) ions concentration of 10 mg/L to be the highest value of 3.08 mg/g at 100 mg/L. This increase in loading capacity of the sorbent with relation to the metal ions concentration can be explained by the high driving force for mass transfer (Barka et al., 2013). Therefore, the more concentrated Cu(II) in the aqueous solution the better the adsorption by *Moringa oleifera* seeds biomass (Ünlü & Ersoz, 2006). Hence when



Figure 10. Sorbed capacity of *Moringa oleifera* seeds biomass versus initial concentration of Cu(II).

metal ion concentrations are increased, binding sites become more quickly saturated as the amount of *Moringa oleifera* concentration remained constant (Chandra Sekhar et al., 2004). Similar results were obtained where the adsorbed amount of metal ions per unit mass of adsorbent (q_c) increases as the initial concentration of the adsorbate solution increases until it reaches maximum then reached a plateau which represents the maximum adsorption capacity of adsorbent (Barka et al., 2013; Nyoni et al., 2017). Therefore, from Figure 10, it may be deduced that the sorption characteristics of *Moringa oleifera* seeds biomass showed that surface saturation depends on the initial Cu(II) ion concentrations.

3.6. Effect of Biomass Dosage

The effect of adsorbent dosage on Cu(II) ion percentage removal and adsorption capacity was investigated using different doses: 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9 and 0.1 g in 100 mL of 20 mg/L Cu(II) by keeping other variables constant (optimal pH of 5.0, temperature: 25°C, agitation speed: 100 rpm and contact time: 35 min) as shown in **Figure 11**. Results showed that with the increase in adsorbent dose from 0.1 to 0.8 g, the percentage removal of the removal efficiency of Cu(II) ion increased from 15.05% a to 64.45% (see **Table 4**). The results showed that as the adsorbent doses were increased, the percentage removal of Cu(II) ions increased up to 0.8 g. This increase in the heavy metal percentage removal with increasing the adsorbent dosage is feasible because of the increase in adsorbent surface area and the availability of more exchangeable binding sites on the surface which are ready for metal ion uptake (Babel & Kurniawan, 2004).

The effect of dosage and the trend of percentage removal were consistent for the metal ions studied. The increase in adsorption with an increase in adsorbent mass up to 0.8 g at maximum level was because of the greater surface area and availability of more active sites of *Moringa oleifera* seeds biomass, thereby leading to the enhancement of metal ion uptake. However, from mass greater than 0.8 g, the *Moringa oleifera* seeds biomass removal efficiency became less dependent on mass because the percentage removal was seen reaching a constant



Figure 11. Effect of *Moringa oleifera* seeds biomass dosage on initial concentration of Cu(II) ion.

Table 4. Effect of *Moringa oleifera* seeds biomass dosage on initial concentration of Cu(II) ion (pH = 5, initial conc. = 20 mg/L, contact time = 35 min, room tempt = 25°C and stirring speed = 100 rpm).

Dosage (g)	<i>C_e</i> (mg/L)	% removal	<i>q</i> e (mg/g)	1/ <i>C_e</i> (L/mg)	1/ <i>q_e</i> (g/mg)	ln <i>C</i> e (mg/L)	ln <i>q</i> e (mg/g)
0.1	16.99	15.05	3.0100	0.0589	0.3322	2.8326	1.1019
0.2	15.83	20.85	2.0850	0.0631	0.4796	2.7619	0.7348
0.3	12.92	35.40	2.3600	0.0779	0.4237	2.5588	0.8586
0.4	11.97	40.15	2.0075	0.0835	0.4981	2.4824	0.6969
0.5	10.32	48.4	1.9360	0.0968	0.5165	2.3340	0.6606
0.6	9.06	54.7	1.8233	0.1104	0.5484	2.2039	0.6007
0.7	8.03	59.85	1.7100	0.1245	0.5848	2.0832	0.5364
0.8	7.11	64.45	1.6113	0.1406	0.6207	1.9615	0.4770
0.9	6.87	65.65	1.4589	0.1456	0.6855	1.9271	0.3777
1	6.07	69.65	1.3931	0.1647	0.7179	1.8034	0.3315

value with respect to *Moringa oleifera* seeds biomass dosage. Metals adsorption efficiency was increased with increase in adsorbent dose. Another reason for efficiency removal to be fairly constant may be due to the particle interactions, such as aggregation, resulting from high sorbent concentration (Rao et al., 2009). Similar study done by Desta (2013) showed that increase in percentage removal when the dosage was increased was attributed to unsaturation of adsorption sites for metal ion attachment. The results demonstrated that the biomass concentration strongly affected the amount of Cu(II) ion removed from aqueous solutions.

