Effect of carbonization on the surface and influence on heavy metal removal by water hyacinth stem-based carbon

Joseph Nyamoko Tinega
Environmental Planning and Management, Kenyatta University, Nairobi, Kenya, and
Charles Mwaura Warui
Physical and Biological Sciences, Murang'a University of Technology, Murang'a, Kenya

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Abstract

Purpose – The aim of this study is to examine the effect of carbonization on the surface and its influence on heavy metal removal by water hyacinth based carbon.

Design/methodology/approach – Dried water hyacinth stem was used as precursor to prepare carbon based adsorbent by pyrolysis method. The adsorbent proximate (ash, volatile matter and fixed carbon) and elemental (carbon hydrogen nitrogen sulfur) composition, surface area, pore size distribution, surface chemistry was examined and compared.

Findings – The results demonstrated that through carbonization in comparison to dried water hyacinth stem, it increased the surface area (from 58.46 to 328.9 m^2/g), pore volume (from 0.01 to 0.07 cc/g), pore size (from 1.44 to 7.557 Å) thus enhancing heavy metal adsorption. The metal adsorption capacity of Cd, Pb and Zn was measured and analyzed through induced coupled plasma-mass spectrometer. At metal concentration of 0.1 mg/l adsorption rate for Cd, Pb and Zn was 99% due to increased large surface area, coupled with large pore size and volume. Furthermore, the adsorbent surface hydroxyl group (OH^-) enhanced adsorption of positively charged metal ions through electrostatic forces.

Practical implications – It is presumed that not only adsorption with synthetic wastewater but real wastewater samples should be examined to ascertain the viability of adsorbent for commercial application.

Originality/value – There are little or scanty data on the effects of carbonization on water hyacinth stem based carbon and subsequent effects on heavy metal removal in effluents.

Keywords Water hyacinth, Adsorption, Adsorbent, Electrostatic force

Paper type Research paper

1. Introduction

According to Research and Markets (2020) forecast, it is projected that global adsorbent demand by industries (water treatment, air separation, drying, packaging, petroleum refining) will be worth USD $ 5.4 billion by 2023 (Global Adsorbent Market Report, 2021). The market driving factors is due to increased domestic water consumption for drinking (WHO, 2019), air purification in coal fired power plants (Mercury control) and increasing stricter laws with regard to environmental restoration and protection (Research and Markets, 2020). Available competitive commercial bio-adsorbents for removal of heavy metals from waste water include but not limited to graphene, activated carbon, carbon nanotubes, rice husk, surfactant modified waste and modified sugarcane bagasse, wheat bran, coconut waste, orange peel waste, sawdust and egg shell among others (Renu and Agarwal, 2017) and activated carbon. In addition, the demand for carbon based adsorbent will increase in tandem with growing focus on sustainability and environmental recovery (Gupta, 2011a, b; Research and Markets, 2020).

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This is because it offers a sustainable alternative to the current conventional wastewater treatment technologies which include: ultrafiltration (Landaburu-Aguirre, 2009; Sampera, 2009), nanofiltration (Murthy, 2008; Muthukrishnan, 2008; Nguyen, 2009; Figoli, 2010), reverse osmosis (Mohsen-Nia, 2007, chemical precipitation (Ku, 2001; Pawar, 2018b), ion exchange (Alyuz and Veli, 2009), electro dialysis (Sadrzadeha, 2009), coagulation (Chang and Wang, 2007; El Samrani, 2008), electrochemical process (Heidmann, 2008), flocculation (Bratskaya *et al.*, 2009), flotation (Polat, 2007) and adsorption (Park, 2007; Kongsuwan, 2009; Guo, 2010; Subbaiah, 2016; Malik, 2017), electrolytic recovery (Al-Gheethi, 2015), electrocoagulation (Pirkarami, 2017; Karimifard, 2018), electro kinetic processes (Kumar, 2012; Sahu, 2018; Alka, 2021), membrane technology (Fu, 2011), nanophyto-remediation (Asante-Badu, 2020; Alka, 2021), phytobial remediation (Roy, 2015), phyto-remediation (Farraji, 2016). The adsorption technique has proven to be an effective and alternative to other conventional methods applied due to low operation cost, high metal removal efficiency, readily available and simple design systems (Malik, 2017).

The carbon materials that are widely used in adsorption process are often derived from fossil-based raw material mainly coal, silica and bauxite (Saleem, 2019). However, these source materials have proven to be unsustainable and expensive, since they are obtained from Earth mineral (Research and Markets, 2020). For this reason, several studies have been carried out on alternative adsorbent materials, particularly carbon derived from lignocellulose based adsorbent (Norshila, 2021). Numerous studies have demonstrated that carbonization improves heavy metal adsorption performance of lignocellulose based adsorbent for instance banana peel (Ajmi, 2018), pineapple peel (Shifera, 2017), orange peel (Ali, 2017), apple peel (Rasheed, 2013), leucaena leucocephala seed pod (Yusuff, 2019), rubber leaf (Nag, 2015), barley straw (Pehlivan, 2012), sugarcane bagasse (Razi, 2018), walnut shell (Ghasemi, 2015), peanut shell (Ali, 2016), rape seed (Morosanu, 2017), soya bean seed (Gaur, 2018), aloe vera leaf (Malik, 2015) neem leaves (Pawar, 2018a), rice husk (Agrafioti, 2014). Carbonization increases surface area, pore size and volume, surface functional group leading to high metal adsorption capacity (Norshila, 2021). Lignocellulose based adsorbents are mainly made up of cellulose 30–35%, lignin 15–25%, hemicellulose 20–40% (Muktham, 2016). The main functional group in a carbonized precursor is pectin which contains key functional group are hydroxyl, carboxyl and methoxyl. The hydroxyl group binds heavy metals which subsequently enhances or increases metal adsorption capacity (Liu, 2019; Gupta, 2020).

