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IDENTIFICATION OF THE PLATEAU OF CADMIUM EXTRACTION FROM AQUEOUS SOLUTION BY INVASIVE MACROPHYTE: EICHHORNIA CRASSIPES

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IDENTIFICATION OF THE PLATEAU OF CADMIUM EXTRACTION FROM AQUEOUS SOLUTION BY INVASIVE MACROPHYTE: *EICHHORNIA CRASSIPES*

by

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December 10, 2016

ABSTRACT

IDENTIFICATION OF THE PLATEAU OF CADMIUM EXTRACTION

FROM AQUEOUS SOLUTION BY INVASIVE MACROPHYTE:

EICHHORNIA CRASSIPES

Micalah Spenrath, B.S. Earth and Environmental Science

The University of Texas at Arlington, 2016

Faculty Mentor: James Grover

Cadmium is an extremely deleterious heavy metal characterized by high toxicity, environmental disruptiveness and difficult removal. Utilizing an aquatic macrophyte, *Eichhornia crassipes*, as a phytoremediant of cadmium has been shown to be experimentally viable and less environmentally degrading than conventional methods of heavy metal remediation. To further understand the time required to optimize cadmium uptake and minimize the rerelease of contaminants, *E. crassipes* was studied to identify the plateau of cadmium extraction. The experimental plants were housed in aquatic environments with cadmium concentrations of 5 ppm for 144 hours. Water samples were analyzed in atmosphere in a Shimadzu EDX- 7000 Energy Dispersive X-ray Fluorescence Spectrometer for 100 seconds per sample to determine cadmium concentration. A singular plateau trend was not observed in this study; instead, cadmium concentrations exhibited an

undulating pattern in which cadmium uptake and release occurred multiple times within a 144-hour window.

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CHAPTER 1

INTRODUCTION

1.1 Statement of Problem

Heavy metal contamination of the environment is a severe and growing problem in an increasingly industrial world, as heavy metal concentrations are compounded with each passing year (Rai et al. 2002; Govindasamy et al. 2011). Heavy metals are of environmental concern due to their notable toxicity to living organisms, their lethality in small quantities, their persistence and accumulation in many environmental compartments and their difficult removal, which often requires large fiscal contribution and environmental upheaval (Ali et al. 2013).

1.2 Phytoremediation Overview

Phytoremediation is an in situ means of heavy metal removal that functions as a less environmentally disruptive alternative to conventional methods such as soil incineration, excavation and landfill, and soil washing and flushing; a few of these processes have aquatic equivalents that result in similar environmental degradation (Mulligan et al. 2001). In addition to environmental disruption, these processes can warrant the use of chemicals or other noxious compounds that have the potential to create secondary contamination. The use of plants to extract and immobilize various heavy metals, organic solvents, and industrial chemicals from the contaminated medium has been well documented in over five hundred species, representing many different plant families, and may serve as a promising alternative remediation technique (Ghosh and Singh, 2005).

1.3 Introduction to Experimental Phytoremediant

Eichhornia crassipes (water hyacinth), an aquatic and invasive macrophyte, has been investigated thoroughly for its ability to function as a phytoremediant; it can extract heavy metals over a spectrum of concentrations—as high as 10,000 times the concentration of the surrounding medium— without exhibiting significant phytotoxic effects and without succumbing to the lethality of heavy metal contamination until high concentrations are reached (Petit et al. 1978; Lu et al. 2004; Tiwari et al. 2007; Jafari 2010; Das et al. 2016). For these reasons, water hyacinth has been identified as a promising candidate to function as a phytoremediant of heavy metals—cadmium in particular.

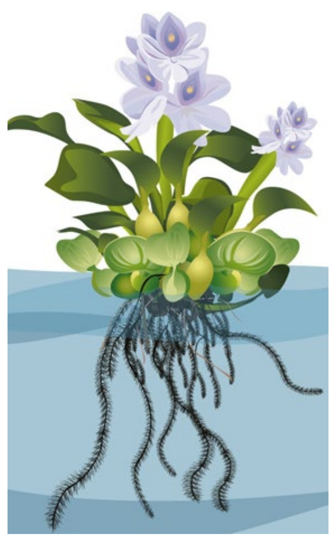


Figure 1.1: A Depiction of Water Hyacinth (agriculture.vic.gov.au, 2016)

Water hyacinth also exhibits advantageous qualities for phytoremediation, such as typical high biomass and a high tolerance for diverse climates. Although utilitarian for phytoremediation, these qualities have led to serious ecological and economic damage.

Being an invasive species, *E. crassipes* is well suited to acclimate to and dominate new regions, typically leading to the reduction of indigenous species diversity (Jafari 2010). However, the diminution of diversity is not the only negative consequence of invasive species introduction and proliferation. Water hyacinth has been known to procreate, sexually and asexually, in such a way that the population can cover entire expanses of water bodies and in such densities that it can block the sun from penetrating the surface of the water. This can greatly and adversely impact trophic level interactions, primary production as well as the livelihood of people who rely on rivers or other waterways for income or sustenance. These negative qualities exhibited by *E. crassipes* make it very desirable to remove from ecosystems as its presence is not beneficial to a healthy ecosystem.

However, for the purposes of phytoremediation, this is a positive quality. After using a plant for remediation purposes in an aquatic medium, it is very likely that the biomass is riddled with hazardous contaminants and therefore must be removed from the polluted region before the plant dies and decomposes; decomposition would release the stored contaminants back into the environment. Removing a large population of a nonessential—in fact, a crippling—plant will not only relieve the ecosystem of its biological oppressor but also remove organic solvents, chemicals or heavy metals simultaneously.

1.4 Introduction to Target Contaminant: Cadmium

One such nonessential heavy metal is cadmium (Cd); this metal is amalgamated into paints, plastic stabilizers and is the product of industrial processes, such as electroplating and mining (Salem et al. 2000; Pulford and Watson, 2003). Cadmium is in the top five most toxic metals of public health concern (Tchounwou et al. 2010). It is toxic to humans and wildlife in very low concentrations due to several factors: the generation of reactive oxygen species and the consequent oxidative stress, the blockage of functional groups in biomolecules, organ damage and carcinogenesis (APHA et al. 1998; Schutzendubel and Polle, 2002; Miretzky, 2006; Tchounwou et al. 2010). Cadmium is also known to cause the disruption of endocrine, the interference of calcium regulation in the body as well as anemia and renal failure. It is currently considered teratogenic and mutagenic (Degraeve 1981; Salem et al. 2000; Awofolu, 2005). In summary, cadmium has many ways of causing lethality. According to the Center for Disease Control (CDC), a cadmium concentration of 0.009 parts per million (ppm) is "immediately dangerous to health and life" (IDHL) (CDC, 2014). This is starkly juxtaposed with highest environmental concentrations being recorded at approximately 15 ppm (Tchounwou et al. 2010).

