

January 2014

# Opuntia ficus-indica Mucilage Potential to Remove Nuclear Active Contaminants From Water Based on a Surrogate Approach

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*Opuntia ficus-indica* Mucilage Potential to Remove Nuclear Active Contaminants From  
Water Based on a Surrogate Approach

by

Jose Adan Leon

A thesis submitted in partial fulfillment  
of the requirements for the degree of  
Master of Science in Chemical Engineering  
Department of Chemical and Biomedical Engineering  
College of Engineering  
University of South Florida

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Date of Approval:  
July 10, 2014

Keywords: cesium, iodide, radionuclide, non-gelling, extract, sustainability

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## **DEDICATION**

I know that this dedication isn't enough to thank my 6 siblings, my hardworking father Pedro and my loving mother Maria Elena. Thank you for never losing faith and your many sacrifices. This couldn't have been possible without you. To my brothers of Lambda Theta Phi Latin Fraternity, Inc. for inspiring Latino success, unity and always striving for the betterment of our people.

## **ACKNOWLEDGMENTS**

I would like to acknowledge my major professor, Dr. Norma Alcantar, thank you for your continued support, dedication and guidance throughout this journey. To the rest of my examining committee, Dr. Babu Joseph and Dr. Mark J. Jaroszeski, thank you for your time and involvement in my progression through this research. Thank you to Dr. Daniela Lima Stebbins, who always took time out of her busy schedule to help me out and provide more guidance when needed. I want to say that I greatly appreciate financial support from the Mayor Hispanic Council fellowship program, which greatly supported my attendance in these graduate studies. Thank you to Dr. Zachary Atlas for aiding in the use of the ICP-MS. In addition, I would like to acknowledge the support of the Gulf of Mexico Research Initiative grant for supporting some of the materials and supplies used in this work.

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## ABSTRACT

Potable water is a necessity and unfortunately, it can be contaminated in many different ways. This paper specifically addresses the case scenario when, water has been contaminated by radionuclides. The mucilage of *Opuntia ficus-indica* (*OFI*), has been proven to be a great flocculating agent, turbidity reducer, crude oil dispersant and an environmentally friendly substance as an absorbent of water contaminants. In this work, the *OFI* mucilage was investigated to evaluate its capacity to separate radioactive ions from water. The surrogate approach is modeled based on water studies performed by Willi A. Brand, who proved that radioactive isotopes behave similar to their stable isotope, which can be easily experimented on without running the risk being exposed to radioactive harm. The surrogate model was used in conjunction with a trial and error method to determine optimum removal of Iodine and Cesium. A wide range of *OFI* concentrations and pH values were tested, which allowed for the determination of the optimal conditions for which cactus mucilage can remove the desired elements. The cactus mucilage is acidic by nature and experiments were performed to determine if its performance is affected by the changes in pH. This work is one of its kind in which a natural material can be used to remove potentially harmful radioactive ions from water.

## CHAPTER 1: INTRODUCTION

### 1.1 Radioactive Isotopes

We can identify elements from the periodic table and their distinguishing characteristics. Although the elements on the periodic table have already been labeled with a set number of protons and electrons, there are different types of isotopes of known elements. These isotopes differ by the number of neutrons that they can accommodate. As determined by the Brookhaven National Laboratory, some of these isotopes are stable while others aren't. For example, Carbon-13 is stable while Carbon-14 isn't. Iodine-131 and Cesium-137 are the known unstable isotopes of their respective neutral elements on the periodic table. [1] These unstable isotopes usually release ionizing radiation in order to reach a stable state. The ionizing energy that is released can be identified as alpha, beta and gamma radiation. When these isotopes produce this radiation, they are said to have decayed on the order of the type of radiation produced. This radiation has many practical uses in the medical, research and construction fields. However, the radiation poses a health hazard if not used properly or if one is exposed to it unwillingly. Exposure to radiation can cause damage to living tissue that can lead to radiation sickness, mutations, cancer and even death. Nuclear radiation can originate from many different sources and can also dissolve and concentrate over time in water, soil and vegetation. [2] The sources for radiation contamination can originate from x-ray machines, particle accelerators and nuclear power plants. Nuclear energy is one of the newest types of alternative energy but is

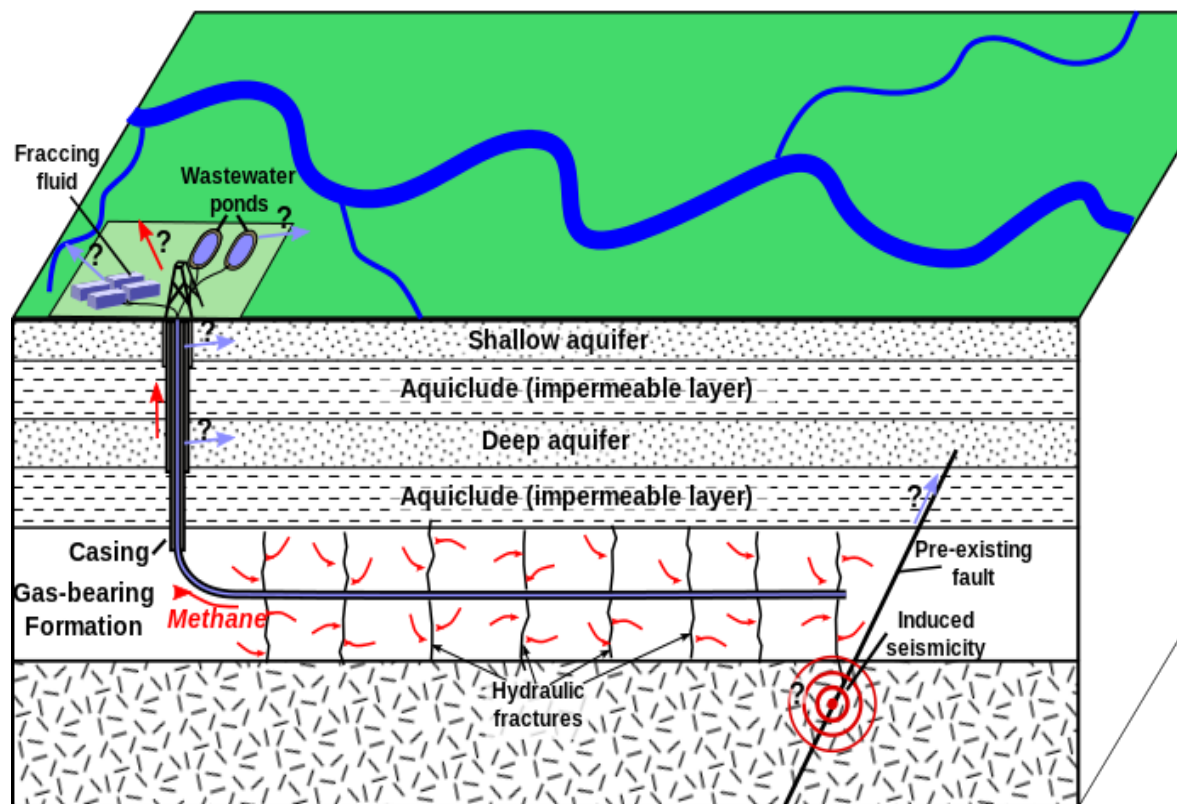


also one of the main contributors to nuclear contamination in water. Nuclear power plants are designed in a specific manner to protect the surrounding from radiation contamination; however, there is still some ways for radiation to leaks out. [2] Whether it is through the lack of insulation or the water that is exposed to the core's energy, some radioactive ions are released out of the nuclear plant into their water-cooling systems or local potable water sources. This leakage of radiation is minute when compared to the radiation that is released in nuclear accidents. The release of nuclear radiation on that type of magnitude leads to the high accumulation of radioactive isotopes, causing areas to become uninhabitable for centuries. [2] It has been reported that within the last 60 years, we have seen close to around 99 accidents involving nuclear power plants. These accidents have caused an estimated US\$21 billion in damage, with Chernobyl being the most costly. [3] Most recently, the one that draws our attention is the Fukushima incident. The international nuclear event scale is intended to show the scale of severity of these nuclear disasters. [3] The scale ranges from 1 to 7, 7 being the most severe, and there has only been two reported cases of level 7 severity. That is, Fukushima and Chernobyl are considered, the two most severe accidents.

