An Artificial Channel Experiment for Purifying Drainage Water Containing Arsenic by Using *Eleocharis acicularis*

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Abstract: This paper reports the results of an artificial channel experiment in which water containing arsenic was purified by using *Eleocharis acicularis*. The experiment was conducted to investigate the feasibility of phytoremediation by *Eleocharis acicularis* in civil engineering projects. In the experiment, 15 m² of *Eleocharis acicularis* mats were laid in an artificial channel. Three sessions of artificial flow were implemented by leading 100.0 L of river water containing 0.234 mg/L of arsenic into the channel each time. The arsenic concentration of the leachate from the channel was analyzed. As the results of experiment, the arsenic concentrations of the leachate for the three sessions were 0.045 mg/L, 0.133 mg/L, and 0.249 mg/L. This shows that the arsenic concentration decreased during the first two sessions, whose flow totaled 200 L. The arsenic concentrations in the *Eleocharis acicularis* were 0.87 mg/kg, 1.01 mg/kg, and 4.16 mg/kg, which show that the plant absorbs arsenic. Moreover, it was found that the amount of sample water was reduced through evapotranspiration from the plant and the artificial channel.

Keywords: Artificial Channel; Purifying Drainage Water; *Eleocharis acicularis*; Arsenic; Evapotranspiration.

1. Introduction

Concentrations of heavy metals such as arsenic, selenium, lead and zinc that leach from soil and rock excavated at road construction sites occasionally exceed the criteria values prescribed for each such metal. When excavated soil and rock are temporarily stored at road construction sites, rainwater or snowmelt that seeps from such soil and rock may be contaminated by heavy metals. The Manual for Controlling Heavy Metal Pollution Caused by Natural Rocks and Soil at Construction Sites [1] proposes leachate treatment as a remedial measure. In this method, by exposing excavated soil and rock to the air at a temporary storage place, heavy metals contained in the leachate are properly treated. However, if heavy metal concentrations in the leachate exceed the corresponding criteria values, treatment of the heavy metals can be expensive, which poses a problem.

The experiments reported herein were conducted for the purpose of evaluating the applicability of phytoremediation to civil engineering work. Phytoremediation, a technique for cleaning up contaminated environments, has been used for purifying mine effluent. This technique has advantages and disadvantages. Its effectiveness is more dependent on weather conditions than is the effectiveness of other techniques for cleaning up environmental contaminants. Additionally, contaminants are removed only in the rhizosphere, and it takes time to grow plants large enough to be useful for phytoremediation. However, this technique is applicable at a relatively low cost, consumes no energy,
and is environmentally sound. This study used *Eleocharis acicularis* (hereinafter: *E. acicularis*), a plant in the Cyperaceae family that absorbs and accumulates heavy metals, because this plant has been proven to be effective in mine effluent treatment [2-4]. *E. acicularis* is tolerant of a wide variety of heavy metals, and it absorbs these metals. The plant is a perennial that grows in clumps at ponds, marshes, reservoirs, and paddy fields, and it is distributed throughout Japan. *E. acicularis* propagates with runners that branch off from the root area. In the experiments reported below, *E. acicularis* was used for purifying river water that contained arsenic and flowed in an artificial channel. The concentrations of arsenic in the river water and in *E. acicularis* were measured.

2. Outline of the experiments

2.1. Experiment site and materials

Experiments were conducted by using an artificial channel that was installed on the roof of a laboratory building (Figure 1). The 50-m-long channel is made of PVC and consists of 5 sections. Each section is 30 cm wide and 10 m long. Short pipes were used for assembling the channel with a hydraulic gradient of 0.5 permillage (‰). In the channel, 15 m² of *E. acicularis* mats with a wet weight of 54.5 kg were placed (Photo 1). The *E. acicularis* used in the experiments was hydroponically cultured, and the roots of adjacent plants were intertwined. The plants were shaped to form mats. Water taken from a river near a hot spring in the city of Sapporo was used for the experiments. The river water includes hot spring water that contains arsenic welling up from the bedrock of the river [5].

