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Comparison of Water Hyacinth (*Eichhornia crassipes*), Nypa palm (*Nypa fruticans*) and Mangrove (*Rhizophora* spp.) Parts as Remediating Agents in Polluted Sites

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ABSTRACT

Environmental pollution from crude oil and heavy metals is a significant challenge, particularly in Nigeria's Niger Delta region. Phytoremediation presents a cost-effective and sustainable alternative to conventional cleanup techniques. This study aimed to compare the effectiveness of water hyacinth (*Eichhornia crassipes*) and mangrove parts as remediating agents in polluted soil. Soil samples from a contaminated site at Eagle Island, Rivers State, were treated with dried and ground parts of water hyacinth, mangrove (stem and seed), and Nypa palm (leaves and seed). The concentrations of heavy metals (Cadmium, Lead, Zinc) and Total Hydrocarbon (THC) were analyzed pre- and post-treatment. The Analysis of Variance (ANOVA) showed no statistically significant difference ($p > 0.05$) among the treatments. The result shows that, although there was no statistical significance, mangrove stems had lower chemical concentrations than Nypa palm and water hyacinth. For instance, the total hydrocarbon concentration in mangroves was lower (12.11 mg/kg) than in Nypa palm (13.07 mg/kg) and water hyacinth (13.51 mg/kg). Similarly, the concentration of THC in soil before the application of the plant parts was twenty-one times higher before (543.3 mg/kg) than after (26.15

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ARTICLE INFO

Received: 28 October 2025 | Revised: 28 November 2025 | Accepted: 11 December 2025 | Published Online: 27 March 2026
DOI: <https://doi.org/10.30564/re.v8i2.12589>

CITATION

Jack, E., Numbere, A., Jude, K., et al., 2026. Comparison of Water Hyacinth (*Eichhornia crassipes*), Nypa palm (*Nypa fruticans*) and Mangrove (*Rhizophora* spp.) Parts as Remediating Agents in Polluted Sites. *Research in Ecology*. 8(2): 173–185. DOI: <https://doi.org/10.30564/re.v8i2.12589>

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mg/kg) the ground parts were added. This study concludes that mangrove parts are the most promising agents for the phytoremediation of crude oil-contaminated soils, offering an effective and environmentally friendly approach to site rehabilitation.

Keywords: Phytoremediation; Crude Oil; Water Hyacinth; *Eichhornia crassipes*; Mangrove; Total Hydrocarbon (THC)

1. Introduction

Environmental pollution is a major environmental concern, particularly in regions affected by crude oil contamination, like the 'Niger Delta' region, also known as the 'oil-producing states' of Nigeria. Currently, it has become a global problem, and it has been estimated that deaths and diseases are caused worldwide due to pollution, and approximately fourteen thousand people die every day due to water pollution^[1]. Generally, the quality of water is influenced by numerous factors: precipitation, soil type, vegetation, geology, climate, groundwater, and human activities^[2]. Water is considered polluted when various quality parameters are compromised as a result of uncontrolled and irregular anthropogenic activities^[3]. The greatest threat to water quality is posed by point sources of industries (including oil spillage from large crude oil-producing companies and refineries) and municipalities. Activities like mining, urban development, and agriculture also affect the quality of water. Non-point source pollution also includes nutrients, sediments, and toxic contaminants^[4].

Pollutants are substances that, when introduced into the environment, cause undesirable effects or spoil resources. These substances are capable of causing short-term to long-term damage^[5]. Crude oil (a naturally occurring liquid petroleum product formed from remnants of animals and plants that lived millions of years ago) is an organic pollutant, so classified due to its hydrocarbon composition, which, when released in large quantities, particularly through oil spillage, can be harmful to the environment^[6]. Anthropogenic (human) causes of petroleum leakage into the environment are known as crude oil contamination.

The most frequent way that oil contamination happens is through oil spills. Large volumes of oil are released into coastal and marine waterways during oil spills, which can have disastrous effects^[7]. Oil spills severely impact the general aquatic ecosystems, causing a reduction in water quality, harming biodiversity, and posing risks to human health^[8]. The location of the occurrence and its subsequent

proximity to environmentally sensitive places and creatures, as well as the magnitude of external physical forces acting on the spilled oil, determine the effects of hydrocarbons lost at sea^[9]. The kind and amount of oil spilled, as well as the biota impact, each species having a varying degree of resilience to the physical effects and toxicity of spilled oil, all significantly influence the detrimental effects^[10]. Remediation of oil spills and their impacts on marine environments primarily depend on careful evaluation of the bulk characteristics and chemical makeup of the oil that was spilled, as well as the weathering reactions that regulate the behaviors and destiny of the oil^[9].

It can be challenging to handle marine spill incidents^[11], particularly when they take place in a dangerous or isolated area like the Arctic, where remediation methods are not easily accessible or simple to use^[10]. Therefore, it is necessary to talk about the significance of harsh environmental conditions and their possible bioremediation using naturally occurring plants.

Bioremediation is a biological mechanism of recycling waste into another form that can be used and reused by other organisms. It is defined as the process whereby organic wastes are biologically degraded under controlled conditions to an innocuous state, or to levels below concentration limits established by regulatory authorities^[12]. Bioremediation is involved in degrading, removing, altering, immobilizing, or detoxifying various chemicals and physical wastes from the environment through the action of bacteria, fungi, plants, and other living organisms.

