

Chapter

Removal of Heavy Metals and Purification of Surface Waters

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Abstract

In many parts of the world, the removal of heavy metals and turbidity in surface waters for potabilization is a focus of study, as it has become a public health problem. Many researchers develop methodologies for the removal of heavy metals; however, these are generally difficult to implement in rural areas due to the danger associated with the use of chemical reagents by individuals with little or no education. That is why this chapter aims to conduct a comprehensive literature review, including an original research project developed by our working group, to identify affordable methods for the potabilization of surface waters in small communities with minimal technology. Additionally, it aims to provide data for better understanding. These economical, sustainable, and efficient methods will help improve the treatment of surface waters for human consumption, using plants and their extracts for the removal of turbidity and various heavy metals. The methods proposed in this chapter for the potabilization of natural water are a contribution to green analytical chemistry. The objective of this chapter is to present metals, removal techniques, and evaluate the efficiency of removing Fe and Mn during phytoremediation processes. To carry out this work, three stages were considered. In the first stage, the quantity of plant material required for the process is selected. In the second stage, the metal removal capacity is determined with the selected mass, and in the third stage, the aim is to understand the removal levels of extracts from *Opuntia ficus-indica* and *Hylocereus triangularis* to compare it with *Hydrilla verticillata* (L.f.) Royle. The determination of metals was performed using atomic absorption spectroscopy with a previously validated method. The *Hydrilla* exhibited a 100% removal of Fe and Mn, as well as a reduction in turbidity and color of 92% and 94%, respectively. The *Hydrilla verticillata* (L.f.) Royle and *Opuntia ficus-indica* are plants that can be used for the removal of Fe, Mn, turbidity, and color in natural waters. The *Hylocereus triangularis* did not show efficient results in removing these metals in natural waters. Similar to *Hylocereus* and *Hydrilla*, *Opuntia* can be used for the removal of turbidity from natural waters, which is useful for rural communities.

Keywords: plant material, manganese, iron, water, removal

1. Introduction

Aquatic ecosystems essential for human consumption are riddled with numerous contaminants, including heavy metals, which constitute a major issue in developing

countries due to the significant pollution they introduce to surface waters [1]. This level of contamination is a result of anthropogenic activities. While various water treatment methods exist, many of them are effective but costly [2]. Hence, there is a need to employ appropriate and low-cost technologies for the removal of such contaminants. Considering that rural areas in developing countries lack the capacity for expensive water treatments, it is essential to highlight the different methods used for contaminant removal. Furthermore, it is of utmost importance to showcase effective and economical methods that enable the removal of heavy metals.

There is interest in a wide variety of heavy metals as they pose a health problem for humans. Among them, we can find zinc (Zn), copper (Cu), cadmium (Cd), lead (Pb), arsenic (As), iron (Fe), manganese (Mn), and chromium (Cr) [2, 3]. These metals can cause harmful effects on the environment and the living organisms inhabiting it [2]. Hence, it is important to monitor water quality concerning the various contaminants that may be present in surface waters.

To assess water quality, the Water Quality Index (WQI) [4] is used, which indicates the condition of a water source. If the WQI falls between 91 and 100, the water quality is considered good; 71–90 indicates acceptable water quality; 51–70 suggests regular water quality; 26–50 denotes poor water quality, and 0–25 implies the lowest level of water quality. This index varies based on the geography and water usage of the country [5]. Water quality regarding heavy metals is determined by two indices: the Heavy Metal Pollution Index (HPI), which shows the combined effect of metals in surface waters [6], and the Heavy Metal Evaluation Index (HEI), which indicates the state of the water body. The state of the water body can be affected by various sources of pollution, including mining, agriculture, volcanoes, forest fires, and urbanization, among others.

One crucial aspect to consider regarding heavy metals is their toxicity, as they jeopardize the natural balance and human health [7]. Prolonged exposure to these metals is associated with various diseases such as Alzheimer's, neurological issues, osteoporosis [2], and can even lead to death. For these and many more reasons, this text aims to conduct a thorough review of different methods for heavy metal removal. We will focus on those methods that are cost-effective and also involve the use of plants or plant extracts for the decontamination of surface waters, such as coagulation/flocculation and phytoremediation. These methods are highly beneficial as they enable the removal of contaminants in a natural way without the use of chemicals.