1.5 Brief Current Scientific Knowledge Overview

The usage of water hyacinth as a phytoremediant of cadmium has been well studied, and these scientific endeavors have yielded significant results. *E. crassipes* accumulates cadmium in the roots and aerial tissues in concentrations many times that of the water or soil (Swain et al. 2014). This implies that utilizing water hyacinth in phytoremediation efforts will allow the magnification of the contaminant inside the plant; this will allow for greater removal per plant upon harvesting. Water hyacinth increases uptake of heavy metals in a manner that is commensurate with the increase in cadmium concentration in the environment. This particular plant will increase uptake despite an increasing contaminant load; this finding has applications in areas where there is a continual input of contamination. Clearly, the aforementioned findings buttress the position that water hyacinth is one of the most promising phytoremediants. Chapter Two contains a more technical and holistic review of the findings of current scientific literature.

1.6 Research Scope

Although *E. crassipes* exhibits these beneficial remediation qualities, at wilting it will begin to lower the pH of the medium due to the release of ions and heavy metals back into the environment; this causes acidification of the water which can in turn augment the mobility of cadmium ions (Hahne and Kroontje, 1973; Soltan and Rashed, 2003). There is a dearth of information regarding the point in time at which this occurs and when the extraction of cadmium plateaus in an aquatic medium. The purpose of this study is to identify the plateau of extraction from an aquatic environment by water hyacinth in the effort of optimizing cadmium removal and completely avoiding the rerelease of contaminants.

CHAPTER 2

LITERATURE REVIEW

2.1 Location of Accumulation

Soltan and Rashed (2003) found that highest concentrations of heavy metals accumulate in the roots of *E. crassipes* through a spectrum of different heavy metals. In comparison to the root concentrations of *E. crassipes* exposed to different heavy metals, those exposed to cadmium retained the lowest concentrations; contrary to this trend, root concentrations were five times greater than the aerial portion within the same plant. Findings of this nature were also noted in another study (Swain et al. 2014). If these findings are an objective characteristic of *E. crassipes*, then under the present study, it can be suggested that the plants will have many times higher cadmium concentration in the root material. These findings also suggest that water hyacinth may have less of an affinity to accumulate cadmium in comparison to other heavy metals.

2.2 Cadmium Uptake

In regards to the extraction of cadmium, many studies have found a strikingly promising result: the uptake of cadmium by *E. crassipes* increases as the concentration of cadmium increases in the roots and external medium (Soltan and Rashed, 2003; Lu et al. 2004). However, this too may have a plateau point as shown by Figure 2.1 adapted from another study (Das et al. 2016).

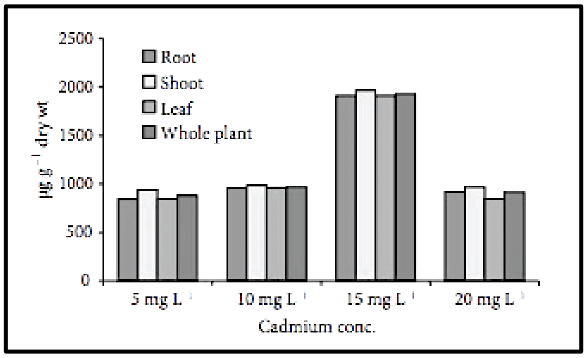


Figure 2.1: Cadmium concentration in multiple plant sections of *E. crassipes* as starting cadmium concentrations increased (Das et al. 2016).

There is a notable decrease in cadmium extraction when increasing the concentration from 15 ppm to 20 ppm; this implies that *E. crassipes* has its peak extraction efficiency at, or near, 15 ppm.

In addition to this behavior, it was also found that cadmium concentration in *E. crassipes* will increase over time (Lu et al. 2004). This can be visualized by Figure 2.2, which depicts the cadmium concentration of the experimental medium as a function of time (Mishra and Tripathi, 2008). As shown by Figure 2.2, as time progresses the amount of cadmium (and other heavy metals) in the surrounding medium decreases; this implies higher quantities are accumulating within the plant.