![Figure 1. Outline of Artificial Channel](image)

2.2. Experimental method

2.2.1. Arsenic removal

After pouring river water into the artificial channel in which *E. acicularis* mats had been put, *E. acicularis* and seepage water were sampled to measure the arsenic content and concentration. A total of 300.0 L of river water was used, and 100.0 L of river water was poured into the channel three times over 2 days. The inflow rate was 0.4 - 0.6 L/min. The experiment regarding arsenic removal was conducted between late July and early August, when the average air temperature was 25 °C or higher. At the onset of the experiment and each time 100.0 L of river water was poured into the channel, 50 ml of seepage water was sampled at the outflow end, 50 m from the inflow end. Values of air
temperature, river water temperature, pH and electrical conductivity (EC) were measured when the experiment was started and every time the seepage water was sampled. At three points (0 m, 25 m and 50 m from the inflow end) in the channel, 50 g of *E. acicularis* was sampled at the onset of the experiment and each time 100.0 L of river water was poured into the channel. Specimens were weighed after excess moisture was wiped off. The wet weight of all specimens was 1,050.6 g. After drying, the weight of these specimens was 195.7 g, 19 % of the wet weight.

![Photo 1. *Eleocharis acicularis* in Artificial Channel](image)

2.2.2. *Experiment to determine the rate of evapotranspiration*

To determine the evaporation rate of water from *E. acicularis* (i.e., the transpiration rate) and from the artificial channel, tap water was poured into the channel five times over 5 days. A total of 500.0 L of tap water was used for this purpose. The inflow rate was 0.4 - 0.6 L/min. The experiment was conducted at the beginning of October. At that time of year, the average air temperature is usually 15 °C or lower. The wet weight of *E. acicularis* used in the experiment was 68.6 kg. When 100.0 L of tap water was poured into the channel without the *E. acicularis*, 3 % of the tap water remained in the channel and the rest ran off from the channel. Although the ratio of the evapotranspiration and the evaporation is obtained as the ratio of the evapotranspiration and the open water evaporation [6]. In the experiment, the transpiration rate for *E. acicularis* and the evaporation rate of water from the channel were estimated by subtracting the total amount of seepage water from the total amount of tap water poured into the channel. The evapotranspiration rate estimated by using river water and that estimated by using tap water were analyzed in light of the difference in the average air temperature at the time when the experiments were conducted by using river water or tap water.

2.2.3. *Analysis method*

The river water used for measuring arsenic content and concentration was sampled, filtered, mixed with nitric acid to yield a 1 wt.% nitric acid solution, and preserved. The preserved river water was analyzed for arsenic concentration by using an Inductively Coupled Plasma Mass Spectrometry; Agilent 7500cx, Agilent Technologies, (hereinafter: ICP-MS). For the purpose of measuring the arsenic content of the *E. acicularis*, sampled *E. acicularis* was rinsed thoroughly with ultrapure water, dried at 80 °C in a dryer for 2 days, and pulverized. The fine powder from pulverization was mixed with 30 wt.% hydrogen peroxide, 61 wt.% nitric acid and 38 wt.% hydrofluoric acid, and the mixture
was evaporated at 98 °C until dry. Then, 61 wt.% nitric acid was added, and the mixture was re-evaporated at 98 °C until dry. The nitric acid solution was prepared by adding 30 wt.% nitric acid to the \(E.\ acicularis\) specimen and analyzing for arsenic content by using an ICP-MS.

3. Results

3.1. Changes in the arsenic concentration of the seepage water

The initial concentration of arsenic in river water was 0.234 mg/L. After the first, second, and third inputs of river water into the channel, the arsenic concentration in seepage water was 0.045 mg/L, 0.133 mg/L, and 0.249 mg/L, respectively (Table 1). The arsenic concentration after the third input of river water was 0.249 mg/L, a value close to the initial concentration of 0.234 mg/L. This suggests that \(E.\ acicularis\) has a limited arsenic absorption capacity under the experiment conditions, but the reductions in the arsenic concentration indicate that \(E.\ acicularis\) helped lower the arsenic concentration in the river water. As the average pH value of the river water was 7.5 before it was poured into the channel and was 7.4 when the river water seeped out, the pH remained neutral during the experiment. Regarding the EC of the river water, the average value was 0.62 mS/m before the river water was poured into the channel, and was 0.64 mS/m when the river water seeped out. These results show that there was no significant change in water quality.

