**UPTAKE OF HEAVY METALS (CADMIUM, LEAD, CHROMIUM AND COPPER) FROM PAINT-BASED EFFLUENT USING *Azolla mycrophylla* (AZOLLA) AND *Eicchornia crassipies* (WATER HYACINTH).**

**ABSTRACT**

Heavy metals are a major risk to life in general that requires urgent attention when found in any environment. The use of plants specifically aquatic macrophytes in the uptake and accumulation of these toxic elements may proffer a more advantageous and economically doable approach. In this study, two aquatic macrophytes *Azolla mycrophylla* and *Eichhornia crassipies* were evaluated for the uptake of four heavy metals (cadmium, chromium, lead and copper) from a paint-based effluent under hydroponic media using two varying dilution factors (50%, TRT 1 and 25%, TRT 2) of the effluent. Results obtained revealed significant (P<0.05) removal efficiencies after a 63 days (both acclimatization and treatment) period of treatment for both plants. *Azolla mycrophylla* reduced cadmium concentration by 90 % and 95%, lead 89% and 78%, chromium 39% and 48% and copper 72% and 99% in both treatments. *Eichhornia crassipies* significantly reduced cadmium by 82% and 48%, lead 51% and 36%, chromium 29% and 11% and copper by 76% and 8% in both treatments respectively. The results obtained from this study suggest the applicability of these two plants grown under hydroponically for bioremediation which promises to be a sustainable and viable option for heavy metal containing effluents.

**KEYWORDS**: *Azolla mycrophylla*, *Eichhornia crassipies*, hydroponics, heavy metals, bioremediation.

**INTRODUCTION**

The issue of environmental pollution has become a worldwide and a global problem as increase in human population has led to increase in the establishment of more industries to meet the growing needs of the growing population. Threat is brought to life and the environment at large when toxic wastes (such as the heavy metals) are improperly handled and managed (Jaskelevičius and Lynikienė, 2009). The different industries have unique wastes composition (organic and inorganic) disposed alongside the wastewater (Mouchet, 1986; Lim *et al*, 2011). Industries produce heavy metal containing effluents that are highly dangerous to the environment (Ogunfowokan *et al,* 2007). Pollution of surface and ground water as well as the soil by the heavy metals is brought about as a result of their high solubility (Ahmadkhan, 2001). Aquatic lives, be it marine or fresh water could be damaged due to heavy metal contamination at different biological magnitude thereby resulting to imbalance in the ecosystem (Zeitoun and Mehana, 2014). Heavy metals are now getting into the sparse water resource availability in Africa (Nriagu, 1992). Arsenic (As), Cadmium (Cd), Chromium (Cr) and Lead (Pb) and Mercury (Hg) are five heavy metals that exhibit toxicity and are carcinogenic even at very minute concentration resulting in harmful effects on human and on environmental ecology (Leon and Chang, 2020). Epidemiologically, heavy metals have been studied and they engulf a vast parcel of industrial waste contaminant (Khalifa and Alkhalf, 2018). Pollutants from the industries on the environment, particularly, those containing heavy metals and nutrients are regarded deadly and toxic to life in general from both zoological and botanical views. There is a rise in the need of paint globally and thus, the paint industries have risen to become a point of attraction (Begum *et al,* 2019). Extenders, cellulosic and non-cellulosic thickeners, dyestuffs, organic and inorganic pigments, emulsifying agents, solvents, anti-foaming and coalescing agents are the typical characteristics of water-based paints (Dey *et al,* 2004). The product “paint” is mainly produced mainly as an ornamental gadget or a preservative and in some cases, for the two purposes concurrently (Virvaghan *et al,* 1991). According to Malakootian *et al* (2006), the paint industry happens to be among the several industries that have heavy metals included in their waste.

Bioremediation is an aspect of environmental biotechnology that is involved with the use of biological potentials (such as the plants) in making environmental contaminants less harmful (Boopathy, 2000). Bioremediation happens to be among the latest technologies that has gained so much interest and attention as it is considered an environmentally friendly and as well as a cost-effective approach in dealing with environmental pollution. An adsorbent is regarded as very economical when it is naturally available or a by-product that requires very minimal processing (Bailey *et al,* 1999).

