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2026-YIL

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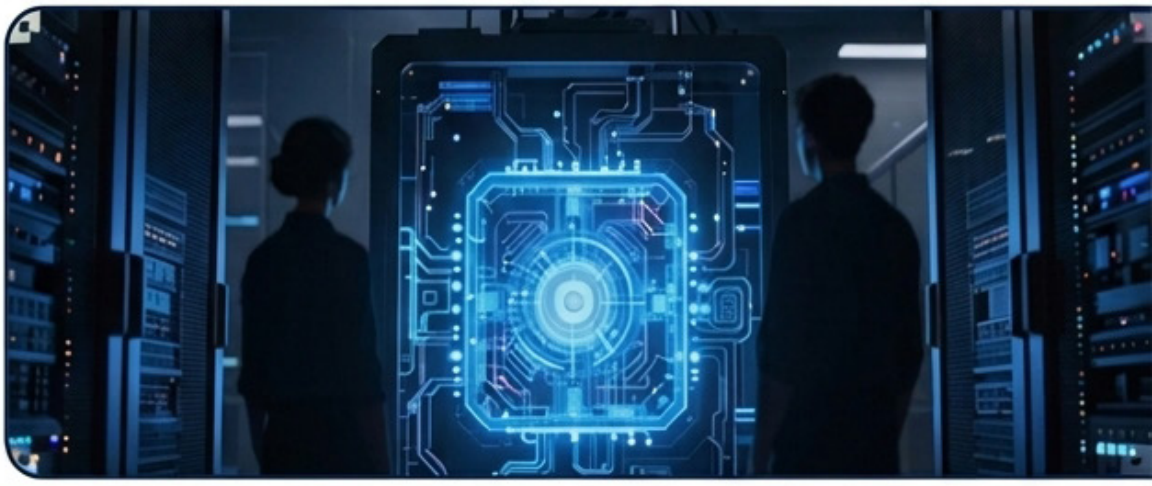
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05.01.02 – Tizimli tahlil, boshqaruv va axborotni qayta ishlash
05.01.03 – Informatikaning nazariy asoslari
05.01.04 – Hisoblash mashinalari, majmualari va kompyuter tarmoqlarining matematik va dasturiy ta'minoti
05.01.05 – Axborotlarni himoyalash usullari va tizimlari. Axborot xavfsizligi
05.01.06 – Hisoblash texnikasi va boshqaruv tizimlarining elementlari va qurilmalari
05.01.07 – Matematik modellashtirish
05.01.11 – Raqamli texnologiyalar va sun'iy intellekt
05.02.00 – Mashinasozlik va mashinashunoslik
05.02.08 – Yer usti majmualari va uchish apparatlari
05.03.02 – Metrologiya va metrologiya ta'minoti
05.04.01 – Telekommunikasiya va kompyuter tizimlari, telekommunikasiya tarmoqlari va qurilmalari. Axborotlarni taqsimlash
05.05.03 – Yorug'lik texnikasi. Maxsus yoritish texnologiyasi
05.05.05 – Issiqlik texnikasining nazariy asoslari
05.05.06 – Qayta tiklanadigan energiya turlari asosidagi energiya qurilmalari
05.06.01 – To'qimachilik va yengil sanoat ishlab chiqarishlari materialshunosligi
05.08.03 – Temir yo'l transportini ishlatish
05.08.06 – "G'ildirakli va gusenisali mashinalar va ularni ishlatish" (texnika fanlari)
05.09.01 – Qurilish konstruksiyalari, bino va inshootlar
05.09.04 – Suv ta'minoti. Kanalizatsiya. Suv havzalarini muhofazalovchi qurilish tizimlari
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08.00.04 – Qishloq xo'jaligi iqtisodiyoti
08.00.05 – Xizmat ko'rsatish tarmoqlari iqtisodiyoti
08.00.06 – Ekonometrika va statistika
08.00.07 – Moliya, pul muomalasi va kredit
08.00.08 – Buxgalteriya hisobi, iqtisodiy tahlil va audit
08.00.09 – Jahon iqtisodiyoti
08.00.10 – Demografiya. Mehnat iqtisodiyoti
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08.00.12 – Mintaqaviy iqtisodiyot
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08.00.14 – Iqtisodiyotda axborot tizimlari va texnologiyalari
08.00.15 – Tadbirkorlik va kichik biznes iqtisodiyoti
08.00.16 – Raqamli iqtisodiyot va xalqaro raqamli integratsiya
08.00.17 – Turizm va mehmonxona faoliyati

Ma'lumot uchun, OAK Rayosatining 2024-yil 28-avgustdagi 360/5-son qarori bilan "Dissertatsiyalar asosiy ilmiy natijalarini chop etishga tavsiya etilgan milliy ilmiy nashrlar ro'yxati"ga texnika va iqtisodiyot fanlari bo'yicha "Muhandislik va iqtisodiyot" jurnali ro'yxatga kiritilgan.