3.7. Langmuir Adsorption Isotherm at Initial Cu(II) Ion Concentration onto Constant Dosage of *Moringa oleifera* Seeds Biomass

This adsorption isotherm is based on these assumptions, adsorbent surface is

uniform, no interaction between adsorbate on neighbouring sites, adsorption occurs through similar process and adsorbate are adsorbed at definite sites on the adsorbent surface (Yao et al., 2010). The equilibrium data was correlated with the Langmuir isotherm over the concentration range of Cu(II) from 10 to 100 mg/L at 25°C. The linear form of Langmuir equation (Equation (5)) was used to describe the analysis of the equilibrium data of Cu(II) ion concentration on *Moringa oleifera* seeds biomass as shown in **Figure 12**. The high value of correlation coefficient of 0.9971 indicate a good agreement between the parameters and confirms the monolayer adsorption of Cu(II) ion onto *Moringa oleifera* seeds biomass for Cu(II) ion obtained from Langmuir equation (Equation (5)) were found to be 3.64 mg/g and 0.32 as shown in **Table 6**. The affinity for sorption was due to interaction forces of Van der Waals between Cu(II) ion and the negatively charged MOSB (Mattuschka & Straube, 1993).

The affinity between the sorbate and sorbent is expressed in terms of a dimensionless constant separation factor (R_L). R_L values between 0 and 1 indicate favourable adsorption while $R_L > 1$, $R_L = 1$ and $R_L = 0$ indicate unfavourable, linear and irreversible adsorption isotherms respectively. This can be computed by substituting the values of b and C_o to the equation and R_L can be calculated by using Equation (7):

$$R_L = \frac{1}{1 + bC_o} \tag{7}$$

Figure 13 gives the plot of separation factor (R_L) versus initial concentration of Cu(II) ion concentration. It was observed that the value of R_L was between 0.0303 and 0.238 (0 < R_L < 1) as shown in **Table 5**, which confirms the favourable adsorption of the Cu(II) ion process by *Moringa oleifera* seed biomass. Therefore, the consistency of lower R_L values at higher initial Cu(II) ion concentrations showed that adsorption was more favourable at higher concentration (Nwagbara & Iyama, 2021). This was also supported by a study done by Mohammad et al. (2013) using *Jatropha* seed husk on lead and El-Araby et al.,







Figure 13. Plot of separation factor versus initial concentration of Cu(II) ion concentration.

Table 5. Dimensionless constant separation factor (R_i) value for Cu(II).

Initial concentration (mg/L)	$Cu(II) (R_L)$
10	0.238
20	0.135
30	0.094
40	0.0725
50	0.0588
60	0.0495
70	0.0427
80	0.0375
90	0.0336
100	0.0303

(2017) using Sesame Husk as adsorbent for Cu(II) ions removal from aqueous solution.

3.8. Freundlich Adsorption Isotherm at Initial Cu(II) Ion Concentrations onto Constant Dosage of *Moringa oleifera* Seeds Biomass

The linear form of Freundlich equation (Equation (6)) was used to describe the analysis of the equilibrium data of Cu(II) ion concentration on *Moringa oleifera* seeds biomass as shown in **Figure 14**. Adsorption capacity (K_d) and Freundlich constant (n) by *Moringa oleifera* seeds biomass for Cu(II) ion obtained from Freundlich equation (Equation (6)) were found to be 0.14 mg/g and 3.14 as shown in **Table 6**. The Freundlich constant (n) value of 3.14 fulfilled the condition of 0 < n < 10 for favourable adsorption of Cu(II) ion onto *Moringa oleifera* seeds biomass (Rao et al., 2009; Nwagbara & Iyama, 2021). The Freundlich type of adsorption isotherm is an indication of surface heterogeneity of MOSB which



Figure 14. Freundlich isotherm for adsorption of Cu(II).

Table 6. Langmuir and Freundlich isotherm models parameters for Cu(II) adsorption onto MOSB (pH = 5, dosage = 0.8 g/100mL, contact time = 35 min, room tempt = 25°C and stirring speed = 100 rpm).