Bioremediation plays an important role in addressing water pollution, which, as noted earlier, poses significant threats to ecosystems and human health. Traditional remediation methods, such as chemical treatments and physical filtration, often involve high costs and may introduce secondary pollutants. Bioremediation offers a sustainable and cost-effective alternative by employing microorganisms and plants to degrade or transform contaminants into less harmful forms^[13].

Applications of bioremediation in water treatment

include oil spill cleanup, industrial wastewater treatment, and heavy metal removal. Hydrocarbon-degrading bacteria, such as *Alcanivorax* and *Pseudomonas*, have been used in marine environments to break down crude oil following major oil spills^[14]. Bioreactors employing microbial consortia have been implemented to treat wastewater from textile, pharmaceutical, and petrochemical industries, reducing the presence of toxic organic pollutants^[15]. Constructed wetlands and plant-based filtration systems effectively remove lead, arsenic, and mercury from contaminated water, reducing their bioavailability and toxicity^[16].

Phyto remediation is the use of plants to clean up or detoxify the environment, most especially the soil. Plants with phytoremediating ability are mostly planted in polluted soils to help absorb pollutants, after which they are uprooted and discarded. However, in this study, rather than planting live plants in contaminated soil, we used ground-dried mangrove parts to absorb soil pollutants, which represents a different approach to phytoremediation and bridges a knowledge gap in the field^[17].

Given that bioremediation is only successful in environments that support microbial growth and activity, its implementation frequently entails adjusting environmental factors to accelerate microbial growth and destruction^[18]. Phytoremediation is the term used to describe plant-assisted bioremediation. For the purpose of treating soils that contain significant concentrations of organic compounds, it encompasses the interaction between plant roots and the bacteria connected to these root systems^[19]. One of the most effective plants for phytoremediation is water hyacinth (*Eichhornia crassipes*), a fast-growing aquatic plant that has shown a remarkable ability to absorb and accumulate contaminants, such as heavy metals and petroleum hydrocarbons, from polluted water bodies. Its extensive root system provides a large surface area for pollutant absorption and microbial interactions, which enhances the breakdown of harmful substances. Water hyacinth is being used more and more for large-scale water decontamination projects because of its high biomass production, rapid growth, and adaptability to a variety of aquatic environments. Water hyacinths are aquatic pest plants that thrive in lakes, rivers, and other bodies of water. In just a few weeks, water hyacinth can grow from its typical size to

twice its original size, forming a mat on the water's surface^[20]. When water hyacinth is present, the amount of oxygen and nutrients in the surrounding environment is decreased. Because it contains useful compounds like lignin, cellulose, and hemicellulose, it is a rich plant. These substances aid in the process of turning water hyacinth into biofuel. Furthermore, it has been demonstrated that water hyacinth is effective in absorbing a variety of heavy metals^[21].

Water hyacinth is capable of treating wastewater by supplying oxygen and surface area. The water hyacinth's stem and leaves have stomata that let oxygen from the outside in. As a result, roots receive oxygen^[22]. The organic stabilization takes place on the water hyacinth root, and the organism's bulk adheres to it. In order to stop algae development and oxygenation, the creatures continue to emit light into the pond^[23].

Water hyacinth is distinguished by quick development, and despite being a notorious and aggressive invader, it has been widely explored as a possible agent for phytoremediation. Its efficiency, however, relies on the type of pollutant, concentration, and eventual storage place in the plant tissues^[21]. The Mangrove forest is a hotspot for biodiversity^[24] because it is home to a wide variety of species, including invertebrates, vertebrates, and micro and macroorganisms. However, because of its location at the land-sea boundary, it is more vulnerable to the effects of hydrocarbon pollution from oil and gas exploration. There is, therefore, a notable increase in heavy metal concentration in mangrove soil as a result of a combination of hydrocarbon pollution and waste in the forest. This leads to poor and stunted growth of young seedlings. Because of their resilient nature and their ability to withstand serious environmental conditions, they are often distinguished from other coastal species^[25].

Due to their ability to absorb and accumulate metals, some species of mangrove are referred to as 'metal-phytes', which exist in two categories: the metal *hyper-accumulators* (for example, *Biscutella laevigata*, which accumulates metals like Lead, cadmium, and thallium) and the *metal excluders* (for example, *Bruguiera gymnorrhiza*, which accumulates copper and cadmium). During oil spillages, the forest exhibits a self-cleaning ability. Given the increasing incidence of oil-related pollution in both

inland and coastal environments, there is a growing need for sustainable and locally available solutions to restore affected sites. Plants like water hyacinth and mangrove species have shown potential in reducing contaminant levels through phytoremediation processes, yet there remains limited comparative research on their effectiveness in crude oil-contaminated soil. This study, therefore, seeks to investigate and compare the phytoremediation potential of water hyacinth and selected mangrove parts in crude oil-impacted soils.

