Research Article

X-ray diffractometric, scanning electron microscopy and Fourier transformed infrared spectroscopy characterization of post-remediation soil and dried water hyacinth (*Eichhornia crassipes*) roots of the Thar-Jath Oilfields, South Sudan

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Abstract

The problems of the current ecological situation in the oil-producing regions are becoming major threats. The main causes and sources of pollution have been identified, starting with the process of developing oil and gas fields and including directly extracting and processing oil and gas resources. It is noted that the main reason for the growing environmental hazard is the deterioration and depreciation of equipment and the low share of innovative activity of oil companies. This study aimed to characterize the soil and roots of dried water hyacinth before and after remediation of soil in Thar-Jath oilfields South Sudan. However, water hyacinth (*Eichhornia crassipes*) is renewable, inexpensive, and are widely available in nature, and its ability to adsorb recalcitrant pollutants with mutagenic and carcinogenic properties, including synthetic dyes and heavy metals. It could remove several heavy metals as well as some organics pollutants. X-ray diffraction (XRD) and scanning electron microscopy (SEM) were used to characterize the soil decontaminated from crude oil with fresh water hyacinth plant. Fourier transformed infrared spectroscopy (FTIR) was used to study the dried roots of water hyacinth employed in the removal of Pb^{2+} from wastewater. SEM results revealed that the soil containing contaminated oil has a very compact structure with reduced porosity before remediation, but a very loose structure with high porosity after remediation. Similarly, XRD analysis showed that only three sharp peaks occurred in the oil-contaminated soil before remediation with mica as the main mineral, but eight sharp peaks were observed in the soil sample after remediation trials with quartz as the main mineral. Results of FTIR analysis revealed that the dried roots of water hyacinth (DWHR) have many surface functional groups such as C=O, O–H, C–O which are suitable for contaminant removal from wastewater. After adsorption, it can be observed that nearly all the groups participated in adsorption, as indicated by the creation of new peaks and disappearance of others in DWHR loaded with Pb^{2+}. XRD, SEM and FTIR techniques can therefore be very effective in monitoring the effectiveness of contaminant removal from soil and wastewater treatment with fresh and dried roots of (*Eichhornia crassipes*).

Keywords: Post-remediation, Water hyacinth, FTIR, SEM, XRD

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RÉSUMÉ

Les problèmes écologiques actuels dans les régions productrices de pétrole constituent des menaces majeures. Les principales causes et sources de pollution ont été identifiées, en commençant par le processus de développement des champs de pétrole et de gaz et par la suite l'extraction et traitement des ressources pétrolières et gazières. Il est à noter que la principale cause de ce risque environnemental croissant est la détérioration et la dépréciation des équipements, ainsi que la faible part d'innovation des compagnies pétrolières. Cette étude visait à caractériser le sol et les racines de jacinthes d'eau séchées avant et après assainissement des champs pétroliers de Thar-Jath, au Soudan du Sud. Cependant, la jacinthe d'eau (*Eichhornia crassipes*) est une ressource renouvelable, peu coûteuse et largement disponible dans la nature. Sa capacité à adsorber les polluants récalcitrants avec les propriétés mutagènes et cancérigènes, notamment les colorants synthétiques et les métaux lourds, pourrait permettre d'éliminer plusieurs métaux lourds ainsi que certains polluants organiques. La diffraction des rayons X (DRX) et la microscopie électronique à balayage (MEB) ont été utilisées pour caractériser le sol décontaminé du pétrole brut par la jacinthe d'eau douce. La spectroscopie Fourier transformée infrarouge (FTIR) a été utilisée pour étudier les racines séchées de jacinthe d'eau utilisées pour l'élimination du Pb^{2+} des eaux usées. Les résultats du MEB ont révélé que le sol contaminé par le pétrole présentait une structure très compacte avec une porosité réduite avant dépollution, mais une structure très amorphe avec une porosité élevée après dépollution. De même, l'analyse DRX a montré que seuls trois pics forts étaient observés dans le sol contaminé par le pétrole avant dépollution, avec le mica comme minéral principal, tandis que huit pics forts ont été observés dans l'échantillon de sol après les essais de dépollution, avec le quartz comme minéral principal. Les résultats de l'analyse FTIR ont révélé que les racines séchées de jacinthe d'eau (DWHR) présentent de nombreux groupes fonctionnels aux surface, tels que C=O, O–H et C–O, qui sont adaptés à l'élimination des contaminants des eaux usées. Après adsorption, on observe que presque tous les groupes participent à l'adsorption, comme l'indiquent la création des nouveaux pics et la disparition d'autres dans les DWHR chargées en Pb^{2+}. Les techniques de DRX, de MEB et de FTIR peuvent donc s'avérer très efficaces pour surveiller l'efficacité de l'élimination des contaminants du sol et du traitement des eaux usées avec des racines fraîches et séchées d'*Eichhornia crassipes*.