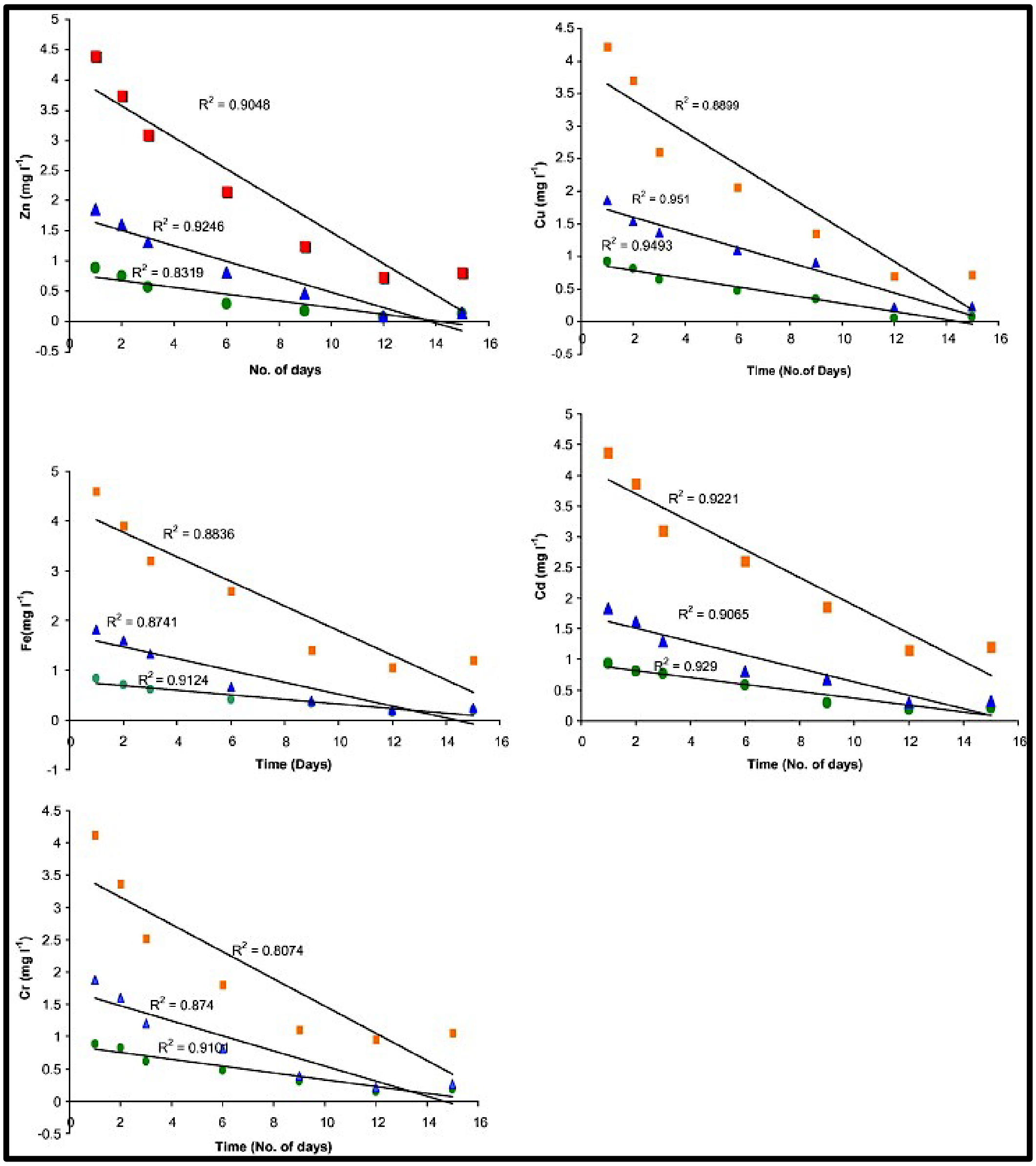


Figure 2.2: Heavy metal removal from experimental medium by *E. crassipes* at different starting concentrations (Mishra and Tripathi, 2008).

Each of these findings enforce that expectation that the uptake of cadmium in the present study will increase over time. Additionally, it has been found that this increasing uptake with increasing concentration does not follow a linear trend (Fritioff and Greger, 2007). It can be deduced that this enhancement of uptake will eventually lead to a maximum uptake rate or maximum uptake concentration at which the plateau is likely occur. This plateau can be visualized by Figure 2.3, adapted from another study (Maine et al. 2001).

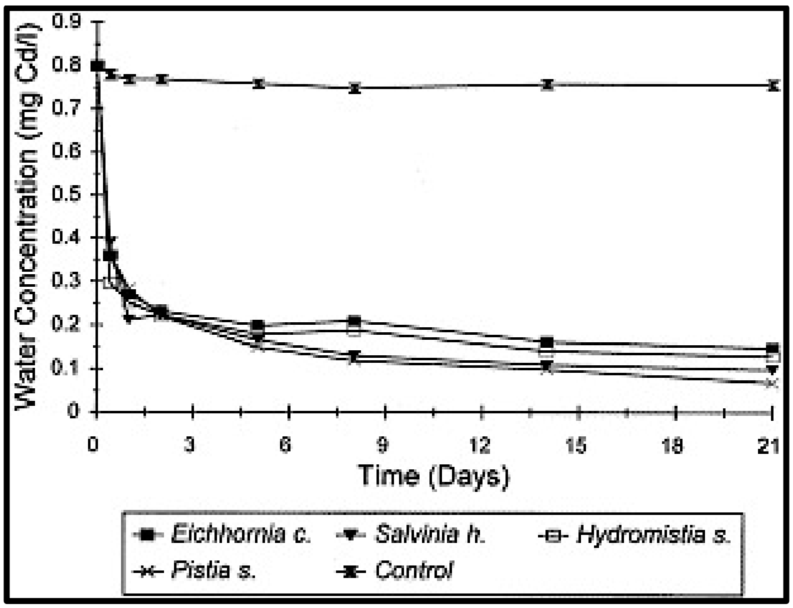


Figure 2.3: This graph depicts the cadmium concentration in water as time progresses when using several different plants as phytoremediants (Maine et al. 2001).

Although this information is probative, there are several factors distinguishing the present study from the aforementioned that produced the results pictorially represented in Figure 2.3. In the present study, *E. crassipes* was used as the main focus of the experiment, and was exposed to a higher concentration of cadmium (5 mg/L) for 144h. This contrasts with the other study in which *E. crassipes* was used only as a reference, and was exposed to 1 mg/L of cadmium for a longer duration: 21 days.

Despite these differences, the information provided from this study has suggested that the plateau of cadmium extraction will occur within the first three days of the experiment when administered using a 1 ppm cadmium concentration in the external medium. It is possible that the plateau will occur at a similar time at an augmented cadmium concentration. Ideally, the present study will be able to more accurately illuminate when the plateau of extraction occurs in order to optimize total extraction and minimize the rerelease of toxic compounds and other harmful ions (Soltan and Rashed, 2003).

CHAPTER 3

METHODOLOGY

The water hyacinth plants (*E. crassipes*) were obtained from Mountain Creek Lake in Dallas, Texas (32°42'38"N 96°58'48"W)—a local, artificial lake with a heavy industrial presence. The plants were thoroughly washed with tap water to remove aquatic macroinvertebrates and insect larva. Three water hyacinth of comparable size were selected (70±10g); two were individually exposed to 5 mg/L of cadmium in deionized water. The cadmium was introduced in the form of $CdCl_2$. The third plant was placed in deionized water that was not supplemented with cadmium and that acted as a control. Another condition, absent of plants, was created and consisted of only deionized water to determine if any desorption of cadmium from the experimental container occurred without the presence of plants. This was an important condition because the experimental containers were plastic and cadmium is used in plastic manufacturing. Utilizing LED growth lamps, the plants underwent a 12-hour photoperiod followed by a 12-hour dark period to simulate natural lighting.

Water samples (5 ml) were taken at 0, 1, 2, 4, 8, and 12 hours and thereafter in 12-hour intervals for a total of 144h. They were analyzed in atmosphere in a Shimadzu EDX-7000 Energy Dispersive X-ray Fluorescence Spectrometer for 100 seconds per sample. The process that allows this technology to work— Energy Dispersive X-ray Fluorescence —is discussed in Appendix A.