Metal ions	Langmuir			Freundlich		
	q_e (mg/g)	<i>b</i> (L/mg)	R^2	N	$K_f(mg/g)$	R^2
Cu(II)	3.64	0.32	0.9971	3.14	0.14	0.9875

shows that the surface of *Moringa oleifera* seeds biomass is made of small heterogeneous pores which are favourable for adsorption that is a physical process.

3.9. Langmuir Adsorption Isotherm at Variable Dosage of *Moringa oleifera* Seeds Biomass at Constant Initial Cu(II) Concentration

Figure 15 illustrates the plot $1/q_e$ versus $1/C_e$ (Langmuir model) for the removal of Cu(II) at variable dosage of *Moringa oleifera* seeds biomass. The maximum adsorption capacities (q_m) of *Moringa oleifera* seeds biomass and Langmuir constant (*b*) were found to be 4.64 and 0.07 respectively as shown in **Table 7**. The Langmuir model effectively described the adsorption data with R² value of 0.9033 for Cu(II) ion and the adsorption isotherms of Cu(II) ions exhibit Langmuir behaviour, which indicates a monolayer adsorption.

3.10. Freundlich Adsorption Isotherm at Variable Dosage of *Moringa oleifera* Seeds Biomass at Constant Initial Cu(II) Concentration

Figure 16 depicts the plot of $\ln q_e$ versus $\ln C_e$ for the removal of Cu(II) ion at variable dosage of *Moringa oleifera* seeds biomass. The adsorption capacity (K_p) and Freundlich constant (n) by variable dosage of *Moringa oleifera* seeds biomass at constant Cu(II) ion concentration obtained from Freundlich equation (Equation (6)) were found to be 0.48 mg/g and 1.67 respectively as shown in **Ta-ble 7**. However, the Freundlich constant (n) value of 1.67 fulfilled the condition



Figure 15. Linear Langmuir isotherm for adsorbent dosage on Cu(II).



Figure 16. Linear Freundlich isotherm for adsorbent dosage on Cu(II).

Table 7. Langmuir and Freundlich isotherm models parameters for Cu(II) adsorption at variable adsorbent dosage (*Moringa oleifera* seeds biomass) (pH = 5, dosage = 0.8 g/100mL, contact time = 35 min, room tempt = 25° C and stirring speed = 100 rpm).

Metal (ions)]	Langmuir			Freundlich	
	$q_m (\mathrm{mg/g})$	<i>b</i> (L/mg)	R^2	N	$K_f(mg/g)$	R^2
Cu(II)	4.64	0.07	0.9033	1.67	0.48	0.8646

of 0 < n < 10 for favourable adsorption of Cu(II) ion onto variable dosage of *Moringa oleifera* seeds biomass (Rao et al., 2009, Nwagbara & Iyama, 2021). The Freundlich type of adsorption isotherm is an indication of surface heterogeneity of *Moringa oleifera* seeds biomass which shows that the surface of *Moringa oleifera* seeds biomass is made of small heterogeneous pores which are favourable for adsorption that is a physical process.

4. Conclusion

The removal of metal ions in polluted water requires rigorous processes that are controlled by numerous factors which adopt rigorous processes of many trends that are dependent on different parameters. This present study demonstrated that *Moringa oleifera* seeds biomass displayed good performance to remove Cu(II) heavy metal ions from aqueous solution. The obtained results showed that ad-

sorption process is a function of the adsorbent and adsorbate concentrations, pH and adsorbent dosage. From the general objective of the study, the investigation showed that *Moringa oleifera* is efficient and its applicability is ideal in the removal of heavy metals in contaminated water. The quantitative analysis of defatted *Moringa oleifera* should be studied in order to have a fair mixing ratio between *Moringa oleifera* seeds biomass and the adsorbate. Similarly, further studies on the investigation of temperature and the sorption capacity of *Moringa oleifera* seeds biomass in salt water (seawater) are advocated. Adsorption kinetics which describes the relationship of solute uptake rate of the adsorption and the adsorption time is recommended to be studied.

There is also the ardent need to work on environmentally friendly disposal of adsorbent after saturation of adsorbent by analyte to avoid secondary pollution.

Acknowledgements

The authors acknowledge the effort of the staff of Mining and Process Engineering at the Faculty of Engineering in Namibia University of Science and Technology in conducting the analysis of the synthetic water samples that were used in this study.