The *B. papyrifera* and *K. paniculata* have been used for manganese removal in soil [8], *Duckweed* and *tape grass* for copper removal in water [9], Water Jacinta (*Eichhornia crassipes*), Water Lettuce (*Pistia stratiotes*) [10, 11] used for water remediation, Guasimo (*Guazuma ulmifolia*), prickly pear cactus (*Opuntia ficus-indica*), and dragon fruit (*Hylocereus triangularis*) [12]. These studies demonstrate that they are an environmentally friendly alternative.

For contaminant removal, it employs various types of hyperaccumulating plants known as macrophytes, which are beneficial in removing metals from water through mechanisms such as phytoextraction, rhizofiltration, phytovolatilization, and phytostabilization [13]. Chelation is the mechanism used by plants to retain heavy metals [14].

Phytoremediation has its advantages and disadvantages. Among its disadvantages is the difficulty of disposing of biomass with adsorbed contaminants. However, there are different disposal mechanisms such as incineration treatments, pyrolysis, gasification, and microbial extraction, among others [13, 15].

Hydrilla Verticillata is an aquatic plant belonging to the *Hydrocharitaceae* family. It is considered an aggressive and invasive species that has been used in studies for

the removal of red dye 120 from simulated wastewater [16, 17] and phosphates in domestic wastewater [18]. The interest in studying this plant lies in its abundance in our aquatic ecosystems, the lack of contaminant removal through conventional treatments, and its potential use in removing Fe and Mn, which contribute to a brown color in the water, giving it an unhygienic appearance.

2. Heavy metals: Their sources and toxicity

2.1 Heavy metals

Heavy metals are considered those whose density is greater than (4 g/cm^3), and they are toxic at low concentrations [19, 20]. Among these, we can find (Hg), (Zn), (Cu), (Cd), (Pb), (As), (Fe), (Mn), (Cr), (Ni), and (Co), among others [3, 20].

Mercury (Hg) is a silver-colored metal, liquid at room temperature, with oxidation states (+4, +2, +1). It accumulates in most living organisms, being extremely toxic and causing diseases such as digestive syndromes (nausea, bad breath, vomiting, diarrhea, etc.), neurological syndromes, ophthalmological syndromes, dermatitis, rhinitis, and hypersensitivity, among others [21].

Zinc (Zn) is an element with oxidation states ($-2, 0, +1, +2$), appearing as a solid with a silver-gray appearance. Although essential for humans, excessive intake increases the likelihood of prostate cancer, elevated cholesterol levels, increased testosterone, and can cause immune dysfunction [22].

Copper (Cu) with oxidation states (+1 and +2), this reddish solid can cause stress to aquatic biota [23]. Additionally, in large quantities, it can exert toxic effects, physiological alterations, and acute toxicity are also consequences of exposure to Cu [24, 25].

Cadmium (Cd) is a metal characterized by a bluish-white solid appearance and oxidation states +1 and +2. This metal possesses the four most dangerous characteristics that can be attributed to a toxic contaminant: bioaccumulation, ease of transport through water and air, toxicity to humans, and persistence in the environment. Due to its bioaccumulative nature, it is a causative factor for conditions in the lungs, bones, and kidneys [26].

Lead (Pb) is a dark-gray element with oxidation states (+2, +4), harmful to the central nervous system and affecting balance, as well as the direction and range of muscle movement [27].

Arsenic (As) with oxidation states (+3, +5), this metal can be found in gray, yellow, and black colors due to its three allotropic states. It is extremely toxic, causing poisonings, as well as a predisposition to cancer in the lungs, skin, and bladder [28].

Iron (Fe) is a gray-silver metal with oxidation states (+2, +3). It can generate free radicals, leading to oxidative stress, and can cause poisoning due to its accumulation in the liver. Iron intoxication affects the central nervous, gastrointestinal, cardiovascular systems, and metabolic functions [29].

Chromium (Cr) with a bright whitish-gray color and oxidation states (+2, +3, +4, +6), can cause damage to the skin and eyes, and it is also carcinogenic. Its intake may lead to kidney failure, bronchitis, hemorrhages, and gastrointestinal damage [30].

Manganese (Mn) is a whitish-gray transition metal, with the most common oxidation states being (+2, +3, +4, +6, +7). It causes respiratory problems, blocks the neurotransmitter system, and also leads to a syndrome called manganism, where the patient exhibits symptoms similar to Parkinson's [31].