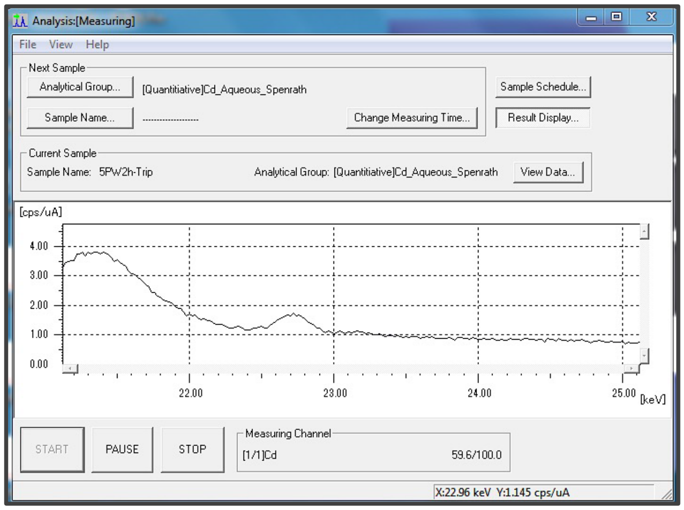


Figure 3.1: Cd analysis window within the PCEDX-PRO software. Signals shown by peaks.

3.1 Analysis Preparation

The Shimadzu EDX-7000 was not calibrated for aqueous cadmium detection and, as such, the first step prior to sample analyses was calibration to ensure reliable results. The calibration method of choice was the calibration curve method, in which multiple solutions of known cadmium concentration were created and input manually into the machine. This allows the machine to irradiate a given sample and compare the returned signal to the known values in the curve. This enhances accuracy. The calibration curve for this project is pictured in Figure 3.2.

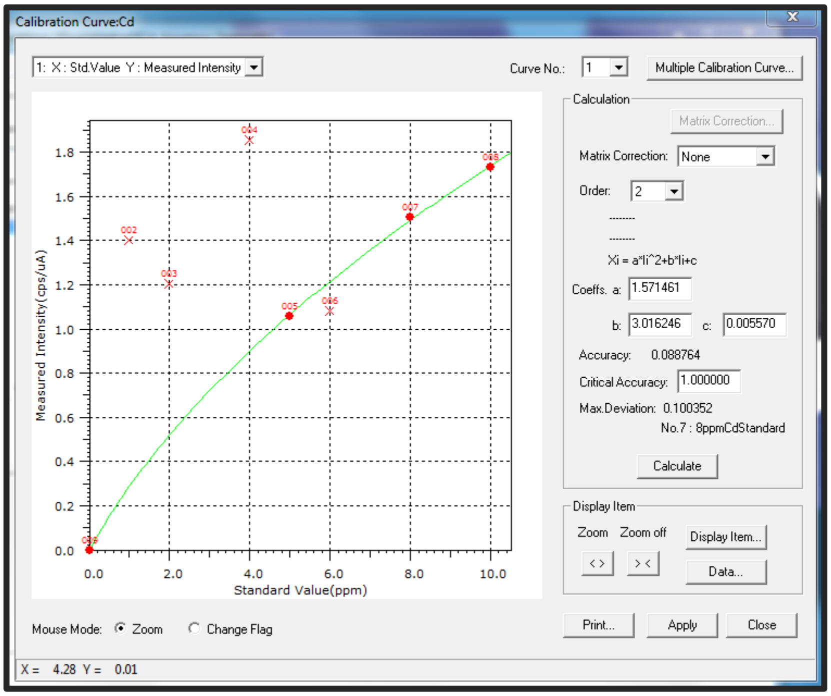


Figure 3.2: The calibration curve, consisting of various Cd concentrations, created for this project.

3.2 Analysis Procedure

After the equipment was calibrated, samples were placed in sample cups that were lined with mylar sheets. The samples were placed in the machine and analysis was run for 100 seconds. After analysis, the samples were placed in a heavy metal waste receptacle, the sample cups were rinsed with deionized water and the mylar sheet was changed to ensure no cross contamination of the samples. At the end of each analysis session, each data point was exported to an EDX report file (Figure 3.3), which included standard deviation (sigma), cadmium concentration detected, and analysis signal and peak.