## **1.2 Hydraulic Fracturing**

Hydraulic fracturing is another source of radioactive contamination that is rather new and many do not consider it a problem. In this process, the fracturing of rocks is achieved by a pressurized liquid. Therefore, hydraulic fracturing or hydro-fracturing, are also recognized as fracking. When water is typically mixed with sand and chemicals, and the mixture is injected at high pressures into a wellbore, the end-up-result is the creation of small fractures underground. These small fractures then allow fluids such as petroleum,

uranium-bearing solutions, brine water, and gas to migrate to the well. [4] The pressure is withdrawn from the well producing small grains of proppant, which mainly consisting of sand or aluminum oxide, to maintain small fractures open until the rock reaches equilibrium. This process provides the definition of “proppant”, which essentially defines it as a ceramic material capable of keeping these fractures open. [4] Figure 1: Hydraulic fracturing job set up [4] shows an illustration of the red vein like passage that hydraulic fracturing creates in a well site. The technique is a common practice in wells for tight gas, shale gas, coal seam gas, hard rock wells and tight oil. [4] Traditionally speaking, any given well is subjected to this technique (which enhances fluid removal and increases well productivity) only once per well life. However, there has been an increasing new trend that aims towards multiple well fracturing as well production declines.



**Figure 1: Hydraulic fracturing job set up [4]**

Most of the well sites that are being operated on are thousands of years old. When drilling begins there is no way to tell exactly what minerals one will find in the well. Once drilling begins or once a fracturing job is performed, well sites have been known to dislodge uranium, radium, radon, thorium, cesium and Iodide. These dislodged minerals then end up in the flowback fluid. [4] This raises the concerns about the concentration of radionuclides in the wash back fluid. The wash back fluid is then placed in a nearby water retention pond that has been manually dug up. The flowback water can then seep into the groundwater. Although, there are attempts to reuse this wash back fluid, there is a limitation and thus poses a threat to public health. In order to monitor progress of the fracturing job, there are tracers that are used in the fluids. These tracers also tend to be radionuclides. The injected radionuclides can be solid, liquid or gas. These tracers provide an injection profile and location of fractures created by the fracturing job. Therefore, whether radioactive ions are put there on purpose or they are dislodged when the fracturing is performed, hydraulic fracturing is a significant contributor of radioactive isotopes that could potentially accumulate in consumable water. [5]

### **1.3 Common Elements**

After nuclear accidents occur, there are usually studies on the environment to determine how the radiation is affecting nearby areas to the harmed areas. For instance, after the Chernobyl accident, the town had to be evacuated because the radiation in the city was too concentrated and could easily cause health complications. Most studies in the literature also take into account the amount of radiation that is in the water, vegetation and soil. [6] [7] [8] Depending on the concentrations, an area can be deemed inhabitable for an extended period of time. Water tracer studies are also performed to see how far water

needs to flow in order to be considered diluted enough to be safe for human consumption and usage.

Water contamination studies on water after nuclear accidents have shown that the isotopes that are commonly found dissolved in water are Iodine-131 and Cesium-137. [7] [8] After the Fukushima accident, water was collected and analyzed to determine the concentration of the radionuclides. It was determined that Cesium-137 was present in concentrations ranges of 130-145 ppm and that Iodine-131 was present in concentrations 120-155 ppm. [7] Iodine-131 has a half-life of 8 days, and Cesium-137 has a half-life of 30 years, making iodine the more dangerous of the two because of its short half-life causing it to produce the most nuclear radiation out of the two. These two isotopes are also found in high concentration in the flowback water from hydraulic fracturing work. [5] Analysis on the flow backwater from hydraulic fracturing revealed that Cesium-137 is present at an approximate concentration of 135 ppm and Iodine-131 at a range of concentrations of 128-155 ppm. [4] These two radionuclides go through beta decay and it is a more harmful type of radiation when compared to alpha decay. Beta particles can easily be stopped by a physical barrier and can be easily contained once trapped. [9] There are many ways to remove these radioactive materials based on the appropriate funding and resources at hand.

#### **1.4 Need for Water Cleansing**

Usable water is a necessity from undeveloped to developed countries. The amount of usable water available can vary from country to country, city to city and town to town. There are many factors that can contribute to it. The main reason for the lack of water in many cases is due to water pollution. Water can be polluted from many sources that can be

a directly attributed to human factors and non-human factors. One of the most noticeable dilemmas of our time is the effect natural disasters have on our quality of water. For instance, the tsunami that hit Japan created a global disaster when hit its coasts. The tsunami itself did not impact the water quality, but the aftermath did. The Fukushima nuclear power plant is undergoing a crisis and is contaminating the water in the surrounding area making it unusable. The Fukushima contamination is still ongoing and the reactors are in the process of being neutralized to eliminate any further damage. [10] Another example of radioactive ion contamination can be seen in hydraulic fracturing flowback waters. [5] This flowback of water can contain anything from man-made radionuclides to naturally occurring radionuclides that are released by hydraulic fracturing. Thus, the dilemma at hand is trying to find a way to cleanse the water in an environmentally friendly way that will also be inexpensive. Due to these incidents and the tremendous amount of radiation that is released in a short time period, there is a lot of radiation contamination to the surroundings. [3] Specifically, water is the most affected and this type of contamination is usually hard to remove. Soluble ions are hard to remove from water. Soluble ions are usually removed by adding chemicals to the water to allow for precipitation type removal. In this specific method, one is usually adding more harmful chemicals to water such as lead and silver. [9] The universally used water filters were invented to achieve the removal of ions without the need of chemical additives. [9] These filters vary from porous membranes to ion removal and insure that any water that is to come in direct contact with humans will be safe. In the United States specifically, the Food and Drug Administration must approve any commercial filter before it can be used to filter