Availability of Data and Materials

All data generated or analysed during this study are included in this published article.

The materials used in this study were sourced locally from Namibia and the chemicals of 99% grade were bought from Medlab Services.

Conflicts of Interest

The authors declare that they have no competing interests in this section.

Funding

The work was supported by the Faulty of Engineering, Namibia University of Science and Technology Windhoek, Namibia.

Author's Contributions

VU did this study for his MSc degree. He interpreted the data regarding the removal of Cu(II) from water using *Moringa oleifera* seed biomass.

HM supervised the study from the beginning to the end as he was the supervisor of VU for his MSc degree.

CK analysed the water samples in the laboratory.

WA and FO substantively revised the study to a standard for submission.

All the authors agreed to the submission of the article.

References

Adelaja, O. A., Amoo, I. A., & Aderibigbe, A. D. (2011). Biosorption of Lead (II) Ions

from Aqueous Solution Using *Moringa oleifera* Pods. *Archives of Applied Science Research, 3,* 50-60.

- Araujo, C. S. T., Carvalho, D. C., Rezende, H. C., Almeida, I. L. S., Coelho, L. M., Coelho, N. M. M., Marques, T. L., & Alves, V. N. (2013). Bioremediation of Waters Contaminated with Heavy Metals Using *Moringa oleifera* Seeds as Biosorbent. In Y. Patil (Ed.), *Applied Bioremediation—Active and Passive Approaches* (pp. 249-255). IntechOpen. https://doi.org/10.5772/56157
- Arnoldsson, E., Bergman, M., Matsinhe, N., & Persson, K. M. (2008). Assessment of Drinking Water Treatment Using *Moringa oleifera* Natural Coagulant. VATTEN, 64, 137-150.
- Aziz, N. A. A., Jayasuriya, N., & Fan, L. (2016). Adsorption Study on *Moringa oleifera* Seeds and Musa Cavendish as Natural Water Purification Agents for Removal of Lead, Nickel and Cadmium from Drinking Water. *IOP Conference Series: Materials Science and Engineering*, *136*, Article ID: 012044. https://doi.org/10.1088/1757-899X/136/1/012044
- Azouaou, N., Sadaoui, Z., Djaafri, A., & Mokaddem, H. (2010). Adsorption of Cadmium from Aqueous Solution onto Untreated Coffee Grounds: Equilibrium, Kinetics and Thermodynamics. *Journal of Hazardous Materials*, 184, 126-134. https://doi.org/10.1016/j.jhazmat.2010.08.014
- Babel, S., & Kurniawan, T. A. (2004). Cr(VI) Removal from Synthetic Wastewater Using Coconut Shell Charcoal and Commercial Activated Carbon Modified with Oxidizing Agents and/or Chitosan. *Chemosphere*, *54*, 951-967. https://doi.org/10.1016/j.chemosphere.2003.10.001
- Barka, N., Abdennouri, M., El Makhfouk, M., & Qourzal, S. (2013). Biosorption Characteristics of Cadmium and Lead onto Eco-Friendly Dried Cactus (*Opuntia ficus indica*) Cladodes. *Journal of Environmental Chemical Engineering*, 1, 144-149. https://doi.org/10.1016/j.jece.2013.04.008
- Begum, S. A. S., Tharakeswar, Y., Kalyan, Y., & Naidu, G. R. (2015). Biosorption of Cd(II), Cr(VI) & Pb(II) from Aqueous Solution Using *Mirabilis jalapa* as Adsorbent. *Journal of Encapsulation and Adsorption Sciences*, 5, 93-104. https://doi.org/10.4236/jeas.2015.52007
- Bhatti, H., Mumtaz, B., Hanif, M. A., & Nadeem, R. (2007a). Removal of Zn(II) Ions from Aqueous Solution Using *Moringa oleifera* Lam. (Horseradish Tree) Biomass. *Process Biochemistry*, 42, 547-553. <u>https://doi.org/10.1016/j.procbio.2006.10.009</u>
- Bhatti, I., Qureshi, K., Kazi, R. A., & Ansari, A. K. (2007b). Preparation and Characterisation of Chemically Activated Almond Shells by Optimization of Adsorption Parameters for Removal of Chromium VI from Aqueous Solutions. *International Journal of Chemical and Molecular Engineering, 1*, 105-110.
- Chandra Sekhar, K. C., Kamala, C. T., Chary, N. S., Sastry, A. R. K., Nageswara Rao, T., & Vairamani, M. (2004). Removal of Lead from Aqueous Solutions Using an Immobilized Biomaterial Derived from a Plant Biomass. *Journal of Hazardous Materials, 108,* 111-117. <u>https://doi.org/10.1016/j.jhazmat.2004.01.013</u>
- Cheraghi, E., Ameri, E., & Moheb, A. (2015). Adsorption of Cadmium Ions from Aqueous Solutions Using Sesame as a Low-Cost Biosorbent: Kinetics and Equilibrium Studies. *International Journal of Environmental Science and Technology*, *12*, 2579-2592. <u>https://doi.org/10.1007/s13762-015-0812-3</u>
- Chong, S. H. (2016). Wither the Concepts of Mole and Concentration: Conceptual Confusion in Applying M₁V₁=M₂V₂. *Universal Journal of Educational Research, 4*, 1158-1162. <u>https://doi.org/10.13189/ujer.2016.040527</u>