Muassis: "Tadbirkor va ishbilarmon" MChJ

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EVALUATION OF THE PHYTOREMEDIATION POTENTIAL OF AZOLLA CAROLINIANA FOR THE REMOVAL OF TOXIC METALS FROM INDUSTRIAL EFFLUENTS

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Abstract. The dynamics of the uptake of heavy metals, particularly chromium and cadmium ions, from wastewater by the *Azolla caroliniana* culture and its efficiency in the bioremediation process were studied. According to the research results, the initial average concentration of chromium in the wastewater environment was 2.27 mg/L. By the 14th day of the cultivation process, the amount of metal in the incubation medium had sharply decreased, and the average uptake value reached 1.54 mg/g. In addition, the uptake of cadmium (Cd) ions, studied as a conditional experiment, also proceeded intensively during the first 14 days, and it was found that the average concentration in the medium decreased from 1.95 mg/L to 0.58 mg/L. During the study, the occurrence of necrosis in *Azolla* leaves after days 14–16 and the cessation of dynamic growth on day 21 were observed. Taking these conditions into account, the necessity of periodically renewing plant biomass in biological wastewater treatment technologies was scientifically substantiated.

Keywords: *Azolla caroliniana*, bioremediation, wastewater, heavy metals, chromium, cadmium, bioaccumulation, biosorption, uptake dynamics, necrosis, phytoremediation, bioclimate.

INTRODUCTION

Nowadays, as a result of the rapid development of industrial sectors and the expansion of urbanization, the contamination of the environment, particularly natural water bodies and wastewater, with heavy metals has become one of the global environmental problems. Highly toxic heavy metals such as chromium (Cr) and cadmium (Cd) contained in wastewater can have serious adverse effects on living organisms even at low concentrations, disrupt the natural balance of aquatic ecosystems, and pose a threat to human health through the food chain. In this regard, the development of economically efficient, environmentally safe biological methods for treating contaminated wastewater based on “green technologies” is one of the most urgent tasks of modern science.

The analysis of scientific literature and conducted studies shows that the use of *Azolla caroliniana* culture among aquatic macrophytes and higher plants provides high efficiency. Scientific sources indicate that although the amount of biomass and nitrogen-fixation activity sharply decreased under the influence of chromium at a concentration of 3 mg/L, the use of the *Azolla caroliniana* culture, which retained its viability, in bioremediation processes is of great scientific and practical significance.

The dynamics of heavy metal uptake by *Azolla* species have been extensively covered in the scientific works of researchers. In particular, under conditions where the initial average concentration of chromium in the nutrient medium of wastewater was 2.27 mg/L, the uptake value was determined to be 0.36 mg/g on the 3rd day, 0.7 mg/g on the 7th day, 1.15 mg/g on the 10th day, and 1.54 mg/g on the 14th day of the cultivation process. In addition, the uptake of cadmium (Cd) ions, one of the other toxic elements, also proceeded intensively during the first 14 days, and the literature reports that the average concentration in the medium decreased from 1.95 mg/L to 0.58 mg/L.

However, an analysis of the existing literature indicates that continuous exposure to metals has a negative effect on plant physiology. In particular, by days 14–16 of cultivation, the occurrence of necrosis in *Azolla* leaves ranging from 8.9% to 23% and the cessation of dynamic growth by day 21 (maximum 1.52 mg/g) were observed. This necessitates the monitoring of plant biomass parameters and its periodic renewal in biological wastewater treatment technologies.

This study is devoted to the comparative investigation of the uptake kinetics and physiological changes of *Azolla caroliniana* culture in relation to chromium and cadmium ions, as well as to the scientific substantiation

of biological treatment processes for industrial wastewater.