Azolla, *Azolla filiculoides* (*A. filiculoids*) is a loosely floating aquatic fern that is most times, breeded in tropical ecosystems (Akhatr *et al*, 2021). It moves freely with water current and wind circulation which belongs to the family of salviniaceae (Deval *et al*, 2012; Tayeb *et al*, 2020) and can double its biomass within three to ten days (Hassan et al, 2009). Aquatic macrophytes possess well-formed root systems which gives them the recognition as superlative bio-accumulator of pollutants (May and Edwards, 2001; Stoltz and Greger, 2002). In the last two decades, plants have been greatly involved in the process of phytotechnologies for the bioremoval of toxicants from the environment and though, the advances are somewhat novel, it has received significant attention (Dhir, 2010). A number of the aquatic plants that have shown to have affinity for heavy metal removal from aquatic ecosystem is being utilized in the restoration of wastewaters (Abbasi and Rasamani, 1999; Kadlec *et al*, 2000). By virtue of the presence of Azolla in the aquatic ecosystem, it is applied in the bioremediation of wastewater at an economical rate and for an environmentally benign outcome (Deval *et al*, 2012). Zhang *et* *al* (2008), have suggested the use of high biomass of *Azolla caroliniana* in the renovation of polluted waters. The bioremoval of heavy metals by the macrophyte, Azolla has been studied with successful outcome (Zhao *et al*, 1999; Antunes *et al*, 2021). A research conducted by Xin wei *et al* (2018), showed that the biomass of Azolla was able to bioabsorb uranium, iron, manganese, copper zinc, lead and cadmium from the industrial effluent gotten from uranium mills tailings repository. In addition, *Azolla caroliniana* was able to remove as high as 93% mercury concentration from municipal wastewater after a period of 12 days (Bennicelli *et* *al*, 2004). In a phytotechnology study carried out by Echiegu *et al* (2021), using three different aquatic macrophytes, they discovered that *Azolla pinnata* showed the highest percentage reduction of the heavy metal contained in the wastewater. Azolla has been successfully grown under hydroponic conditions in wastewaters for heavy metal bioremoval (Deval *et al*, 2012; Echiegu *et al*, 2021).

Water hyacinth, *Eichhornia crassipes* (*E. crassipes*) can be described as a free-floating aquatic macrophytes that belongs to the family of pontedericeae and genus Eichhornia which has close correlation with the lily family (Gupta *et al*, 2012; Ali *et al*, 2020). This free floating invasive macrophyte can be found in all the regions of Asia and also in some other continents and usually forms a heavy covering on the aquatic ecosystem (Cherian and Joseph, 2022). It possesses very rapid growth rate (doubles biomass in five to fifteen days), easy to propagate and can successfully contend with other aquatic plants (Nayanathara and Bindu, 2017). Water hyacinth can reproduce both asexually and sexually (Villamagna, 2009) with height measuring up to 1.5 meters or more (Center *et al*, 2005). According to Ali *et al* (2020), water hyacinth is the most intrusive and widely distributed tracheophytes worldwide. It has the ability to withstand and grow under diverse environmental conditions from nutrient variation to temperature (Mahfooz *et al*, 2020). According to Lu (2017), one of the very outstanding characteristic of water hyacinth is the bioremoval of heavy metals e.g, lead, chromium, cadmium and mercury from contaminated waters. It is very potent in the treatment of industrial wastewater and domestic effluent at an eco-friendly rate (Lin and Li, 2016; Feng *et al*, 2017). Macrophyte are a useful tool when of comes to the balancing of the ecosystem (Gupta *et al*, 2012) and it is therefore regarded as an effective material for wastewater remediation and removal of pollutants (Cherian and Joseph, 2022). It is greatly recommended for treating industrial effluents as it possess high absorption rate of pollutants and can withstand highly contaminated environment (Jafari, 2010). Water hyacinth has been used in the accumulation and phytoremediation of heavy metals (silver, lead, cadmium, chromium, copper and selenium) from polluted wastewaters (Zhu *et al*, 1999). In addition, it was able to reduce the levels of heavy metals in an acid mine drainage and also silver from and industrial effluent within the shortest of time (Pinto *et al*, 1987). Furthermore, it has been able to remediate wastewater containing lead, chromium, cadmium and mercury (Lu, 2017). Water hyacinth is a plant that can be cultured under hydroponics with plant stems above the water level taking its nutrient straight from the water without soil (Nayanathara and Bindu, 2017). Water hyacinth has been successfully grown hydroponically for wastewater treatment (Echiegu *et al*, 2021).