**Table 1. Results of experiments for river water.**

| Number of inflow | Test Water (*:At the start/end of experiment  -:Unmeasured) | Elodea acicularis | Arsenic Concentration (mg/kg) |
|------------------|----------------------------------------------------------|------------------|-------------------------------|
| Initial          | 0.234                                                     | -                | 0.14                          |
| 1                | 0.045, 24.6/31.9, 26.2/31.0, 7.51/6.72, 0.52/0.38, 2.5, 100/8.9 | 0.07, 0.41, 0.15 |
| 2                | 0.133, 31.9/30.4, 31.9/34.5, 7.57/7.87, 0.64/0.63, 4.5, 100/66.8 | 1.01, 0.71, 0.31 |
| 3                | 0.249, 27.5/ - , 31.0/26.5, 7.50/7.52, 0.70/0.90, 4.5, 100/22.8 | 4.16, 2.46, 1.10 |
| Total            | -                                                         | -                | -                             |

3.2. Changes in the arsenic content of the \(E.\ acicularis\)

At the point 0 m from the inflow end of the channel, the initial arsenic content in \(E.\ acicularis\) was 0.14 mg/kg. After the first, second and third inputs of river water into the channel, the arsenic content was 0.87 mg/kg, 1.01 mg/kg, and 4.16 mg/kg, respectively. The arsenic content in the \(E.\ acicularis\) was the highest at the point 0 m from the inflow end and the lowest at the point 50 m from the inflow end. This suggests that the \(E.\ acicularis\) at the points 25 m and 50 m from the inflow end had the capacity to absorb more arsenic at the end of the experiment. The experiment results show that \(E.\ acicularis\) has the capacity to absorb and accumulate arsenic. However, because this capacity varies depending on the arsenic concentration in water and the inflow rate of water, it is necessary to examine conditions under which \(E.\ acicularis\) absorbs arsenic more efficiently.

**Table 2. Results of experiments for tap water.**

| Number of Inflow | Test Water (*:At the start/end of experiment  -:Unmeasured) | Arsenic Concentration (mg/kg) |
|------------------|----------------------------------------------------------|-------------------------------|
| Temperature* (℃) | Humidity* (%): Water Temperature* (℃): Inflow Time (Hour): Quantify of Water* (L) |
| 1                | 16.7/11.5, 41.7/70.7, 16.5/10.9, 17.0, 100/56.2 |
| 2                | 11.5/8.1, 64.1/72.1, 16.3/9.2, 21.0, 100/54.4 |
| 3                | 11.3/13.6, 58.4/59.0, 16.2/12.5, 24.0, 100/69.0 |
| 4                | 13.6/10.2, 59.0/73.7, 16.2/100, 22.0, 100/58.5 |
| 5                | 10.2/-, 73.7/-, 16.0/-, 9.0, 100/56.9 |
| Total            | -                                                          | -                             |

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3.3. The quantity of water used, and the quantity of seepage water
When the experiment using river water was conducted, the air temperature was between 27.3 °C and 29.8 °C, and the average air temperature was 28.3 °C. Because the quantity of river water used for the experiment was 300.0 L and the total volume of seepage water was 108.5 L, 64 % of the river water was lost during the experiment. When the experiment using tap water was conducted, the air temperature was between 9.5 °C and 17.6 °C, and the average air temperature was 12.6 °C (Table 2). The quantity of tap water used was 500.0 L and the total volume of seepage water was 295.0 L; thus, 41 % of the tap water was lost. The difference between the volume of water poured into the channel and the volume of seepage water was understood as the volume of evapotranspiration. It was confirmed that the volume of evapotranspiration varies depending on the average air temperature.

4. Discussion

4.1. Total content of arsenic in seepage water
The total arsenic content in the seepage water after it seeped out of the *E. acicularis* was estimated on the basis of the total content of arsenic in the river water used in the experiment. The total content of arsenic in the river water was defined as the product of the volume of river water and its initial arsenic concentration. The total arsenic content in the seepage water after it seeped out of the *E. acicularis* was obtained by subtracting the arsenic content of the water remaining in the channel and the product of the seepage water volume and the arsenic concentration of the seepage water from the total content of arsenic in the river water. The total content of arsenic in the river water is calculated as follows:

\[
\text{Total content of arsenic in the river water} = 0.234 \text{ mg/L (initial arsenic concentration)} \times 300.0 \text{ L (total volume of river water)} = 70.2 \text{ mg}
\]

The arsenic content remaining in the channel is calculated as shown below by using 1) the volume of water remaining in the channel before *E. acicularis* was placed in it, and 2) the volume of water retained within or on the surface of the *E. acicularis* (i.e., a value obtained by subtracting the weight of *E. acicularis* after drying from the wet weight of *E. acicularis*).

\[
\text{The volume of water remaining in the channel before the } E. \text{ acicularis was placed in it} = 3.0 \text{ L (3 % of total inflow water)}
\]
\[
\text{The volume of water retained within or on the surface of the } E. \text{ acicularis} = 54.5 \text{ kg (wet weight of } E. \text{ acicularis placed in the channel)} \times (100.0 \text{ - } 19.0 \text{ %}) = 44.2 \text{ L}
\]