Niquel (Ni) Elemento solido de color blanco ligeramente amarillento con estados de oxidación (+3, +2, 0). Su exposición prolongada u ingesta puede provocar embolia pulmonar, fallos respiratorios, mareos, bronquitis crónica, erupciones cutáneas y cáncer de pulmón entre otras [32].

Nickel (Ni) is a solid element with a slightly yellowish-white color and oxidation states (+3, +2, 0). Prolonged exposure or ingestion can lead to pulmonary embolism, respiratory failure, dizziness, chronic bronchitis, skin rashes, and lung cancer, among other effects [32].

Cobalto (Co) is a metal pesado de color blanco azulado con estados de oxidación (+5, +4, +3, +2, +1, -1). Su ingesta puede ocasionar alteraciones en epitelios de la mucosa bucal [33], alteraciones visuales, hipotiroidismo, cardiomiopatía, erupciones en la piel [34].

Cobalt (Co) is a heavy metal with a bluish-white color and oxidation states (+5, +4, +3, +2, +1, -1). Its ingestion can cause alterations in the epithelium of the oral mucosa [33], visual disturbances, hypothyroidism, cardiomyopathy, and skin rashes [34].

2.2 Sources

According to the World Health Organization (WHO), contaminated waters are those whose composition has been altered in such a way that it no longer maintains optimal conditions for human consumption. Surface water sources receive a wide variety of contaminants from numerous natural and anthropogenic events, including mining, forest fires, agroindustry, urbanization, and volcanoes [2]. Each of these events releases a significant amount of heavy metals into the environment, posing a threat to human health and ecosystems (**Figure 1**).

Primarily due to anthropogenic activities, surface waters can become contaminated with a range of heavy metals, through pesticides, insecticides, and mining, among others. Specifically, for water used for human consumption, the presence of



Figure 1.
Heavy metal sources. Water pollution by heavy metals.

high concentrations of heavy metals in the body can lead to failures in the organisms that are exposed to it. In (**Table 1**), the heavy metals, their sources, ailments caused by these metals, and the maximum allowable amount in water are shown.

Metals	Sources	Suffering	Maximum allowed in drinking water (WHO)	Ref.
Cr	Corrosion	Kidney failure, bronchitis, bleeding, and gastrointestinal damage	0.05 mg/l	[3, 30, 35–37], [WHO]
Pb	Mining, corrosion, agriculture, and cattle farming	Loss of sense of balance and direction and range of muscle movement	0,01 mg/l	[3, 27, 35–38]
Zn	Mining, corrosion, agriculture, and cattle farming	Prostate cancer, increased cholesterol, testosterone, and immune dysfunction	3 mg/l	[3, 22, 35–37]
Ni	Mining, corrosion	Pulmonary embolism, respiratory failure, dizziness, bronchitis, skin rashes, and lung cancer	0,02 mg/l	[3, 32, 35–37]
Cu	Mining, corrosion, agriculture, and cattle farming	Physiological alterations and acute toxicity	2 mg/l	[3, 24, 25, 35–37]
Cd	Mining, corrosion	Conditions in the lungs, bones, and kidneys.	0,003 mg/l	[3, 26, 35–37]
As	Mining, agriculture, and cattle farming	Poisoning, carcinogenic prevalence in lungs, skin, and bladder	0.01 mg/l	[3, 28, 35–38].
Fe	Corrosion	Effects on the central nervous system, gastrointestinal, cardiovascular	NGL**	[3, 29, 35, 37, 39]
Co	Corrosion	Alterations in epithelia of the oral mucosa, visual, hypothyroidism, cardiomyopathy, skin rashes	NM	[3, 33–35, 37, 39]
Mn	Agriculture and cattle farming	Respiratory problems, blockage of the neurotransmitter system, and manganism syndrome	0,5 mg/l	[3, 31, 35, 37]
Hg	Mining	Nausea, vomiting, diarrhea, neurological syndromes, ophthalmological syndrome, dermatitis, rhinitis, and hypersensitivity	0,001 mg/l	[21, 36, 38]

NM = Not mentioned; NGL = No Guideline, because it occurs in drinking water at concentrations well below those at which toxic effects may occur**No Guideline, because it is not of health concern at concentrations normally observed in drinking water, but may affect the acceptability of water at concentration above 0,3 mg/l.

Table 1.
Major heavy metals present in surface waters and their anthropogenic sources.