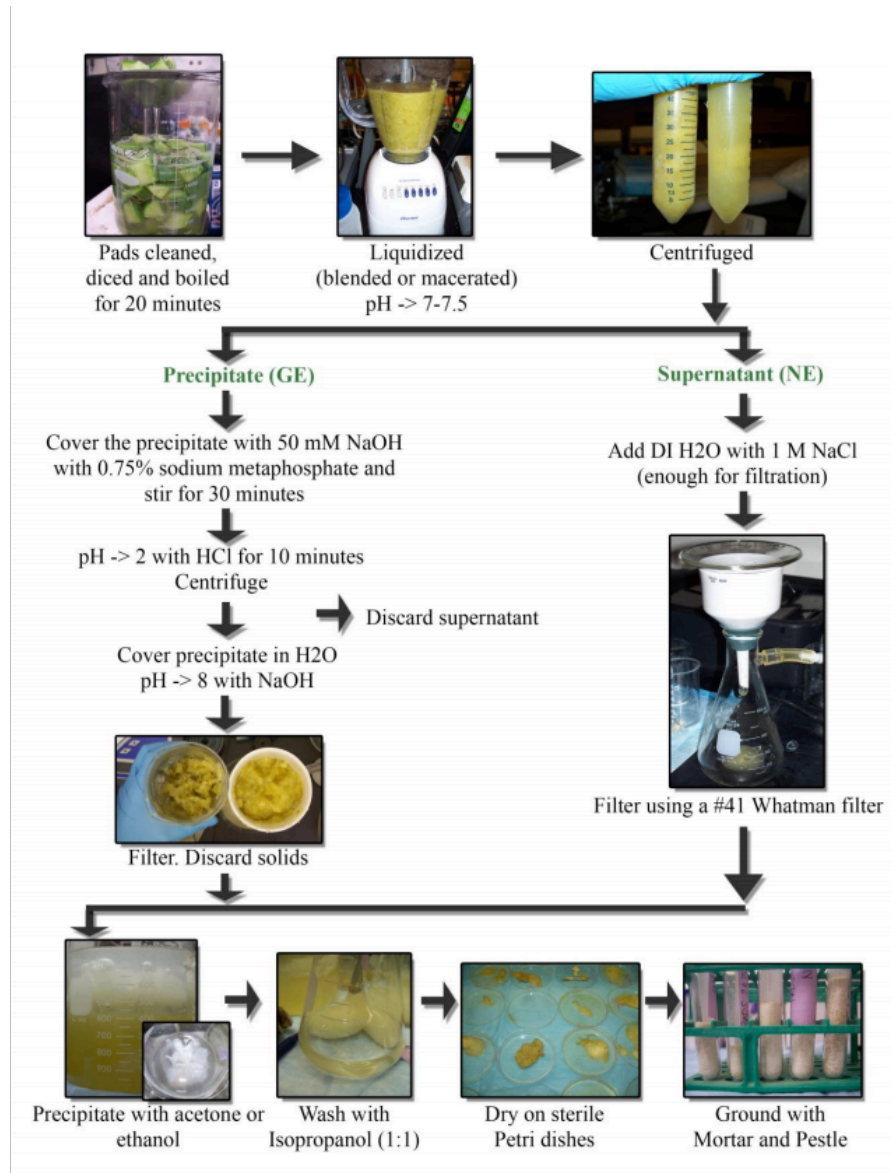
water. [9] For radiation-contaminated water, the current methods used to separate the isotopes from water are also using filters. [9]

These filters have been designed to reduce the concentration of the amount of radiation to a safe dose that meet the World Health Organization (WHO). [9] It is not as deadly to have small doses of radiation over a long time versus the short-term excess dosage. The water filters that are effective at removing radioactive contamination from water are: ion trapping, reverse osmosis, activated carbon and ion exchange. [9] Ion trapping is the most effective method because it is a multiple staged filter that includes adsorption, ion exchange and physical filtration. While an ion exchange filter is least affective because it only relies on the charge of the ions to determine if will be captured or not. The effectiveness of each type of filter is also a direct correlation to its monetary cost, which vary between \$50-\$100. [9] These filters have been created to also insure that once any radiation has been trapped it remains within the filter and it is treated as radioactive waste that must be disposed of properly, thus justifying their high cost. There is a need for an affordable way to clean water that is renewable and sustainable. This work is based on a natural material capable of removing radioactive ions from water. Since this material is obtained through sustainable agriculture, it is abundant and inexpensive; it can be considered as a renewable and sustainable material. [11]

## CHAPTER 2: APPROACH

### 2.1 Mucilage Application

The desired method of removal will get rid of water contaminants without leaving behind any harmful chemicals and while ensuring that the method is renewable and inexpensive. "The mucilage of *Opuntia ficus-indica* is a thick, gummy substance and is what provides the cacti's natural ability to store large amounts of water. When in water, the mucilage swells, producing unique surface-active properties seen in many natural gums, giving the mucilage a suspected ability to precipitate particles and ions from aqueous solutions." [12] Cesium and iodine are ions that are dissolved in water that can be removed. Thus, it can be proposed that cactus mucilage may be used to achieve the separation between water and the radionuclides. It has been shown that the cactus mucilage can be used as a flocculating agent and is inexpensively available from the cactus plant. Mucilage has also been proven to reduce the turbidity of water solutions, creating better quality water that can be consumed. [11] [12] Mucilage comes from a natural source and is therefore biodegradable. If excess amounts of mucilage were to be used it will not bioaccumulate over time, react adversely to its surroundings nor cause damage on the environment over the long term.



**Figure 2: Modified extraction method by Audrey Buttice [11]**

Cactus is naturally available and can be bought in grocery stores and markets where it is not naturally growing. This plant is extremely abundant and inexpensive, which makes it a good method to be applied at a worldwide level. “A case study surveying a Nopal farm just outside of Mexico City reported vegetation production (dry weight) from the plant to be as much as 20,000-50,000 kg/(ha\*yr) in established plantations.” [12]

Developing countries are the ones who usually are in more of a need for an application like this, since some of the modern technologies that are applied in developed countries are



very expensive. Mucilage is extracted through an inexpensive process. One could obtain mucilage by simply boiling the plant and letting the water used in the process to concentrate with it. However, this method leads to a mixture of mucilage fractions. These fractions can be isolated in the lab in a control extraction process as represented in Figure 2 (which is the modified and most up to date extraction process). [11] The process is outlined and the chemicals needed for each step is are also provided. This extraction produces a non-gelling extract (NE) and a gelling extract (GE). The NE is usually more abundant. In this research project, NE extract was used exclusively because it is more easily attainable, less material is needed to produce and it is the most concentrated fraction when it is extracted in non-laboratory conditions.

## **2.2 Approach**

It is a potential health hazard to directly experiment with radioactively contaminated water so an alternative approach was found. In general, the various isotopes of an element have very similar chemical properties or as it was stated by Brand et. al., “the physical properties of isotopes are very similar, except for those that are related to mass. The most striking differences are observed for hydrogen and deuterium, with the largest relative mass difference.” [13] The mass difference between the radioactive iodine and cesium is less than or equal to 1 g/mol. This makes the surrogate approach suitable for our purposes. The desired experiments depend on the interaction of the ions and water, these ions with other ions and these ions with the mucilage molecule. The stable isotope of radioactive elements can thus serve as a suitable surrogate to perform experiments. The concentrations of surrogate ions can be determine via any analytical method such as Inductively coupled plasma mass spectrometry (ICP-MS) or atomic absorption

spectroscopy (AAS). This can be straightforward if analytical instrumentations are available at hand. ICP-MS will be used to analyze the solutions because it can measure changes in concentrations in the low ppb ranges. ICP-MS has a greater analyzing speed, better precision and a higher sensitivity than AAS. Since this work focuses on only two elements being investigated it makes ICP-MS the most suitable method to analyze our water samples.

The surrogate approach will help to construct a model in order to provide guidance when it comes to directly applying the method to actual radionuclides. Once the surrogate model has been established, the work presented in this thesis can be used to optimize the mucilage performance by knowing the factors that greatly influence the removal of radioactive ions. Fast approximations, constraints and window of efficacy have been established in order to minimize the time needed to guess and check the method.

