Article

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Removal of water arsenic by dry biomass and activated carbon of nopal (*Opuntia ficus-indica*)

Remoción de arsénico en agua mediante biomasa seca y carbón activado de nopal (*Opuntia ficus-indica*)

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Abstract

The capacity of dry and ground nopal biomass, chemically activated nopal charcoal, and a combination of both to adsorb arsenic (As) in contaminated well water was analyzed. The charcoal was chemically activated with phosphoric acid at 500°C. Water samples with As were collected from communities and the municipality head of Abasolo, Guanajuato. The adsorbents were then tested with three different As concentrations (0.1, 0.025, and 0.02 mg/L). The concentration of As was determined after filtration and the physicochemical parameters (pH, conductivity, and turbidity) were measured. The results were compared to limits established in Mexican environmental regulations. The results show that the combination of nopal biomass and activated nopal carbon achieved removals of 93.3, 60, and 50% for the previously mentioned concentrations, respectively. The effectiveness of activated nopal carbon to remove As in contaminated water is a viable and economical solution to address the environmental and public health problems that this contaminant represents.

Arsenic, Biosorption, Conductivity, Activated carbon, Nopal, Removal

Resumen

Se analizó la capacidad de adsorción de biomasa seca y molida de nopal, de carbón activado del mismo y de la combinación de ambos en aguas de pozo contaminadas con Arsénico (As). El carbón se activó químicamente con ácido fosfórico a 500°C. Se recolectaron muestras de agua con As de comunidades y de la cabecera municipal de Abasolo, Guanajuato. Posteriormente se probaron los adsorbentes con tres diferentes concentraciones de As, 0.1, 0.025 y 0.02 mg/L. La concentración de As se determinó después de la filtración y se midieron sus parámetros fisicoquímicos (pH, conductividad y turbidez). Los resultados se compararon con los límites establecidos en la normatividad ambiental mexicana. Los resultados muestran que la combinación de la biomasa y el carbón activado del nopal lograron remociones de 93.3, 60 y 50% para las concentraciones anteriormente mencionadas, respectivamente. La efectividad del carbón activado de nopal para remover As en aguas contaminadas es una solución viable y económica para abordar la problemática ambiental y de salud pública que representa este contaminante.

Arsénico, Biosorción, Conductividad, Carbón activado, Nopal, Remoción

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Introduction

Heavy metals are often found in the earth's crust in the form of minerals, salts, or other compounds. These can be absorbed by plants and subsequently incorporated into the food chain. They can also be released into the atmosphere through volatilization, moving towards groundwater or surface water. This contamination can be caused by both natural and human-related activities, such as industrial processes. However, these heavy metals cannot be easily degraded naturally or biologically, as they do not have specific metabolic functions for living beings.

Arsenic is a highly toxic chemical element that can cause serious harm to the environment and human health. When released into the environment, arsenic can contaminate the air, water, and soil, which can have a negative impact on local flora and fauna. Arsenic can be absorbed by plants and animals through their roots, skin, or hair, and can accumulate in the tissues of living beings. This can cause serious illnesses, including cancer and damage to the nervous system. Additionally, arsenic can be a threat to human health if ingested through contaminated water or food. Therefore, it is important to take measures to prevent arsenic contamination and protect the environment from its harmful effects.

Arsenic (As) can be found both naturally and anthropogenically worldwide. However, there are some countries that have high levels of this contaminant in water intended for human consumption, such as India, Bangladesh, Mongolia, Thailand, the United States, Argentina, Chile, Brazil, and Mexico, which creates serious health problems (Comisión Nacional del Agua [CONAGUA], 2006). Arsenic can cause irreversible damage to people's health, such as reproductive and neurological damage, vascular changes, diabetes, and lung, liver, bladder, and prostate cancer (Arzola & Li, 2016).

Humans can be exposed to As through food, drinking water, and air pollution. They can also be exposed through contact with soil or water containing As. High concentrations of As in irrigation water are a significant concern for agriculture and human health. Those most at risk of exposure are those who work with arsenic, those who drink large amounts of wine, those who live in houses with wood preservatives, and those who live on farms where arsenic pesticides have been used. (López-Pérez et al., 2018; Rodríguez, 2017).