Environmental pollution, particularly from heavy metals, petroleum hydrocarbons and crude oil, poses a major global threat to soil fertility, water quality, plant growth, and human health. Industrial activities, poor waste management, and crude oil spills have led to widespread contamination [26]. Heavy metals are non-biodegradable and linked to severe health conditions, including cancer and neurological disorders [27]. Likewise, petroleum hydrocarbons are hazardous due to their toxic and carcinogenic properties [28]. Crude oil, with its complex mixture of hydrocarbons and toxic compounds, poses severe risks to human health and biodiversity, causing long-term damage to water bodies [29]. Conventional remediation methods, such as excavation and chemical treatments, are costly, slow, and may introduce secondary pollutants [30].

Phytoremediation, which utilizes plants to extract, degrade, or stabilize contaminants, has emerged as a promising alternative to conventional techniques. Water hyacinth (*Eichhornia crassipes*) is of particular interest due to its rapid growth, high biomass yield, and extensive, fibrous root system, which collectively facilitate the uptake and sequestration of pollutants [31]. Recent studies have demonstrated that water hyacinth can effectively reduce concentrations of heavy metals and organic contaminants from wastewater [32,33]. However, while its capacity to remove heavy metals has been well documented, its efficacy in remediating water contaminated specifically by crude oil remains underexplored.

According to preliminary research, water hyacinth may facilitate the breakdown of crude oil through rhizofiltration and rhizodegradation mechanisms. The roots of the plant serve as a home for microbial communities that can break down complex hydrocarbons into less harmful

compounds, improving the overall quality of the water [34,35]. However, despite these encouraging results, there are still important questions that need to be answered, including the best conditions for water hyacinth to maximize the removal of crude oil, the kinetics of contaminant uptake, the fate of accumulated pollutants within the plant tissues, and the handling of contaminated biomass to prevent secondary pollution [36].

In order to advance water hyacinth-based phytoremediation as a feasible way to clean crude oil-contaminated water bodies, these issues must be resolved. This study intends to methodically examine the potential of water hyacinth and mangrove parts to remediate crude oil-polluted water, with a particular focus on their capacity to lower TPH levels, promote microbial degradation in the rhizosphere, and safely manage contaminated biomass. The findings of this study may open the door to the development of integrated, sustainable water treatment systems that provide an environmentally friendly substitute for conventional remediation techniques [17].

To compare the effectiveness of Water Hyacinth (*Eichhornia crassipes*) and Mangrove parts as phytoremediation agents in polluted cities.

Objectives of the Study

1. To assess the ability of water hyacinth and mangrove parts to remediate crude oil-contaminated soils.
2. To compare the efficiency of a water plant (water hyacinth) and a land plant (mangrove) in crude oil remediation.
3. To compare the physicochemistry of soil before and after treatment with water hyacinth and mangrove parts.
4. To evaluate the heavy metal concentration and total hydrocarbon contents in soil remediated with water hyacinth and mangrove parts.

2. Materials and Methods

2.1. Description of Study Area

The study took place in a section of a deforested and sand-filled mangrove forest behind the Rivers State University at Eagle Island (coordinates: 4°47' N and 6°58' E,

Figure 1) in the Niger Delta in Southern Nigeria. Eagle Island was once a dense mangrove forest that was cut and later used for sand mining activity, where extracted sand is dumped. These sand mining activities went on for up to three years and were later abandoned. The waterfront of the sand mine then became a site for marine transportation (speed boats used as vehicles of transportation, conveying passengers across the river to neighboring village(s)). The environmental conditions of the study area, Eagle Island in Rivers State, Southern Nigeria, are characterized by distinct physicochemical parameters that influence its ecological dynamics. The region experiences high annual rainfall, with an average of 3567.4 mm, contributing to a consis-

tently warm climate. Temperatures in the area typically range from 28 °C to 34 °C, reflecting its tropical location. As a coastal system, Eagle Island is influenced by saltwater, with the adjoining river exhibiting a salinity range of 1.45% to 1.62%. This broad range indicates a dynamic estuarine environment where freshwater and saltwater mix. The soil composition in the study area is predominantly swampy, varying from sandy to muddy textures. The color of the soil ranges from white to dark brown, with some areas displaying a reddish hue due to the presence of iron (II) compounds. The soil pH in the study area is generally neutral to slightly acidic, ranging from 6 to 7. This pH range is typical for many coastal and estuarine environments.