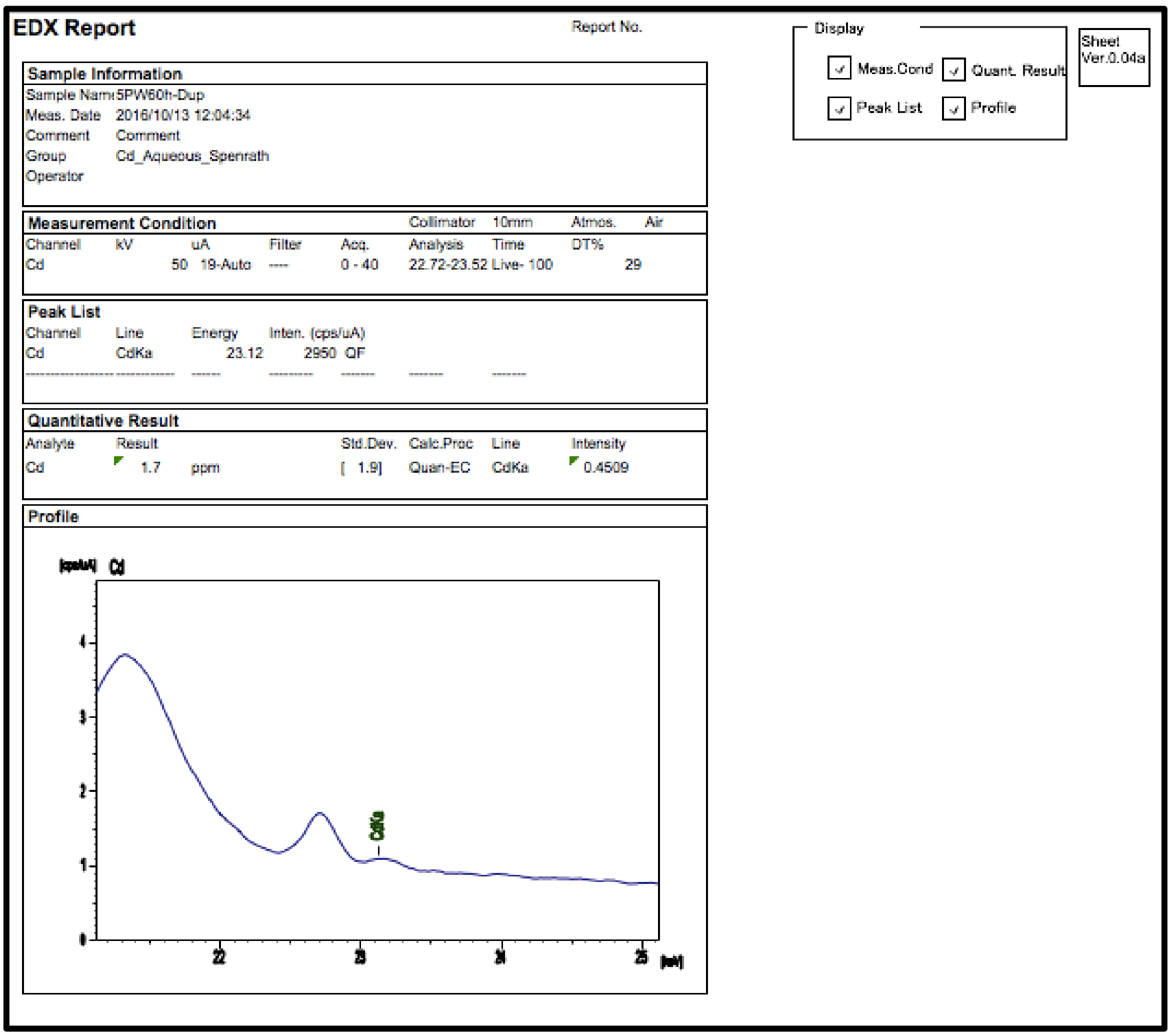


Figure 3.3: The exported data report from the Shimadzu EDX- 7000 for the sample taken from the 5 ppm cadmium concentration environment at 60 hours into the experiment.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Results from Present Study

Contrary to the implications presented by former scientific literature, *E. crassipes* did not exhibit a conspicuous plateau in regards to cadmium extraction in the present study. The detected concentrations of cadmium in the water samples increased and decreased many times within the 144-hour experiment window, as can be seen in Figure 4.1. This oscillating pattern is easily identified by the sixth order polynomial regression for each experimental condition. There is a maximum detected cadmium concentration of 5 ppm, in which the plant has not extracted any of the contaminant from the system and the lowest detected concentration is recorded at 0 ppm. This implies that *E. crassipes* does have the potential to fully remove Cd from an aquatic environment. Lowest cadmium concentrations occur at approximately 4, 12, 96 and 108 hours with a momentary increase at 48 hours. At 4, 12, 96 and 108 hours it would be optimal to harvest the plants from the environment to maximize cadmium extraction. The other conditions that were to determine desorption of cadmium from experiment containers and preexisting contamination of the water hyacinth yielded zero or negligible cadmium concentrations consistently (0 ppm ± 0.2). This implies that there was no preexisting cadmium in the plants and that there was no significant desorption of cadmium from the containers.

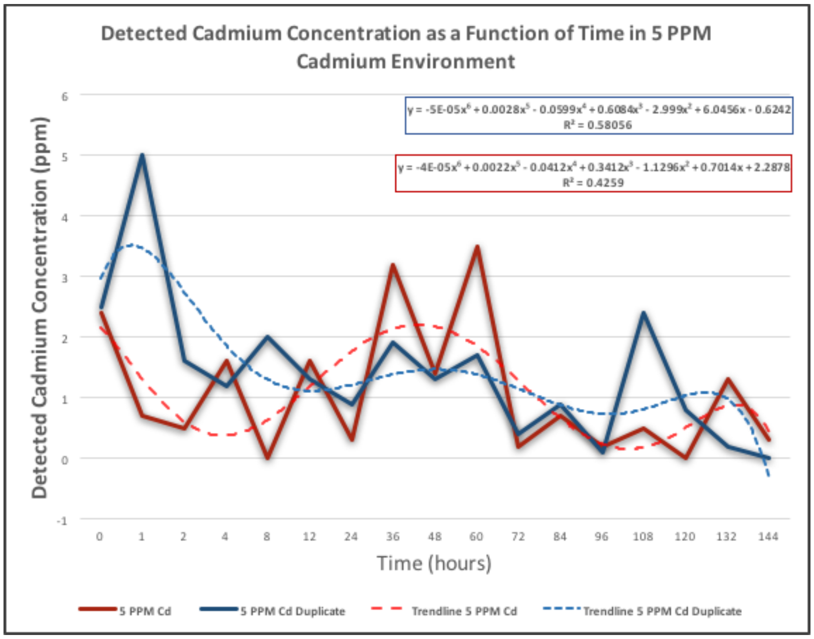


Figure 4.1: A graph depicting changing cadmium concentrations (ppm) over time (hours) for all experimental conditions.

4.1.1 Implications and Significance of Results

Based on the results of this study, the usage of this invasive macrophyte as a phytoremediant would be useful in areas with relatively low contaminant concentrations, low contaminant percolation and in areas that are not prone to contaminant accumulation. In other words, due to the fact that *E. crassipes* uptakes cadmium and releases in a repetitious manner, it would be best suited in an environment that does not sorb cadmium to other materials such as minerals or soil particulates upon reintroduction. Utilizing *E.crassipes* in such an environment would be counterproductive to the ultimate goal of complete contaminant extraction. This is the case because as the plants release cadmium back into the aquatic ecosystem, the cadmium ions have the potential to sorb with minerals or other particulates which would then make them unavailable for the plants to reabsorb;

this would lead to increasing concentrations of cadmium over time in the environment despite the presence of the phytoremediant plants.

An advantage of this oscillating behavior is that there are many opportunities to harvest the plants while extracting sizeable amounts of contaminant—this allows for flexibility when utilizing the plants to remediate a site. A disadvantage to this behavior is that *E. crassipes* does not hold cadmium very long before it reintroduces it to the environment; as such, the plants must be harvested promptly and quickly to ensure maximal contaminant removal.

4.2 Limitations of Present Study

The present study was limited in terms of detection limits on available equipment and analytical error. The Shimadzu EDX-7000, although an extremely versatile machine, had detection limits very close to the cadmium concentration ranges of this study. In addition to mechanical limitations, there was relatively large variability associated with the data; this indicated that the data was less reliable than desired. This high variability can be attributed to the close proximity of the analytical peak (signal produced by cadmium) to the noise peak (signal produced by the X-Ray within the machine). The different peaks can be visualized in Figure. 4.2.

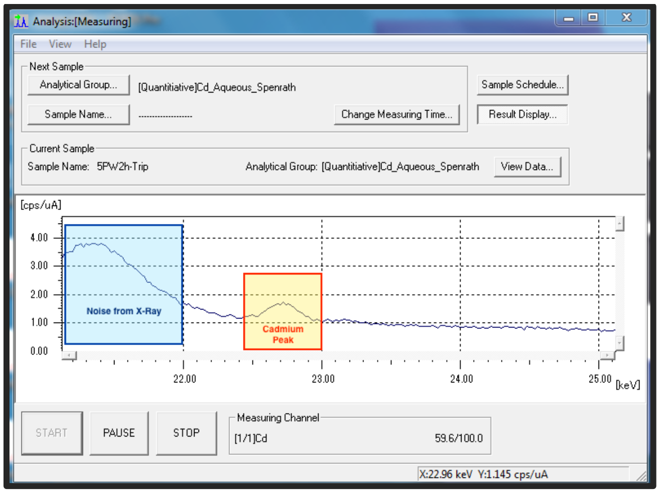


Figure 4.2: Sample analysis window depicting noise peak and Cadmium peak.