Traditional processes for removing metals from water are costly and inefficient, especially when the metal concentration is low (Vera et al., 2016). Biosorption is a cost-effective and efficient alternative, especially at low concentrations. This technique is used to remove heavy metals from industrial wastewater, using biological materials such as algae, fungi, bacteria, fruit shells, agricultural products, carbons, and biopolymers as adsorbents (Tejada-Tovar et al., 2015).

This technique is an effective and economical alternative to traditional water treatment methods such as filtration and disinfection and has been shown to be effective in removing a wide range of contaminants, including heavy metals, organic chemicals, and excessive nutrients. Biosorption also has minimal environmental impact and can be used in a variety of contexts, from purifying industrial wastewater to improving the quality of water for human consumption. Due to its effectiveness and low cost, the use of biosorption technologies is increasing worldwide, and is expected to continue to be used in the future. The purpose of this research is to remove As present in contaminated water using a combination of dry biomass and activated carbon of nopal (*Opuntia ficus indica*) as adsorbent materials in a biosorption process. Nopal is a very useful plant for the industry, due to its properties. For example, its mucilage is used as a coagulant in wastewater to remove heavy metals and to improve the hardness of concrete in construction (Aguilar & Sulla, 2022). It is also used in reforestation projects, as it develops well in environments with extreme temperatures, irregular precipitation, and variations in the concentration of CO_2 in the atmosphere (Alcántara & Colin, 2020).

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Activated carbon is a porous, amorphous material prepared chemically to increase its porosity and provide an extensive internal surface area. These characteristics, combined with the chemical composition of the carbon atoms that make it up, give it the ability to attract and retain certain molecules from the fluid surrounding the carbon (García & Granillo, 2017).

The document is structured as follows; in the objectives section, the intention to verify the process of adsorption of arsenic using dry biomass and activated carbon of *Opuntia ficus-indica* is highlighted. In the theoretical framework, the concepts of bioadsorption, the problem of arsenic and the need to use biological techniques to remove heavy metals are discussed. Subsequently, the methodology used in the research is detailed and the results and conclusions obtained are presented.

Research objectives

The purpose of this research was to verify whether dry biomass and activated carbon made from nopal (*Opuntia ficus-indica*) could serve as absorbent materials capable of reducing the level of arsenic in water contaminated with this element. To do this, dry nopal leaves were collected, activated carbon made from nopal was prepared, water samples were taken, arsenic-contaminated water was filtered through the different nopal treatments, and the physicochemical parameters (arsenic concentration, pH, electrical conductivity, and turbidity) were measured.

Theoretical framework

The world's largest reserve of potable water is underground water, hence the importance of conserving it and keeping it free from anthropogenic contamination. However, the geomorphological composition in different parts of the world determines the presence of different elements and inorganic compounds in underground water, some of which can be harmful to humans, such as arsenic (Cruz, Lara, & Li, 2016).

In Mexico, as in many other countries around the world, there is a serious problem with the supply of potable water due to the contamination of aquifers with arsenic (As). The elimination of this substance is crucial, as prolonged exposure of living beings through the consumption of contaminated water and food can cause cancer, skin lesions, developmental problems in babies, cardiovascular diseases, neurotoxicity, diabetes, and infertility (Quansah, et al., 2015).

Arsenic is found in concerning amounts in the groundwater aquifers of 16 Mexican states located in arid and semi-arid regions, including Coahuila, Nuevo León, Durango, Chihuahua, Sonora, Nuevo León, Baja California Sur, Sinaloa, San Luis Potosí, Zacatecas, Aguascalientes, Guanajuato, Jalisco, Morelos, Guerrero, and Hidalgo (López et al., 2019).

In the state of Guanajuato, arsenic, along with chromium and fluoride, is one of the main pollutants (Arzola & Li, 2016). The origin of arsenic is often unknown, as the element is naturally found in some groundwater deposits and poses a danger to the health of those exposed, as it can cause liver cancer and death (Litter, Farías & Armienta 2009).

The Pénjamo - Abasolo aquifer contains underground waters of the sodium bicarbonate family, which are mainly found in basaltic and rhyolitic volcanic rocks. These waters are used for agricultural, potable, and industrial purposes. Due to its natural conditions, it is common to find arsenic in various areas of the municipality of Abasolo (Amézaga, 2016).