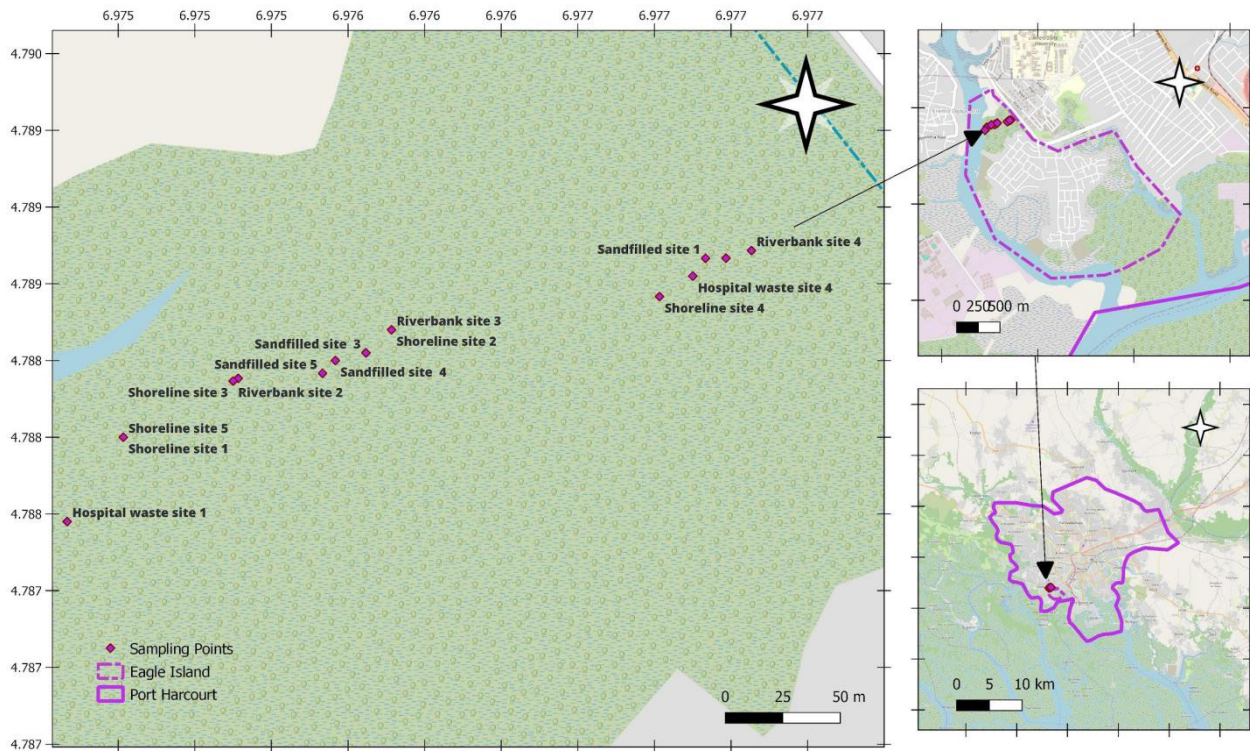


Figure 1. Map of the study area: Eagle Island, Rivers State, Nigeria.

Source: Geography Department, University of Port Harcourt.

2.2. Study Plot

The designated study plot is situated approximately 91 m from the main river course. This proximity to the river results in tidal influences, where water inundates the sand-filled area during high tide through a synthetic opening in the side embankment and recedes during low tide, depositing leaves and seeds of water hyacinth.

2.3. Experimental Design

The samples were collected in June 2025. The soil samples were collected from the different plots, digging up to 5 cm below the surface following the example of Numbere [37]. The plastic deposition site is made up of 90% sand; the semi-muddy soil is made up of a mixture of sand and mud (30% clay and 50% sand); and the muddy soil is

made up of 90% silt ^[38]. The deposition sites were geo-referenced with a Garmin GPS (USA).

2.4. Sample Collection

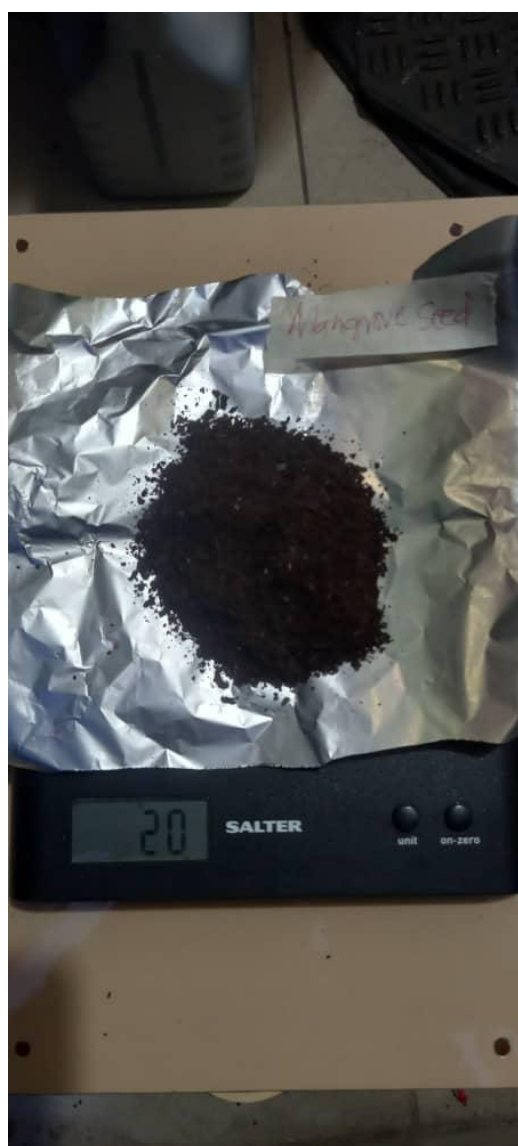
Different parts of the mangrove plant were taken from the tree in Eagle Island. Water Hyacinth was taken from Yenagoa in Bayelsa State. They were then subjected to heat in an oven at 70 °C for 48 h, grinded and taken to the laboratory for further analysis.