Water hyacinth (*Eichhornia crassipes* (Mart.) Solms 1883) is an invasive pan tropical aquatic weed and belongs to the family of Pontederiaceae (Barret, 1988; Pellegrini, 2018). In 1993, it was discovered at Lake Victoria basin, Kenya (Kateregga, 2009). The weed has reemerged rapidly as a result of climate change impact and anthropogenic activities (Albright, 2004). Its rapid spread is attributed to increasing effluent release from sewer facilities, rural agriculture and local industries (Opande, 2004; Pellegrini, 2018). This has led to high nutrient level exacerbating rapid growth and invasion of water hyacinth (Luilo, 2008). Water hyacinth infestation gives rise to anoxic conditions thus inhibiting decomposition of organic matter and subsequent fish decline (Champion and Tanner, 2000; Toft, 2003; Hestir, 2015). Current conventional control methods which include mechanical, biological and chemical methods have been applied but proven to be ineffective and unsustainable due to their rapid multiplication within short period of time (Hill, 1999; Julien, 2000; Hestir, 2015). Therefore, a sustainable abatement method is necessary in the long term.

Previous studies have demonstrated the potential ability of water hyacinth adsorbent in metal removal. This research study explored the effect of carbonization on the surface and subsequent influence on heavy metal removal by water hyacinth stem. Prior to its application in wastewater treatment, an understanding of its physio-chemical properties and subsequent influence on heavy metal adsorption is necessary. Langmuir isotherm adsorption model was applied to depict metal adsorption at equilibrium.

2. Material and methods

2.1 Adsorbent preparation and characterization

Dried water hyacinth stem was obtained from Lake Victoria, Kenya. During adsorbent preparation, 10 g of dried water hyacinth stem was weighed by Precisa XT 220 A and placed in the muffle furnace (Bello, 2017) at 200 °C for 1 h. The carbonized sample was then placed in a desiccator to cool down and washed with distilled water. It was then dried in a drying oven at 105 °C. Thereafter the sample was then grinded and sieved to fine particles using pestle and mortar and the testing sieve (400 μm and 0.25 mm) respectively (Bulta and Michael, 2019).

Elemental analysis was carried out using Elemental Analyzer, Flash 2000 Thermo-fisher (Januszewicz, 2020). Proximate experiment was conducted as follows: 1 g of dried water hyacinth stem was placed in a crucible covered with lid and then dried in a drying oven. A temperature of 900 °C the crucible was placed in the furnace for 15 min to determine the volatile matter content, then the sample was cooled in a desiccator. On the other hand, ash content was determined at 900 °C for 1 h at constancy, after which the sample was cooled in a desiccator. Fixed carbon was calculated as shown in Eq. (1):

$$\text{Fixed carbon dry} = 100 - (\text{Volatile content} + \text{Ash content}) \tag{1}$$

Brunauer Emmett Teller (BET) surface area, Autosorb IQ, Quanta chrome (Stehmann, 2017) was used to estimate adsorbent surface area, pore size diameter and volume. The samples were treated by outgas method at 100 °C for 4 h. The pore volume and surface area of the adsorbent was obtained from the amount of N_2 adsorbed at relative pressure P/Po of 0.999, t-Method by de Boer.

Background spectrum analysis was carried out with no sample. It was then uniformly spread on the crystal surface. The clamp was adjusted to hold the sample firmly and then analyzed. After analysis the sample was cleaned using non-abrasive material. Resolution and wavenumber setting was 4–8 cm^{-1} and 4000–400 cm^{-1} (Bello, 2017).

The sample was dried in a drying oven at 110 °C, then it was mounted onto a substrate with a conductive material. The sample specimen was coated with a thin film of conductive material since it is non-conductive material. The coating was performed by vacuum evaporation to obtain a uniform thickness during scanning of the sample (Januszewicz, 2020).

2.2 Research design

2.2.1 Batch adsorption design. The stock solution of 1 g/l of Zn, Cd and Pb was prepared by dissolving 1 g of $ZnCl_2$, $CdCl_2$, $PbCl_2$ obtained from Duksan Pure Chemicals in 1000 ml conical flask using distilled water. The sample solution was then mixed by Magnetic stirrer (Jenway 1,000) (Abdolmohammad Zadeh, 2020) for 30 min. Thereafter the standard solution was further diluted with distilled water between 0.1 and 50 mg/l solution for adsorption studies.

Adsorption isotherm was carried out in by adding 1 g of carbonized water hyacinth stem into 100 ml solution with initial concentration of Zn, Pb and Cd ranging from 0.1 to 50 mg/l in duplicate. The initial pH value was 4. The flasks were agitated in a shaking incubator (VS-8480 F) at 25 °C from 15 min to 5 h. The solution pH was controlled using 0.1 N HCl or 0.1 N NaOH and mixed with magnetic stirrer. After adsorption, the solution was filtered using MF membrane filters, Millipore 0.45 μm prior to heavy metal analysis by ICP, PerkinElmer Optima 2100DV (Shahbazi, 2019). The heavy metal adsorption capacity (q_e) and removal rate % of carbonized water hyacinth stem were calculated in Eqs (2) and (3) respectively (Sabir, 2020). The adsorption data were analyzed using Minitab 17 software and presented using graphs and table:

$$\text{Removal rate } \% = \frac{(C_o - C_e)}{C_o} \times 100 \tag{2}$$

$$\text{Adsorption capacity } q_e = \frac{(C_o - C_e)V}{M\ (g)} \tag{3}$$

where C_e represents equilibrium concentration and C_o is the initial concentration and $M\,(g)$ is the mass of the adsorbent. Studies on the effect of surface area, pore size and volume, surface functional group were performed in the range of 5–8 pH, 0.2–1 g/100 ml adsorbent dosage, 1 h contact time and 30 °C temperature.

Langmuir adsorption isotherm model was applied for linear regression analysis to describe (correlation coefficient, R^2) heavy metal adsorption at equilibrium. Langmuir model is an adsorption isotherm model that assumes mono-molecular layer is formed when adsorption occurs and no interaction between adsorbed molecules (Langmuir, 1918). The Langmuir isotherm model in linear form is expressed as shown in Eq. (4):

$$\frac{C_e}{q_e} = \frac{1}{q_b} + \frac{C_e}{q} \tag{4}$$

b is the Langmuir constant which represents adsorption energy, q_e is the adsorption capacity at equilibrium, C_e is the metal concentration at equilibrium (mg/l) and q is the monolayer adsorption capacity. The Langmuir adsorption in dimensionless form R_L is expressed in Eq. (5):

$$R_L = \frac{1}{1 + k_L C_o} \tag{5}$$

$R_L > 1$ means adsorption is unfavorable, $R_L = 1$ adsorption is linear, if it is between $0 < R_L > 1$ means adsorption is favorable while $R_L = 0$ means adsorption is irreversible.