Mots-clés : Post-remédiation, Jacinthe d'eau, FTIR, MEB, DRX

Introduction

An increase in human activities with a lack of adherence to environmental protection laws has led to the indiscriminate discharge of unwanted substances into the environment. The effect of this oilfields waste discharge results in different forms of pollution in most developing and underdeveloped countries such as South Sudan. Pollution is defined as the release of harmful unwanted materials into the environment that result from the excessive discharge of harmful gases (CO, SO2, and NO_2) and various forms of waste. These unwanted materials eventually bring out potentially hazardous elements known as "heavy metals" (major and trace) such as arsenic, lead, copper, and cadmium. These metals, when released in concentrations above acceptable levels, become toxic in the air, waters (both ground and surface), stream sediment, and soil, and they invariably enter humans through the food chain GWRTAC (1997), Singh (1997). Therefore, it is crucial to explore ways to reduce the emission of these toxic metals from industries, hospitals, households, pharmaceuticals, and oil production industries to conserve the environment from pollution Hawken et al. (2007). Environmental sustainability is the act of having responsible interaction with the environment to prevent the degradation of natural resources. Environmental sustainability allows for long-term environmental quality that pertains not only to the physical environment but also intersects with public health. The act of environmental sustainability meets the present societal needs without affecting the rights of future generations. It also ensures the assessment of the future impact of human activities and how they can be sustained Elleuch et al. (2018), Sherman et al. (2016); World

Commission on Environment and Development, (1987). Soil, stream sediments, waters (both surface and ground), and air are crucial components of the environment that become altered due to uncontrolled release of potentially hazardous elements Xie et al. (2016). These metals find their way into the soil and become contained without being exposed or washed off Khan et al., 2008, Zhang et al. (2010). From the soil, these metals then move into the groundwater through leaching. Vegetables cultivated in such soils may bioaccumulate the metals easily; thus, becoming a major environmental menace through the food chain and posing risks to public health Ji et al. (2018), Ling et al. (2007), Maslin and Maier (2000), McLaughlin et al. (2000a, 2000b). Biosorption can be defined as the ability of biological material to remove pollutants from wastewater through physical–chemical mechanisms present in its structure Ahalya et al. (2003). Some of the advantages related to the use of bio-materials in the treatment of contaminated water are the good performance to remove contaminants, low cost, relative abundance in nature, and efficiency compared to materials such as, for example, ion exchange resins Aravindhan (2007). Among the biological materials tested as adsorbents can be mentioned: peat, seaweed, chitosan, lignin, fungi, yeasts, and bacteria, among others Park et al. (2004). However, the dead biomass demonstrates an adsorption capacity equal to or higher than the living biomass, does not require a supply of nutrients, has easy regeneration, and can be stored for long periods at room temperature without the risk of deterioration Aravindhan (2007). The contaminants present in aqueous media are removed by different mechanisms that can occur in different parts of its cellular structure like complexation, coordination, chelation, ion exchange, or adsorption Volesky and Holan (1995). According to Volesky (2007), the biosorption process is associated with important functional groups present in biomolecules, the aquatic plants such as water hyacinth show potential for use in the remediation of pollutants from aquatic environment Ibrahim et al. (2007). It could be utilized in aquatic macrophytes treatment system (AMATS) which is a well-established environment protective technique as a phytoremediation procedure for removing pollutants Zhang et al. (2007). Water hyacinth, which belongs to the family *Pontederiaceae,* is a challenging and highly productive invasive aquatic plant that poses an extreme risk to ecosystems. It has also been found to have high nitrogen content, and in combination with cow dung, can be used for biogas production UN et al. (2002). Water hyacinth has high tolerance to pollution, and its heavy metal and nutrient absorption capacities qualify it for use in wastewater treatment ponds. The application of water hyacinth in effluent treatment indicates its biosorption capacity for treating wastewater, including heavy metals and some industrial effluents El-Ashtoukhy et al. (2008). Nevertheless, phytoremediation is easy to operate, cost-effective, and can convert wastewater nutrients to valuable biomass. Moreover, aquatic plants can directly absorb nutrients from wastewater and do not compete with crops for agricultural land Yonggui. Z et al. (2014). A host of aquatic plants, such as water hyacinth, duckweed, water lettuce, pennywort, Canna Lily, and reed, have been used for wastewater treatment. Numerous previous studies have shown that, among these aquatic plants, water hyacinth has the highest production rates (more than 140 t/ha/year) and the best wastewater treatment performance El-Ashtoukhy et al. (2008). However, comprehensive comparisons, including biomass production, nutrient recovery efficiency, and the utilization potential of biomass, were not assessed in these studies. Additionally, previous studies show that duckweed has the higher protein (more than 40%), starch content (more than 45%) and lower fiber content than the other aquatic plants,