- Desta, M. B. (2013). Batch Sorption Experiments: Langmuir and Freundlich Isotherm Studies for the Adsorption of Textile Metal Ions onto Teff Straw (*Eragrostis tef*) Agricultural Waste. *Journal of Thermodynamics, 2013,* Article ID: 375830.
- Dowlatshahi, S., Torbati, A. R. H., & Loloei, M. (2014). Adsorption of Copper, Lead and Cadmium from Aqueous Solutions by Activated Carbon Prepared from Saffron Leaves. *Environmental Health Engineering and Management*, *1*, 37-44.
- El-Araby, H. A., Ibrahim, A. M. M. A., Mangood, A. H., & Abdel-Rahman, A. A. H. (2017). Sesame Husk as Adsorbent for Copper(II) Ions Removal from Aqueous Solution. *Journal of Geoscience and Environment Protection*, *5*, 109-152. https://doi.org/10.4236/gep.2017.57011
- Ferrer, A., Alciaturi, C., Faneite, A., & Ríos, J. (2016). Analyses of Biomass Fibers by XRD, FT-IR, and NIR. In S. Vaz (Ed.), *Analytical Techniques and Methods for Biomass* (pp. 45-83). Springer International Publishing. https://doi.org/10.1007/978-3-319-41414-0_3
- Gebrehawaria, G., Hussen, A. M., & Rao, V. M. (2014). Removal of Hexavalent Chromium from Aqueous Solutions Using Barks of Acacia albida and Leaves of Euclea schimperi. International Journal of Environmental Science and Technology, 12, 1569-1580. https://doi.org/10.1007/s13762-014-0530-2
- Gurgel, L. V. A., & Gil, L. F. (2009). Adsorption of Cu(II), Cd(II) and Pb(II) from Aqueous Single Metal Solutions by Succinylated Twice-Mercerized Sugarcane Bagasse Functionalized with Triethylenetetramine. *Water Research*, 43, 4479-4488. https://doi.org/10.1016/j.watres.2009.07.017
- Han, R., Zhang, L., Song, C., Zhang, M., Zhu, H., & Zhang, L. (2010). Characterization of Modified Wheat Straw, Kinetic and Equilibrium Study about Copper Ion and Methylene Blue Adsorption in Batch Mode. *Carbohydrate Polymers*, 79, 1140-1149. https://doi.org/10.1016/j.carbpol.2009.10.054
- Harder, P., Grunze, M., and, Dahint, R., Whitesides, G. M., & Laibinis, P. E. (1998). Molecular Conformation in Oligo(Ethylene Glycol)-Terminated Self-Assembled Monolayers on Gold and Silver Surfaces Determines Their Ability To Resist Protein Adsorption. *The Journal of Physical Chemistry B*, 102, 426-436. <u>https://doi.org/10.1021/jp972635z</u>
- Horsfall, M., & Spiff, A. I. (2004). Studies on the Effect of pH on the Sorption of Pb²⁺ and Cd²⁺ Ions from Aqueous Solutions by *Caladium bicolor* (Wild Cocoyam) Biomass. *Electronic Journal of Biotechnology, 7*, 14-15.
- Iyama, W. A., Edori, O. S., & Ede, P. N. (2018). Heavy Metals and Nutrient Status of Surface Water Quality around Sagbama Creek, Bayelsa State, Nigeria. *Journal of Applied Chemical Science International*, 9, 161-167.
- Jarup, L. (2003). Hazards of Heavy Metal Contamination. British Medical Bulletin, 68, 167-182. <u>https://doi.org/10.1093/bmb/ldg032</u>
- Khan, M. N., & Sarwar, A. (2007). Determination of Points of Zero Charge of Natural and Treated Adsorbents. *Surface Review and Letters, 14*, 461-469. https://doi.org/10.1142/S0218625X07009517
- Koller, M., & Saleh, H. M. (2018). Introductory Chapter: Introducing Heavy Metals. In H.
 E. M. Saleh, & R. F. Aglan (Eds.), *Heavy Metals* (pp. 1-11). IntechOpen.
 <u>https://www.intechopen.com/books/heavy-metals/introductory-chapter-introducing-heavy-metals</u>
 <u>https://doi.org/10.5772/intechopen.74783</u>
- Kullgren, E., & Perdell, J. (2010). Vulnerability and Risk Assessment of Artificial Recharge of the Oanob Aquifer, Namibia. Master's Thesis, Chalmers University of Technology. <u>http://publications.lib.chalmers.se/records/fulltext/127464.pdf</u>