3. Results and discussion

3.1 Proximate and elemental analysis

Results obtained on proximate and elemental analysis (Table 1), revealed no presence sulphur content in the carbonized adsorbent washed with deionized water. In addition, a 5% increase in carbon content was observed which was due to the removal of impurities (organic materials). As a result, the carbon content of an adsorbent is not only dependent on the raw material but the preparation process (Norshila, 2021).

Parameters	Values %
Moisture content	4.93
Ash content	14.01
Volatile matter content	22.41
$Carbon_w$	48.83
$Carbon_{nw}$	44.53
Compressive strength	9.0 MPa
Hydrogen	3.88
$Sulphur_w$	0
$Sulphur_{nw}$	0.13

Note(s): $Carbon_w$ -carbon obtained from carbonized WH stem washed with deionized water
$Carbon_{nw}$ -carbon obtained from carbonized WH stem not washed with deionized water
$Sulphur_w$ -Sulphur obtained from carbonized WH stem washed with deionized water
$Sulphur_{nw}$-Sulphur obtained from carbonized WH stem not washed with deionized water

Table 1.
Physio-chemical analysis of carbonized water hyacinth (WH) stem

3.1.1 BET surface area. Table 2 reveals high BET surface area for carbonized WH stem 328.9 m^2/g compared to the dry WH stem 58.46 m^2/g. In addition, high total pore volume 0.07 cc/g and pore size of 7.557 Å was also observed in carbonized WH stem. This was attributed to the breakdown of strong covalent bond that holds the lignocellulose structure during carbonization (Benaddi, 2000; Muktham, 2016).

3.1.2 Surface chemistry. The Fourier transform infrared spectroscopy (FTIR) spectra of carbonized WH stem is illustrated in Figure 1. The adsorbent *r*-stretching at 3,429 cm^{-1} was due to OH group while 2918.99 cm^{-1} is attributed to aliphatic group (C-H) (Kennedy, 2005; Hastuti, 2017). The band at 1,619.04 cm^{-1} represents C=C stretch while weak bands appearing at 1,318.39–591.59 cm^{-1} is attributed to C=O and C-O stretching (Biniak, 1999; Liu, 2019). Negatively charged OH group has a great influence on the surface chemistry of adsorbent. During adsorption the positively charge metal ions are easily held by hydroxyl group due to electrostatic forces (Benaddi, 2000; Gupta, 2020).

3.1.3 Pore structure. Figure 2 demonstrates the pore structure of carbonized WH stem. The SEM image shows the pore structure of the adsorbent at magnification of 50 µm. The formation of mesopore is attributed to carbonization process which resulted in the breakdown of covalent bonds in the lignocellulose structure (Xu, 2014). The large mesopore size is able to hold large molecule size compared to micropore structure (Radovic, 2001; Kaykhaii, 2018; Contescu, 2018).

3.2 Metal adsorption with synthetic wastewater

3.2.1 Effect of metal concentration. Figure 3 reveals that metal removal rate decreased with an increase in initial heavy metal concentration. At the initial concentration of 0.1 mg/l the

Samples	Surface area m^2/g	Total pore volume cc/g	Pore size Å
Dry WH stem	58.46	0.01	1.44
Carbonized WH stem	328.9	0.07	7.557