To clarify the results of the current study, a duplicate study should be run with higher cadmium concentrations that would not be near the noise produced by the machine X-ray. Also, another technique could be used in which samples are analyzed in an ICP-AES—a machine specifically designed to detect trace metals. Unfortunately, this technology was not available for the present study.

Although the data is a bit ambiguous, there was visual confirmation of cadmium adsorption to the root tissue via a scanning electron microscope (SEM) (Appendix D). It is likely that this contamination is from the introduced cadmium chloride and not from preexisting contamination from the lake from which the plants were harvested; this is due to the lack of cadmium in the experimental environments designed to test for such contamination. The general trend proposed by the data has the potential to illuminate the behavior of *E. crassipes* when it functions as a phytoremediant of cadmium. The data suggests that there is not merely one point in time that could result in the maximum removal of cadmium but that there are multiple opportunities for this to occur.

4.3 Limitations of Phytoremediation

Although phytoremediation is a more sustainable alternative to conventional heavy metal remediation techniques, it is not without its limitations: time, contaminant concentration and location, number of contaminants, biodiversity and hazardous biomass production (Ghosh and Singh, 2005).

4.3.1 Time

Unlike conventional methods, when utilizing the technique of phytoremediation to remove contaminants time is a factor of consequence. In fact, depending on several variables, it can take years to fully remediate a contaminated site. This is a rather large time investment compared to traditional methods.

The time incurred is likely due to plant acquisition, installation and growth. Growth is a necessity and a condition that cannot be expedited; it is commonly the mature form of the plant that can accumulate the most heavy metals without succumbing to their toxicity. Therefore, as an example, if a particular species of metallophyte took three years to become an adult, then that time commitment is likely the minimum before remediation efforts are in full commencement. However, minimization of this commitment may be possible through the careful selection of plant species.

4.3.2 Contaminant Concentration and Location

Another limitation when using plants in the effort of remediation is that they can operate only within a constricted range of contaminant concentrations. Unfortunately, these concentrations tend to be relatively low. Furthermore, the location of the contaminant is important. The majority, if not all, of plants intake contaminants through their root systems, and as such the contamination needs to be in an area that the roots can reach. This vertical depth is considered shallow: perhaps 1 meter for large grasses and a few meters for trees. Unfortunately, this constricts the number of regions that are candidates for phytoremediation. If the contaminants are in the groundwater or several meters underground, then the usage of phytoremediant plants would not prove to be an efficient method of pollutant removal.

4.3.3 Number of Contaminants

The presence of numerous contaminants may negatively impact the ability of plants to extract the target pollutant from the environment. As in the case of heavy metals, the presence of more than one metal (binary and ternary systems) caused antagonistic interactions which led to the decrease in absorption of a few metals in *E. crassipes* (Mahamadi and Nharingo, 2010). This information implies that if optimal contaminant extraction is the desired outcome, it would be best to use phytoremediation in systems with a singular contaminant. This requirement will prove to be more arduous to fulfill as environmental pollution continues.

4.3.4 Biodiversity

As briefly discussed in the introduction, biodiversity is a concern when introducing new plants to an area for they have the potential to become invasive. However, introducing plants into a new area, is commonly a requirement for phytoremediation due to the lack of indigenous metallophytes. It would be counterproductive to introduce a plant species that collects the contaminants but destroys the preexisting ecosystem. This consideration must be carefully cogitated in order to select the best remediation candidate that has the lowest potential for invasive behavior.

4.3.5 Hazardous Biomass Production

One of the most challenging limitations of phytoremediation is the production of hazardous biomass and its difficult disposal. As remediation efforts come to completion, the hazardous biomass accumulates to very large volumes. There are a few theoretical solutions to this problem, such as composting and compaction (Raskin et al. 1997; Hetland et al. 2001), as well as combustion and gasification (Bridgewater et al. 1999). Although these methods solve the dilemma of volume, they do not address the presence of contaminants in the byproducts of these processes—leachate and ash, respectively— as they maintain heavy metal loads. It is clear that the leachate and ash must undergo secondary processing, but the exact methods of heavy metal removal have not been thoroughly investigated.

Pyrolysis and phytomining are very promising disposal methods. Pyrolysis is the anaerobic decomposition of hazardous biomass material without emissions that produces a substance called "coke"; the heavy metals are sequestered in the coke which can be recycled for industrial processes. The degree to which the metals can be recycled has yet to be thoroughly investigated (Ghosh and Singh, 2005). Phytomining is the combustion of the biomass for the purpose of creating energy, which introduces an economic benefit, and the subsequent extraction of heavy metals from the bio-ore produced from the process. The heavy metals extracted from the bio-ore will go on to be reused in other processes (Ali et al. 2013). These methods, through energy conversion and material recycling, are the most sustainable thus far but have not been experimentally studied in depth. As such, there are many unknowns about these processes. Despite the current limitations of phytoremediation technologies, there are many examples of successful phytoremediation projects. These can be seen in Appendix B.

4.4 Future Work

In light of the problem of disposing of hazardous biomass waste generated by phytoremediation, it is likely that future work will be done to find sustainable methods of waste disposal or ways of enhancing current methods. Studies could be done to investigate the efficiency of heavy metal extraction and recycling after the processes of phytomining, pyrolysis and general combustion. More work may be done to provide a method of combustion that eradicates all emissions without the generation of heavy metal laden materials.

Another avenue of future work may include methods of enhancing phytoremediation efficiency in the contaminated site. Several methods of doing this have been suggested: genetic engineering, induced phytoextraction, increasing bioavailability of heavy metals, chelate-assisted phytoextraction and decreasing phytoremediation period by accelerating plant growth (Ghosh and Singh, 2005; Karami and Shamsuddin, 2010). However, these methods are in need of further investigation and elucidation. Work could also be done to evaluate the potential for using bark, lignin, dead biomass, chitin and chitosan as sorbents of heavy metals in place of utilizing live plants (Bailey et al. 1999).