thus providing it with greater utilization potential Parvathi K et al. (2007). It is indicated that, carboxyl group plays an important role in the removal of pollutants Zhu et al. (2008). Mechanism of pollution control using modified water hyacinth has re-introduced the possible interaction between the modified plant and Cd Ibrahim et al. (2007). A model is prepared in order to describe the mechanism of its interaction with the surrounding inorganic structures. Furthermore, the investigation was conducted for comparison between the plants physical as well as chemical treatment. It is shown that the crystallinity of the plant is partially enhanced after microwave heating; which means that physical treatment of the plant could enhance its atomic arrangements. Based on these studies water hyacinth could be described as cellulose like material. Recently microsphere from chitosan and dried water hyacinth was shown to be capable of potentially removing Pb^{2+} from wastewater 1.62 times higher than the dried water hyacinth Ammar et al. (2014). In this studies, FTIR, SEM, and XRD techniques are employed to investigate soil and fresh water hyacinth plant and dried water hyacinth plant roots in post-remediation processes in a selected oilfield in South Sudan with the aim to evaluate the efficacy of these remediation methods.

Materials and methods

The Study Sites (Thar-jath)

This research study was conducted in the Thar-Jath Oilfields of Unity State, South Sudan as shown in Figure 1. Thar-Jath is a town found on the Unity Plateau in the eastern part of Unity State. The Thar-Jath plateau is located between latitude 8.743947°N and longitude 30.140401°E with an estimated area of 20,591 km^2 forming the southernmost tip of the Unity State (Figure. 1a). The land-cover includes two main classes: black cotton soil (vertisol), a soil rich in montmorillonite (clay), and wetlands nearby the White Nile European Coalition on Oil in Sudan (2003). With respect to the geological setting, the study area is inside the Muglad Basin that extends for 120,000 km^2 from Sudan to South Sudan. The basin is composed of three rift cycles: Early Cretaceous (140–95 Ma), Late Cretaceous (95–65 Ma) and Paleogene (65–30Ma) and is well-known for its hydrocarbon accumulations. The largest oilfields until now discovered are Heglig and Unity (Figure 1b): the first is outside Block 5A and the second adjoins the block. Inside Block 5A we find the Mala and Thar Jath oilfields that are well known for their Nile Blend, a medium low-sulfur waxy crude oil Pedersen et al. (2014).

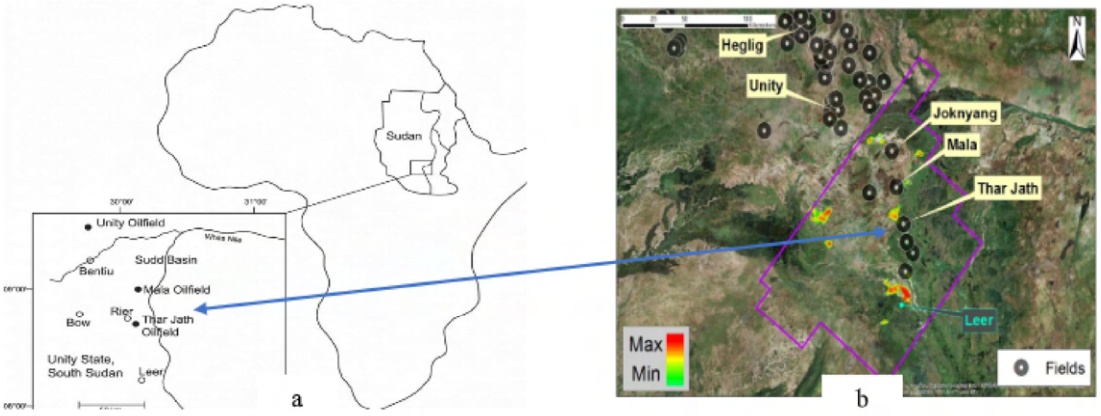


Figure 1. Location of study area in South Sudan (a) location of the studied oilfield, (b) oilfields within the Block 5A licensing block. Oilfields and micro seepage signals detected from remote sensing imagery. The scale minimum (min) and maximum (max) refers to seepages.