2.3 Toxicity of heavy metals

Heavy metals such as chromium (VI), beryllium, arsenic, nickel, and cadmium have been classified by the International Agency for Research on Cancer (IARC) as human carcinogens, along with aluminum production and iron and steel foundries [38].

Some divalent metal cations are structurally similar, as is the case with Co^{2+} , Fe^{2+} , Zn^{2+} , Cu^{2+} , Ni^{2+} , and Mn^{2+} . It is likely that they may compete with each other, leading to complications in physiological functions within the cell [40]. An example of this is Ca, which is found in membranes and can be displaced by other metals, causing functional disorders [41].

The ingestion and/or prolonged exposure to heavy metals can lead to multiple diseases such as cancer, neurological syndromes, ophthalmological syndromes, dermatitis, rhinitis, hypersensitivity [21], visual impairments, hypothyroidism, cardiomyopathy, skin rashes [34], elevated cholesterol levels, increased testosterone, and immune dysfunction [22], conditions in lungs, bones, and kidneys [26], kidney failure, gastrointestinal damage [30], a syndrome called manganism [31], poisonings, among others [28]. This emphasizes the importance of researching and improving various methods for removing contaminants from waters intended for human consumption (**Figure 2**).

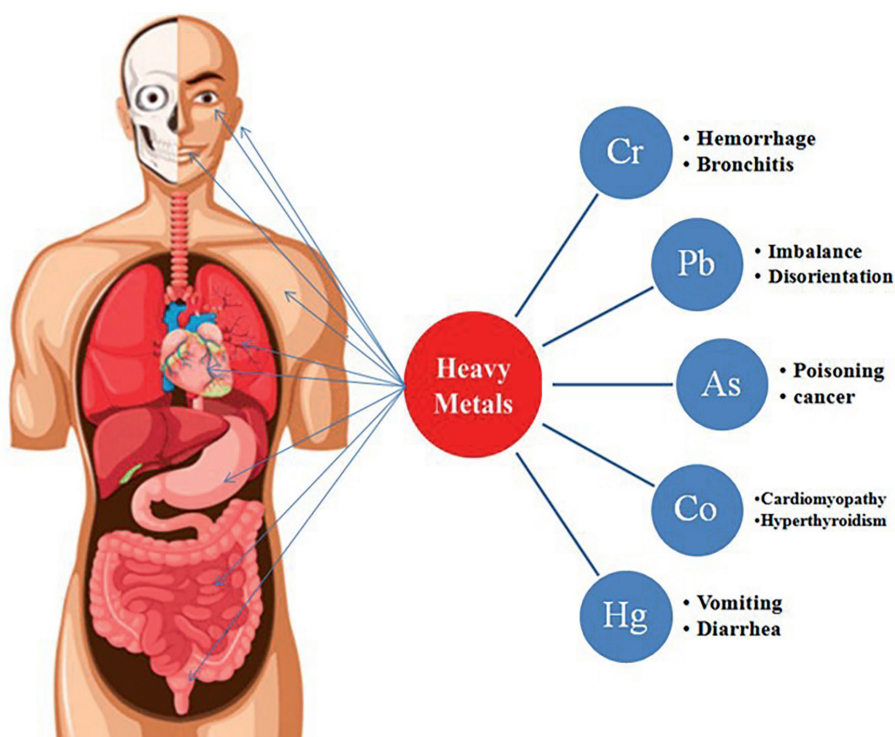


Figure 2.
Alterations and toxicity in humans caused by ingestion of heavy metals.

3. Methods for removal of heavy metals

There are various methods for treating surface waters, including chemical, physicochemical, and biological methods. Biological and physicochemical methods can involve the use of plants for water decontamination (phytoremediation) [7] (coagulation/flocculation). These two methods are significant as they can be employed in rural areas where large infrastructure for the treatment of surface waters for human consumption may be lacking.

3.1 Coagulation/flocculation

The method that uses plants or plant extracts with the ability to absorb contaminants, followed by a coagulation/flocculation process that allows for the easy separation of contaminants. However, this method generates a secondary pollution [42].

3.2 Phytoremediation

The method that uses plants to remove contaminants from water is environmentally friendly though it is a slow process and requires large land areas [43].

3.3 Photocatalysis

Photocatalysis este método posee la capacidad de degradar complejos de metales pesados, dispone de un alto poder oxidativo, descompone complejos orgánicos y además no produce lodos, su limitación es el alto costo a causa del equipamiento necesario para su funcionamiento [44].