The main methods for removing arsenic from water are adsorption, filtration, and reverse osmosis. However, there are numerous methods under evaluation that have been proposed as alternatives. However, the main difficulty for the application of these methods in Mexico is the cost, and the high content of minerals (mainly magnesium and calcium carbonates) in the water, which makes the application of any proposed method expensive (Nava, 2019). In this context, biosorption is a viable solution.

Biosorption offers numerous advantages compared to conventional techniques, such as low cost, high efficiency, minimization of chemical products and biological sludge, no additional nutrients are required, regenerability of biosorbents and metal recovery (Tejada-Tovar et al., 2015). In addition, it does not require a large investment, as the operating costs are quite low (Areco & Dos Santos, 2011).

Although biosorption has been used for some time, it is now even more attractive because of the use of novel materials that replace traditional ones, thus improving their results compared to other alternatives (Arango, 2004). The use of biosorbents is an excellent option for the sanitation of drinking water in developing countries, due to its low cost and the possibility of implementing them in rural areas, a situation that is exacerbated in these locations. Among these new materials that are being used as biosorbents is the nopal.

The family of arboreal cacti has an endemic plant of America, the nopal, which reaches a height of 3 to 5 meters. This plant is characterized by its fleshy paddles called cladodes, 30 to 60 cm long, 20 to 40 cm wide and 2 to 3 cm thick, and by its spines, up to 5 mm long (Zavala, 2012). The nopal has a high-water content (90-92.5%), minerals (calcium, potassium, silicon, sodium, iron, aluminum, magnesium, and zinc), carbohydrates, nitrogen compounds, amino acids, and organic acids (Ovando, 2012). The nopal belongs to the genus Opuntia of which there are 258 recognized species, 100 of them are found in Mexico.

Activated carbon is a very porous form of carbon that can effectively filter organic materials such as chlorine and other harmful chemicals. This form of carbon has been used for many years in various applications, from the treatment of drinking water to the treatment of wastewater. The benefits of using activated carbon include better water quality control, less water pollution, and more efficient wastewater treatment.

Activated carbon is a natural product made from coconut shells, wood, charcoal, or other carbon-rich materials. Activated carbon is characterized by its high specific surface area per unit weight, which allows it to trap various chemical compounds. Activated carbon has been shown to be an effective adsorbent for removing a wide range of organic and inorganic contaminants from the aquatic environment (Correa-Calderón & Romero-Salinas, 2021). This is due to its porous surface areas, which range from 500 to 1500 m2/gr, as well as a wide range of functional surfaces, which makes it accessible to various reagents (Caviedes Rubio et al., 2015). Activated carbon is considered an eco-material due to the great benefit of using it for refining, water purification and wastewater treatment. It is also useful for immobilizing harmful gas emissions to the atmosphere (Fiestas & Millones, 2019).

Methodology

Collection of dried cladodes of nopal

The collection of nopal biomass was carried out on the hill of the community of Loma de la Esperanza, Abasolo, Gto., with coordinates at 20°40'7.00"N and 101°32'54.30"O, at an altitude of 1754 m.a.s.l. Dry cladodes from different nopal plants were collected, which were naturally dry, taken from different specimens to avoid damaging the plant.

Pretreatment of dry nopal biomass

The dry cladodes of nopal were subjected to pretreatment with a 1% hydrochloric acid solution. Then, this solution was sprayed onto the dehydrated raw material with an atomizer to increase the porosity of the biomass and, in this way, increase its biosorption capacity. Finally, the biomass was dried in the open air for 3 hours.

Once the nopal biomass was dry, it was ground to obtain a greater surface area and metal removal. For this, an industrial INTERNATIONAL® model LI-5A blender was used for approximately 10 minutes, the obtained biomass was sieved to obtain smaller particles and increase its surface area, as seen in Figure 1A and 1B.

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Figure 1 A) Biomass collected from dried cactus stalks and B) Ground dry cactus biomass

Elaboration of activated carbon

The process of activated carbon production began with the use of the largest pieces of dry nopal biomass. The biomass was burned in an appropriate container. Once most of it was burned, it was covered with a metal sheet to prevent oxygen from entering, which allows the biomass to carbonize evenly. The process lasted between 3 and 4 hours, producing the activated carbon.