- Kwaambwa, H. M., Chimuka, L., Kandawa-Schulz, M., Munkombwe, N. M., & Thwala, J. M. (2012). Situational Analysis and Promotion of the Cultivation and Utilisation of the Moringa oleifera Tree in Selected Sub-Saharan Africa Countries.
- Madsen, M., Schlundt, J., & Omer, E. F. (1987). Effect of Water Coagulation by Seeds of *Moringa oleifera* on Bacterial Concentrations. *The Journal of Tropical Medicine and Hygiene*, *90*, 101-109.
- Mahamadi, C. (2019). On the Dominance of Pb during Competitive Biosorption from Multi-Metal Systems: A Review. *Cogent Environmental Science*, *5*, Article ID: 1635335. https://doi.org/10.1080/23311843.2019.1635335
- Mapani, B., Ellmies, R., Hahn, L., Schneider, G., Ndalulilwa, K., Leonard, R., Zeeuw, M., Mwananawa, N., Uugulu, S., Namene, E., Amaambo, W., Sibanda, F., & Mufenda, M. (2014). Contamination of Agricultural Products in the Surrounding of the Tsumeb Smelter Complex. *Communications of the Geological Survey of Namibia*, 15, 92-110.
- Mattuschka, B., & Straube, G. (1993). Biosorption of Metals by a Waste Biomass. *Journal of Chemical Technology & Biotechnology, 58*, 57-63. https://doi.org/10.1002/jctb.280580108
- Mohammad, M., Yaakob, Z., Rozaimah, S., & Abdullah, S. (2013). Carbon Derived from Jatropha Seed Hull as a Potential Green Adsorbent for Cadmium (II) Removal from Wastewater. *Materials, 6,* 4462-4478. <u>https://doi/10.3390/ma6104462</u>
- Nwagbara, V. U., & Iyama, W. A. (2019). Road Infrastructure in Countries: A Study of the Namibia Scenario. *Journal of Geoscience and Environment Protection*, 7, 86-101. https://doi./10.4236/gep.2019.712006
- Nwagbara, V. U., & Iyama, W. A. (2021). Adsorption Potentials of Binary Metal Aqueous Solution by *Moringa oleifera* Seeds Biomass. *Applied Journal of Environmental Engineering Science*, 7, 431-453
- Nyoni, S., Edmore, S., Muchanyereyi, N., & Shumba, M. (2017). Comparative Biosorption of Pb²⁺ Ions from Aqueous Solution Using *Moringa oleifera* Plant Parts: Equilibrium, Kinetics and Thermodynamic Studies. *African Journal of Biotechnology, 16*, 2215-2231. https://doi.org/10.5897/AJB2017.16066
- Özgenç, Ö., Okan, O., Umit, C., & Deniz, I. (2013). Wood Surface Protection against Artificial Weathering with Vegetable Seed Oils. *BioResources, 8*, 6242-6262. https://doi.org/10.15376/biores.8.4.6242-6262
- Pandey, K. K., & Pitman, A. J. (2004). Examination of the Lignin Content in a Softwood and a Hardwood Decayed by a Brown-Rot Fungus with the Acetyl Bromide Method and Fourier Transform Infrared Spectroscopy. *Journal of Polymer Science Part A: Polymer Chemistry*, 42, 2340-2346. https://doi.org/10.1002/pola.20071
- Putra, W. P., Kamari, A., Yusoff, S. N. M., Ishak, C. F., Mohamed, A., Hashim, N., & Isa, I. M. (2014). Biosorption of Cu(II), Pb(II) and Zn(II) Ions from Aqueous Solutions Using Selected Waste Materials: Adsorption and Characterisation Studies. *Journal of Encapsulation and Adsorption Sciences*, 4, 25-35. https://doi.org/10.4236/jeas.2014.41004
- Rabiee, A. R. (2011). Acrylamide-Based Cationic Polyelectrolytes and Their Potential Applications: A Survey. In 2011 International Conference on Management and Service (pp. 1-3). https://doi.org/10.1109/ICMSS.2011.5999328
- Rao, M. M., Ramana, D. K., Seshaiah, K., Wang, M. C., & Chien, S. W. C. (2009). Removal of Some Metal Ions by Activated Carbon Prepared from *Phaseolus aureus* Hulls. *Journal of Hazardous Materials, 166*, 1006-1013. https://doi.org/10.1016/j.jhazmat.2008.12.002