LITERATURE REVIEW

The contamination of water resources with heavy metals, resulting from the development of industrial enterprises and the increase in anthropogenic impact, is considered one of the pressing environmental problems. Akhtar and his colleagues analyzed the natural and anthropogenic factors that lead to the deterioration of water quality and, as a result of industrial activity, they pointed out the significant impact of pollutants that contaminate the water environment on ecological systems [1].

Using aquatic plants to remove heavy metals from the aquatic environment using a biological method is considered one of the promising approaches. Specifically, Bennicelli and others studied the ability of *Azolla caroliniana* to remove Hg(II), Cr(III), and Cr(VI) ions from aqueous solutions and demonstrated that this plant has the potential to be used in the biological treatment of heavy metals [2]. In the studies conducted by Rai, the effectiveness of using *Azolla pinnata* in phytoremediation of cadmium and cesium present in industrial wastewater was evaluated [3].

In Pandey's studies, the possibilities of phytoremediation in an environment contaminated with heavy metals were investigated using *Azolla caroliniana*. The author notes the plant's ability to accumulate metals in its environment and indicates that using *Azolla* biomass in phytoremediation processes is a viable option [4]. Naghipour and his colleagues studied the processes of separating nickel, cadmium, and cadmium ions from an aqueous medium using *Azolla filiculoides*, and evaluated the biosorption properties of this plant in relation to several heavy metal species [5].

In recent years, there has also been an increase in generalizing research aimed at using *Azolla* species to treat water and wastewater. Al-Baldawi and other authors have analyzed the role of *Azolla* species in water purification and clarified their environmental and technological advantages [6]. Goala, Bachheti, and Kumar have summarized the latest advances in using *Azolla* species to phytoremediate water, and they have also analyzed the possibilities of reducing heavy metals and other pollutants using biological methods [7].

Al-Najjar and his colleagues have explored the possibilities of using *Azolla filiculoides* biomass as an adsorbent for treating wastewater. Their research shows that *Azolla* biomass can be used not only as a green plant but also as a recycled biosorbent [8]. Golchin and his colleagues also evaluated the ability of various aquatic plants to remove cadmium from the aquatic environment under different pollution conditions. This study shows that environmental conditions can affect the effectiveness of phytoremediation [9].

Local researchers are also paying attention to this area. In the studies conducted by Azimov, Khujamshukurov, Murodkhodjaeva, Turabjanov and Kuchkarova, the issues of biological treatment of environments contaminated with chromium using macrophytes were examined. This research is significant because it demonstrates the possibility of using macrophytes to reduce chromium levels through biological methods in the context of Uzbekistan [10].

In the studies by Hassanzadeh, Zarkami, and Sadeghi, the accumulation of heavy metals in the water environment and in the composition of *Azolla filiculoides* was examined in the Anzali waterlogging ecosystem. The research findings provide an opportunity to evaluate the property of *Azolla* biomass to accumulate heavy metals from the perspective of environmental monitoring and phytoremediation [11]. Ajanya and other researchers have studied the process of reducing heavy metals such as cadmium, mercury, chromium, and lead in the production of bauxite using *Azolla microphylla* and *Eichhornia crassipes* [12].

Furthermore, recent studies have also focused on the physiological and biochemical responses of *Azolla* species under metal stress conditions. Studies focused on comparing metal-tolerant and sensitive *Azolla* species in synthetic aqueous conditions have also evaluated the impact of heavy metals on plant physiology alongside the phytoremediation potential [13]. This approach shows that, in addition to determining the concentration of heavy metals in water, it is also necessary to monitor the state of the biomass.

RESEARCH METHODOLOGY

This study was aimed at investigating the dynamics of the uptake of heavy metals, particularly chromium and cadmium ions, from wastewater by the *Azolla caroliniana* culture, its biosorption properties, and the physiological condition of the plant. The experiments were conducted under laboratory conditions based on the relevant methodologies.

In order to organize the research methodologically correctly, a nutrient medium (W) artificially contaminated with heavy metals, namely chromium and cadmium, was prepared under laboratory conditions. The *Azolla caroliniana* culture, which showed a decrease in biomass and nitrogen-fixation activity under the influence of

chromium at a concentration of 3 mg/L but retained its viability, was selected as the research object.