Table 2.
Carbonized WH stem surface area and pore size

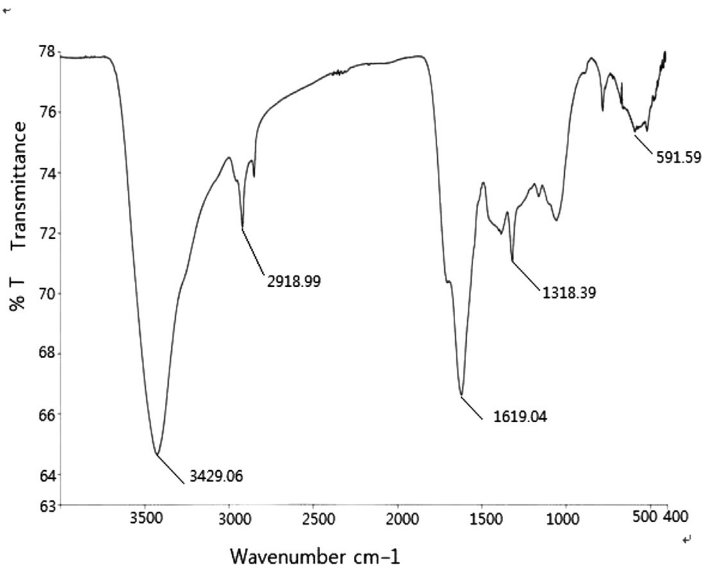

Figure 1.
FTIR spectrum of carbonized Water hyacinth (WH) stem

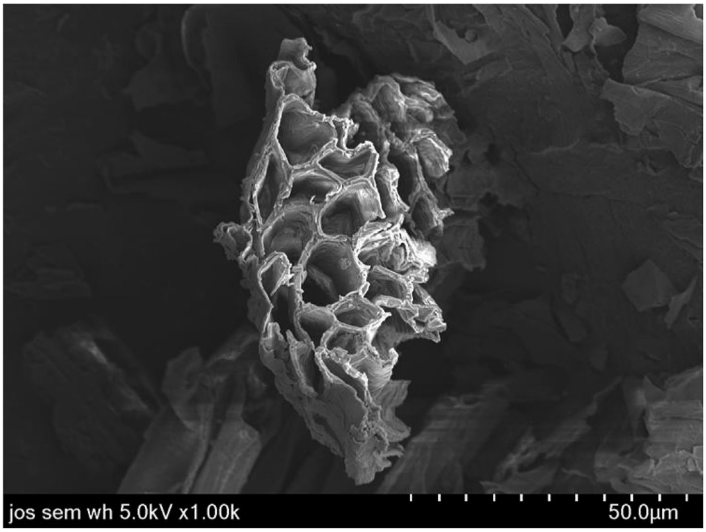

Figure 2.
SEM image of carbonized WH stem

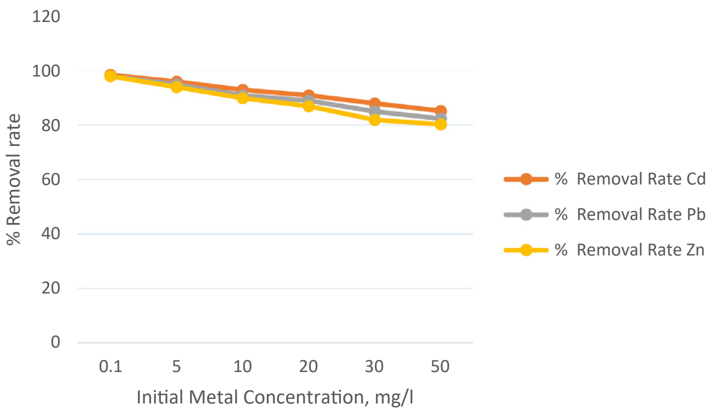

Figure 3.
Effect of Initial concentration on Pb, Zn, Cd adsorption by Carbonized WH stem (Conditions: C_o = 0.1–50 mg/l, Adsorbent dose 0.4 g/100 ml, Temp = 30 °C, Time = 1 h)

percentage removal rate for Cd, Pb and Zn was 99%, however when the initial concentration increased to 50 mg/l the removal rate gradually decreased to 85.26, 82.41 and 80.31% respectively. High removal rate at initial 0.1 mg/l was due to the high driving force that led to mass transfer of metal ions to adsorbent surface and also sufficient number of available active sites and pore volume. As the initial concentration increased to 50 mg/l the adsorption of metal ions was limited by the few available active sites (Aroua, 2008; Maduabuchi, 2018).

3.2.2 Effect of surface area and pore volume. Figure 4 demonstrated that adsorption capacity increased with increasing adsorbent dose. An increase in the amount of adsorbent dosage 0.2–1 g was accompanied by high removal rate of Pb, Zn and Cd ions increasing from approximately 80% to a maximum 100%. At 0.4 g adsorbent dose, the number of available active sites, pore volume and surface area increased leading to high adsorption capacity whereas at initial 0.1 g adsorbent dose adsorption of metal ions was limited by the few available active sites, pore number and small surface area (Guo and Lua, 2003; Xu, 2014; Kaykhaii, 2018).

3.2.3 Effect of surface functional group. Figure 5 reveals at pH 5 maximum removal rate of 99.6, 99.08 and 99% for Cd, Pb and Zn respectively was achieved. As the pH increased 5–8, the metal removal rate gradually decreased to 88.14, 81.12 and 73.98% respectively. At pH 5, maximum adsorption was attained due to low competition between the positively charged metal ions and negatively charged OH group, however at pH above 8 metal removal rate decreased due to precipitation of metal ions (Hastuti, 2017). Previous studies have shown that at low pH in the range 1–3 there is low metal uptake due to competition between H_3O^+ and metal ions leading to hydrolysis (Gupta, 2020).

3.3 Langmuir isotherm model

Figure 6 illustrates a graph of Langmuir isotherm for Pb, Cd and Zn ions adsorption by carbonized water hyacinth adsorbent. It was determined that the correlation coefficient, R^2 for Langmuir isotherm model was closer to 1 as illustrated in Table 3. This satisfies the Langmuir model assumptions. From the results analyzed, it demonstrates that Langmuir

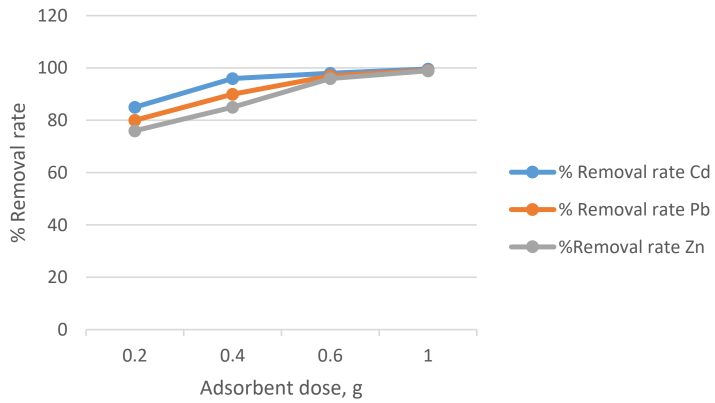

Figure 4.
Effect of surface area and pore size on Pb, Zn and Cd adsorption by carbonized WH stem (Conditions: C_o = 50 mg/l, T = 30 °C, Time = 1 h)

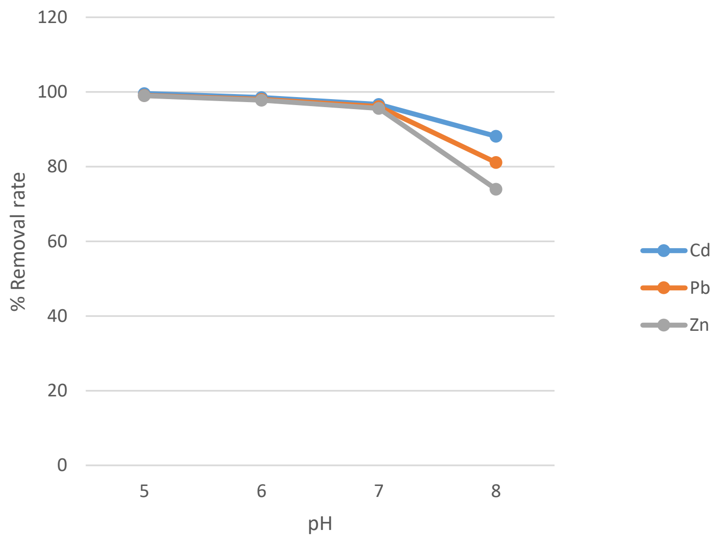

Figure 5.
Effect of surface functional group on Pb, Zn, Cd adsorption by carbonized WH stem (C_o = 50 mg/l, Adsorbent dose 1 g/100 ml, T = 30 °C, Time = 1 h)