XRD, SEM characterization of crude oil contaminated soil before and after phytoremediation using fresh water hyacinth

Plant Collection and remediation studies

Water hyacinth (*Eichhornia crassipes*) was harvested from Nam River in Unity State by handpicking the plant during the daytime and planted in a different contaminated concentration of Crude Oil as shown in Figure 2. Freshly harvested E. crassipes were shredded in pieces using a knife after washing with clean water following Friest et al. (2006). Before that, the collected plant sample was oven-dried at 80°C and ground into powder using a grinding mill.

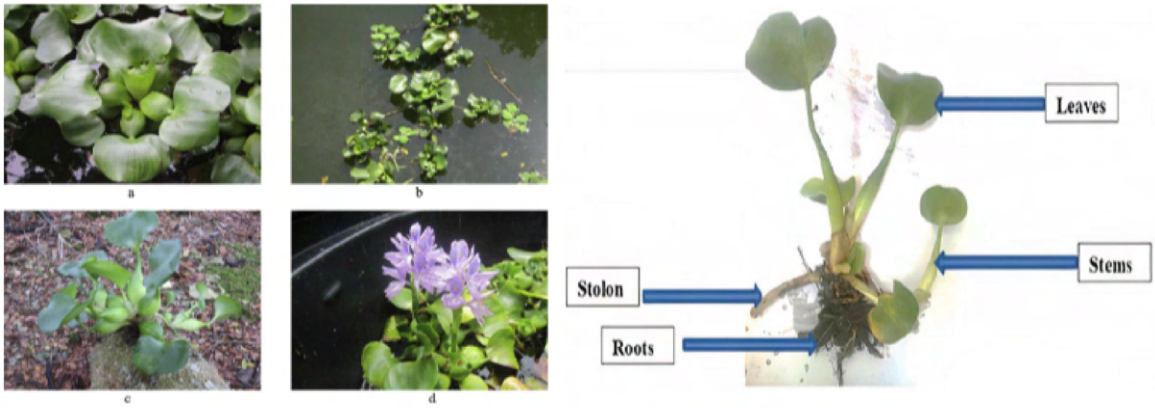


Figure 2. Eichhornia crassipes (Source: the Authors)

Soil sampling before and after remediation for XRD analysis

Soil samples was collected at a depth not exceeding 30 cm in Thar-Jath oilfield (Fig. 1a), before and after remediation trials. Portions of soils were collected using the non-metallic plastic shovel and introduced in to polythene bags for storage by decantation. The samples were appropriately labeled on the spot to avoid mix-ups, and then used for XRD analysis without any further treatment.

Scanning electron micrograph (SEM) and X-ray diffraction (XRD) analysis

The microstructure of the compacted soil was investigated by SEM. Small specimens with a volume of 1cm -2cm^3 were taken from the sample. Freeze drying was selected for the study as an alternative to oven drying to prevent as much as possible the effect of shrinkage during drying on the sample microstructure. Soil pieces were quickly frozen with liquid nitrogen (temperature of -196) and then placed in a freeze-drier for the sublimation of water. The samples were coated with gold for study with SEM HITACHI SX50 (LaB6) equipped with an energy dispersive X-ray spectrometer (Quantum 200) coupled with Bruker detector SDD X-Flash. The microscope was operated at an accelerated voltage of 15Kv. The mineral phases present were analyzed by X-ray Diffraction technique. The multipurpose X-ray diffractometer (Bruker D8 Advance Powder X-ray Diffractometer) operated at a voltage of 40 kV, and a current of 40 mA under CuK± radiation was used. Data was collected at 2, angle ranging from 10 to 80°. The peaks obtained were compared to sample XRD patterns of water hyacinth plant in literature for identification.