## **2.3 Research Goals**

### **2.3.1 Goal 1: Simple Removal**

The first goal of this research project is to determine the specific water contaminants, cesium and iodine ions, could be removed when mucilage solutions are added. Thus, the first set of experiments was to evaluate if significant removal of preset-concentration of aqueous solutions of cesium and iodine ions could be measured, and demonstrated proof of concept for further studies. Based on the water analysis, it was apparent that a concentration of 130 ppm for both elements was a good reference point for these experiments. Note that the pH was not controlled in these samples. The metrics of success were that if more than 80% removal for each ion was attained, then the final water quality of the samples met health regulations set by the World Health Organization. These

samples were tested with a range of mucilage concentrations to determine which concentration of mucilage was optimal and could be used as a reference for further optimization.

### **2.3.2 Goal 2: pH Effects on Removal Rates**

The cactus mucilage is acidic by nature and this leads us to believe that the experiments from the first goal will have pH readings below 7. Based on previous work, it was observed that pH can greatly affect the removal rates of the contaminant. [12] To test this theory in this work, experiments were performed following the protocol previously discussed for Goal 1, except that the pH was controlled to stay at a value of 7. The results were then compared to the results from Goal 1. In addition, another reason for this Goal was to ensure that once cleansed, the water quality met a pH value around the neutral zone.

### **2.3.3 Goal 3: Range of Concentration**

As a flocculating agent, the mucilage's ability to perform depends on the concentration of the elements that is going to be targeted for removal. In this case, we varied the cesium and iodine concentrations from a range of 500 ppm to 1 ppb. This window of concentrations provides a broad spectrum that allowed us to determine how the concentration of the pollutant could change the percent removal. Further, this Goal also allowed us to determine at what concentrations the mucilage removal method could work. Note that the concentration of mucilage used during these tests was determined based on the results of experiments from Goals 1 and 2.

## CHAPTER 3: EXPERIMENTAL PROCEDURE

### 3.1 Sample Preparation

Experiments were performed on a small scale in standard test tubes. Each sample was prepared to be 15 ml. Water samples were prepared using deionized (DI) water. Iodide and cesium were purchased in their salt forms to ensure ease of dissolution in DI water. Sodium iodide (S324-100) and cesium chloride (C24-25) were purchased from Fisher Scientific. Stock solutions for each salt and mucilage were made. Based on a literature research, it was determined that the common concentration for the radioactive pollutant isotope was around 130 ppm. [5] Thus, the required initial concentrations for cesium was 0.165 g/l and for iodide was 0.463 g/l. Equation 1 is the dilution equation used to determine how much of each stock solution was required to achieve the working concentrations. The mucilage concentrations ranged from 0.001 mg/l to 100 mg/l

$$C_1V_1 = C_2V_2 \quad (1)$$

Once the iodine and cesium samples were prepared, measures were taken to ensure that the samples to be analyzed would be preserved. The reason for doing this was primarily because samples have to wait for available time with the ICP-MS. The preservation of samples was accomplished by simple acidification with HCl or HNO<sub>3</sub>. This process insures that ions remained in solution for a large period of time. [14] However, before the samples were acidified, the pH was recorded. Each combination of concentrations was repeated twice to warrant sufficient statistical data for the error analysis. A total of two separate sets of experiments were performed resulting in 4 different tests..

### 3.2 ICP-MS Analysis

ICP-MS was used to determine the concentration of iodine and cesium before and after being treated with mucilage. The ICP-MS used was a Perkins Elmer device. This instrument was chosen because it can detect metals and non-metals at trace concentrations (as low as part per trillion) with high accuracy. In this case, the elements being detected are a metal and a non-metal at with high sensitivity and precision when it comes to analysis of water samples. The biggest benefit of this instrument is its ability to perform fast analysis. On average, each sample takes between 2 and 3 minutes to be analyzed thoroughly. This method is quicker when compared to atomic absorption spectroscopy (AAS).

The water samples were prepared in accordance to the ICP-MS protocol. After the solutions were mixed in the correct concentrations, they were agitated in a vortex for 20-30 seconds to ensure homogenous concentrations. The samples were left to settle overnight. The following morning, the samples were filtered using a syringe and filter cap with 0.45 micrometer pore size, and acidified with HCl or HNO<sub>3</sub>, to ensure their preservation. The preservation step usually only required just a few drops of the acid. Additionally, all samples were diluted to ppb ranges to follow the ICP-MS sample preparation protocol. Thus, all of our samples were diluted approximately 1000 times. Every sample whether it was treated with mucilage or not was diluted. The stock solutions of 130 ppm iodine or cesium were also diluted 1000 times and used as the control and reference point to determine the percent removal.

The ICP-MS reference protocol also requires that standard solutions of known concentration of the elements to be detected be measured to maintain high accuracy. Therefore, standard solutions were prepared by having both elements in the same

container at 25 ppb, 50 ppb, 100 ppb, 150 ppb and 200 ppb for each ion. Each standard was created by simply diluting National Institute of Standard and Technology (NIST) stock solutions (1000 mg/L). Once the results were obtained, calculations using M.S. Excel allowed us to determine the percent removal as well as calculate the deviation between results. The percent removal is calculated by determining the difference between the control sample and each experimental sample. The control is a sample of 130 ppm of each respective ion that has been acidified and has not been exposed to the mucilage. The error bars were calculated on the standard deviations of the different readings for each concentration and trial.

## CHAPTER 4: RESULTS

### 4.1 Simple Removal Test

The first tests performed were to determine the nominal pollutant removal when mucilage at different concentrations was added to the iodine or cesium presat concentrated solutions. . These tests were performed by combining NE mucilage and respective salt in 15 ml test tubes. Once combined pH readings for each case were taken. After the samples were left overnight, filtered and to be in the ppb ranges, they were analyzed with ICP-MS.

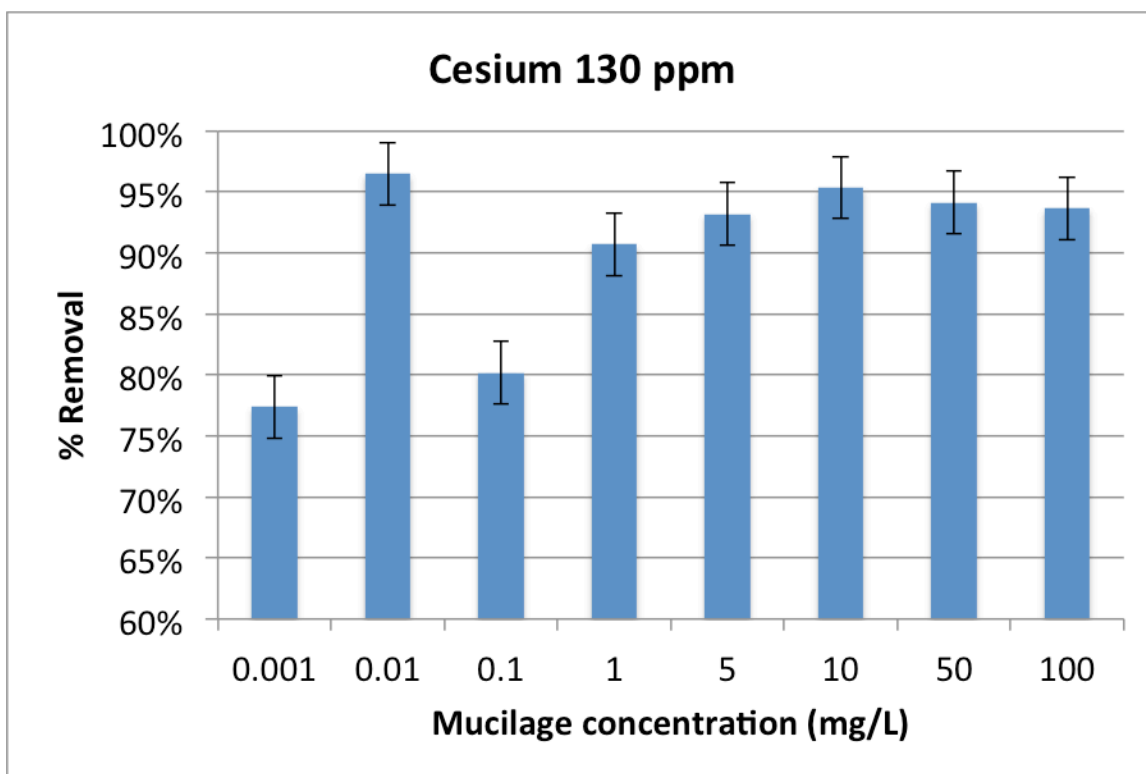
To determine how much removal occurred, a totalmass balance was computed as shown in Eqn. 2:

$$mass_{in} - mass_{out} = mass_{removed} \quad (2)$$

Once the removed amount of pollutant was determined, then the following calculation was performed to calculate percent removal

$$mass_{in} - mass_{out} = mass_{removed} \quad (3)$$

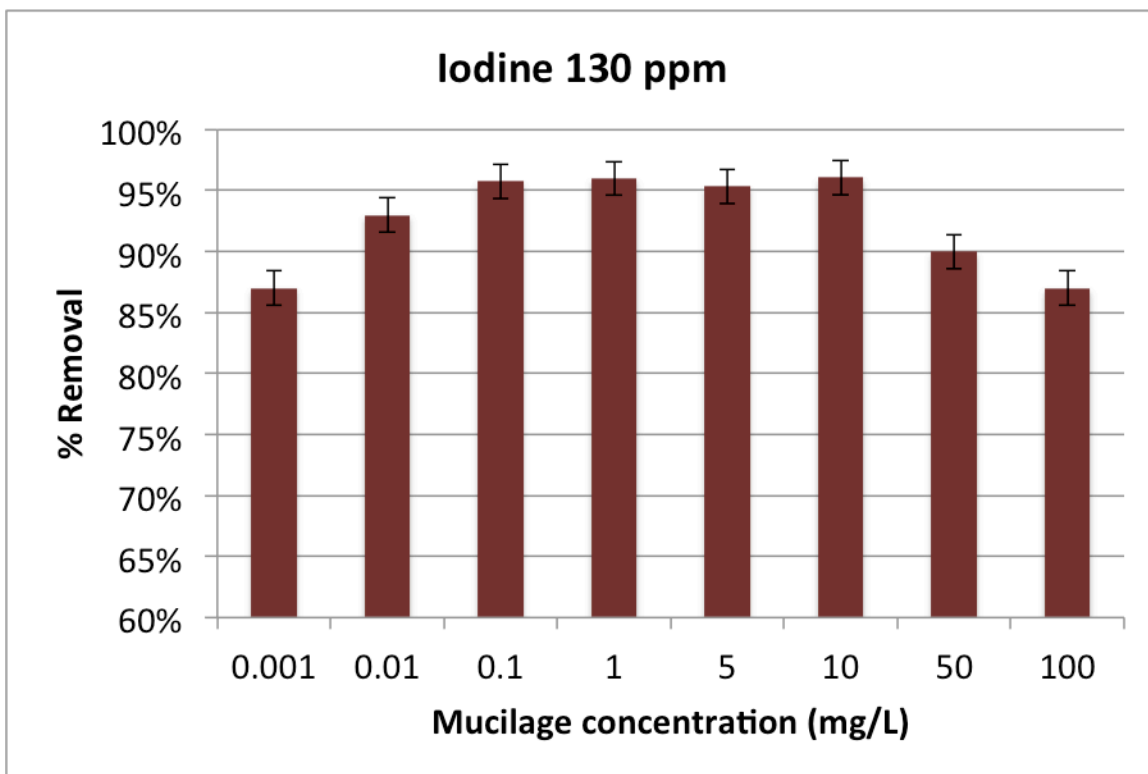
Figure 3 shows the percent removal for the different concentrations of NE mucilage when 130 ppm cesium samples were treated. . We observed that for most of the mucilage concentrations evaluated, % removal higher than 65 % were was obtained. Based on WHO safety regulations for cesium consumption [13], it is necessary that removal % be above 90% or below 12 ppm. Based on that criteria, mucilage, concentrations of 0.001 mg/L and 0.1 mg/L do not meet this requirement.. Later results will show that this effect is due to pH values inconsistencies.



**Figure 3: Removal % of cesium as a function of mucilage concentration. For most mucilage concentrations, removal % was above 90%, except for 0.001 and 0.1 mg/l. The initial cesium concentration was 130 ppm. The fraction of the mucilage tested was NE. All experiments were done at room temperature (22°C). Note that the pH was not controlled and ranged from 3.3 to 6.5 depending on NE concentration.**

Figure 4 shows results for the simple removal of iodine with a concentration of 130 ppm. The same procedure that was used for cesium was also implemented for experiments with iodine. Percent removals of iodine were determined to be on average higher than those of cesium despite the fact that both experiments initially started with the same concentration. The removal difference might be due to the charge of the particles that are being removed. [16] [17] Iodine has a negative charge while cesium has a positive charge, and once dissolved in water mucilage might have a higher affinity for iodine than for cesium.