The activation process began with the spraying of a 20% phosphoric acid solution onto the carbon. The carbon was then introduced into a TERLAB® TE-H61D drying oven to remove moisture. It was then activated in an ARSA® AR-3040 electric muffle furnace for 1 hour at a temperature of 500 °C. Once activated, the carbon was cooled to room temperature and washed with a 1 N NaOH solution, and the pH adjusted to between 6.5 and 8.5. Finally, it was rinsed with distilled water, dried in an oven for 2 hours at 110 °C, and finely ground using a mortar to increase the surface area, as seen in Figure 2.

Figure 2 Pulverized nopal activated carbon

Analysis of nopal activated carbon

The activated nopal carbon was visualized under a MOTIC® SMZ-171-TLED stereoscope. Three different samples of activated carbon were viewed under the stereoscope, the first of the calcined nopal biomass, the second of the unwashed nopal activated carbon, and the third of the nopal activated carbon. In Figure 3 A), the calcined biomass is observed to be of an opaque black color and in some parts it appears brown. In Figure 3 B), the color is black, more uniform, but some residues of the acid reaction with the biomass can be seen. In Figure 3 C), the nopal activated carbon appears to be a deeper black color, which is a characteristic of activated carbon and indicates that the activation process was carried out correctly.

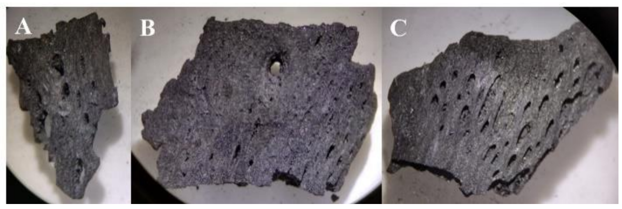

Figure 3 A) Calcined biomass, B) Unwashed activated carbon and C) Nopal activated carbon

Sampling of contaminated water

Water sampling was carried out at different points in the municipality of Abasolo and was performed following the methodology described in NOM-230-SSA1-2002 (Secretaria de Salud, 2005). The selected samples belong to the communities of Rancho Nuevo de la Cruz with a concentration of 0.02 mg/L, Loma de la Esperanza with a concentration of 0.025 mg/L, and the Los Pinos neighborhood in Abasolo, Gto. with a concentration of 0.1 mg/L. The samples were selected based on the maximum permissible limits (MPL) established in the environmental regulations NOM-127-SSA1-2021 (Secretaria de Salud, 2022), with a value of 0.025 mg/L, so that there are values below, equal to, and above the MPL.

Determination of As in drinking water samples

The samples were analyzed using a MQuant® As - Arsenic Test portable kit for the determination of arsenic, which consists of a colorimetric method with test strips and reagents with a measurement range of 0.005 - 0.50 mg/l of arsenic. To obtain more accurate results, the determinations were repeated three times. This procedure was carried out both before and after filtration with the nopal treatments, to determine the initial and final concentration of As after biosorption and to determine the percentage of removal of the contaminant.

Treatments and filtrations

Three treatments were designed to verify whether dry nopal biomass and activated carbon (*Opuntia ficus-indica*) can be used as absorbent materials capable of reducing the level of arsenic. These treatments are presented in Table 1. The water samples with arsenic were obtained from the Los Pinos neighborhood- 0.1 mg/L (M1), the communities of Loma de la Esperanza-0.025 mg/L (M2), and Rancho Nuevo de la Cruz-0.02 mg/L (M3).

Treatment	Description	Concentrations of arsenic in water samples to be filtered in mg/L
T1	Dried and ground nopal biomass	0.1
		0.025
		0.02
T2	Activated carbon from nopal	0.1
		0.025
		0.02
T3	Dried and ground nopal biomass + Activated carbon from nopal	0.1
		0.025
		0.02

Table 1 Description of treatments

One-liter plastic bottles were used for the filtrations. A fine-pore filter paper was placed in the outlet hole, then it was filled with ground dry nopal biomass (T1), activated nopal carbon (T2), and a combination of ground dry nopal biomass and activated nopal carbon (T3), the water sample was added, and the filtration was allowed to continue until the last drop was obtained. The process was repeated three times for each treatment. Images 4, 5, and 6 show the filtrations carried out with the different samples and treatments.