In the experimental variants, the initial planting material was placed according to the specified standards and cultivated in wastewater media with different concentrations. The process of heavy metal uptake by the culture was regularly monitored over time, namely on the 3rd, 7th, 10th, 14th, and 21st days of cultivation. The residual amounts of chromium and cadmium ions in the nutrient medium and the research object were determined through spectrophotometric measurements. Based on the obtained quantitative indicators, the degree of metal adsorption was calculated in mg/g.

ANALYSIS AND RESULTS

According to the research results, the average amount of chromium in the nutrient medium across the experimental variants was 2.27 mg/L. On the third day of cultivation, it was determined that 1.82 mg/L of chromium remained in the nutrient medium containing 3.0 mg/L chromium, under which the *Azolla caroliniana* culture demonstrated viability. This indicator amounted to 0.36 mg/g relative to the total amount of chromium.

In Variant 1, the chromium concentration in the nutrient medium, where the initial chromium amount was 2.18 mg/L, decreased to 1.82 mg/L on the third day of cultivation. Under these conditions, the chromium uptake value of the *Azolla caroliniana* culture was observed to be 0.36 mg/g.

In Variant 2, in the nutrient medium with an initial chromium amount of 2.43 mg/L, the chromium amount on the 3rd day of cultivation was 2.11 mg/L. In this variant, the chromium uptake value of the *Azolla caroliniana* culture was 0.32 mg/g.

In Variant 3, in the nutrient medium with an initial chromium amount of 2.23 mg/L, the chromium amount on the 3rd day of cultivation was 1.98 mg/L. Under these conditions, the chromium uptake value of the *Azolla caroliniana* culture was determined to be 0.25 mg/g.

In Variant 4, in the nutrient medium with an initial chromium amount of 2.17 mg/L, the chromium amount decreased to 1.87 mg/L on the third day of cultivation. In this variant, the chromium uptake value was 0.30 mg/g.

In Variant 5, in the nutrient medium with an initial chromium amount of 2.32 mg/L, the chromium amount on the third day of cultivation was 1.92 mg/L. In this variant, the chromium uptake value of the *Azolla caroliniana* culture was determined to have reached 0.40 mg/g.

In the studies, the *Azolla caroliniana* culture, which showed a sharp decrease in biomass and nitrogen-fixation activity under the influence of chromium at a concentration of 3 mg/L but retained its viability, was used as the research object. In order to organize the studies methodologically correctly, all experimental variants were artificially contaminated with chromium, and the degree of adsorption of this metal by the research object was investigated. The overall results of the study are presented in Figure 1.

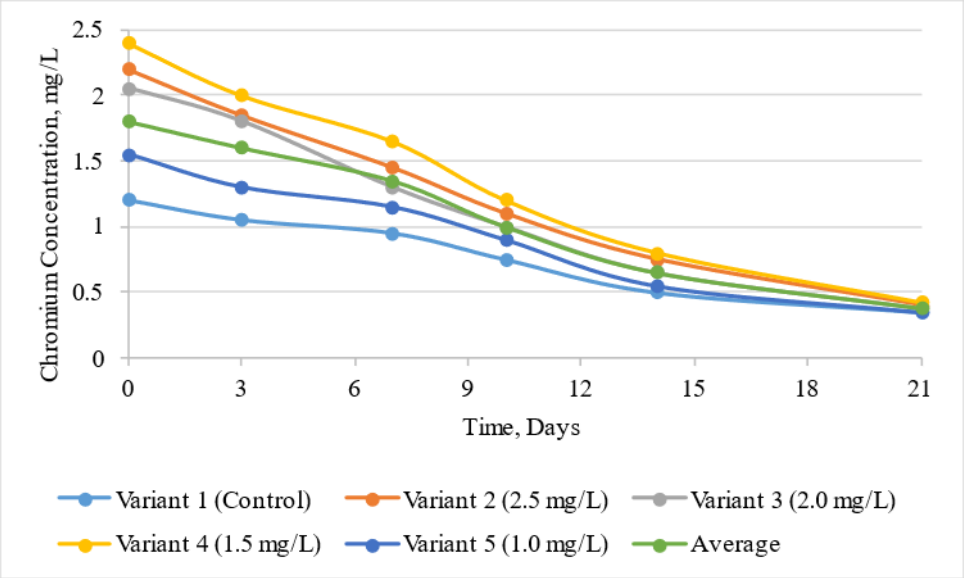


Figure 1. Dynamics of Chromium Concentration in the Nutrient Medium during Cultivation of *Azolla caroliniana*