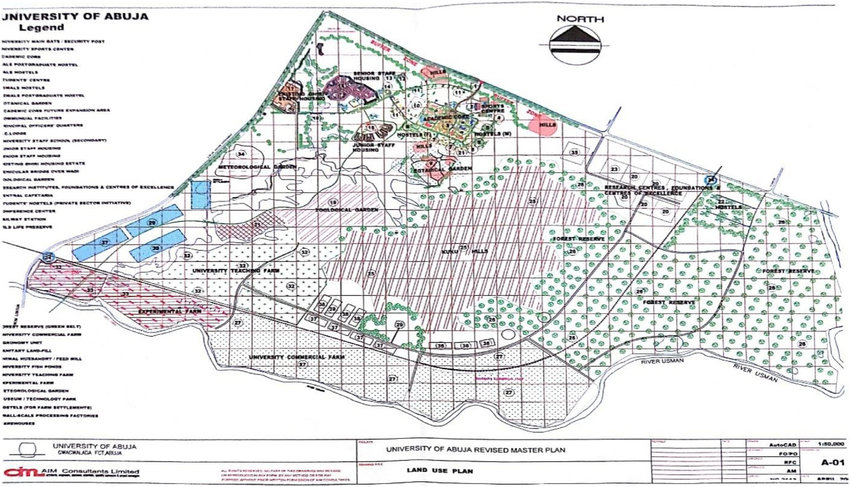
Hydroponics is a system that makes use of nutrients in an aqueous solution to grow plants without soil (Gardea-Torresdey *et al,* 2005). According to Houman *et al* (2011), hydroponics refers to a soil-less culturing of plants in a controlled domain making use of mineral supplements present in water whereby the roots of the plants are dipped in a nutrient containing liquid medium. Reports have shown that a good number of terrestrial plants and aquatic macrophytes grown hydroponically have accumulated heavy metals (Ignatius *et al,* 2014; Woraharn *et al,* 2021). Hydroponic systems have been applied in the economical remediation and detoxification of contaminants effectively (Davamani *et al,* 2021) and has been recommended as an alternative technology for the effective treatment of water and wastewaters with special reference to the use of both terrestrial and aquatic plants (Moogouei and Chen, 2020).

This study is therefore, aimed at investigating the bioremediation potentials of two aquatic plants (*Azolla mycrophylla* and *Eichhornia crassipies*) grown hydroponically in the uptake of cadmium, lead, chromium and copper from a paint-based effluent.

**MATERIALS AND METHODS**

**Sampling Location**

This study was undertaken in the university of Abuja main campus located in Abuja, Nigeria. The university of Abuja which is in Nigeria’s capital city lies between latitude 8o58’ north of the equator and longitude 7o10’ east of the Greenwich meridian. The university is bounded in north by Anagada village, Giri by the west, Kuje is located on the east and south while on the south-west, it is bounded by Gwagwalada (Amarachukwu *et al*, 2020).



**Map showing University of Abuja main campus. (Amarachukwu *et al*, 2020).**

**Collection and Preparation of Plants**

The collection of the sample plants *Azolla microphylla* and *Eichhornia crassipes* was done as described by Savitha and Rajan (2018). *Eichhornia crassipes* was gotten via a farm from Jabi Lake, Abuja FCT, Nigeria, while *Azolla microphylla* was obtained from a farm in Onitsha (Strategic Time Fish Farm), Anambara state, Nigeria. The plants were afterwards, left to acclimatize and established to their new environment for some time (Gupta *et al*, 2022). Plants with similar root length and shoot area were selected and after which, they were thoroughly washed under running tap water and then hydroponically propagated in a nutrient solution (Van Delden *et al*, 2020) for a period of about 14 days before being subjected to the effluent for the bioremoval study. This was to help the test plants acclimatize to the experimental conditions and also, to have enough biomass before the experiment (Borker *et al*, 2013; Tablang *et al*, 2021).

**Effluent** **Collection**

The effluent collection followed the pattern described by Nanda *et al* (2010) and Woldeamanuale and Hassen (2017). The raw paint effluent was gotten from the discharge tank from a paint industry located at Madala, Zuba, Abuja, Nigeria. The effluent sample was collected in newly acquired plastic bottles that were thoroughly washed, cleaned followed by rinsing with tap water to make it very clean same as all the glass wares (Gupta *et al*, 2022). Preservation of samples was done by storing the samples at 4oC until the time of usage.

**Acid Digestion of the Effluent for Heavy Metal Determination**

The acid digestion of the wastewater sample for the heavy metal determination was carried out according to the method described by Juliani *et al* (2021), and United States Environmental Protection Agency (USEPA), (1994). Acid mixture of Nitric acid, HNO3 (heavy metal measurement grade) and hydrogen chloride (Hcl) was added to the effluent sample in 9:1 ratio after which it was digested in the laboratory microwave oven. Digestion was then adjusted to a pressure of 800 pounds per square inch (PSI) and set to a temperature of 200oC for a period of 15 minutes. Cellulose acetate membrane filter 0.45 nm was then used to filter the digested sample.

**Determination of Heavy Metal**

The determination of heavy metal contents of the paint based industrial effluent and the test plants for this study was carried out using the Atomic Absorption Spectroscopy (AAS) Hanna HI Variian AAS SpectraAA 240FS, Italy. A standard solution was run with certified reference material in line with (Zulkafflee *et al,* 2020).