Preparation of Plant Samples Used for Remediation

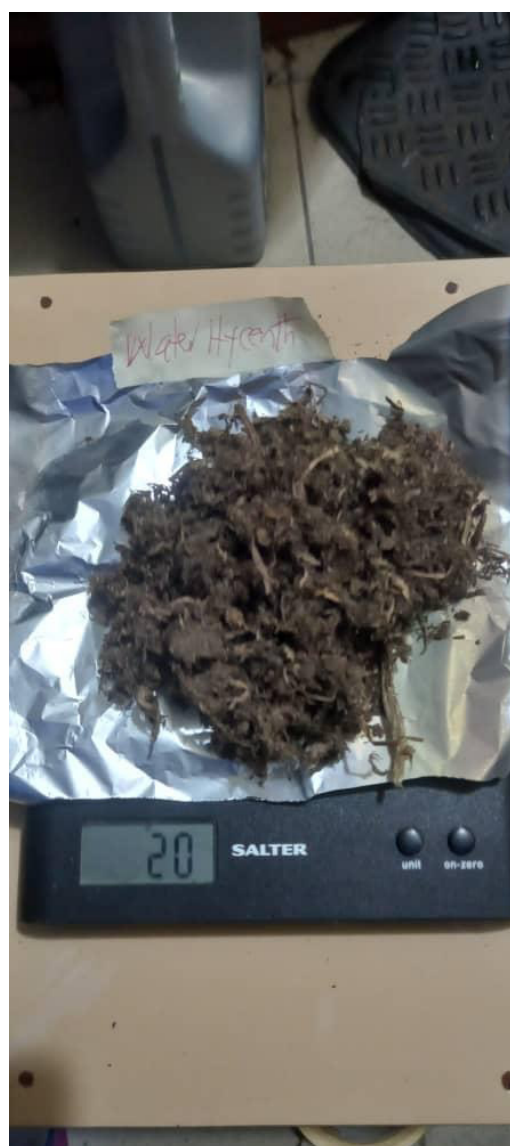
Some grounded dried Nypa leaves and seeds, man-

grove stem and seed, and whole water hyacinth plant were placed on a weighing machine (Model: Salter, UK), and 20 g of the samples were weighed out for the experiment (Figure 2).

Similarly, some soil samples were collected from the study site and placed in medium-sized polyethylene bags weighing about 0.5 kg. Twenty grams of all the ground leaf samples were then poured into the polyethylene bags containing mangrove soil and mixed. A control soil without grounded leaf samples was set up. All samples were left in the open under semi-natural conditions and watered daily for 6 months.



(a)



(b)

Figure 2. Dried and grinded samples: (a) Mangrove seed; (b) Water Hyacinth collected from Eagle Island Rivers and Bayelsa States, Nigeria, respectively.

2.5. Laboratory Analysis

2.5.1. Analysis of Heavy Metals

Cadmium, lead, magnesium, and zinc were determined using the method of Aigberua and Tarawou (2018)^[38], where aliquots of 0.25 g of air-dried sediment samples were weighed into a Teflon inset of a microwave digestion vessel, and 2 mL concentrated (90%) nitric acid (Sigma-Aldrich, Dorset, UK) was added. The metals were extracted using a microwave accelerated reaction system (MARS Xpress, CEM Corporation, Matthews, North Carolina) at 1500 W power (100%), ramped to 175 °C in 5.5 min, held for 4.5 min, and allowed to cool down for 1 h. The cool digest solution was filtered through a Whatman 42 filter paper and made up to 100 mL in a volumetric flask with deionized water. The detection limit for the metals analyzed was 0.001 mg/L.

2.5.2. Total Hydrocarbon (THC)

A spectrophotometer was used to determine the THC with a calorimeter (HACH DR, 890). 2 g of grinded samples was added into a beaker with 20 mL of hexane and then stirred. The mixture was then filtered through a glass funnel with wool, silica gel, and anhydrous sodium sulphate. 10 mL of organic extract was added to a 10 mL sample cuvette and put in the calorimeter.

2.6. Statistical Analysis

ANOVA (Analysis of Variance) was used to statistically assess the study's data. Each group's mean ± standard error of the mean (SEM) was used to express the results. One-way analysis of variance (ANOVA) was used for statistical comparisons across groups in order

to identify significant differences between the treatment and control groups. A 95% confidence level was selected, and a *p*-value of less than 0.05 was deemed statistically significant. A post-hoc Tukey's HSD test was done to investigate pairwise mean differences between groups. All analyses were performed in the R statistical environment, version 3.1.0^[39].

3. Results

This work presents the results of the study on the remediation of polluted soils using water hyacinth, mangrove parts, and Nypa palm. In order to determine the mean values of heavy metal and THC concentrations in soil and water, samples were statistically analyzed, and the results are given below.

3.1. Comparison of Heavy Metal and Total Hydrocarbon Contents in Soil Remediated with Mangrove and Nypa Palm Parts

Analysis of Variance (ANOVA) of the result ($F_{4,20} = 22, p > 0.05$, as seen in **Table 1** and **Figure 3**) shows that there is no significant difference in the chemical concentration between soils treated with different mangrove and Nypa palm parts, hence the null hypothesis is accepted.