According to the obtained results, the average amount of chromium in the nutrient medium across the experimental variants was 2.27 mg/L. On the third day of cultivation of the *Azolla caroliniana* culture, the

amount of chromium in the nutrient medium was found to have decreased to 1.82 mg/L, while the uptake value relative to the total chromium amount was 0.36 mg/g. In particular, in Variant 1, in the nutrient medium with an initial chromium amount of 2.18 mg/L, the chromium amount decreased to 1.82 mg/L on the 3rd day, and the chromium uptake value of the *Azolla caroliniana* culture was 0.36 mg/g. In Variant 2, in the medium with an initial chromium amount of 2.43 mg/L, the chromium amount reached 2.11 mg/L by the 3rd day, with an uptake value of 0.32 mg/g. In Variant 3, in the medium with an initial chromium amount of 2.23 mg/L, this indicator was 1.98 mg/L on the 3rd day, and the uptake value reached 0.25 mg/g. In Variant 4, the initial chromium amount was 2.17 mg/L, which decreased to 1.87 mg/L on the 3rd day, and the uptake value was 0.30 mg/g. In Variant 5, the initial chromium amount was 2.32 mg/L, which decreased to 1.92 mg/L on the 3rd day, while the uptake value reached 0.40 mg/g.

During the studies, on the 7th day of cultivation, when the average amount of chromium in the nutrient medium was 1.57 mg/L, the average chromium uptake value across the experimental variants was 0.7 mg/g. Comparison of the results obtained after three and seven days showed that, with an increase in biomass, the chromium uptake value also increased dynamically.

On the 10th day of cultivation, when the amount of chromium in the medium decreased to 1.11 mg/L, the average chromium uptake value across the experimental variants reached 1.15 mg/g. On the 14th day, the average amount of chromium in the medium was 0.72 mg/L, while the average chromium uptake value by *Azolla caroliniana* increased to 1.54 mg/g.

However, during the observations, by the 14th–16th days of cultivation, it was observed that processes of biomass loss resembling necrosis began in 8.9% to 23% of the leaves of the *Azolla caroliniana* culture. On the 21st day, under conditions where the amount of chromium in the medium was 0.71 mg/L, the average chromium uptake value was 1.52 mg/g.

Comparative analysis of the obtained results showed that no dynamic growth was observed on the 21st day compared with the 14th day. It was also determined that the *Azolla caroliniana* culture can uptake chromium at a maximum level of 1.52–1.54 mg/g. Therefore, periodic renewal of *Azolla caroliniana* biomass is of important practical significance in the biological treatment of chromium-contaminated wastewater (Figure 2).

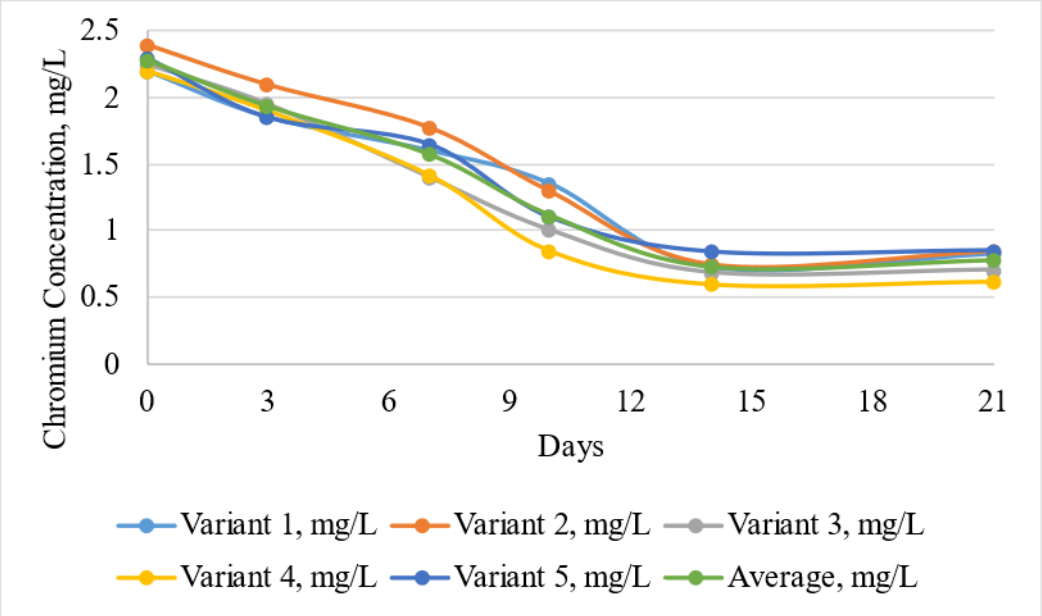


Figure 2. Dynamics of Chromium Concentration in the Nutrient Medium across Experimental Variants