**Experimental Setup**

For this study, the experimental design and the greenhouse maintenance followed the pattern described by Kumar *et al* (2018), Wang *et al* (2018) and Savitha and Rajan (2018), with a slight modification. Acclimatized test plants, *Azolla microphylla* and *Eichhornia crassipes*)was transferred and uniformly spread into plastic pails with a water capacity of 5 litres that contained different dilution factors Treatment 1 had 50% dilution rate (i.e. 50% effluent and 50% tap water), treatment 2 had 25% dilution rate (25% effluent and 75% tap water). Each of the test plants followed the treatments described above. The pot experiments were carried out under a greenhouse condition at a controlled temperature at the Biological garden, faculty of Science, University of Abuja, Nigeria under maintained temperature. The treatments pails were positioned in such a way that the plants could get adequate sunlight to enhance photosynthesis. The pails were arranged in complete randomized block design. effluent was withdrawn on the start and the final day (after 6 weeks) (Echiegu *et al*, 2021) to analyse the heavy metal reduction potential of the study plants *A. microphylla* and *E. crassipes*, this was carried out by comparing the initial heavy metal concentration and the final heavy metal concentration. The acclimatization and the experimental period lasted for a total of 63 days (9 weeks).

**Determination of Removal Efficiency (%) of the Test Plants**

Removal Efficiency was calculated using the following formula (APHA, 2012).

Removal Efficiency (%) = Ci - Ce x 100 …………………….. Equation I

Ci

Where;

Ci = initial concentration of the pollutant.

Ce = final concentration of the pollutant.

**Determination of Relative Growth Rate of the Test Plants**

The relative growth rate was evaluated at the start and at the end of the uptake study where the harvested plant was weighed for the final weight and compared to the initial fresh weight of the biomass. The length of the leaves and root was also taken with the use of measuring inch tape as described by (Kumar *et al,* 2018) and (Gupta *et al*, 2022).

The formula below was used to calculate the relative growth rate (Aron, 1949).

Relative Growth Rate (RGR) = Ln W2 – Ln W1  ………… Equation II

T2 – T1

Where;

W1 = initial weight of fresh biomass

W2 = final weight of the harvested biomass

T1 and T2 = the duration of the experiment in days.

**Statistical Analysis**

All values described were the means of the replicates. Microsoft excel were used in the calculation of mean, standard error, standard deviation and in the plotting of statistical graphs. Statistical Package for the Social Sciences (SPSS) version 25 for Windows was used. Descriptive statistics were employed. Kolmogorov-Smirnov-Test was used to check if the data were normally distributed. One-way Analysis of Variance (ANOVA) and Turkey Post Hoc Test were used to compare means between treatments and other parameters measured. Other statistical tools were deployed as well. Significance was used at 95% confidence interval. Mixed model ANOVA was also used to compare between treatments.

**RESULTS AND DISCUSSION**

This study is aimed at investigating the potentiality of two aquatic plants; *Azolla mycrophylla* and *Eichhornia crassipies* in the bioremediation of heavy metal containing paint-based effluent under a hydroponic system. The bioremediation of four heavy metals; lead, cadmium, chromium and copper were studied.

**Uptake of Lead**

The concentration of lead was analyzed before and after the treatment with the test plants in two different treatments/dilutions (TRT 1, 50% and TRT 2, 25%). From the results obtained in the treatment 1 (50% dilution), *A. mycrophylla* (Azolla) recorded the highest (P<0.05) uptake of lead which reduced the concentration from 5.34 mg/L to 1.6 mg/L from the effluent at 89%. *Eichhornia crassipes* (Water hyacinth) reduced the concentration significantly (P<0.05) of lead from 5.34 mg/L to the final level of 2.30 mg/L at 51%. In TRT 2, *Azolla mycrophylla also* recorded the highest (P<0.05) uptake of lead from the effluent sample from 2.9 mg/L to 0.62 mg/L at 78% and *Eichhornia crassipies* (P<0.05) from 2.9 mg/L to 1.81mg/L at 36% (Figure 1).

**Figure 1. Removal efficiency (%) of Lead by the two plants**.

**Uptake of Cadmium**

The uptake of cadmium was also carried out by comparing the initial and final concentration of the element after the study. From the results obtained in TRT 1, *Azolla mycrophylla* significantly reduced cadmium concentration from 7.77 mg/L to 0.16 mg/L at 90% and *Eichhornia crassipies* to 0.33 mg/L at 82%. In TRT 2, *Eichhornia crassipies* recorded the highest (P<0.05) uptake of cadmium from the effluent from the initial concentration of 3.96 mg/L to a final concentration of 0.07 mg/L at resulting to 98% removal while *Azolla mycrophylla* reduced to 0.24 mg/L at 95% (figure 2).