3.4 Chemical precipitation

It is an economical and straightforward method that removes a significant amount of heavy metals from water, although it has some limitations such as the use of chemicals, generation of sludge, as well as handling expenses [45].

3.5 Electrochemical treatment

The method that minimizes the use of chemicals and is also an effective technique for recycling heavy metals. The limitations of this method include its lack of sensitivity, stability, and efficiency, as well as its high cost [46].

3.6 Reverse osmosis

The method that can be complemented with other methods, no use of chemicals is estimated, and it is simple to operate. Among the limitations, we can find reduced water permeability, the membrane may become contaminated, large amounts of energy are required, and there are high operation and equipment costs [47].

3.7 Flotation

Method for water treatment where physical phenomena are predominant, which can be low-cost when purchasing equipment, although maintenance and operational costs are some of its limitations [48].

3.8 AOPs

This method involves minimal chemical consumption and does not generate sludge. However, one of the major limitations of this method is its inapplicability on a large scale [49].

3.9 Ion-exchange

The method that uses a resin that maintains good regeneration and is also cost-effective. Its limitations are based on the adsorption of organic substances and difficulty in handling [50].

3.10 Membrane filtration

This method has good selectivity and provides efficient separation under low-pressure conditions. Its limitation lies in its expensive operability and difficult handling after use [51].

3.11 Adsorption

An efficient separation method, easy to use, with low costs, and applicable over a wide pH range. The limitation of this method is the need to regenerate the adsorbent [52].

As can be observed, all the methods shown above have their associated limitations. However, in this text, we want to highlight the method in which plants or plant extracts are used (phytoremediation). This method can be reproducible in rural areas where there are limited resources for the treatment of surface waters.

4. Methodology

4.1 Experimental design

To carry out this work, three stages were considered, for which glass experimental units with a capacity of 10 L were used, (2) for each evaluated factor. To assess the removal efficiency of Fe and Mn in natural water, *Hydrilla verticillata* (L.f.) Royle plants, and extracts from cactus (*Opuntia ficus-indica*) and dragon fruit (*Hylocereus triangularis*) were employed.

4.1.1 Stage 1

The amount of plant material, *Hydrilla verticillata* (L.f.) Royle, to be used in the subsequent stages of the work was determined. Four quantities of the plant were considered: 20,000, 80,000, 120,000, and 160,000 mg per 10 L of water.

The plant was extracted from a natural pond with all its roots and fresh foliar system, immediately weighed on a scale (Pioneer, TM Ohaus), and introduced into the experimental unit.

Initially, the levels of Fe and Mn present in the raw water were determined by AAS using a Thermoelectronatomic absorption system model S4AA System (ThermoFisher Scientific, MA, USA).

200 mL of metals at a concentration of 2 ppm were added to each experimental unit. Every two hours after the start of the process (9 am, 11 am, 1 pm, and 3 pm), water samples (1 L) were taken from each experimental unit at a depth of 0.5 cm from the surface to determine the levels of Fe and Mn. This allows understanding of the influence of mass and determining the time range during which solar radiation has the greatest impact on removal.

4.1.2 Stage 2

Four experimental units with a capacity of 10 L each were taken, and (200 mL) of a concentration of 1.5, 2.0, 3.0, and 4.0 mg metal/L were added. The mixtures were homogenized through rapid mixing at 100 rpm for 1 minute and slow mixing at 30 rpm for 60 minutes.

The selected mass was distributed among the experimental units and remained for 18 days. Three samples were collected at 3 pm every six days, and the levels of total Fe and Mn, as well as other physicochemical parameters, were determined at the beginning, during, and at the end of the experiment. This was done to understand the influence of time and the maximum amount of plant absorption.

4.1.3 Stage 3

Obtaining the extracts 500 g (wet weight) of Pitahaya (*Hylocereus triangularis*) and Cactus (*Opuntia ficus-indica*) were weighed. They were manually grated and filtered three times under pressure with surgical gauze. Due to the viscosity and instability of the concentrated extracts, 10% and 20% (w/v) solutions were prepared for the cactus and dragon fruit, respectively. These solutions were then stored at 4°C [12]. To determine the appropriate dose for each extract, a jar test was conducted (*Standard Practice for Coagulation-Flocculation Jar Test of Water*).