Although there is no significant difference, the result shows that soils treated with mangrove stems have the lowest chemical concentration. This means soils treated with mangrove stem have the lowest mean values of cadmium (0.27 mg/kg), lead (6.40 mg/kg), zinc (21.70 mg/kg), and THC (6.01 mg/kg), and mangrove parts are better used for bioremediation than Nypa and water hyacinth parts (**Table 1**). In contrast, soils treated with water hyacinth and mangrove seed had relatively higher concentrations of pollutants.

Table 1. Concentration of heavy metal and total hydrocarbon contents (THC) in soil treated with different mangrove and Nypa palm parts collected from Eagle Island, River State, Nigeria (±SE).

Sample	Cadmium	Lead	Magnesium	Zinc	THC
Nypa Leaves	0.3 ± 0.02	9.42 ± 0.2	1059.28 ± 106.2	24.95 ± 1.2	15.52 ± 1.1
Nypa Seed	0.41 ± 0.1	12.25 ± 0.13	1034.53 ± 103.4	28.5 ± 1.5	10.62 ± 1.0
Mangrove Stem	0.27 ± 0.09	6.40 ± 0.34	1057.64 ± 107.2	21.70 ± 2.3	6.01 ± 0.95
Mangrove Seed	0.41 ± 0.11	8.41 ± 0.5	1048.38 ± 105.3	23.99 ± 1.6	18.21 ± 0.12
Water Hyacinth	0.36 ± 0.01	10.26 ± 0.43	1054.57 ± 106.8	31.61 ± 1.09	13.51 ± 0.4

Note: Values are presented in mean ± SE.

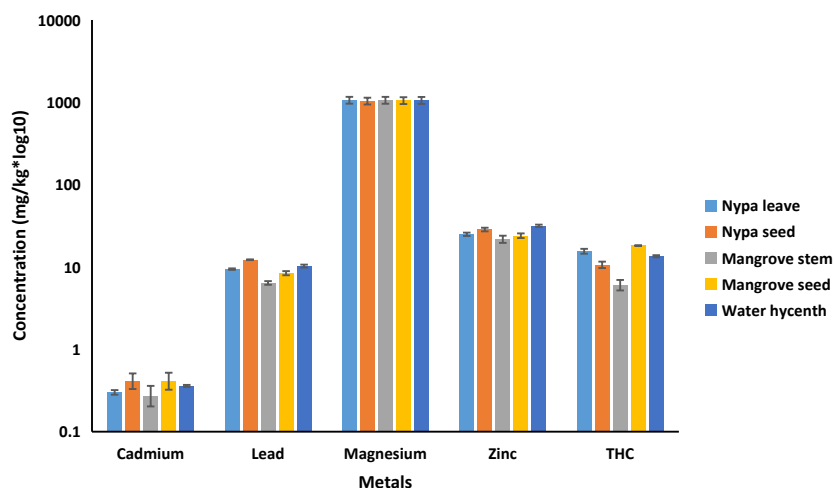


Figure 3. Mean concentration of heavy metal and total hydrocarbon concentration in soils treated with different plant parts (±SE).

Note: Nypa Palm Parts (Leaves and Seeds), Mangrove Parts (Stem and Seed), and Water Hyacinth Mangrove and Nypa palms were retrieved from Eagle Island, while water hyacinth was collected from Bayelsa State, Nigeria.

3.2. Comparison of Heavy Metal and THC in Soils Treated with Different Plant Species

Analysis of Variance (ANOVA) of the result ($p > 0.05$ ($F_{4,20} = 22, p > 0.05$), as seen in **Table 2** and **Figure 4**) shows that there is no significant difference in the chemical concentration across species, hence the null hypothesis is accepted.

However, the result revealed that mangrove-treated soil had the lowest chemical concentration compared to other Nypa palm and water hyacinth (**Table 2** and **Figure 4**). In contrast, water hyacinth-treated soil had the highest concentration of chemicals, meaning that mangrove parts are better remediation agents than water hyacinth.

Table 2. Concentration of heavy metal and THC in soil treated with different plant species collected at Eagle Island, Rivers State ± SE.

Sample	Cadmium	Lead	Magnesium	Zinc	THC
Mangrove	0.34 ± 0.07	7.41 ± 1.01	1053.01 ± 4.63	22.85 ± 1.15	12.11 ± 4.63
Nypa Palm	0.36 ± 0.06	10.84 ± 1.42	1046.91 ± 12.38	26.73 ± 1.78	13.07 ± 2.45
Water Hyacinth	0.36 ± 0.01	10.26 ± 0.02	1054.57 ± 0.03	31.61 ± 0.1	13.51 ± 0.00

Mg/kg ± SE

Note: Values are presented in mean ± SE.