**Figure 2. Removal efficiency (%) of cadmium by the two plants**.

**Uptake of Chromium**

Chromium was the third heavy metal which the uptake from the effluent was studied. Similar to lead and cadmium, both the initial and final concentrations were recorded. In treatment 1, the highest uptake of chromium from the effluent was observed in the treatment with *Azolla mycrophylla* which reduced the concentration significantly (P<0.05) from 0.20 mg/L to 0.15 mg/L with the removal efficiency of 39%% while *Eichhornia crassipies* reduced to a final concentration of 0.18 mg/L at 29%. In treatment 2, the highest uptake was observed in the treatment inoculated with *Azolla mycrophylla* from the initial concentration of 0.14 mg/L to 0.08 mg/L at 48%. *Eichhornia crassipies* on the other hand had 0.12 mg/L as against the initial concentration of 0.14 mg/L at 11% (figure 3).

**Figure 3. Removal efficiency (%) of Chromium by the two plants**.

The uptake of copper was investigated. The initial and final concentrations of copper in the water sample were evaluated accordingly. In treatment 1 (TRT 1), *Eichhornia crassipies* had highest (P<0.05) uptake from 0.53mg/L to 0.13mg/L with the removal efficiency of 76% while *Azolla mycrophhylla* had the final concentration of 0.15 mg/L at 72%. However, reverse was the case in the second treatment (TRT 2) where *Azolla mycrophylla* had the highest (P<0.05) uptake from 0.27 mg/L to 0.004 mg/L at 99% and *Eichhornia crassipies* had the final concentration of 0.25 mg/L at 8% respectively (figure 4).

**Figure 4. Removal efficiency (%) of Copper by the two plants**.

**Relative Growth Rate (RGR)**

The relative growth rate (RGR) is used to measure the growth index of plants or a system. For this study, the RGR was evaluated for both plants. The comparison was drawn between the two treatments and the control. There was a reduced growth rate recorded for *Azolla mycrophylla* however, *Eichhornia crassipies* showed a slight increase in the relative growth rate after the study in both treatments (figure 5).

**Figure 5. Relative Growth Rate of the Plants.**

**DISCUSSION**

The aim of this study was to check for the heavy metal uptake potential of *Azolla mycrophylla* and *Eichhornia crassipies* from a heavy metal containing paint effluent. The plant acclimatization and the heavy metal uptake study lasted for a period of 9 weeks after which the samples were analyzed for the potential of the different plants in the reduction of the heavy metals present in the effluent. The use of plants for the remediation of heavy polluted systems is beginning to gain so much interest due to the many advantages over the conventional waste treatment technologies. Similar observation to the obtained in this study has been reported in a research carried out under hydroponic condition for the uptake of heavy metals from an electroplating effluent using *Eichhornia. crassipies* (water hyacinth), the removal efficiency recorded was between 90-100% (Savitha and Vel Rajan, 2018). In another hydroponic study carried out for the uptake of heavy metals using different grasses, the data reported showed percentage removal of the heavy metals from the solution at 89% and 97% (Hasssan *et al*, 2020). Photosynthetic plants have shown potency in the absorption, hyper accumulation and can put up with heavy metal toxicity either from the water or soil via their roots.

The relative growth rate (RGR) of the test plants after a 6-week sampling period was evaluated. This gives a clue on the growth of plant within a specified period of time. A slightly notable growth was observed for *Eichhornia crassipies* in both treatments. However, a reduced growth was observed for *Azolla mycrophylla*. . Both increased and reduced biomass yield of plants has been recorded in previous research (Salehi and Shariat, 2024). For the first few days of exposure, the plants seemed to be growing well until some changes in the features began to emerge. Most of the green leaves started to fade and started turning yellow and some eventually turned brownish. A similar observation has also been reported (Phuenghphai *et al*, 2020). In their report, they found out that heavy metals at high levels resulted in the death of some plants which can be linked to the extreme destruction on different metabolism. Reduced plant growth rate due to the presence of heavy metals have also been reported (Anoliefo *et al*, 2005; Vwioko and Fashemi, 2005; Şentűrk *et al*, 2022).

**CONCLUSION**

There is a need for an efficient remediation of paint-based effluent as most of the heavy metals were found to be above the permissible limits. The data obtained in this study suggests the potentiality of *Azolla mycrophylla* and *Eichhornia crassipies* grown hydroponically in the uptake of heavy metals (Cadmium, lead, copper and chromium) from multi metal containing effluent considering the toxicity that comes with the presence of heavy metals in the environment.