To find and select the appropriate dose of the extracts, each 1 L container was filled with raw water, and increasing doses of 0.008, 0.01, 0.012, 0.015, and 0.020 L of the solutions previously prepared with the extracts under study were added. It underwent rapid and slow mixing at 100 rpm for 1 minute and 30 rpm for 60 minutes, respectively. The mixture was allowed to settle for 60 minutes.

5. Statistical analysis and analytical control

To determine the mass of plant material, a completely randomized design (CRD) was used for each of its masses, selecting the mass with the best performance through the *Tukey HDS* multiple range test. Assumptions of normality and homogeneity of variance of errors in the proposed designs were tested using *Shapiro-Wilk* and *Cochran* tests, respectively. When it was not possible to ensure them, the non-parametric *Kruskal-Wallis* test was used. All tests were carried out using the statistical package *Statgraphics Centurion 16* and *Excel 2016*.

	Fe	Mn
Linear range	0.050–4000 mg/L	0.050–4000 mg/L
LDM	0.018 (+/–0.003) mg/L	0.021(+/–0.002) mg/L
LCM	0.050 (+/–0.004) mg/L	0.050 (+/–0.004) mg/L
Precision	1.11%	2.98%
Accuracy	99.69%	97.15%
Uncertainty	1.500(+/–0.119) mg/L	1.600(+/–0.088) mg/L

To ensure that there were no changes in the calibration curve during measurements, r^2 , $m \pm s$, $b \pm s$ of the line, and residuals were checked every 12 measurements using a standard.

Table 2.
Method validation parameters.

For metal determinations, the direct flame atomic absorption method was used, following digestion with sulfuric-nitric acid for Fe and Mn. The method validation parameters are shown in the following **Table 2**.

6. Results and discussion

See **Table 3**.

The results indicate that the mass of plant material influences the removal of these metals, with the best results observed for the mass of 160,000 mg in both cases, at different times of the day, with an average of 78.84% for Fe and 66.56% for Mn, respectively.

It is observed that the lowest removal occurred in the morning hours for both metals at all masses. This is due to the short exposure time of the material to the metals dissolved in natural water.

In contrast, for water with longer exposure times to the plant, a higher percentage of metal removal is observed at all masses, as seen at midday (4 h) and in the afternoon (6 h). However, no significant differences in removal are observed between daytime hours in both cases (**Table 4**).

After six days of the experiment, experimental unit 1 shows a removal of 100% for both metals. Additionally, it is observed that as the concentration of metals

% removal Fe	20,000 mg	80,000 mg	120,000 mg	160,000 mg
Morning (2 h)	54.92 (± 0.5)	59.58 (± 0.3)	69.16 (± 0.3)	75.19 (± 0.4)
Half day (4 h)	65.32 (± 0.7)	69.98 (± 0.1)	73.54 (± 0.4)	79.29 (± 0.6)
Afternoon (6 h)	73.27 (± 0.4)	75.46 (± 0.7)	78.47 (± 0.5)	82.04 (± 0.6)
% removal Mn				
Morning (2 h)	59.81 (± 0.1)	60.46 (± 0.2)	61.93 (± 0.5)	65.52 (± 0.3)
Half day (4 h)	60.79 (± 0.2)	62.26 (± 0.4)	63.24 (± 0.7)	66.67 (± 0.2)
Afternoon (6 h)	62.26 (± 0.2)	64.05 (± 0.5)	65.85 (± 0.9)	67.48 (± 0.1)

Table 3.
Percentage removal of Fe and Mn (*Hydrilla verticillata*) as a function of solar radiation and mass.

	Expe Unit 1		Expe Unit 2		Expe Unit 3		Expe Unit 4	
	mg. Initial	mg. Final	mg. Initial	mg. Final	mg. Initial	mg. Final	mg. Initial	mg. Final
Fe	17.34	0	17.44	0.73	17.64	1.54	17.84	3.07
Mn	0.92	0	1.02	0.24	1.22	0.35	1.42	0.43
Turbidity NTU**	41.02	3.11	41.02	3.96				
%removal Fe	100		95.82		91.29		81.67	
%removal Mn	100		76.27		71.57		69.52	
% Turbidity NTU	92.42		90.35					

**Nephelometric turbidity units.

Table 4.