Reddy, D. H. K., Seshaiah, K., Reddy, A. V. R., Rao, M. M., & Wang, M. C. (2010). Bio-

sorption of Pb²⁺ from aqueous solutions by *Moringa oleifera* Bark: Equilibrium and Kinetic Studies. *Journal of Hazardous Materials, 174*, 831-838. https://doi.org/10.1016/j.jhazmat.2009.09.128

- Smidt, E., & Meissl, K. (2007). The Applicability of Fourier Transform Infrared (FT-IR) Spectroscopy in Waste Management. *Waste Management*, 27, 268-276. https://doi.org/10.1016/j.wasman.2006.01.016
- Tchounwou, P. B., Yedjou, C. G., Patlolla, A. K., & Sutton, D. J. (2012). Heavy Metal Toxicity and the Environment. In A. Luch (Ed.), *Molecular, Clinical and Environmental Toxicology* (pp. 133-164). Springer. <u>https://doi.org/10.1007/978-3-7643-8340-4_6</u>
- Ünlü, N., & Ersoz, M. (2006). Adsorption Characteristics of Heavy Metal Ions onto a Low Cost Biopolymeric Sorbent from Aqueous Solutions. *Journal of Hazardous Materials*, *136*, 272-280. <u>https://doi.org/10.1016/j.jhazmat.2005.12.013</u>
- Ushakumary, E. R., & Madhu, G. (2014). Removal of Cadmium, Chromium, Copper, Lead and Zinc Ions by *Alisma plantago aquatic. International Journal of Environment and Waste Management*, *13*, 75-89. https://doi.org/10.1504/IJEWM.2014.058796
- Vijayaraghavan, G., Sivakumar, T., & Kumar, A. V. (2011). *Application of Plant Based Coagulants for Waste Water Treatment. International Journal of Advanced Engineering Research and Studies, 1*, 88-92.
- Wuana, R. A., & Okieimen, F. E. (2011). Heavy Metals in Contaminated Soils: A Review of Sources, Chemistry, Risks and Best Available Strategies for Remediation. *International Scholarly Research Notices*, 2011, Article ID: 402647. https://doi.org/10.5402/2011/402647
- Yao, S., Sun, S., Wang, S., & Shi, Z. (2016). Adsorptive Removal of Lead Ion from Aqueous Solution by Activated Carbon/Iron Oxide Magnetic Composite. *Indian Journal of Chemical Technology*, 23, 146-152. http://nopr.niscair.res.in/handle/123456789/34080
- Yao, Z. Y., Qi, J. H., & Wang, L. H. (2010). Equilibrium, Kinetic and Thermodynamic Studies on the Biosorption of Cu(II) onto Chestnut Shell. *Journal of Hazardous Materials*, 174, 137-143. <u>https://doi.org/10.1016/j.jhazmat.2009.09.027</u>
- Yu, L. J., Shukla, S. S., Dorris, K. L., Shukla, A., & Margrave, J. L. (2003). Adsorption of Chromium from Aqueous Solutions by Maple Sawdust. *Journal of Hazardous Materials*, 100, 53-63. <u>https://doi.org/10.1016/S0304-389400008-6</u>