Figure 4 Arsenic water filtration process using ground dried cactus biomass as adsorbent

Figure 5 Arsenic water filtration process using nopal activated carbon as an adsorbent

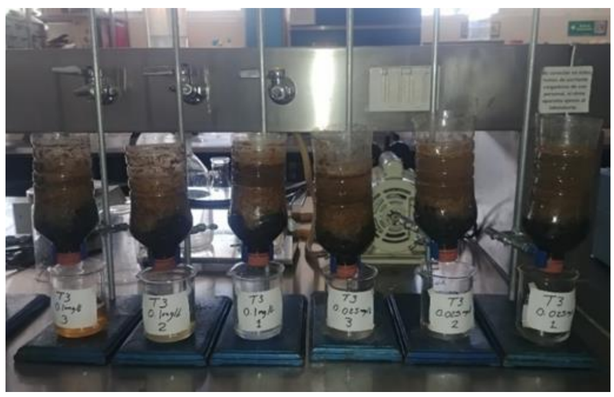

Figure 6 Arsenic water filtering process using the combination of biomass and activated carbon as an adsorbent

Determination of physicochemical parameters (pH, conductivity, and turbidity)

The physicochemical parameters were measured before and after filtration to determine the initial and final conditions of the water, to understand its behavior. A portable Hach Co.® 2100QIS01 turbidimeter was used to measure the turbidity. The portable pH/EC/TDS HI98130 meter from Hanna® was used to measure the pH and conductivity.

Results

The results obtained from the filtrations were compared to the values indicated in NOM-127-SSA1-2021, which establishes a maximum permissible limit of 0.025 mg/L for arsenic, a pH of 6.5 to 8.5, electrical conductivity of 1500 µS/cm, and a turbidity of 0 to 5 NTU. The final concentration of arsenic was also compared to the maximum permissible limit established by the World Health Organization [WHO] (World Health Organization, 2003) and the Environmental Protection Agency [EPA] (Environmental Protection Agency, 2018), which is 0.1 mg/L. Table 2 shows the results obtained from the filtrations carried out with the three treatments and their retention time, as well as the removal percentages.

Treatment	Concentration of arsenic (mg/L)		Removal (%)	Retention time (hr, min)
	Initial	Final		
T1	0.1	0.02	80	03:18
	0.025	0.018	26.67	04:10
	0.02	0.015	25	05:15
T2	0.1	0.05	50	04:28
	0.025	0.02	20	03:10
	0.02	0.013	33.3	01:20
T3	0.1	0.007	93.3	03:05
	0.025	0.01	60	03:10
	0.02	0.1	50	03:28

Table 2 Final As values in the different treatments, the values in mg/L and in percentages of removal are appreciated

Table 3 shows the results of the measurement of the physicochemical parameters in the water samples that were filtered in the different treatments.

Treatment	Samples (mg/L)	pH		Conductivity (µS/cm)		Turbidity (NTU)	
		Initial	Final	Initial	Final	Initial	Final
T1	0.1	8.5	8.9	710	31	0.77	---
	0.025	8.5	8.6	573	5	0.22	---
	0.02	8.5	8.2	550	52	0.31	---
T2	0.1	8.6	4.9	732	56	0.81	0.5
	0.025	8.6	5.4	575	46	0.49	9.6
	0.02	8.5	8.2	550	14	0.31	10.9
T3	0.1	8.4	6.4	718	85.7	0.41	---
	0.025	8.6	7.6	582	68.3	0.69	---
	0.02	7.7	5.6	552	14	0.62	---

--- Non-measurable range

Table 3 Results of physicochemical parameters (pH, conductivity, turbidity)

Discussion

Treatment 3 is the best for removing As at a concentration of 0.1 mg/L, with a removal of 93.3% and a final concentration of 0.007 mg/L, a value accepted by NOM-127-SSA1-2021, WHO, and the EPA. Treatment 1 achieved a removal of 80% of As and a final concentration of 0.02 mg/L, a value accepted by NOM-127 but rejected by international organizations. Treatment 2, on the other hand, achieved a removal of 50% of As and a final concentration of 0.05 mg/L. Although a significant removal was achieved, the final concentration is higher than the limits established in NOM-127 and by international organizations.