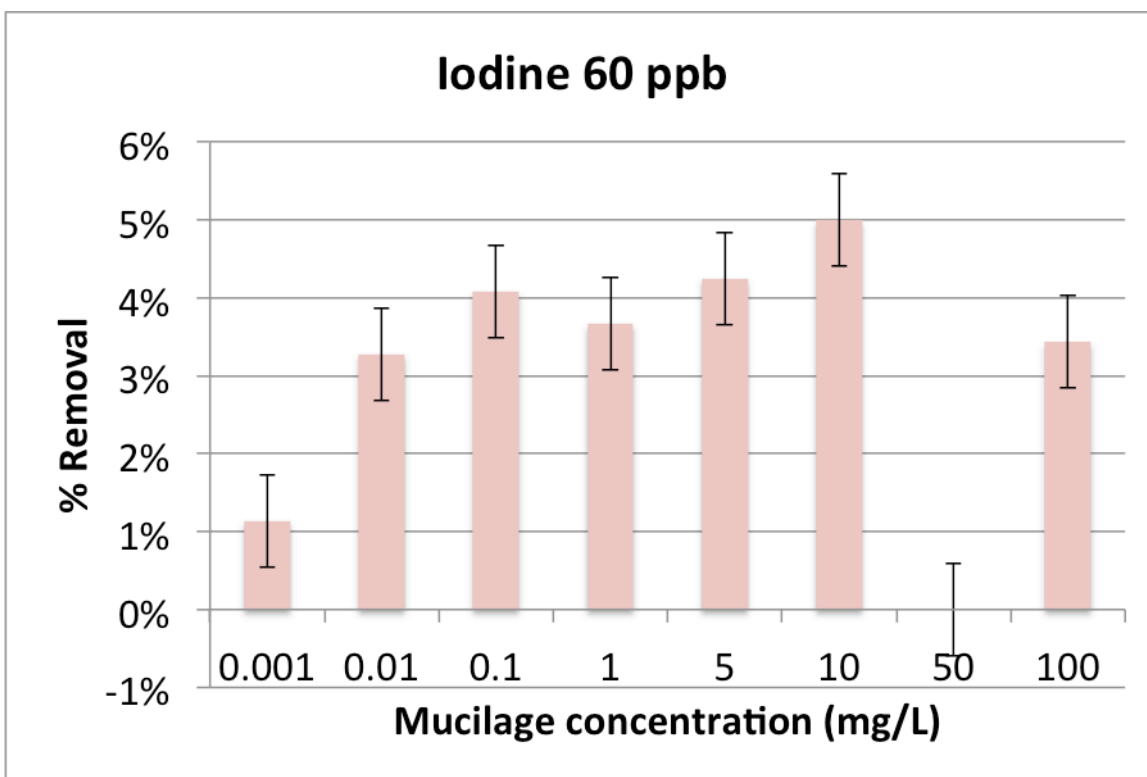


**Figure 4: Removal % of iodine as a function of mucilage concentration. For most mucilage concentrations, removal % was above 90%, except for 0.001, 50 and 100 mg/l. The initial iodine concentration was 130 ppm. The fraction of the mucilage tested was NE. All experiments were done at room temperature (22°C). Note that the pH was not controlled and ranged from 4.5 to 6.7 depending on NE concentration.**

The next experiment that was performed was on iodine samples with a concentration of 60 ppb. This concentration was selected because local tap water (from USF's ground water wells) was found to have a concentration of iodine of approximately 60 ppb. This water didn't seem to have any traces of Cesium and the ICP-MS was only able to pick up Iodine readings. Figure 5 shows the results for this experiment. It is observed right away that the % removal is less than 5%. We speculate that this effect is due to the fact that mucilage interacts not only with iodine but also with other ions present in natural tap water. We also observed that there were some inconsistencies due to the variation in total ion concentration of tap water. We therefore can state that when the analyzed water

contains multiple ions, a different range of mucilage concentrations must be tested to lead to a suitable removal.

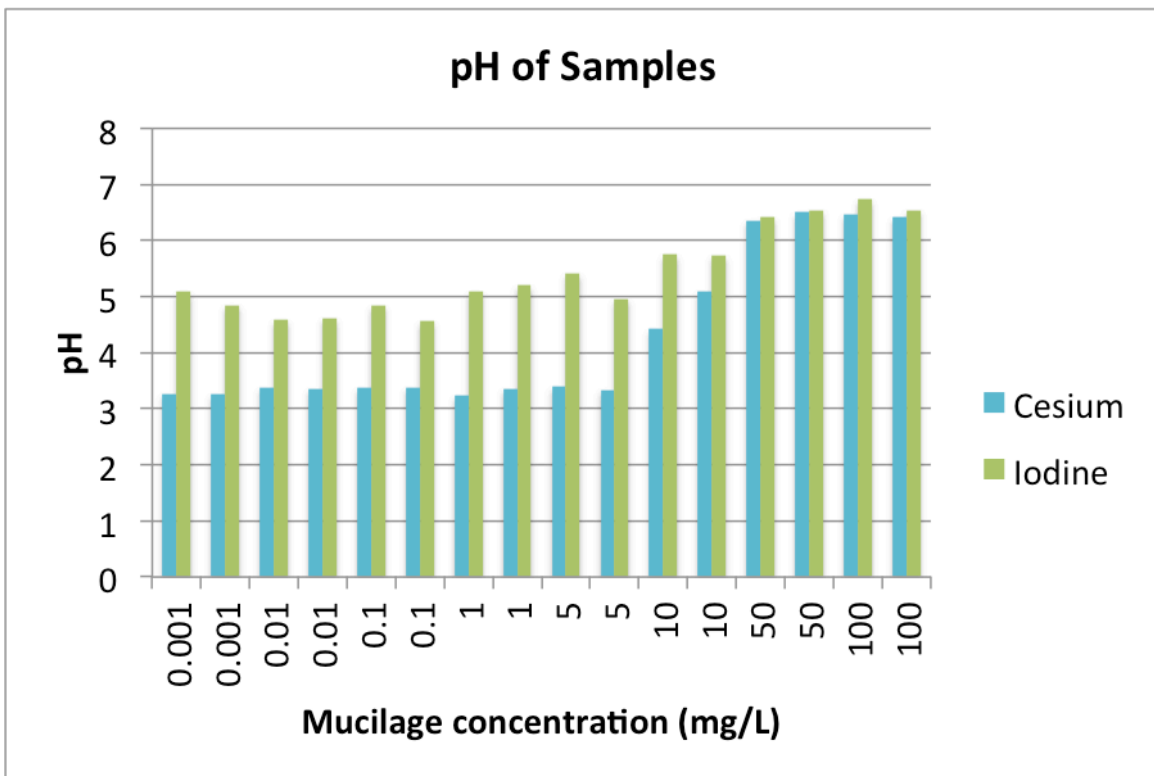
Previous research with mucilage has determined that the pH of the solutions can affect the removal process. [11] These pH values in these initial experiments were recorded and results can be seen in Figure 6. The contents of the *Opuntia ficus-indica*, is naturally acidic so it was not surprising that the pH values for most samples were below 7. Cesium samples on average were more acidic than iodide samples. The higher pH of the iodide samples could also be a reason why we observed a higher average removal percentage when compared to that of the cesium samples.



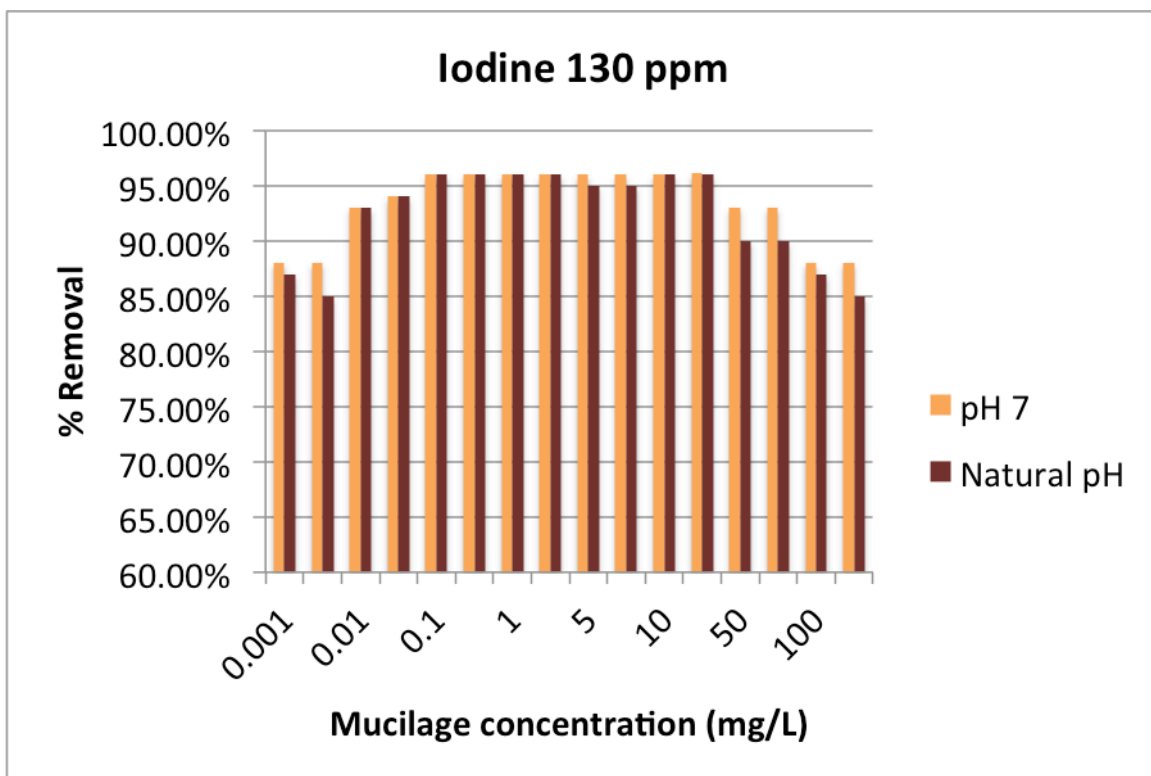
**Figure 5: Removal % of iodine as a function of mucilage concentration. For most mucilage concentrations, removal was below 10%. The initial iodine concentration was 60 ppb. The fraction of the mucilage tested was NE. All experiments were done at room temperature (22°C).**