FTIR Characterization of dried water hyacinth roots before and after its use in Lead Ions removal from wastewater

Plant sampling and treatment for Pb^{2+} removal from wastewater

Water hyacinth (*Eichhornia crassipes*) was harvested from Nam River in Unity State by handpicking the plant during the daytime. The Freshly harvested

E. crassipes were washed with clean water, then oven-dried at 80°C. The dried roots were separated using a knife, ground into fine powder using a grinding mill and used for the removal of Pb^{2+} from wastewater. The choice of lead was based on the study of Pragsta et al. (2017), who reported very high concentrations of lead and barium in water and hairs of the rural population in the Thar-Jath oilfields in South Sudan caused by the presence of drilling muds barite ($BaSO_4$) and galena (PbS). Pb^{2+} sorption experiments by dried water hyacinth root (DWHR), were carried out at room temperature (25 ± 2 °C) in 500mL beaker using a rotatory shaker at 150 rpm at fixed adsorbent dose. After agitation, the synthetic solutions were filtered after stirring using Whatman filter paper No. 40 (8 ¼m particle retention). The filtration was done to separate the dried root biomass from the synthetic solution. Dried roots before and spent (after Pb^{2+} sorption) were dried overnight in a vacuum drying oven (Labtech) and used for FTIR analysis.

Fourier Transform Infrared Spectroscopy (FTIR) analysis of DWHR before and after Pb(II) sorption

JASCO FTIR 430 Fourier Transform Infrared Spectrometer was used for recording the obtained IR spectra. Spectra were recorded in a spectral range of 4000-400 $cm^{"1}$, resolution of 4 $cm^{"1}$ and scanned speed of 2 mm/s. The samples were also introduced as KBr pellet.

Results & Discussions

XRD, SEM characterization of contaminated soil before and after phytoremediation using water hyacinth

The morphology of the soil before and after crude oil removal by water hyacinth is shown in Figure 3a before and Figure 3b after remediation. From Figure 3a, it can be observed that the soil has a very compact structure with reduced porosity before remediation studies. While the compact structure may be due significantly to oil deposition on it with little tendency to migrate below due to low soil porosity, literature review shows that soils in South Sudan generally have low pore space due to the high clay content Yong and Deng (2020), Ruley et al. (2019). However, after remediation (Figure 3b), the soil is seen to have a very loose structure with high porosity. SEM results obtained in this study are similar to those of Moses et al. (2019) who employed Scanning electron microscopy (SEM) to characterize the structural morphology of both the crude oil-contaminated and treated soil samples using nanomaterial adsorbents. Their results showed that the crude oil-contaminated soil had a compacted soil matrix held together by oil particles due to weak Vander Waal forces with the aggregated soil exhibiting impermeability to air and water, hence making the soil unsuitable for adequate plant germination and growth. Meanwhile after treatment, the soil demonstrated well-dispersed soil grains that are nearly discrete, with minimal oily film on their surface following the nano remediation treatment. The presence of numerous porous spaces facilitates the flow of air and water through the soil, thereby enhancing seedling germination and subsequent growth. Mosoarca et al. (2020) studied surface morphologies of Syringa vulgaris leaves powder adsorbent before and after adsorption of methylene blue from aqueous solutions. According to their findings, before adsorption, the surface of the adsorbent had many pores with different shape and sizes, which provide a large number of active sites available for dye adsorption. However, after adsorption, the pollutant molecules filled the pores and the surface of adsorbent becomes saturated, and covered by pollutant molecules and creating a very compact structure with reduced porosity. Lignocellulosic materials are used in removing contaminants in wastewater Sebeia et al. (2019). The cellulose and lignin contents of E. crassipes varieties explain the adsorption process in the system and can prove that indeed water hyacinth

varieties are feasible in adsorbing Pb^{2+} in wastewater. The SEM micrographs before and after adsorption process in Figure 3a and 3b for E. crassipes revealed that adsorption of contaminants indeed happened due to the transition of rough surfaces of each of the adsorbent before adsorption to smooth surfaces after adsorption.

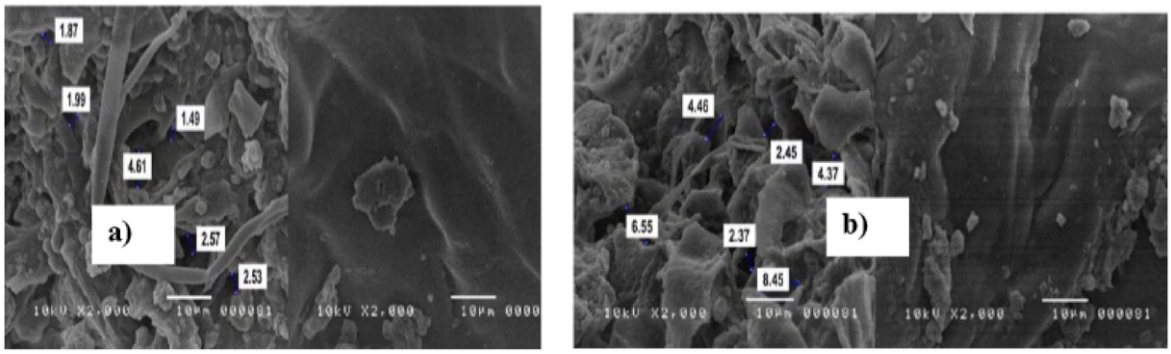


Figure 3. SEM observations pattern of contaminated soil a) before remediation, and b) after remediation