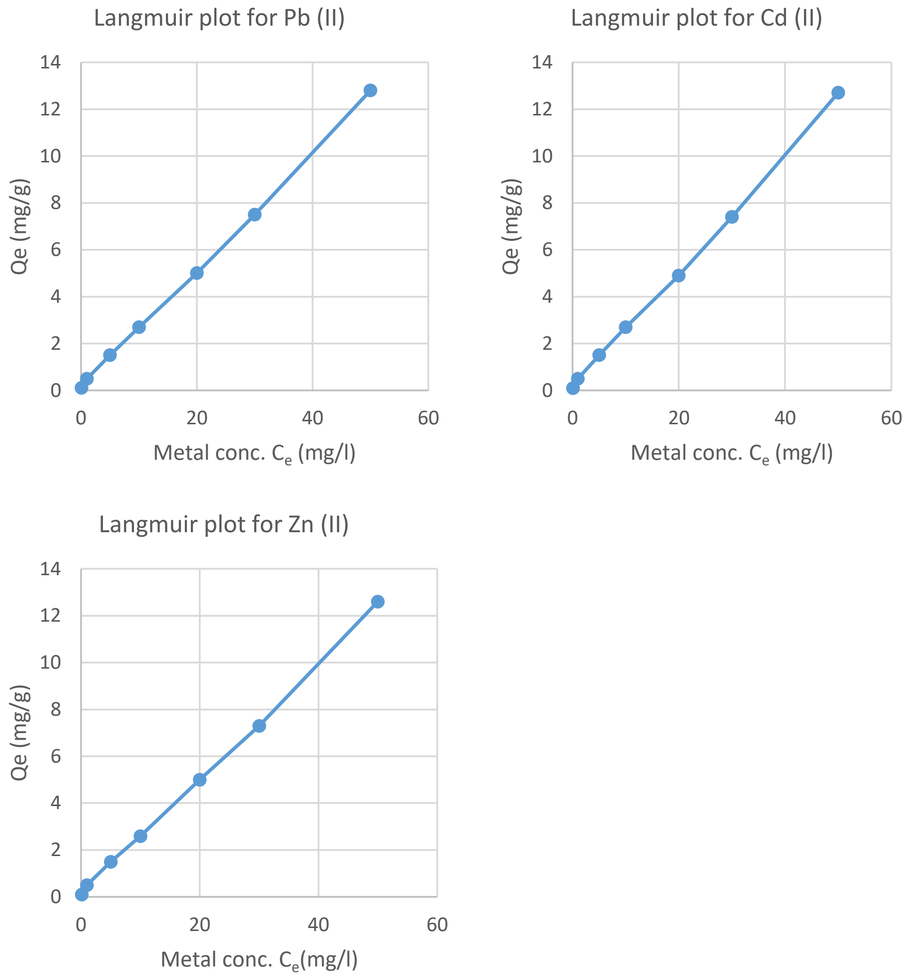

Figure 6.
Langmuir isotherm plot for Pb (II), Cd (II) and Zn (II) ions adsorption

Table 3.
Langmuir isotherm for Pb (II), Cd (II) and Zn (II) adsorption

Metal ions	q_e (mg/g)	b l/mg	R^2	R_L
Pb	12.263	0.005	0.999	0.801
Cd	12.304	0.013	0.999	0.607
Zn	12.213	0.230	0.999	0.871

isotherm was effective in evaluating the adsorption capacity of Pb, Cd and Zn metal ions by carbonized water hyacinth stem (Aboul-Fetouh, 2010; Saltabas, 2012).

4. Conclusion

Water hyacinth is an invasive aquatic weed which has become highly impractical to manage from aquatic systems, though its metal biosorption and adsorption potential has given a possible way for application in wastewater management. In this study, the effects of carbonization on the surface and influence on heavy metal adsorption by water hyacinth stem was investigated. Based on the experimental data obtained the conclusion was that, metal removal was dependent on physio-chemical characteristics and metal ion species. The adsorbent high surface area (328.9 m^2/g), total pore volume (0.07 cc/g), pore size (7.557 Å) and main functional group OH 3429.08 cm^{-1} had a great influence on adsorption capacity of Zn, Cd and Pb in synthetic wastewater. Adsorption process was also pH dependent, and the maximum removal rate of Pb, Zn and Cd was pH 5 at low metal concentration. Pb, Zn and Cd ion removal rate from synthetic wastewater decreased with increasing initial concentration from 0.1 to 50 mg/l. As the initial concentration increased, the adsorption of metal ions was limited by available active sites. Furthermore, adsorbent dosage dose of 1 g with metal concentration at 50 mg/l led to 99% metal removal rate. This occurred as result of increase in surface area and available active sites.

There is limited study carried out on direct application of carbonized water hyacinth stem at industrial scale particularly using wastewater effluent from various industries. This is probably due to complex nature of industrial effluent containing both organic and inorganic chemicals. Further research is necessary to obtain high metal removal efficiency in wastewater management plants with respect to modification in physio-chemical properties of water hyacinth adsorbent or the design system and its parts that can be researched further.

References

Abdolmohammad Zadeh, H.S. (2020), "A magnetic adsorbent based on salicylic acid-immobilized magnetite nano-particles for pre-concentration of Cd(II) ions", *Frontiers of Chemical Science and Engineering*, Vol. 15 No. 2, doi: 10.1007/s11705-020-1930-0.

Aboul-Fetouh, M.E.-K.-A. (2010), "Water hyacinth stems a potential natural adsorbent for the adsorption of acid green 20 dye", *Environmental science*, Vol. 5 No. 4, pp. 257-266.

Agrafioti, E.K. (2014), "Ca and Fe modified biochars as adsorbents of arsenic and chromium in aqueous solutions", *Journal of Environmental Management*, Vol. 146, pp. 444-450, doi: 10.1016/j.jenvman.2014.07.029.

Ajmi, R.N. (2018), "Bioabsorbent of chromium, cadmium and lead from industrial waste water by waste plant", *Journal of Pharmaceutical Sciences and Research*, Vol. 10 No. 3, pp. 672-674.

Al-Gheethi, A.A. (2015), "Removal of heavy metals and antibiotics from treated sewage effluent by bacteria", *Clean Technologies and Environmental Policy*, Vol. 17 No. 8, pp. 2101-2123, doi: 10.1007/s10098-015-0968-z.

Albright, T.M. (2004), "The rise and fall of water hyacinth in Lake Victoria and the Kagera river basin 1989-2001", *Journal of Aquatic Plant Management*, Vol. 42, pp. 73-84.

Ali, R.H. (2016), "Potential of using green adsorbent of heavy metal removal from aqueous solutions: adsorption kinetics, isotherm, thermodynamic, mechanism and economic analysis", *Ecological Engineering*, Vol. 91, pp. 317-332.