CHAPTER 5

CONCLUSION

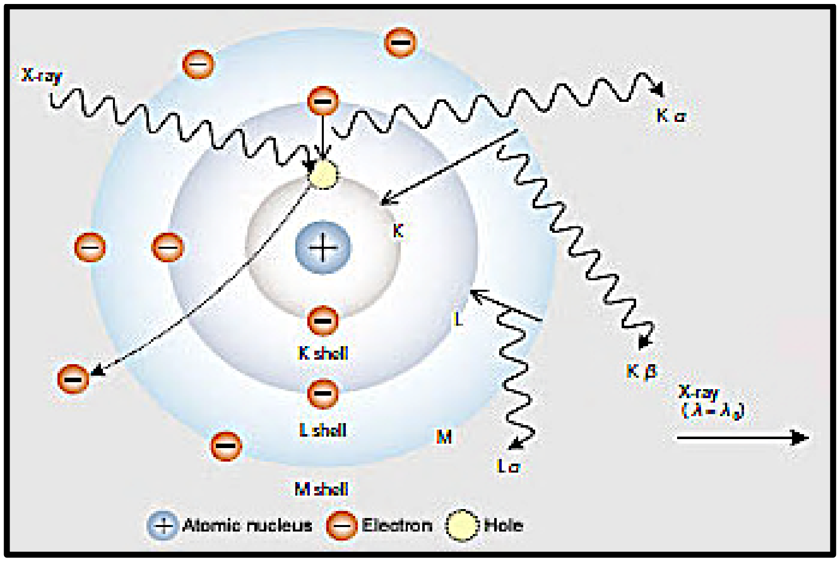
Heavy metals are hazardous compounds that have found their way into the environment largely through industrial processes; many are toxic, carcinogenic, teratogenic, mutagenic and environmentally mobile and persistent. Environmental concentrations of these hazardous compounds are increasing in many different environmental compartments as the years pass. As the presence of these compounds is of ecological and public health concern, it is imperative that sustainable methods of remediation be found and implemented in place of the conventional methods, which are characterized by environmental disruption and degradation.

One such promising method may be phytoremediation, utilizing *Eichhornia crassipes* as the phytoremediant. Although further investigation would be beneficial, the present study has shown that *E. crassipes* will uptake and release cadmium in a repetitious manner and that uptake is maximal at approximately 4, 12, 96 and 108 hours. The plants did not succumb to phytotoxicity for the duration of the experiment—verifying that they can survive cadmium contamination at 5 ppm. Based on this behavior, this method of remediation may be best suited for surficial and low concentration contamination. Although phytoremediation has environmental benefits, it also has certain limitations and therefore must be considered only for contamination sites where it will be most effective. Future work will enhance efficiency of metal uptake, decrease time commitment and solve the problem of hazardous metal contamination removal in the harvested phytoremediation biomass.

As scientific endeavors continue to focus on phytoremediation, the questions and limitations surrounding the process will fade away until it is a more commonly used remediation technology.

APPENDIX A

PRINCIPLE OF FLUORESCENT X-RAY GENERATION



An illustration of X-ray fluorescence of an atom (Shimadzu Corporation, 2016).

When a sample is irradiated with X-rays from an X-ray tube, the atoms in the sample generate unique X-rays that are emitted from the sample. Such X-rays are known as "fluorescent X-rays", and they have a unique wavelength and energy that is characteristic of each element that generates them. Consequently, qualitative analysis can be performed by investigating the wavelengths of the X-rays. As the fluorescent X-ray intensity is a function of the concentration, quantitative analysis is also possible by measuring the amount of X-rays at the wavelength specific to each element (Shimadzu Corporation, 2016). This is the process that allows the machine to determine contaminant concentrations.

APPENDIX B

SUCCESSFUL PHYTOREMEDIATION PROJECTS

Location	Application	Plants	Performance
Chernobyl, Ukraine	Rhizofiltration near nuclear disaster	Sunflowers *Helieanthus anuus*	90% reduction ^{137}Cs, ^{90}Sr in 2 weeks, 8000 X normal concentration in roots
Ashatabula, OH	Rhizofiltration of energy wastes	Sunflowers *Helieanthus anuus*	95% removal of U in 24 h (350 ppb to <5 ppb)
Trenton, NJ	Phytoextraction of 200×300 ft brownfield	Indian mustard *Brassica juncea*	In one season, reached below action level
Rocky Flats, CO	Rhizofiltration of landfill leachate	Sunflowers and mustard	In progress
Pennsylvania	Phytoextraction of mine wastes	*Thlaspi* spp.	Uptake of Zn and Cd rapid but soil difficult to decontaminate
San Francisco, CA	Phytovolatilization of refinery wastes and agricultural soils	*Brassica* sp.	Se is partly taken-up and volatilized but soil difficult to decontaminate

Tabulated characteristics of successful phytoremediation projects (Mulligan et al. 2001)

APPENDIX C

GLOSSARY

Adsorption: to gather (a gas, liquid, or dissolved substance) on a surface in a condensed layer

Biomass: the total quantity or mass of organisms in a given area or volume

Carcinogenic: any substance or agent that tends to produce a cancer

Heavy Metal: any metal with a specific gravity of 5.0 or greater, especially one that is toxic to organisms

Invasive Species: any kind of living organism that is not native to an ecosystem and that causes harm to that ecosystem

Macroinvertebrates: the term used for invertebrate fauna that can be captured by a 500-µm net or sieve. This includes arthropods (insects, mites, scuds and crayfish), molluscs (snails, limpets, mussels and clams), annelids (segmented worms), nematodes (roundworms), and platyhelminthes (flatworms)

Macrophyte: an aquatic plant that grows in or near water and is either emergent, submergent, or floating