The X-ray Diffraction behavior of crude oil contaminated soil before and after remediation is given in Figure 4. From Figure 4a, before remediation, the peaks are not sharp (only three sharp peaks occurring at 2é of 23, 35 and 55 Table 1) and not well defined indicating significant impurities/contaminations as observed in the pattern formation. The micas occurring at 2 theta 35 was the most dominant. Micas are all silicate minerals, known as sheet silicates because they form in distinct layers. Micas are fairly light and relatively soft, and the sheets and flakes of mica are flexible. After remediation (Figure 4b), the peaks are sharp and well defined and no significant impurities observed in the XRD pattern formation indicating high purity of the product. This is evident with the appearance of many peaks at 2 theta 26, 30, 43, 51, 52, 62, 68 and 70. These peaks are mainly quartz (SiO_2), calcite and hematite the insoluble and more resistant phases.

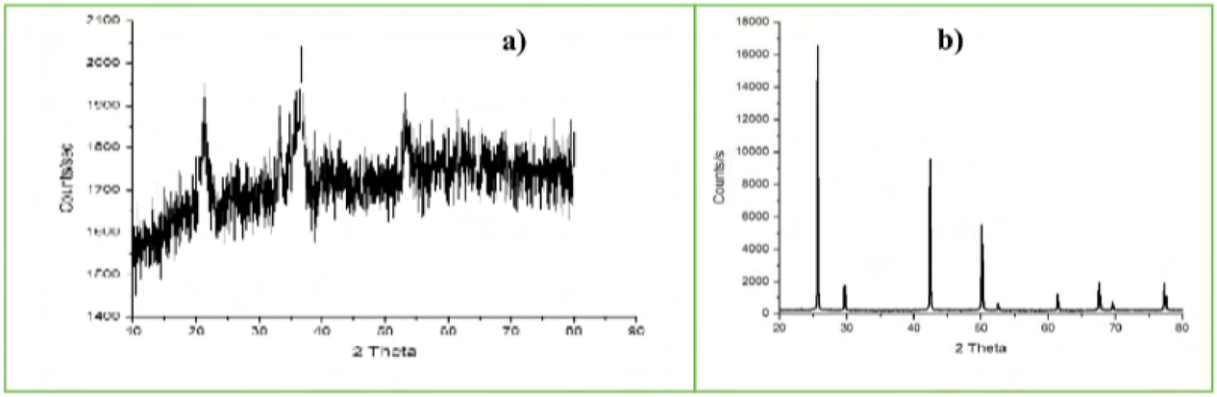


Figure 4. XRD pattern of the crude oil contaminated soil a) before remediation, and b) after remediation

Table 1: XRD data values for the contaminated soil before and after remediation

Before soil remediation			After soil remediation		
Sharp 2θ values	Assignment (Flogeac et al., 2005; Singh and Agrawal)	Intensity	Sharp 2θ values	Assignment (Flogeac et al., 2005; Singh and Agrawal)	Intensity
23	Kaolin	1750	26	Quartz (SiO_2)	16800
35	Micas	2050	30	Franklinite	≈1900
55	Anatase (TiO_2)	1600	43	Calcite	9000
			51	Quartz (SiO_2)	6000
			52	Quartz (SiO_2)	<500
			62	Quartz (SiO_2)	≈1000
			68	Quartz (SiO_2)	2000
			70	Hematite	<500
			77	Hematite	≈1900

FTIR Characterization of dried water hyacinth roots before and after its use in Lead Ions removal from wastewater

The FTIR spectrum of DWHR revealed the presence of many functional groups, indicating the complex nature of the molecular structure of roots of water hyacinth. Figure 5a shows the FTIR spectra of dried water hyacinth roots before adsorption while that for the roots after lead adsorption is shown in Figure 5b. The summary of the functional groups present in both samples is summarized in Table 2. The FTIR spectrum shows that dried hyacinth root contain many functional groups that can effectively bind Pb^{2+} ions from water.