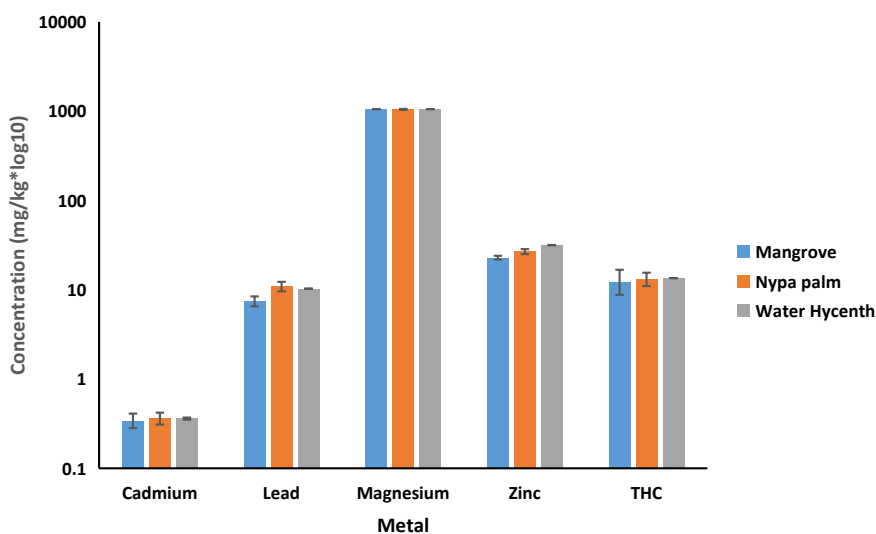


Figure 4. Mean concentration of heavy metal and total hydrocarbon concentration across species.

3.3. Comparison of the Physicochemistry of Soil before and after Treatment with Different Plant Parts

Analysis of Variance (ANOVA) of the result ($p > 0.05$ ($F_{4,20} = 22, p > 0.05$), as seen in **Table 3** and **Figure 5**) shows that there is no significant difference in the chemi-

cal concentration across species before and after treatment with plant parts, hence the null hypothesis is accepted.

Although there was no significant difference, the result revealed that there was a reduction in Cadmium, Manganese, Zinc, and THC, while there was an increase in Lead and Magnesium after treatment (**Table 3** and **Figure 5**).

Table 3. Concentration of heavy metals and THC in soil before and after treatment with plant parts collected at Eagle Island, Rivers State, Nigeria.

Sample	Cadmium	Lead	Magnesium	Manganese	Zinc	THC
Before	1.54 ± 1.08	9.30 ± 5.69	824.7 ± 0.10	27.77 ± 10.77	19.59 ± 9.70	543.3 ± 390.82
After	0.35 ± 0.03	9.35 ± 0.97	1050.88 ± 4.49	12.78 ± 2.10	0.35 ± 0.03	26.15 ± 1.75

Note: Values are presented in mean ± SE.

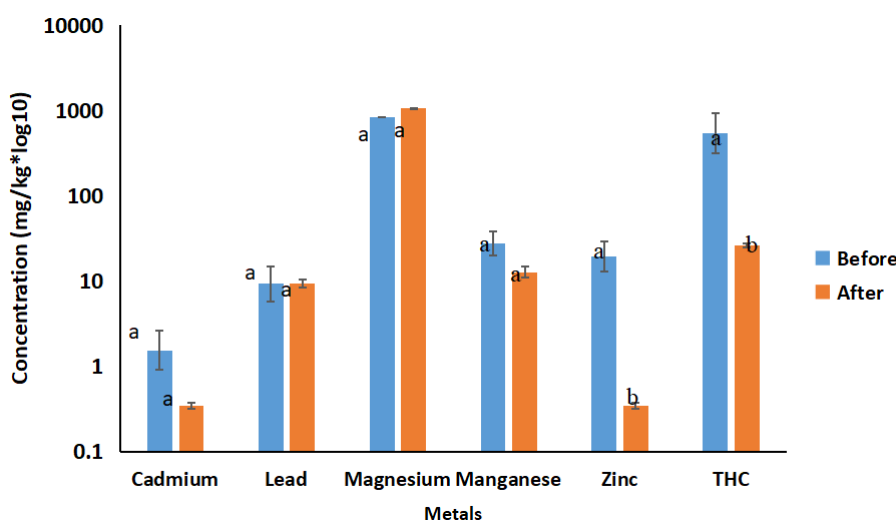


Figure 5. Concentration of heavy metals and THC in soil before and after treatment with plant parts.

Note: Different alphabet indicates a significant difference. Similar alphabet means not significantly different, while a different alphabet means significantly different.

4. Discussion

In this study, different species of plants (mangrove parts: stem and seeds), *Nypa* palm parts (leaves and seeds) were compared for their effectiveness as phytoremediation agents in polluted cities. Phytoremediation agents help enhance the process of removing, degrading, or stabilizing pollutants from contaminated media.

The enhanced performance of mangrove stems could be attributed to their lignified tissues and associated rhizospheric microbial communities^[40,41], which are known to facilitate hydrocarbon degradation and heavy metal immobilization in polluted soils.