**COMPETING INTERESTS DISCLAIMER**:

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

**REFERENCES**

1. Abbasi, A.S. & Ramasami, E. 1999. Biotechnological Methods of Pollution Control. Universities Press, Hyderabad: 168.
2. Ahmadkhan, A. 2001. In Brief News of World. *Water and Environment Journal*, 46: 34-35.
3. Akhtar, M., Sarwar, N., Ashraf, A., Ejaz, A., Ali, S. & Rizwan, M. 2021. Beneficial Role of *Azolla* sp. in Paddy Soils and their Use as Bioremediators in Polluted Aqueous Environments: Implication and Future Perspectives. *Archives in Agronomy* *and Soil Science,* 67(9): 1242-1255.
4. Ali, S., Abbas, Z., Rizwan, M., Zaheer, I.E., Yavas, I., Unay, A., Abdel-Daina, M.M., Bin-Jumah, M., Hasanuzzaman M. & Kalderis, D. 2020. Application of Floating Aquatic Plants in Phytoremediation of Heavy Metal Polluted Water: A Review. *Sustainability,* Amarachukwu, E., Evuti, A.M., Salam, K.A. & Silas, S.S. (2020). Determination of Waste Generation, Composition and Optimized Collection Route for University of Abuja Main Campus using “MyRouteOnline” Software. *Scientific African*, 10: e00569.
5. Anoliefo, G.O., Isikhuemhen, O.J. & Agbuna, S.O. 2005. Small Scale Industrial Village in Benin City (Nigeria): Establishment, Failure and Phytotoxicity Assessment from Soils from Abandoned Site. *Water, Air and Soil Pollution*, 131: 169-183.
6. Antunes, E., VUppaladadiyam, A.K., Sarmah, A.K, Varsha, S.S.V., Pant. K.K, Tiwani, B. & Pandry, A. 2021. Application of Biochar for Emerging Contamination Mitigation. In: Advances in Chemical Pollution, Environmental Management and Protection. Eslevier, 7: 65-91.
7. APHA, 2012. In: Standard Methods for the Examination of Water and Wastewater. Washington (DC): American Public Health and Association.
8. Aron, D. 1949. Copper Enzymes Isolated Chloroplast, Polyphenoloxidase in *Beta vulgaris*. *Plant Physiology*, 24: 1-15.
9. Begum, T., Hog, I., Bulbul, Z.H., Mahmud, J., Pramanik, K., Kamal, A.H.M., Islam, N. & Khan, R.A. 2019. Biodegradation of Hexavalent Chromium from Paint Industry Effluent by Indigenous Bacteria. *Scientific Review*, 5(2): 45-52.
10. Boopathy, R. 2000. Factors Limiting Bioremediation Technologies. *Bioresource Technology*, 74(1): 63-67.
11. Borker, A.R., Mane, A.V., Saratale, G.D. & Pathade, G.R. 2013. Phytoremediation Potential of *Eichhornia crassipies* for the Treatment of Cadmium in Relation with Biochemical and Water Parameters. *Emirates Journal* *for Food and* *Agriculture*, 25(6): 443-456
12. Center, T.D., Van, J.K., Dray, F.A.Jr., Franks, S.J., Rebelo, M.T., Pratti, P.D. & Rayamajhi M.B. 2005. Herbiovery Alters Competitive Interactions Between 2 Invasive Aquatic Plants. *Biological Control*, 33: 173-185.
13. Cherian, E. & Joseph, S. 2022. Water Hyacinth: A Potential Source for Phytoremediation and Biofuel Production. Bioenergy Crops. 1st Edition. CRC Press: 18
14. Davamani, V., Parrameshwari, C.I., Subramanian, A., John, J.E. & Poornima, R. (2021). Hydroponic Phytoremediation of Paperboard Mill Wastewater by using Vetiver (*chrysopogon zizanioides*). *Journal of Environmental Chemical Engineering*, 9(4): 105528.
15. Deval, C.G., Mane, A.V., Joshi, N.P. & Saratale, G.D. 2012. Phytoremediation Potential of Aquatic Macrophyte *Azolla caroliniana* with Reference to Zinc Plating Effluent. *Emirates Journal of Food and Agriculture*, 24(3): 208-223.
16. Dey, B.K., Hashim, M.A., Hassan, S. & Gupta, B.S. 2004. Microfiltration of Water-based Paint Effluent. *Advances in Environmental Research*. 8(3-4): 455-466.
17. Dhir, B. 2010. Use of Aquatic Plants in Removing Heavy Metals from Wastewater. *International of Environmental Engineering*, 2: 185-201.
18. Echiegu, E.A., Ezimah, C.O., Okechukwu, M.E. & Nwoke, O.A. 2021. Phytoremediation of Emulsion Paint using *Azolla Pinnata Eichhornia crassipies* and *Lemna minor*. *Nigerian Journal of Technology*, 40(3): 550-557.
19. Feng, W., Xiao, K., Zhou, W., Zhu, D., Zhou, Y., Yuan, Y., Xia, O.N., Wan, X., Hua, Y. & Zhao, J. 2017. Analysis of Utilization Technologies for *Eichhornia* *crassipies* Biomass Harvested after Restoration of Wastewater. *Bioresource Technology*, 223: 287-295.