Percentage of removal of Fe and Mn from each experimental unit after six days of exposure.

increases, the removal decreases, suggesting that there is a maximum concentration that the plant can tolerate. In experimental units 2, 3, and 4, the plants show signs of deterioration, and some died, possibly due to the surrounding climate (temperature, sunlight) and environmental conditions (sodium chloride, nutrients, and pH) [13], as these experiments were conducted in situ, where the plants were extracted.

The experimental units were set up under artisanal roofs. On days 12 and 18, it was not possible to carry out the experiment for the reasons mentioned above.

In experimental unit 1 and 2, after six days, a turbidity removal of 92.42% and 90.35%, respectively, was observed, indicating the usefulness of *Hydrilla* in the natural removal of turbidity. It can be used for this purpose in rural communities to avoid the use of chemicals and the risks associated with them.

In studies conducted by Lans et al. [12], turbidity removal percentages of 98.97% and 95% were observed for natural extracts of *Opuntia ficus-indica*, *Hylocereus trian-gularis* and *Guazuma ulmifolia*, respectively.

Figures 3 and 4 show the appearance of the water before and after treatment with the plant material. As can be seen, there is a drastic reduction in turbidity, as well as a decrease in Fe and Mn. *Hydrilla* is sensitive to high temperatures, so it must be controlled, and 323 K is the appropriate temperature [17]. Hence, it changes in appearance after being exposed to direct sunlight and high temperatures. This allowed us to avoid direct radiation on the plant to continue with the experiment (**Figure 5**).

Hydrilla verticillata has also been used to assess the removal efficiency of BOD, COD, and phosphates in freshwater and domestic wastewater, achieving removal efficiencies of up to 84% for BOD, up to 63% for COD, and up to 87% for phosphates [18].

Table 5 shows an efficient reduction in Fe levels by *Opuntia* and *Hydrilla*, 98.04% and 86.6% respectively, and 95.12% and 85.37% reduction in Mn for *Opuntia* and *Hydrilla* respectively. The Pitahaya extract showed a very poor reduction in these metals. *Opuntia* demonstrates a higher recovery level than *Hydrilla*; however, it is essential to consider that *Opuntia* requires an extract, involving prior work. For this reason, *Hydrilla* has an advantage, as it is only exposed to the water being treated. It is worth mentioning that this process is slower, as a specific waiting time is required



Figure 3.
Untreated raw water.



Figure 4.
*Water condition after six days of contact with 160 g of *Hydrilla* mass.*



Figure 5.
Change in the appearance of the plant after 1 day with direct sunlight and temperatures exceeding 32°C.

for removal. On the other hand, with *Hydrilla*, there is a risk that the plant may die without completing its work if Fe and Mn levels are too high.

Particularly, it was observed that the processes of turbidity and color removal by *Hydrilla* are slow compared to the *Opuntia* extract, where the result is almost immediate. Therefore, the plant material was left for a longer period (24 hours) after the process started. The removal of Fe and Mn is possibly due to the adsorption of these metals through an endothermic process [17].

	Ext. <i>Opuntia</i>		<i>Hydrilla</i>		Ext. <i>Hylocereus</i>	
	[]. Initial	[]. Final	[]. Initial	[]. Final	[]. initial	[]. Final
Fe	1.704 ± 0.43	0.033	1.704 ± 0.43	0.228 ± 0.030	1.704 ± 0.43	1.557 ± 0.031
Mn	0.062 ± 0.02	0.003	0.062 ± 0.02	0.009 ± 0.004	0.062 ± 0.02	0.057 ± 0.010
% removal Fe	98.04		86.6		8.43	
% removal Mn	95.12		85.37		7.32	
[]= Concentration						

Table 5.
Percentage removal of Fe and Mn by *Hydrilla verticillata* vs. extracts of *Opuntia ficus* and *Hylocereus triangularis*.

The *Opuntia* extract showed a removal different from *Hydrilla* and achieved better short-term results, both in turbidity and color, with removal values of 97% and 92%, respectively.

7. Conclusions

- The *Hydrilla verticillata* (l.f.) Royle, *Opuntia ficus indica* proved to be efficient in the removal of Fe, Mn, turbidity, and color in natural waters.
- The extracts of *Hylocereus triangularis* were found to be inefficient in the removal of the studied metals in natural waters.
- Similarly to *Opuntia* and *Hylocereus*, *Hydrilla* can be used for the removal of turbidity from natural waters, making it useful for rural communities.

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