In the study, the *Azolla caroliniana* culture, which showed a sharp decrease in biomass and nitrogen-fixation activity under the influence of chromium at a concentration of 3 mg/L but retained its viability, was used as the research object. In order to organize the study methodologically correctly, all experimental variants were artificially contaminated with chromium, and the degree of adsorption of this metal by the research object was investigated.

The overall results of the study are reflected in the graph above. According to the obtained data, the average amount of chromium in the nutrient medium across the experimental variants was 2.27 mg/L. On the third day of cultivation of the *Azolla caroliniana* culture, the average amount of chromium in the nutrient medium was found to have decreased to 1.94 mg/L.

In particular, in Variant 1, in the nutrient medium with an initial chromium amount of 2.18 mg/L, the

chromium concentration was 1.82 mg/L on the 3rd day, 1.61 mg/L on the 7th day, 1.33 mg/L on the 10th day, 0.74 mg/L on the 14th day, and 0.73 mg/L on the 21st day of cultivation.

In Variant 2, the initial chromium amount was 2.43 mg/L, and it was 2.11 mg/L on the 3rd day, 1.78 mg/L on the 7th day, 1.36 mg/L on the 10th day, 0.71 mg/L on the 14th day, and 0.84 mg/L on the 21st day of cultivation.

In Variant 3, the initial chromium amount was 2.23 mg/L, which decreased to 1.98 mg/L on the 3rd day, 1.38 mg/L on the 7th day, 0.98 mg/L on the 10th day, 0.68 mg/L on the 14th day, and 0.70 mg/L on the 21st day.

In Variant 4, the initial chromium amount was 2.17 mg/L, which was 1.87 mg/L on the 3rd day, 1.42 mg/L on the 7th day, 0.84 mg/L on the 10th day, and 0.62 mg/L on both the 14th and 21st days.

In Variant 5, the initial chromium amount was 2.32 mg/L, which was 1.92 mg/L on the 3rd day, 1.64 mg/L on the 7th day, 1.04 mg/L on the 10th day, and 0.84 mg/L on both the 14th and 21st days of cultivation.

During the study, a consistent decrease in the amount of chromium in the nutrient medium over time was observed. By the 14th–21st days, the chromium concentration approached a certain equilibrium state and was established within an average range of 0.72–0.75 mg/L. Therefore, the graphical data clearly demonstrate the ability of the *Azolla caroliniana* culture to uptake chromium over time during the biological treatment of chromium-contaminated wastewater.