The best treatment for removing As at a concentration of 0.025 mg/L of As is Treatment 3 with a removal of 60% of As and a final concentration of 0.1 mg/L, a value accepted by both NOM-127, WHO, and the EPA. It is followed by Treatment 1 with a 26.67% removal of As and a final concentration of 0.018 mg/L, and finally, Treatment 2 with a 20% removal of As and a final concentration of 0.02 mg/L. Both values are acceptable by NOM-127 but exceed the limits set by international organizations.

Lastly, the best treatment for removing As at a concentration of 0.02 mg/L is Treatment 3, achieving a removal of 50% and a final concentration of 0.01 mg/L, a value acceptable by both NOM-127, WHO, and the EPA. It is followed by Treatment 2 with a 33.3% removal of As and a final concentration of 0.013 mg/L, and finally, Treatment 1 obtained a removal of As of 25% and a final concentration of 0.015 mg/L. Likewise, both values are acceptable by NOM-127 but exceed the limits set by international organizations.

Regarding the results of the physicochemical parameters, for a concentration of 0.1 mg/L of As, the pH for Treatment 2 and Treatment 3 is below the limit indicated in NOM-127, while in Treatment 1 it is higher, so no value is within the range indicated in the current environmental regulations. The conductivity in all treatments is acceptable by presenting a value lower than the regulated one, and the turbidity in Treatment 1 and Treatment 3 is outside the measurement range, while in Treatment 2 a value of 0.5 NTU was obtained, which is within the established range.

For the sample of 0.025 mg/L, for Treatment 3 the pH is acceptable according to NOM-127, while in Treatment 1 the value exceeds the limit with a pH of 8.6, as well as in Treatment 2 with a value of 5.4 and being below the range, the conductivity is acceptable in all treatments by presenting values below the limit, while the turbidity in all treatments exceeds the MPL.

Finally, for the sample of 0.02 mg/L, the pH in Treatment 1 and Treatment 2 is acceptable according to NOM-127, however, in Treatment 3 the pH is acidic, with a value of 5.6, the conductivity in the three treatments for this concentration is within the range, while the turbidity in all treatments exceeds the MPL.

The nopal biomass has a basic character and the activated carbon still contains some acid residues. The combination of these components helps to stabilize the pH. In samples that exceed 5 NTU of turbidity, it is necessary to carry out a clarification process to stabilize it. In addition, it is necessary to treat the pH to adjust it. In the case of acidic samples, sodium or potassium carbonate can be added, and in basic samples, citric or phosphoric acid can be added.

Conclusions

The dry ground nopal biomass, the activated carbon from it, and the combination of both, are a viable option for treating potable water contaminated with arsenic. This combination can achieve removals of between 20% and 93.3% of the arsenic present in the water.

It is necessary to investigate how the treatments used affect the physicochemical parameters obtained after filtration. This will allow us to determine how they influence pH, electrical conductivity, and turbidity. In addition, it is important to analyze the adsorption capacity of the treatments in other heavy metals that are an environmental and public health problem, such as aluminum, copper, chromium, fluoride, iron, mercury, and lead.

It is necessary to investigate the effectiveness of activated carbon from nopal by activating it for two and three hours at temperatures between 400°C and 750°C. Temperature is a key factor in increasing the porosity of carbon. It is also important to impregnate the carbon with phosphoric acid at percentages of 25% to 80% and analyze the removal of activated carbon in waters with arsenic or other heavy metals. It is also important to look for better washing methods to remove as much of the residual acid and base used in the process as possible.

However, it is important to continue researching the effectiveness of activated carbon from nopal with different concentrations of the contaminant and activation conditions to optimize its use and obtain better results in the removal of arsenic. In addition, it is necessary to carry out tests on different types of contaminated water to determine the generalizability of the results obtained in this research. This could expand its use in different contexts and contribute to solving the problem of water pollution by arsenic in different communities.

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