The arsenic content of the water remaining in the channel is obtained by multiplying the volume of water remaining in the channel by the arsenic concentration measured after the third water input (0.249 mg/L).

\[
\text{The arsenic content of the water remaining in the channel} = 0.249 \text{ mg/L} \times (3.0 \text{ L + 44.2 L}) = 11.8 \text{ mg}
\]

The total arsenic content in the seepage water before it seeped out of the *E. acicularis* can be obtained by subtracting the arsenic content of the water remaining in the channel from the total arsenic content of the river water poured into the channel.

\[
\text{The total arsenic content in the seepage water before it seeped out of the } E. \text{ acicularis} = 70.2 \text{ mg - 11.8 mg} = 58.4 \text{ mg}
\]
The seepage water volume is multiplied by the arsenic concentration of the seepage water for the first, second, and third water inputs, and the three products are summed as shown below:

\[
\text{The sum of the products:} = 8.9 \text{ L} \times 0.045 \text{ mg/L} + 66.8 \text{ L} \times 0.133 \text{ mg/L} + 32.8 \text{ L} \times 0.249 \text{ mg/L}
\]
\[
= 17.5 \text{ mg}
\]

Because the arsenic content for the total amount of the seepage water before it seeped out of the *E. acicularis* is 58.4 mg and because that after it seeped out of the *E. acicularis* is 17.5 mg, we conclude that 40.9 mg of arsenic was absorbed by the *E. acicularis*. This reduction in arsenic content is equivalent to a 58% reduction of the total content of arsenic in the river water (i.e., 70.2 mg) used for the experiment.

4.2. Rate of evapotranspiration

The rate of evapotranspiration was estimated per unit area of *E. acicularis* mats per hour. The total area of *E. acicularis* mats was 15 m², the total duration of river water input was 11.5 hours (Table 1) and the total duration of tap water input was 93.0 hours (Table 2). Regarding the experiment using river water, the rate of evapotranspiration is obtained by dividing the amount of water loss by the total area of *E. acicularis* mats and by the total duration of water input.

\[
\text{The rate of evapotranspiration in the experiment using river water} = \frac{300.0 - 108.5 \text{ L}}{15 \text{ m}^2 / 11.5 \text{ h}}
\]
\[
= 1.1 \text{ L/m}^2/\text{h}
\]

Regarding the experiment using tap water, the rate of evapotranspiration is obtained by dividing the amount of water loss by the total area of *E. acicularis* mats and by the total duration of water input.

\[
\text{The rate of evapotranspiration in the experiment using tap water} = \frac{500.0 \text{ L} - 295.0 \text{ L}}{15 \text{ m}^2 / 93.0 \text{ h}}
\]
\[
= 0.2 \text{ L/m}^2/\text{h}
\]

When the experiment using river water was conducted, the air temperature was 27.3 - 29.8 °C (28.3 °C on average). The air temperature was 9.5 - 7.6 °C (12.6 °C on average) when tap water was used for the experiment. The difference in the rate of evapotranspiration per unit area per hour is understood to be attributable to the difference in the average temperature. In the experiments conducted by using an artificial channel, *E. acicularis* was found to absorb arsenic. At the same time, it was found that *E. acicularis* and the channel were useful for reducing the volume of water poured into the channel through evapotranspiration.

5. Conclusions

The findings of the experiments explained above are as follows:

1. The results of the experiment conducted on using *E. acicularis* to remove arsenic in an artificial channel show that *E. acicularis* helps lower the arsenic concentration in seepage water and that the capacity of *E. acicularis* to absorb arsenic depends on the volume of water. The arsenic content in the *E. acicularis* increased with increase in the number of water inputs, and the arsenic content in the *E. acicularis* was higher at the upper reach of the channel and lower at the lower reach.

2. The total arsenic content in the seepage water was equivalent to 58% of the total content of arsenic in the river water used for the experiment.

3. The volume of water was reduced due to evapotranspiration by 64% when the average air temperature was 25 °C or higher, and by 41% when the average air temperature was 15 °C or lower. The reduction rate of the water volume per unit area per hour was 1.1 L/m²/h when the average air temperature was 25 °C or higher, and it was 0.2 L/m²/h when the average air temperature was 15 °C or lower.
In the future, research and analysis will be continued for the following purposes at a site that is subjected to the constant inflow of drainage water: confirming arsenic removal by \textit{E. acicularis} and the arsenic absorption rates of \textit{E. acicularis} under various weather conditions; and identifying elements that are contained in water evaporated from channels.

6. References

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