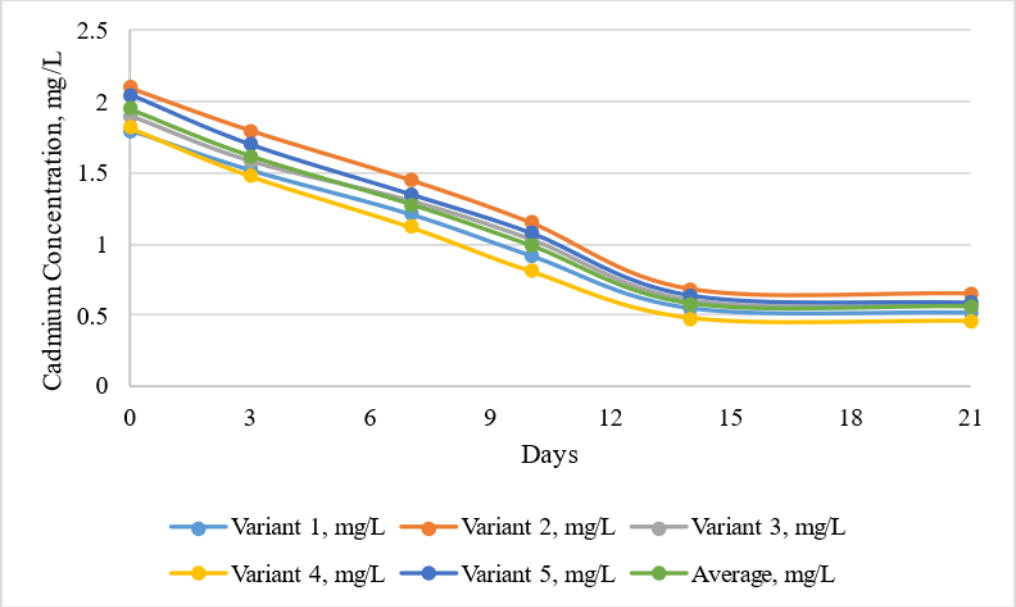


Figure 3. Dynamics of cadmium ion uptake

The conditional experimental results obtained on the dynamics of cadmium (Cd) ion uptake from wastewater by the *Azolla caroliniana* culture were scientifically analyzed as follows.

According to the research results, the initial average concentration of cadmium in the wastewater medium was 1.95 mg/L, and the amount of cadmium in the medium consistently decreased over the days during the cultivation process. The following dynamic changes were recorded across the experimental variants.

In Variant 1, the initial cadmium amount was 1.85 mg/L, which was 1.52 mg/L on the 3rd day, 1.21 mg/L on the 7th day, 0.92 mg/L on the 10th day, 0.55 mg/L on the 14th day, and 0.53 mg/L on the 21st day of cultivation.

In Variant 2, the initial value was 2.10 mg/L, which decreased to 1.78 mg/L on the 3rd day, 1.45 mg/L on the 7th day, 1.15 mg/L on the 10th day, 0.68 mg/L on the 14th day, and 0.65 mg/L on the 21st day.

In Variant 3, the initial cadmium amount was 1.95 mg/L, which was 1.62 mg/L on the 3rd day, 1.28 mg/L on the 7th day, 0.98 mg/L on the 10th day, 0.59 mg/L on the 14th day, and 0.57 mg/L on the 21st day.

In Variant 4, the initial value was 1.80 mg/L, which decreased to 1.48 mg/L on the 3rd day, 1.12 mg/L on the 7th day, 0.81 mg/L on the 10th day, 0.48 mg/L on the 14th day, and 0.46 mg/L on the 21st day. At the same time, the lowest residual cadmium concentration in the medium was recorded in this variant.

In Variant 5, the initial cadmium amount was 2.05 mg/L, which decreased to 1.71 mg/L on the 3rd day, 1.35 mg/L on the 7th day, 1.04 mg/L on the 10th day, 0.62 mg/L on the 14th day, and 0.60 mg/L on the 21st day.

The uptake of cadmium ions proceeded intensively during the first 14 days, and the average concentration in the medium decreased from 1.95 mg/L to 0.58 mg/L. During the period from the 14th to the 21st day, the process was observed to become relatively stabilized and approach an equilibrium state. During this period, the average concentration of cadmium in the medium was 0.56 mg/L.

These results indicate that the *Azolla caroliniana* culture possesses high bioaccumulation properties even

under conditions of a cadmium-contaminated medium. At the same time, it was determined that the optimal period for the treatment process is 14 days and that it is advisable to renew the plant biomass after this period.

CONCLUSION AND RECOMMENDATIONS

The studies conducted on the dynamics of the uptake of heavy metals, particularly chromium and cadmium ions, from wastewater by the *Azolla caroliniana* culture and its bioremediation efficiency showed that the plant has the ability to effectively uptake heavy metals during the first 14 days. The average chromium uptake value reached 1.54 mg/g, while the average concentration of cadmium in the medium decreased from 1.95 mg/L to 0.58 mg/L.

However, from the 14th–16th days of cultivation, 8.9% to 23% necrosis was observed in the leaves of *Azolla caroliniana*. In addition, by the 21st day, cessation of dynamic growth and the chromium uptake value remaining at a maximum level of 1.52 mg/g were determined.

In this regard, in order to achieve high efficiency in biological treatment (bioremediation) technologies for wastewater contaminated with heavy metals, regular monitoring of the condition of *Azolla caroliniana* biomass and its periodic renewal are of important practical significance.

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