Ali, H.A.-S. (2017), "Removal of some heavy metals from aqueous solutions using natural wastes orange peel activated carbon", *Journal of Applied Sciences*, Vol. 3 No. 3, pp. 13-30.

Alka, S.S. (2021), "Arsenic removal technologies and future trends: a mini review", *Journal of Cleaner Production*, Vol. 278, pp. 1-14, doi: 10.1016/j.jclepro.2020.1.

Alyuz, B. and Veli, S. (2009), "Kinetics and equilibrium studies for the removal of nickel and zinc from aqueous solutions by ion exchange resins", *Journal of Hazardous Materials*, Vol. 167, pp. 482-488.

Aroua, M.L. (2008), "Real-time determination of kinetics of adsorption of lead (II) onto palm shell-based activated carbon using ion selective electrode", *Bioresource Technology*, Vol. 99, pp. 5786-5792.

Asante-Badu, B.K. (2020), "Phytoremediation of organic and inorganic compounds in a natural and an agricultural environment: a review", *Applied Ecology and Environmental Research*, Vol. 18 No. 5, pp. 6875-6904.

Barret, S. (1988), "Evolution of breeding systems in Eichhorniae (Pontederiaceae): a review", *Annals of Missouri Botanical Garden*, Vol. 75 No. 3, pp. 741-760.

Bello, O.A. (2017), "Preparation and characterization of a novel adsorbent from Moringa oleifera leaf", *Applied Water Science*, Vol. 7, pp. 1295-1305, doi: 10.1007/s13201-015-0345-4.

Benaddi, H. (2000), "Surface functionality and porosity of activated carbon obtained from chemical activation of wood", *Carbon*, Vol. 38 No. 5, pp. 669-674, doi: 10.1016/S0008-6223(99)00134-7.

Biniak, S.P. (1999), "Effect of activated carbon surface oxygen and/or nitrogen-containing groups on adsorption of copper (II) ions from aqueous solution", *Langmuir*, Vol. 15, pp. 6117-6122.

Bratskaya, S.Y., Pestov, A.V., Yatluk, Y.G. and Avramenko, V.A. (2009), "Heavy metals removal by flocculation/precipitation using N-(2-carboxyethyl) chitosans", *Colloids and Surfaces*, Vol. 339, pp. 140-144.

Bulta, A.L. and Micheal, G.A.W. (2019), "Evaluation of the efficiency of ceramic filters for water treatment in Kambata Tabaro zone, Southern Ethiopia", *Environmental Systems Research*, Vol. 8 No. 1, doi: 10.1186/s40068-018-0129-6.

Champion, P.D. and Tanner, C.C. (2000), "Seasonality of macrophytes and interaction with flow in a New Zealand lowland stream", *Hydrobiologia*, Vol. 441, pp. 1-12.

Chang, Q. and Wang, G. (2007), "Study on the macromolecular coagulant PEX which traps heavy metals", *Chemical Engineering Science*, Vol. 62, pp. 4636-4643.

Contescu, C.I. (2018), "Activated carbons derived from high-temperature pyrolysis of lignocellulosic biomass", *Journal on Carbon Research*, Vol. 4 No. 51, pp. 1-16, doi: 10.3390/c4030051.

El Samrani, A.G.L.B. (2008), "Chemical coagulation of combined sewer overflow: heavy metal removal and treatment optimization", *Water Research*, Vol. 42, pp. 951-960.

Farraji, H.Z. (2016), "Advantages and disadvantages of phytoremediation: a concise review", *International Journal of Environmental Science and Technology*, Vol. 2, pp. 69-75.

Figoli, A.C.A. (2010), "Influence of operating parameters on the arsenic removal by nanofiltration", *Water Research*, Vol. 44, pp. 97-104.

Fu, F.W. (2011), "Removal of heavy metal ions from wastewaters: a review", *Journal of Environmental Management*, Vol. 92 No. 3, pp. 407-418, doi: 10.1016/j.jenvman.2010.11.011.

Gaur, N.K. (2018), "Adsorptive removal of lead and arsenic from aqueous solution using soya bean as a novel biosorbent: equilibrium isotherm and thermal stability studies", *Applied Water Science*, Vol. 8 No. 4, pp. 1-12, doi: 10.1007/s13201-018-0743-5.

Ghasemi, M.G. (2015), "Synthesis of a high characteristics activated carbon from walnut shell for the removal of Cr (VI) and Fe (II) from aqueous solution: single and binary solutes adsorption", *Iranian Journal of Chemistry and Chemical Engineering*, Vol. 12 No. 4, pp. 28-51.

Global Adsorbent Market Report (2021), Global Adsorbent Market Report, available at: https://www.theexpresswire.com/pressrelease/Global-Adsorbent-Market-Report-2021-2026-With-Top-Countries-Data-Research-Reports-Industry-Size-In-Depth-Qualitative-Insights-Explosive-Growth-Opportunity-Regional-Analysis-With-Covid-19-Analysis_12699771.

Guo, M.X.Q.G. (2010), "Poultry litter-based activated carbon for removing heavy metal ions in water", *Waste Management*, Vol. 30, pp. 308-315.

Guo, J.L. and Lua, A.C. (2003), "Textural and Chemical properties of adsorbent prepared from palm shell by phosphoric acid activation", *Materials Chemistry and Physics*, Vol. 80, pp. 114-119.

Gupta, V.K.A.S. (2011a), "Synthesis and characterization of alumina coated carbon nanotube and their application on lead removal", *Journal of Hazardous Materials*, Vol. 185 No. 15, pp. 17-23.

Gupta, V.K.J.R. (2011b), "Removal of the hazardous dye-tartrazine by photodegradation on titanium dioxide surface", *Materials Science and Engineering C*, Vol. 31, pp. 1062-1067.

Gupta, S.S. (2020), "Latest trends in heavy metal removal from wastewater by biochar based sorbents", *Journal of Water Process Engineering*, Vol. 38, p. 101561, doi: 10.1016/j.jwpe.2020.101561.

Hastuti, B.T. (2017), "Gree adsorbent of pectin from carrot peel and its application as removal of Pb (II)", *Proceedings of Researchfora International Conference*, pp. 4-7.