The band at 3340 cm^{-1} is attributed to O-H stretch vibration Cordeiro et al. (2011). The band at 2924.17 cm^{-1} is attributed to C-H stretch vibration for alkanes (Liu *et al.* (2006). The band at 2297.45 cm^{-1} was probably due to C–O stretching and CH or OH bending indicate the existence of hemicellulose structures Mosoarca et al. (2020). The peak at 1628.41 cm^{-1} is assigned to the C = O stretch vibration of carboxylate. Liu *et al.* (2006) reported a similar peak on water hyacinth nanofibers. The bands at 1419 cm^{-1} and 1321.6 cm^{-1} are attributed to C-H bending vibrations or C-H deformation Pandey and Pitman (2003). The strongest peak in DWHR was observed at 1004.62 cm^{-1}, which is assigned to C-O (stretches C–O stretching/O–H deformation). The presence of C-O stretch indicates the presence of alcoholic hydroxyl groups Lim et al. (2008b), especially that of primary alcohols. This hydroxyl group of primary alcohols can be found in columbary alcohols, which is one of the building units of lignin (Tan 2010). Thus, the strongest peak at 1,004.62 cm^{-1} confirms the lignin structure of water hyacinth roots. Besides, the peaks at 797.05 and 687.94 cm^{-1} are attributed to -CH = CH- (cis) bonds. Thus, the most intense bands in the FTIIR of freshwater hyacinth root biomass are 1004.62, 1628.41 and 3340 cm^{-1}, attributed to C-O stretches typical of lignin, C = O stretch vibration of carboxylate and O-H stretches typical of cellulose, respectively Cordeiro et al. (2011). Ibrahim et al. (2007) compared the FTIR spectra of cellulose and roots of DWHR and confirmed that the plant is not only a cellulose-like material as reported by previous studies but it is close to cellulose–lignin blend. When the FTIR spectra were compared between fresh and spent DWHR the FTIR spectra of DWHR as presented in Figure 5b shows that functional groups were changed due adsorption of Pb^{2+}. This shows that nearly all the groups participated in adsorption as indicated in (+) and (-) values of the differences (Table 2). There is also the

creation of an adsorption peak at 1237.45 cm^{-1} after adsorption and complete disappearance of the mainly C-H peaks at 2297.45, 1419, 797.05, and 687.94 cm^{-1}. The shifts in the bands indicate that there were binding processes taking place on the surface of the biosorbent, and the greater the shift, the stronger the bond between the biosorbent and the adsorbed metal Karnib et al. (2014). The (+) signs indicate a probably partial adsorption of between Pb^{2+} on the group while (-) indicate enhanced reaction of the Pb^{2+} and the functional group. The disappeared functional groups may be due to process conditions such as stirring and heating since they are light hydrocarbons. Kumar and Chauhan (2019) reported similar findings in their study using chemically modified dried water hyacinth root (DWHR) as an adsorbent for the removal of chromium (VI) from the synthetic aqueous solution. They reported that functional groups from FTIR analysis were changed due adsorption of chromium (VI).

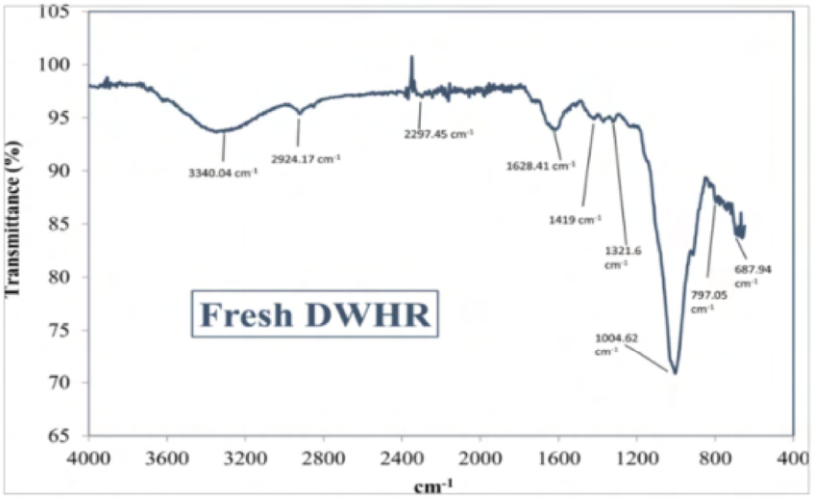


Fig 5a. FTIR graph for dried water hyacinth roots (DWHR).