Soils treated with water hyacinth and *Nypa* palm

leaves, on the other hand, showed relatively higher concentrations of heavy metals and hydrocarbons, which is indicative of lower remediation efficiency. This aligns with Zhang et al.^[42], who report water hyacinth as more effective in aquatic systems than in soil environments, where its roots may not interact optimally with contaminants; hence, even though it improves the quality of the soil, it is a better remediating agent in water. Similarly, the softer tissues of *Nypa* leaves may limit their absorptive capacity compared to woody mangrove stems. An interesting result was noted when soils treated with mangrove seed exhibited the highest total hydrocarbon content (THC) values. This result, although unexpected, could suggest that seed tissues either release organic compounds that in-

terfere with hydrocarbon breakdown or lack the structural and microbial support necessary for effective remediation. Nevertheless, the presence of reduction trends across most plant parts demonstrates that phytoremediation, even with varying levels of efficiency, can contribute to lowering pollutant loads in contaminated soils.

The results of the species comparison showed that although ANOVA revealed no statistically significant difference ($p > 0.05$) among the plant species tested, clear variations were evident in the mean values of heavy metals and total hydrocarbon concentration (THC). Soils treated with mangrove species consistently recorded the lowest concentrations of cadmium, lead, zinc, and THC. This indicates that mangroves possess a higher remediation potential compared to *Nypa palm* and water hyacinth, somewhat of what has been seen before. The effectiveness of mangrove species in polluted soil environments can be attributed to their adaptive root systems and strong association with hydrocarbon-degrading microorganisms in the rhizosphere, which enhance both heavy metal stabilization and hydrocarbon breakdown^[43]. Soils treated with water hyacinth showed the highest concentrations of contaminants, with zinc and THC being particularly elevated, suggesting what was confirmed before, that water hyacinth is less effective in soil remediation compared to its known effectiveness in aquatic environments, further aligning with the study by Zhang et al.^[42]. Its fibrous root system is better adapted for filtering pollutants in water rather than immobilizing contaminants in soil matrices, which could explain the lower efficiency observed here. *Nypa palm* performed moderately, reducing some contaminant levels but not as effectively as mangroves. The relatively higher lead and THC in *Nypa*-treated soils suggest a limited capacity for remediation. This might be due to physiological differences between *Nypa palm* tissues and mangrove roots, as well as reduced microbial associations. Overall, results comparing the potential of the different plant species showed that while all species showed some level of remediation, mangrove species remain the superior phytoremediation agents in soil environments, amongst the species studied (Mangrove, *Nypa palm* parts, and water hyacinth), likely due to their evolutionary adaptation to polluted and saline environments. This supports previous findings that mangrove ecosystems play a vital role in hydrocarbon degradation and

heavy metal stabilization in oil-polluted coastal regions.

Mangrove parts have a higher remediation capacity than *Nypa palm* and water hyacinth because they tend to absorb more pollutants from the soil than the other plants. This is because mangroves decompose faster than palms in a polluted environment. Faster decomposition of mangrove leaves is facilitated by their softer, less fibrous leaves compared to the tough leaves of palms and water hyacinth, and by their easy breakdown by microbes. Thus, the compost produced by mangroves absorbs soil contaminants more quickly than that produced by other plants. Similarly, pollutants from the soil are transported through the roots to the mangrove leaves, where they are defoliated to expel harmful chemicals that could contaminate the mangrove tree.

The use of mangrove parts is an alternative way to remediate polluted sites, a nature-based solution. Mangrove's affinity for mangrove soil provides better acclimation of its parts to the mangrove environment than water hyacinth, a macrophyte that grows in stagnant water. In the same vein, mangroves are habitat-specific and grow only in mangrove soil, whereas *Nypa palm* and water hyacinth grow in a diverse environment; hence, they are habitat-generalists. Phytochemicals between mangrove and mangrove soil are similarly compared to water hyacinth and mangrove soil.

Large-scale use of mangrove parts for practical application may lead to the deforestation of mangrove trees, which may not be ideal for conservation. However, using mangrove parts is preferable to chemical remediation.

5. Conclusion

The study provides a practical nature-based solution to mangrove remediation. Mangrove litter can be recycled and converted into plant biomass to produce a soil treatment formula for cleaning contaminated soils. Soil treatment formula for cleaning contaminated wetlands. The results of this study provide a less expensive way to clean pollutants from coastal soils.

The study will be expanded in the future by using larger quantities of ground mangrove parts, carried out as a natural experiment. The large-scale study will test the effectiveness of using mangrove parts in a real-world setting.

6. Recommendations

Based on the results of this study, the following are recommended:

1. Further comprehensive research should be conducted to investigate the phytoremediation mechanisms of mangrove plants and water hyacinth, including long-term field evaluations under different pollutant conditions.
2. Environmental agencies, policymakers, and industries responsible for the remediation of hydrocarbons and heavy metals in contaminated ecosystems should consider and explore the use of mangrove parts as effective bioremediation agents.
3. There should be more sensitization and awareness campaigns on the remediation properties of plants as reliable agents of remediation.

Author Contributions

E.J. conducted the research and compiled the manuscript; A.N. supervised, edited, and revised the work; K.J., S.C., M.U. and E.B. reviewed and edited the final copy; while A.N. coordinated the project. All authors have read and agreed to the published version of the manuscript.

Funding

This work received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

Data would be made available on request to the corresponding author.

Acknowledgments

We wish to thank Mr. Chimezie Brown Iwuji for assistance in sample collection.

Conflicts of Interest

The authors declare no conflict of interest.

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