Heidmann, I.C.W. (2008), "Removal of Zn(II), Cu(II), Ni(II), Ag(I) and Cr(VI) present in aqueous solutions by aluminium electrocoagulation", *Journal of Hazardous Materials*, Vol. 152, pp. 934-941.

Hestir, E.L.B.V. (2015), "11 Measuring freshwater aquatic ecosystems: the need for a hyperspectral global mapping satellite mission", *Remote Sensing of Environment*, Vol. 167, pp. 181-195.

Hill, M.J. (1999), *Proceedings of the First IOBC Global Working Group Meeting for the Biological and Integrated Control of Water Hyacinth*, ARC-PPRI, Pretoria, pp. 25-29.

Januszewicz, K.K.P. (2020), "Activated carbon produced by pyrolysis of waste wood and straw for potential wastewater adsorption", *Materials (Basel)*, Vol. 13 No. 9, p. 2047, doi: 10.3390/ma13092047.

Julien, M.H. (2000), "Proceedings of the second meeting of global working group for the biological and integrated control of water hyacinth", *ACIAR, Canberra, Australia proceedings*, Vol. 102, ACIAR, Canberra, Australia, pp. 89-95.

Karimifard, S.A. (2018), "Application of response surface methodology in physicochemical removal of dyes from wastewater: a critical review", *Science of the Total Environment*, Vols 640-641, pp. 772-797, doi: 10.1016/j.scitotenv.20.

Kateregga, E.S. (2009), "Lake Victoria fish stocks and the effects of water hyacinth", *Journal of Environment and Devolpment*, Vol. 18 No. 1, pp. 62-78.

Kaykhaii, M.S. (2018), "Removal of dyes from the environment by adsorption process", *Chemical and Materials Engineering*, Vol. 6 No. 2, pp. 31-35, doi: 10.13189/cme.2018.060201.

Kennedy, L.V. (2005), "Electrical conductivity study of porous carbon composite derived from rice husk", *Materials Chemistry and Physics*, Vol. 91, pp. 471-476.

Kongsuwan, A.P.P. (2009), "Binary component sorption of Cu(II) and Pb(II) with activated carbon from Eucalyptus camaldulensis Dehn bark", *Journal of Industrial and Engineering Chemistry*, Vol. 15, pp. 465-470.

Ku, Y.J.I. (2001), "Photocatalytic reduction of Cr(VI) in aqueous solutions by UV irradiation with the presence of titanium dioxide", *Water Research*, Vol. 35, pp. 135-142.

Kumar, P.A. (2012), "Status of adsorptive removal of dye from textile industry effluent", *Desalination and Water Treatment*, Vol. 50 Nos 1-3, pp. 226-244, doi: 10.1080/19443994.2012.719472.

Landaburu-Aguirre, J.G.´ (2009), "The removal of zinc from synthetic wastewaters by micellarenhanced ultrafiltration: statistical design of experiments", *Desalination*, Vol. 240, pp. 262-269.

Langmuir, I. (1918) "The adsorption of gases on plane surface of glass, mica and platinum", *Journal of the American Chemical Society*, Vol. 40 No. 9, pp. 1361-1402, doi: 10.1021/ja02242a004.

Liu, L.G. (2019), "Adsorption behaviours and mechanisms of heavy metal ions' impact on municipal waste composts with different degree of maturity", *Environmental Technology*, Vol. 40 No. 22, pp. 2962-2976, doi: 10.1080/09593330.2018.1458908.

Luilo, G. (2008), "Lake Victoria water resources management challenges and prospects: a need for equitable and sustainable institutional and regulatory frameworks", *African Journal of Aquatic Science*, Vol. 33, pp. 105-113.

Maduabuchi, M. (2018), "Agricultural waste materials as a potential adsorbent for removal of heavy metals in waste water", *Journal of Waste Management and Xenobiotics*, Vol. 1 No. 1, pp. 1-4.

Malik, R.L. (2015), "Removal of heavy metal from waste water by the use of modified aloe leaf powder", *International Journal of Basic and Applied Chemical Sciences*, Vol. 5 No. 2, pp. 6-17.

Malik, D.J. (2017), "Removal of heavy metals from emerging cellulosic low-cost adsorbents: a review", *Applied Water Science*, Vol. 7 No. 5, pp. 2113-2136, doi: 10.1007/s13201-016-0401-8.

Mohsen-Nia, M.M.P. (2007), "Removal of Cu2? and Ni2? from wastewater with a chelating agent and reverse osmosis processes", *Desalination*, Vol. 217, pp. 276-281.

Morosanu, I.T. (2017), "Biosorption of lead ions from aqueous effluents by rapeseed biomass", *New Biotechnology*, Vol. 39, pp. 110-124, doi: 10.1016/j.nbt.2016.08.002.

Muktham, R.B. (2016), "A review on 1st and 2nd generation bioethanol production- recent progress", *Journal of Sustainable Bioenergy Systems*, Vol. 6 No. 3, pp. 72-92, doi: 10.4236/jsbs.2016.63008.

Murthy, Z.P.C.L. (2008), "Application of nanofiltration for the rejection of nickel ions from aqueous solutions and estimation of membrane transport parameters", *Journal of Hazardous Materials*, Vol. 160, pp. 70-77.

Muthukrishnan, M.G.B. (2008), "Effect of pH on rejection of hexavalent chromium by nanofiltration", *Desalination*, Vol. 219, pp. 171-178.

Nag, S.M. (2015), "Removal of chromium(VI) from aqueous solutions using rubber leaf powder: batch and column studies", *Desalination and Water Treatment*, Vol. 57 No. 36, pp. 16927-16942, doi: 10.1080/19443994.2015.1083893.

Nguyen, C.M.B.S. (2009), "Performance and mechanism of arsenic removal from water by a nanofiltration membrane", *Desalination*, Vol. 245, pp. 82-94.

Norshila, A.B.N.O. (2021), "An insight review of lignocellulosic materials as activated carbon precorsor for textile wastewater treatment", *Environmental Technology and Innovation*, Vol. 22 No. 6, p. 101445, doi: 10.1016/j.eti.2021.101445.

Opande, G.O. (2004), "Lake Victoria: the water hyacinth (Eichhornia crassipes [MART.] SOLMS), its socio-economic effects, control measures and resurgence in the Winam gulf", *Limnologica*, Vol. 34, pp. 105-109.