#### 4.2 pH Effects on Removal Percentage for a Set Neutral pH Value

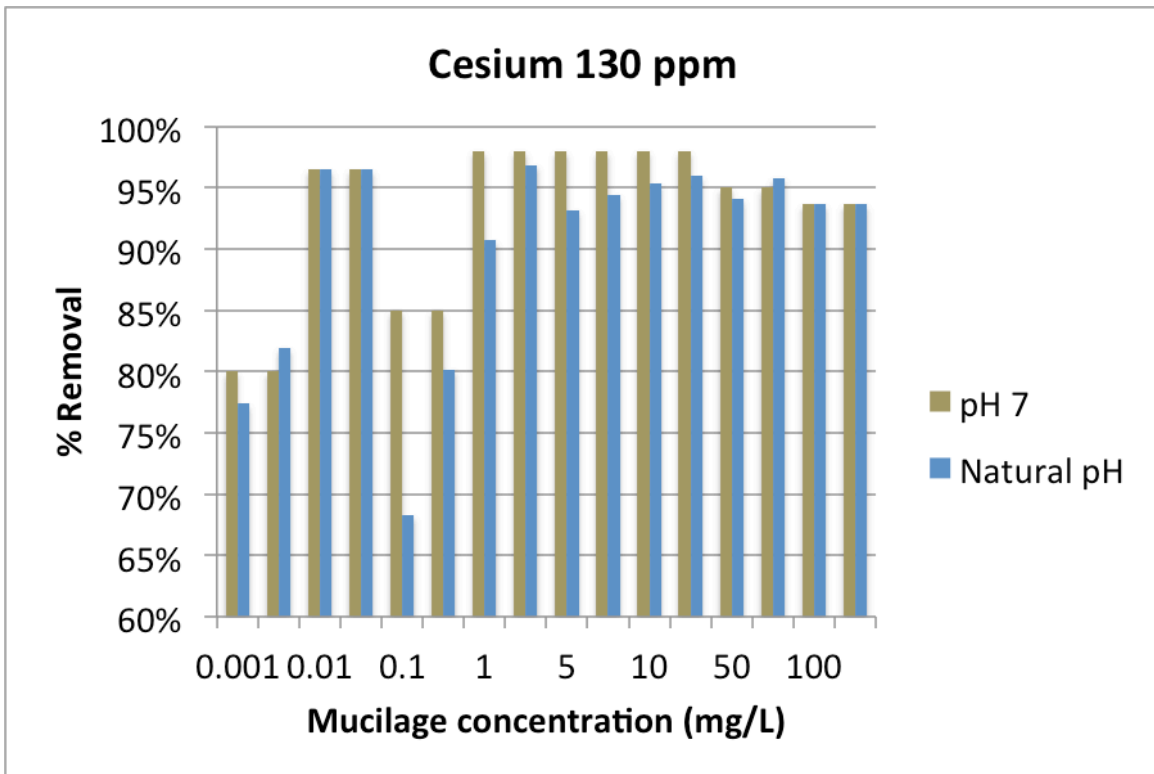
To investigate if pH was a determining parameter in the removal of these pollutants, we set the pH of the working solutions to be neutral (i.e., pH = 7). Figures 7 and 8 show the results of these tests. The first visual observation is that the removal percentages are more consistent for the majority of the mucilage concentrations. Furthermore, overall higher percent removal was observed for when pH is set to neutral (pH = 7) than that for when the pH is left to vary depending on the mucilage concentrations. . Thus, the pH of the solutions is a determining parameter and directly affects the amount of heavy ions to be removed from contaminated water. By keeping the pH at a neutral value, the removal percentage was more homogenous and the mucilage treatments performed more efficiently.



**Figure 6: pH values as a function of mucilage concentration. Initial Cesium and iodine concentrations are 130 ppm. As the concentration of mucilage increases above 50 mg/l, pH values of the working solutions tend to increase towards neutrality (pH = 7). Multiple readings for one case are shown, to demonstrate the varying pH.**



**Figure 7: Removal % of iodine as a function of mucilage concentration. Double experimental results are shown to point out experimental consistency. For most mucilage concentrations, removal was above 85%. The initial iodine concentration was 130 ppm. The fraction of the mucilage tested was NE. All experiments were done at room temperature (22°C).**