20. Gardea-Torresdey. J.L., Peralta-Videa, J.R., la Rosa, G. & Parsons, J.G. 2005. Phytoremediation of Heavy Metals and Study of the Metal Coordination by X-Ray Absorption Spectroscopy. *Coordination Chemistry Reviews*, 249(1218): 1797-1810.
21. Gupta, P., Surendra, R. 2012. Amit, B.M. treatment of Water using Water Hyacinth, Water Lettuce and Vetiver Grass. A Review. *Resources and Environment*, 2(5): 202-215.
22. Gupta, U., Sharma, S.K., Goya, S.K. & Sharma, R. 2022. Removal of Heavy Metals from Integrated Wastewater (IIWW) using Canna Lilly (*Canna indica L.*): A Hydroponic System for Phytoremediation Potential. *International Advances Research Journal in Science, Engineering and Technology*, 9(4): 17-29.
23. Hassan, M.M., Haleem, N. Bac, M.A. & Jamal, Y. 2020. Phytoaccumulation of Heavy Metals from Municipal Solid Waste Leachate using Different Grasses under Hydroponic Condition. *Scientific Reports*, 10: 1-8.
24. Houman, H., Vasandra, M. & Nuthan, D. 2011. Hydroponics and Aeroponics as Alternative Production System for High-Value Medicinal and Aromatic Crops: Present Scenario and Future Prospects. *Journal of Medicinal and Aromatic Plant Sciences*, 33(4): 397-403.
25. Ignatius, A., Arunbabu, V., Neethu, J. & Rasamy, E.V. 2014. Rhizofiltration of Lead using an Aromatic Medicinal Plant *Plectranthus amboinicus* Cultured in a Hydroponic Nutrient Film Technique (NFT) System. *Environmental Science and Pollution Research*, 21: 13007-13016.
26. Jafari, N. 2010. Ecological and Socio-Economic Utilization of Water Hyacinth (*Eichhornia crassipies* mart solms). *Journal of Applied Sciences and Environmental Management*. 14(2): 43-49.
27. Jaskelevičius, B. & Lynikienė, V. 2009. Investigation of Influence of Lapes Landfall Leachate on Ground and Surface Water Pollution with Heavy Metals. *Journal of Environmental Engineering and Landscape Management*, 17 (3): 131-139.
28. Juliani, A., Rahmawati, S. & Yoneda, M. 2021. Heavy Metal Characteristics of Wastewater from Batik Industry in Yogyakarta Area, Indonesia. *International Journal of GEOMATE*, 20(80): 59-67.
29. Kadlec, R.H., Knight, R.L., Vymazol, J., Brix, H., Cooper, R. & Habert, R. 2000. Constructed Wetlands for Pollution Control. Control Processes, Performance, Design and Operation. IWA Pub. London: 164.
30. Khalifa, F.K. & Alkhalf, M.I. 2018. Phytoremediation as a Cleansing Tool from Nanoparticles and Pharmaceutical Wastes Toxicity. In: Ansari A., Gill R., R. Lanza G. 435-464.
31. Kumar, V., Singh, J. & Chopra, A.K. 2018. Assessment of Growth Attribute, Bioaccumulation, Enrichment and Translocation of Heavy Metal in Water Lettuce (*Pistia stratiotes L*.) Grown in Sugar Mill Effluent. *International Journal of Phytoremediation*, 20(5): 507-521.
32. Lim, S., Chu, W. & Phang, S. 2010. Use of Chlorella vulagris for Bioremediation of Textile Wastewater. *Journal of Bioresource Technology*. 101: 7314-7322.
33. Lin, Y. & Li, B. 2016. Removal of Pharmaceuticals and Personal Care Products by *Eichhornia crassipies* and *Pistia stratistes*. *Journal of Taiwan Institute of Chemical Engineering*, 58: 318-323.
34. Lu, X. 2017. Impact of Water Hyacinth on Removal of Heavy Metals and Organic Pollutants. Water Hyacinth. 1st edition. CRC Press, 33.
35. Mahfooz, Y., Yasar, A., Islam, Q.U., Rasheed, R., Naeem, U. & Mukhtar, S. 2020. Field Testing Phytoremediation of Organic and Inorganic Pollutants of Sewage Drain by Bacteria Assisted Water Hyacinth. *International Journal of Phytoremediation*, 1-13
36. Malakootian, M., Vaghmaeian, K. & Malakootian, M. 2006. Wood Ash Effectiveness in Cadmium Removal from Paint Industrial Effluent. *Pakistan Journal of Biological Sciences*, 9 (2): 248-252.
37. Moogouei, R. & Chen, Y. 2020. Removal of Cesium, Lead, Nitrate and Sodium from Wastewater using Hydroponic Constructed Wetland. *International Journal of Environmental Science and Technology*, 17: 3495-3502.