Park, H.G.K.T. (2007), "Activated carboncontaining alginate adsorbent for the simultaneous removal of heavy metals and toxic organics", *Process Biochemistry*, Vol. 42, pp. 1371-1377.

Pawar, P.R. (2018a), "Experimental dose optimization for Cu removal from water using neem leaves", *International Journal of Current Engineering and Technology*, Vol. 8 No. 5, pp. 1329-1332.

Pawar, P.R. (2018b), "Heavy metal toxicity, health hazards and their removal technique by natural adsorbents: a short overview", *International Journal of Current Engineering and Technology*, Vol. 8 No. 2, pp. 400-406, doi: 10.14741/ijcet/v.8.2.35.

Pehlivan, E.A. (2012), "Modified barley straw as a potential biosorbent for removal of copper ions from aqueous solution", *Food Chemistry*, Vol. 135, pp. 2229-2234, doi: 10.1016/j.foodchem.2012.07.017.

Pellegrini, M.O. (2018), "Total evidence phylogeny of Pontederiaceae (Commelinales) sheds light on the necessity of its recircumscription and synopsis of Pontederia L", *PhytoKeys*, Vol. 108, pp. 25-83, doi: 10.3897/phytokeys.108.27.

Pirkarami, A.O. (2017), "Removal of dye from industrial wastewater with an emphasis on improving economic efficiency and degradation mechanism", *Journal of Saudi Chemical Society*, Vol. 21, pp. 179-186, doi: 10.1016/j.jscs.2013.12.008.

Polat, H.E.D. (2007), "Heavy metal removal from wastewater by ion flotation", *Journal of Hazardous Materials*, Vol. 148, pp. 267-273.

Radovic, L.M.-C.-U. (2001), *Chemistry and Physics of Carbon*, Marcel Dekker, New York, p. 27.

Rasheed, A.F. (2013), "Kinetic study of metal removal using apple peels: closed batch approximation model", *International Journal of Chemical Engineering*, Vol. 4 No. 5, pp. 281-285.

Razi, M.A.-G. (2018), "Removal of heavy metals from textile wastewater using sugarcane bagasse activated carbon", *International Journal of Engineering and Technology*, Vol. 7 No. 4.30, pp. 112-115, doi: 10.14419/ijet.v7i4.30.22066.

Renu, M.A. and Agarwal, M. (2017), "Heavy metal removal from wastewater using various adsorbents: a review", *Journal of Water Reuse and Desalination*, Vol. 7 No. 4, pp. 387-419. doi: 10.2166/wrd.2016.104.

Research and Markets (2020), "Adsorbents-market-analysis", available at: https://www.industryarc.com/Report/11669/adsorbents-market-analysis.html (accessed 8 October 2020).

Roy, M.G. (2015), "Integrated phytobial remediation for sustainable management of arsenic in soil and water", *Environment International*, Vol. 75, pp. 180-198, doi: 10.1016/j.envint.2014.11.010.

Sabir, A.A.F. (2020), "Agricultural waste absorbents for heavy metal removal", in Inamuddin, A.M., Lichtfouse, E. and Asiri, A. (Eds), *Green Adsorbents to Remove Metals, Dyes and Boron from Polluted Water*, Environmental Chemistry for a Sustainable World, Vol. 49, doi: 10.1007/978-3-030-47400-3_8.

Sadrzadeha, M.M.T. (2009), "Neural network modelling of Pb2? Removal from wastewater using electrodialysis", *Chemical Engineering and Processing*, Vol. 48, pp. 1371-1381.

Sahu, O.S. (2018), *Significance of Bioadsorption Process on Textile Industry Wastewater*, Woodhead Publishing, Vol. 13.

Saleem, J.S. (2019), "Production and applications of activated carbons as adsorbents from olive stones", *Biomass Conversion and Biorefinery*, Vol. 9, pp. 775-802, doi: 10.1007/s13399-019-00473-7.

Saltabas, O.T. (2012), "Biosorption of cationic dyes from aqueous solution by water hyacinth roots", *Global Nest Journal*, Vol. 14 No. 1, pp. 24-31.

Sampera, E.R. (2009), "Removal of metal ions at low concentration by micellar-enhanced ultrafiltration (MEUF) using sodium dodecyl sulfate (SDS) and linear alkylbenzene sulfonate (LAS)", *Separation and Purification Technology*, Vol. 65, pp. 337-342.

Shahbazi, K.B. (2019), "Comparison of three methods for measuring heavy metals in calcareous soils of Iran", *Applied Sciences*, Vol. 1, p. 1541, doi: 10.1007/s42452-019-1578-x.

Shifera, L.S. (2017), "Adsorption of lead (II) and chromium (VI) onto activated carbon prepared from pineapple peel: kinetics and thermodynamic study", *Indian Journal of Chemical Technology*, Vol. 24 No. 2, pp. 145-152.

Stehmann, F.W. (2017), "Decomposition of dimethyl carbonate caused by adsorption onto activated carbon", *Adsorption*, Vol. 23, pp. 341-348, doi: 10.1007/s10450-016-9858-x.

Subbaiah, M.V.-S. (2016), "Adsorption of methyl orange from aqueous solution by aminated pumpkin seed powder: kinetics, isotherms, and thermodynamic studies", *Ecotoxicology and Environmental Safety*, Vol. 128, pp. 109-117, doi: 10.1016/j.ecoenv.2016.02.016.

Toft, J.D.S.C. (2003), "The effects of introduced water hyacinth on habitat structure invertebrate assemblages and fish diets", *Estuaries*, Vol. 26, pp. 746-758.

WHO (2019), World Health Organisation- Drinking water report, available at: https://www.who.int/news-room/fact-sheets/detail/drinking-water 2019 report (accessed 24 October 2020).

Xu, H.M. (2014), "Preparation and characterization of mesoporous activated carbon from alligator weed with H3PO4", *Advanced Materials Research*, Vol. 936, pp. 868-874, doi: 10.4028/www.scientific.ne.

Yusuff, A.S. (2019), "Adsorption of hexavalent chromium from aqueous solution by leucaena leucocephala seed pod activated carbon: equilibrium, kinetic and thermodynamic studies", *Arab Journal of Basic and Applied Sciences*, Vol. 26 No. 1, pp. 89-102, doi: 10.1080/25765299.2019.1567656.

Corresponding author
Joseph Nyamoko Tinega can be contacted at: tinegahj@yahoo.com