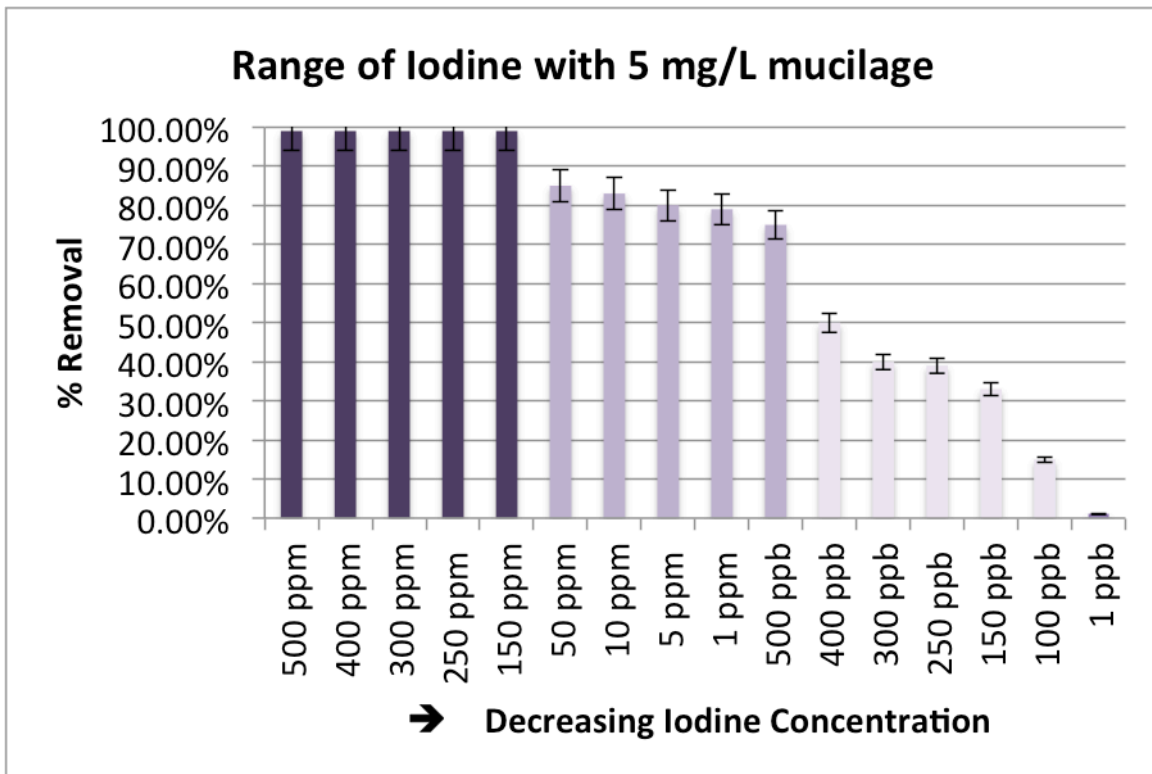


**Figure 8: Removal % of cesium as a function of mucilage concentration. Double experiments are shown to point out experimental consistency. For most mucilage concentrations, removal was above 85%, except .001 and .1 The initial iodine concentration was 130 ppm. The fraction of the mucilage tested was NE. All experiments were done at room temperature (22°C).**

#### 4.3 Effect of Pollutant Concentrations

The next set of experiments was performed to determine the range of concentrations at which there is a significant removal for the given elements. A fixed mucilage concentration of 5.0 mg/L was chosen because previous experiments demonstrated that most of the removal capacity of mucilage occurred in the range of 1.0-10.0 mg/L (5 mg/L being the midpoint of the range of mucilage concentrations). In this case, only iodine samples were analyzed as a representative behavior for both ions. Although, it is suggested that cesium analysis should also be performed in the future to corroborate our observations. Data presented in in Figure 9, shows three distinct regions: First, at and above 150 ppm, the percent removal is above 95%. Second, test performed on

iodine concentrations less than 150 but more than 400 ppb resulted in removal percentages less than 85% but more than 70%. Third, removal of less than 50% was observed for iodide concentrations less than or equal to 400 ppb. Consequently, for iodine concentrations below 100 ppb, removal percentage recorded was less than 15%, which is consistent with experiments performed at 60 ppb in tap water. The WHO declared water with an iodide concentration below 50 ppb to be safe for human consumption. [12] Based on WHO specifications, removal about 95% is what is required in these experiments. Above 500 ppb, the NE was able to meet the specifications. By having Lower concentrations of the pollutant in the water, makes it harder for the mucilage to interact with this ions and therefore, it is less efficient than when the pollutant is readily available. Thus, mucilage's performance to remove these pollutants highly depends on the concentration of the element to be removed. This suggests that maybe multiple mucilage treatments may be needed to attain pollutant's concentrations within the accepted values by the WHO.



**Figure 9: Removal % of iodine as a function of iodine concentration. Varying Concentration of iodine at 7 pH with 5 mg/L of NE Mucilage. All experiments were done at room temperature (22°C). Removal happens at 3 levels: above 99%, between 90% -75% and below 50%.**

## CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

### 5.1 Conclusion

A surrogate model representing radioactive iodine and cesium pollutants in aqueous solutions was tested in a trial and error method to determine that the mucilage can in fact remove such pollutants from water successfully. Based on the WHO criteria, it is necessary to achieve 90% removal of the tested 130 ppm cesium and 95% removal for iodine at the same concentration. Based on that criteria, mucilage concentrations of above 0.1 mg/L, were proven to be successful. Percent removals for iodide samples were determined to be on average higher than those of the cesium experiments, despite the fact that both experiments initially started with the same concentration of each respective element. The removal difference might be due to the charge that these particles exhibit in solution. [17-18] Iodide removal was also attempted at 60 ppb in tap water but was proven to be unsuccessful. Removal tests revealed that the natural pH of mucilage treated iodine cesium water samples were acidic. To determine the effect of pH, further experimentation were performed at neutral pH values. At a pH of 7, results showed to be more homogeneous for a larger range of mucilage concentrations and indicated that a higher percent removal was achieved overall. This indicates that pH is a determining parameter in terms of removing water pollutants efficiently by cactus mucilage.

Further, it was determined that the effect of iodine concentrations also depended on the pollutant concentration. When the cactus mucilage concentration was fixed at 5 mg/l



water analysis showed that between 500 and 150 ppm of iodine, cactus mucilage was extremely effective in removing sufficient iodide mass to meet WHO's water quality requirements. For iodine concentrations below 500 ppb, removal percentages ranged were not enough to meet the WHO regulations, and in this case, multiple treatment stages is recommended.

## **5.2 Recommendations**

It is my recommendation that kinetic experiments involving cactus mucilage with these elements are performed. In this case, water samples were agitated to ensure uniform concentrations of the mucilage and the desired elements. Kinetics information will lead to provide insights about the possible mechanism(s) of action to explain how this natural material acts to remove radioactive pollutants from water. It will also allow us to determine if mucilage removal depends on transitory or diffusional parameters. .

It was found that the pH has a significant effect on removal performance, since the percent removal increased for when the pH was control to a neutral value. Tests at pH values higher than 7 are also suggested to determine the range of optimal values that potentially would lead to effective removal at concentrations of the pollutants below 150 ppb.

We determined that at mucilage concentrations between 1-10 mg/L, percent removal was effective. It is recommended that further experimentation is directed to tune the minimum amount of mucilage needed to achieve maximum removal. The manipulation of the pH can also be performed to determine if there is a 'perfect' pH that these test should be administered.

Some of the results from the research work brought up a question that might be worth looking into. That is, since mucilage is a combination of sugars and carbohydrates that tend to balance its own charge, it is still unknown if there is a way to enhance its affinity for r charged particles. Perhaps, more tests can be done with the same two elements used in these experiments to determine how charge may affect the removal.

The amount of money, certification needed and health risks are all very high in order for one to handle radioactive isotopes. However, research in this field is imminent. Therefore, the surrogate approach that was used to get a feel of whether mucilage can remove these two elements is recommended. Further, I recommend that other elements such as Carbon-14 could be tested to study the effect of effective mass of the radioactive ion.

Although, the experiments to determine the effect of pollutant concentration focused on iodine, it is recommended that experiments for cesium be completed. Data obtained for iodide provided insight as to what concentrations there will be removed and if it is worth experimenting with those parameters.

The last recommendation and overall reason for this research is to attempt actual experiments on the radioactive isotopes. Although the surrogate approach ensures that time and money is not wasted, we now have realistic information to determine that mucilage effective performance is attainable. However, before doing so, it is highly recommended that the surrogate-based experiments be fully optimized in order to minimize the number of experiments with radioactive isotopes and thus decreasing the risk associated with nuclear radiation and to minimize the amount of potential waste that could be generated in each experiment.

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## **APPENDICES**

## Appendix A: Permission

### A.1 Permission to Use “Removal of Sediment and Bacterial from Water Using Green Chemistry” by Audrey Buttice.



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