38. Mouchette, P. 1986. Algal Reactions to Mineral and Organic Micro-Pollutants, Ecological Consequences and Possibilities for Industrial Scale Application, A Review. *Water Research*, 20: 397-421.
39. Nanda, M., Sharma, D. & Kumar, A. 2010. Removal of Heavy Metals from Industrial Effluent using Bacteria. *International Journal of Environmental Sciences*, 2(2): 781-787.
40. Nayanathra, O.S. & Bindu, A.G. 2017. Effectiveness of Water Hyacinth and Water Lettuce for The Treatment of Grey water. A Review. *International Journal of Innovative Research in Science and Engineering*, 3(1): 349-355.
41. Nriagu, J.O. 1992. Toxic Metals in Africa. *Science Total Environment*, 121: 1-37.
42. Ogunfowokan, A.O., Durosinmi, L.M., Oyekunle, J.A.O., Ogunkunle, O.A. & Igbafe, I.T. 2007. Removal of Heavy Metals from Industrial Wastewater using Local Alum and other Conventional Coagulants- A Comparative Study. *Ife Journal of Science*, 9(2): 185-190.
43. Phuengphai, P., Sai-ngam, D., Seckor, S., Kheangkhum, N. & Wattanakoonsiri, A. 2020. Phytoremediation of Lead II using Aqueous Plants. *International Journal of Sciences*, 17(2): 17-36.
44. Salehi, A. & Shariat, A. 2024. Comparative Performance of *Populus spp* and *Salix spp* for Growth, Nutrition and Heavy Metal Uptake in a Wastewater Hydroponic System. *International Journal of Phytoremediation*, 26(9): 1309-1378.
45. Savitha, J. & Vel Rajan, T.V. 2018. Industrial Effluent Treatment by Phytoremediation. *International Journal of Innovative Research in Sciences, Engineering and Technology*, 7(1): 477-482.
46. Senturk, I., Divarci, N.S.E. & Ozturk, M. 2022. Phytoremediation of Nickel and Chromium Containing Industrial Wastewater by Water Lettuce (*Pistia stratiotes*). *International Journal of Phytoremediation*, 25(5): 550-561.
47. Stoltz, E. & Greger, M. 2002. Accumulation Properties of Arsenic, Cadmium, Lead and Zinc by four Wetland Plant Species Growing in Submerged Mine Tailing. *Botany Environmental and Experimental*, 47: 271-280
48. Tablang, J.O., Temanel, F.B., Campos, R.P.C. & Ramos, C. 2021. Bioaccumulation of Lead by Pepper Elder [*Peperromia pellucida (L.)*] Kunth in a Lead-Contaminated Hydroponic System. *Environment and Natural Research Journal*, 19(4): 282-291.
49. Tayeb, N., Hadj, B., Zahra, A., Djamila, A., Brahim, M.M. & Badji, A. 2020. Growth and Biochemical Response of *Azolla caroliniana* to Soluble NPK Fertilizers. *Studia Universitatis*, 30(4): 193-199.
50. Villamagna, A.M. 2009. Ecological Effects of Water Hyacinth (*Eichhornia crassipies*) on a Lake Chapala Mexico. Ph.D. Thesis, Fisheries and Wild Life Sciences, Virginia Polytechnic Institute and State University, Blacksburg, Virginia.
51. Vwioko, D.E. & Fashemi, D.S. 2005. Growth Response of *Ricinus communis L.* (Castor oil) in Pent Lubricating Oil Polluted Soil. *Journal of Applied Science and Environmental Management*, 9: 73-79.
52. Wang, Y., Lv, N., Mao, X., Yan, Z., Wang, J., Tan, W., Li, X., Liu, H., Wang, L. & Xi, B. 2018. Cadmium Tolerance and Accumulation Characteristics of Wetland and Emergent Plants under Hydroponic Conditions. *Royal Society of Chemistry*, 8(50): 33383-33390.
53. Woldeamanuale, T.B. & Hassen, A.S. 2017. Toxicity Study of Heavy Metal Pollutants and Physico-Chemical Characterisation of Effluents Collected from Different Paint Industries in Addis Ababa, Ethiopia. *Journal of Forensic Sciences*, 5(5): 001-006.
54. Woraharn, S., Meeinkuirt, W., Phusantisampan, T. & Chayapan, P. 2021. Rhizofiltration of Cadmium and Zinc in hydroponic Systems. *Water Air* *and Soil Pollution*, 232(2021): 204-221.
55. Xin Wei, H., Yondong, W., Nan, H., Yinhua, S. & Dexin, D. 2018. Bioremediation of Effluent from Uranium Mill Tailing Repository in South China by Azolla-Anabacteria. *Journal of Radioanalytical and Nuclear* *Chemistry*, 317: 739-746.
56. 56: 1149-1155.
57. Zhao, M., Duncan, J.R., & Hille, R.P., 1999. Removal and Recovery of Zinc from Solution and Electroplating Effluent using *Azolla filiculoides*. *Water Research*, 33:1516–1522.