Nevertheless, the aquatic herb E. crassipes was since to have good performance in the adsorption of heavy metals such as Ni, Zn, Cd, Pb, Cr, and Cu, in aqueous solutions, carried out by its dried biomass or its respective ash Mahmood et al (2010). However, the removal of organic contaminants through phytoremediation process varies according to the surface properties of the biosorbent, metal concentration, pH of the aqueous medium, and heavy metal-ion species present in the solution Tseveendorj (2017). The high reproduction rate, high pollution tolerance, and the great adsorption capacity of chemical species, such as heavy metals, qualify E. crassipes as an alternative and promising biosorbent Priya and Selvan (2017). The chemical composition of the lignocellulosic structure of E. crassipes also includes potassium, calcium, magnesium, phosphorus, silica, carbon, and nitrogen whose quantities present in the biomass of this aquatic macrophyte depend strongly on its environment Gunnarson and Petersen (2007). Due to the structure of E. crassipes with functional groups such as: $–NH^{2+}$ (amines), –COOH (carboxyls), –OH (hydroxyls), –SH (sulfhydryl), –C=O (carbonyls), among others involved in the removal of pollutants of the water Bartmeyer et al (2019). The main advantage of using E. crassipes as a biosorbent is the combination of low cost (due to its high availability) together with its effectiveness as a hyper accumulator Mahmood et al (2010).

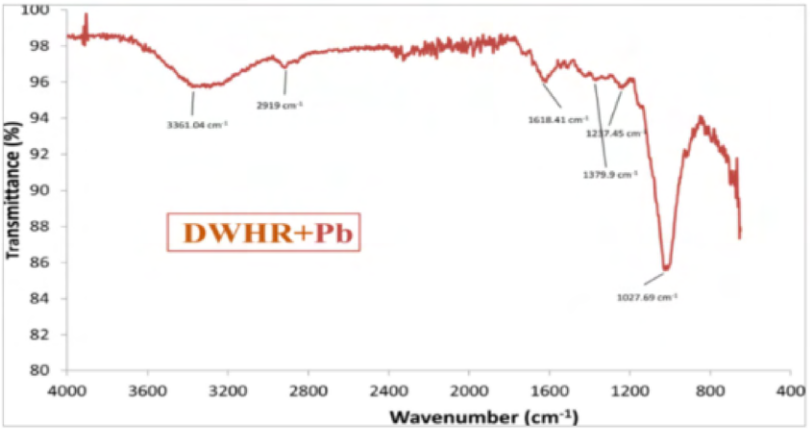


Figure 5b. FTIR spectrum of spent DWHR laden with Pb Ion.

Table 2: IR bands (cm^{-1}) of dried water hyacinth roots before and after adsorption of Pb^{2+} from wastewater

Before Adsorption	After Adsorption	Difference
3340.04	3361.04	+21
2924.17	2919	-5.17
2297.45	-	-2297.45
1628.41	1618.41	-10
1419	-	-1419
1321.6	1379.9	+58.3
-	1237.45	+1237.45
1004.62	1027.69	+23.07
797.05	-	-797.05
687.94	-	-687.94

Conclusions

The following conclusions can be drawn from this study

1. The application of water hyacinth in effluent treatment indicate high bio sorption capacity for the treatment of inorganic contaminants in soil including heavy metals removal as well as some other industrial effluents especially from oilfield polluted environments.

2. The FTIR results revealed that more functional groups present in E. crassipes translates its effectiveness as biosorbent. On the other hand, the SEM micrographs showed the presence of small and large particle sizes in E. crassipes along with its porous surfaces which act as the active sites for the biosorption. It was discovered that the factors influencing the biosorption were statistically significant. It can be concluded that E. crassipes can be an efficient biosorbent for removing contaminants in wastewater and its baseline parameters when it will be used in adsorption column was already established based on the results of this study.

3. Phytoremediation process is easy to operate and cost-effective as changes in soil texture and mineralogy show significantly improvements as remediation.

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Author Contributions

Prof. FOZAO KENNEDY FOLEPAI, Prof. TSAMO CORNELIUS facilitated and conceptualized the whole research process and write-ups construction; Prof. CHEO EMMANUEL SUH edited and proofread the final paper; BIOR J. AKOI conducted the research, analyzed the data, and wrote the paper; all authors approved the final revision of the paper.

Declarations

Conflict of interest on behalf of all authors; the corresponding author states that there is no conflict of interest

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