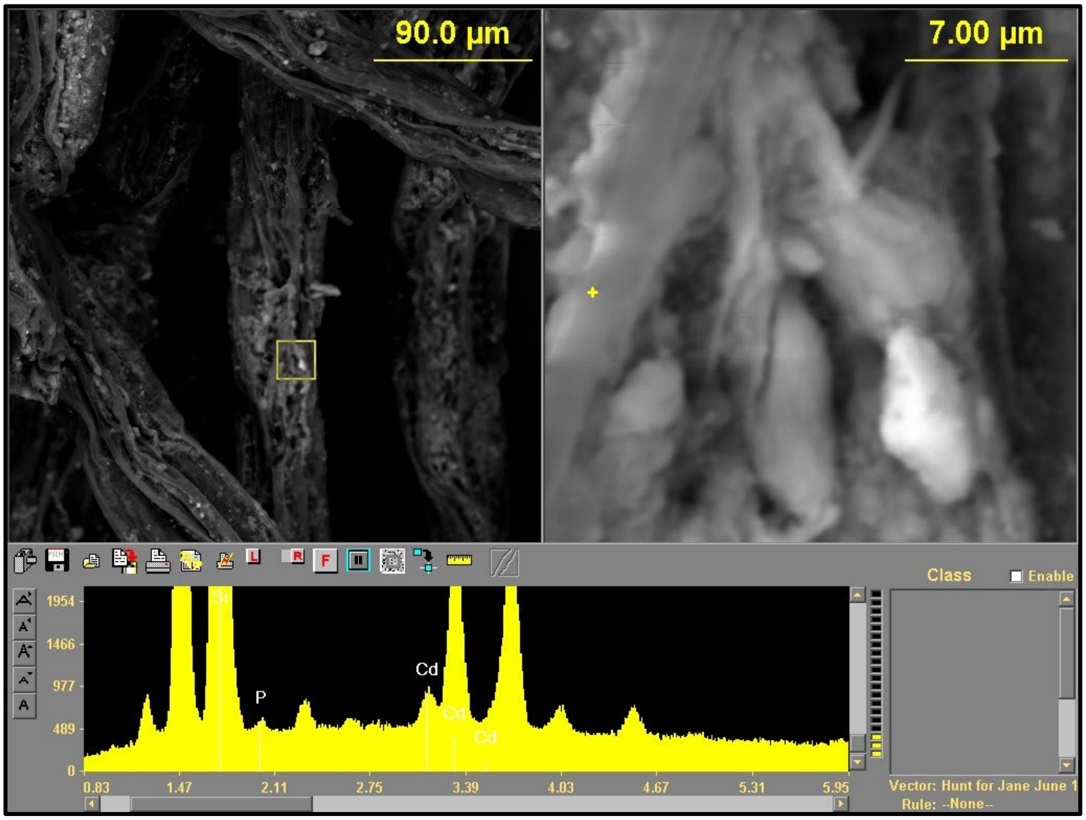
Mutagenic: capable of inducing mutation or increasing its rate of occurrence

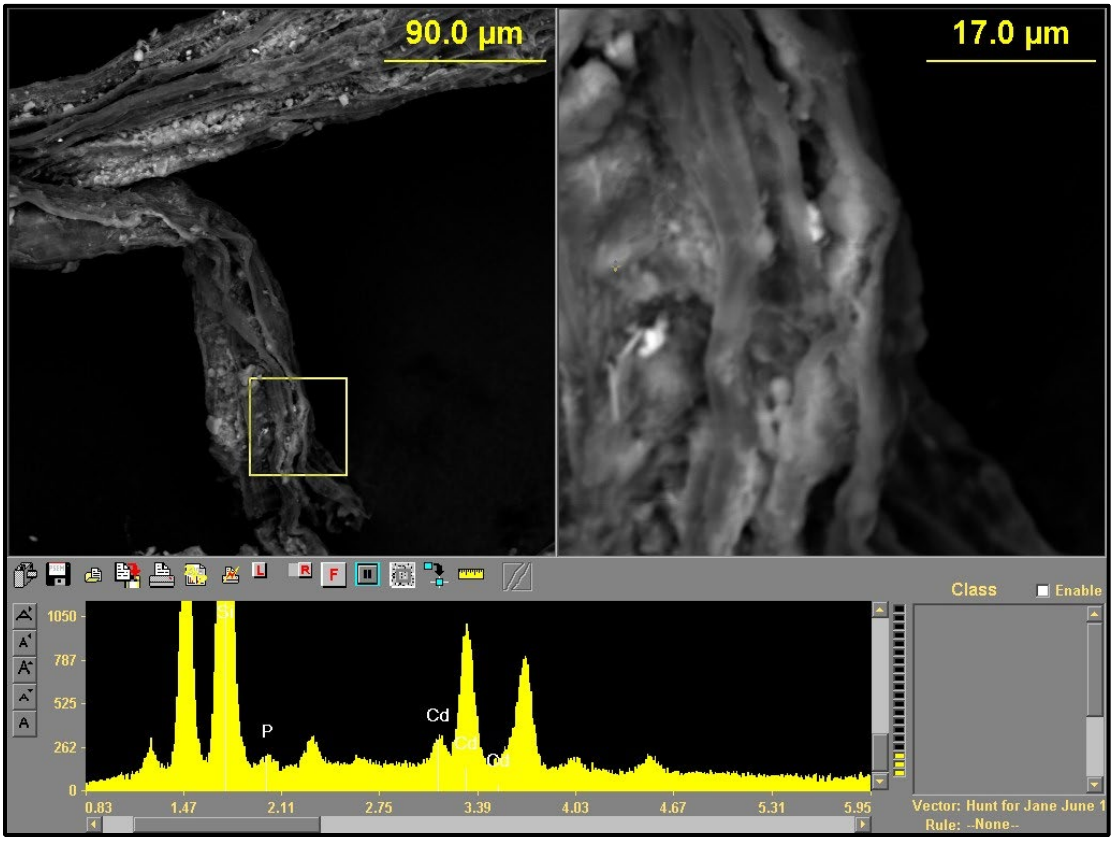
Sorb: to attach to without absorbing into the structure of the compound itself, surface attachment

Teratogenic: capable of interfering with the development of a fetus, causing birth defects

APPENDIX D

MICROSCOPIC ROOT TISSUE


90.0 µm
7.00 µm
Class
Enable
1954
1466
977
489
0
Si
P
Cd
Cd
Cd
0.83
1.47
2.11
2.75
3.39
4.03
4.67
5.31
5.95
Vector: Hunt for Jane June 1
Rule: --None--



Images courtesy of Dr. Andrew Hunt

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BIOGRAPHICAL INFORMATION

Micalah G. Spenrath, originally from San Antonio, Texas, came to the University of Texas at Arlington with one clear goal: to obtain a research internship for each year that she attended college. Today, having several research internships under her belt, she has met that goal and even raised the bar higher. She has participated in research that pertains to gas production from the degradation of organic materials in landfills, chemical analysis of different environmental compartments, particle size distribution in soils, environmental forensics as well as heavy metal contamination of aquatic ecosystems. She has interned through the College of Engineering and on the Savannah River Environmental Science Field Station in South Carolina. Micalah has engaged in the McNair Scholars Program through which she presented her research on phytoremediation at the 25th Annual National Ronald E. McNair Research Conference in Wisconsin. Not only interested in academic endeavors, she has been a volunteer with the Arlington Animal Shelter and with a national organization, Communities in Schools. She has participated in Strategies for Ecology, Education, Diversity and Sustainability (SEEDS) as the President and attended the annual SEEDS Leadership Conference in which she travelled to the Coweeta Hydrologic Laboratory in North Carolina. Micalah will graduate from the University of Texas at Arlington with an Honors Bachelor of Science in Earth and Environmental Science. She plans to attend graduate school to study environmental geochemistry and environmental law.