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The Role of Ceratophyllum Demersum in Heavy Metal Adsorption: Analysis of Mechanisms, Efficiency, and Environmental Impacts Review

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Abstract

Heavy metal contamination presents a considerable risk to aquatic ecosystems and human health. This research examines the viability of Ceratophyllum demersum (often referred to as hornwort) as a sustainable and economical biosorbent for the extraction of heavy metals from polluted water. The review emphasizes the plant's distinctive adsorption mechanisms, encompassing biosorption and bioaccumulation, and analyses the elements affecting its efficiency, including pH, temperature, and contact duration. A comparative analysis with other aquatic plants, including Eichhornia crassipes and Hydrilla verticillata, reveals the better efficacy of C. demersum in heavy metal adsorption. The review examines the environmental uses of C. demersum in phytoremediation and water treatment systems, highlighting its potential to enhance environmental sustainability. Future research avenues are proposed to enhance its application in extensive implementations.

Keywords: Ceratophyllum demersum, Heavy metal adsorption, Phytoremediation, Biosorption mechanisms

Introduction

Heavy metals Pollution endangers the ecosystem and human health via its accumulation in the food chain. It possesses an atomic density of 4 g/cm³, which is five times that of water [1]. Heavy metals are a significant environmental pollutant that endangers both ecosystems and human health [2]. Heavy elements (lead, cadmium, mercury, copper, zinc, arsenic, selenium) are the most dangerous toxic substances that pollute soil, water and air[3],that must be disposed of by appropriate methods. Numerous remedial strategies have been utilized for decades to tackle this environmental issue. These techniques, encompassing conventional and biological procedures, have exhibited differing levels of effectiveness in the cleanup of hazardous metals[4]. Reverse osmosis, ion exchange, chemical precipitation, and electrolysis are some of the conventional techniques but , There are many disadvantages to these it[5]. One of the more promising methodologies for removing dangerous metals from natural and industrial streams is the bioremoval[6] . Adsorption has proven to be an excellent technique for treating industrial wastewater, offering significant advantages like cost-effectiveness, accessibility, profitability, operational simplicity, and efficiency[7]. The utilization of bio sorption for environmental remediation has emerged as a prominent study domain over the past decade. Owing to substantial economic costs, numerous researchers are concentrating on identifying more affordable materials and cost-effective adsorbents for wastewater treatment applications[8]. Bio-sorption of heavy metals from aqueous solutions is a novel method that has demonstrated significant effectiveness in eliminating pollutants from wastewater[9]. Inexpensive agricultural waste can be transformed into adsorbent materials for the effective removal and recovery of heavy metal ions from wastewater[10]. Increased levels of metals in water bodies are the result of this contamination being made worse by elements like industrial discharges and urban runoff. Studies have shown, for example, that different aquatic plants have different capacity for absorbing heavy metals, which is important to comprehend bioremediation techniques[11]. One such aquatic plant is Ceratophyllum demersum (C.D).

Overview of Ceratophyllum demersum (C.D):

Ceratophyllum demersum which is a popular undesirable plant in quiet streams and ponds. Ceratophyllum demersum ((C.D) also known as raccoon tail or hornwort is a dicotyledonous angiosperm and submerged aquatic plant belonging to Ceratophyllaceae family[8]. This family consists of three species: C. demersum, C. submersum and C. muricatum. C. demersum sometimes branches but with a single branch produced for each node. The plant has spread globally through the aquarium trade because its parts can survive for months in aquatic environments and can grow at depths where other aquatic plants and grasses cannot survive[12]. The plant can grow submersed ,floating, or naturally growing in mud and stagnant , low –movement nutrient –rich and turbid water at a temperature between (15-30)[13]. The plant is prevalent in temperate and tropical regions, frequently located in North America, Europe, and Asia, a map may be incorporated to depict the worldwide distribution of (C.D) (Fig. 1) [8].

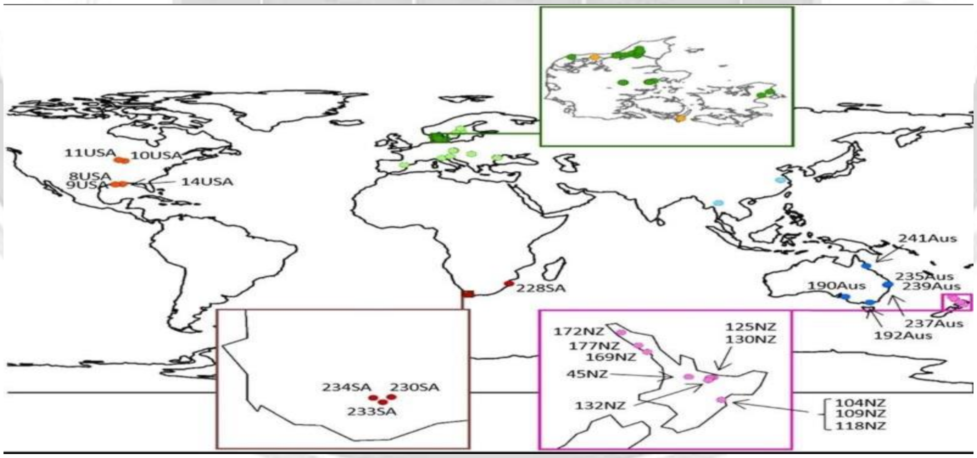

Figure 1. Ceratophyllum demersum (C.D): Europe (light green), Denmark (dark green), Asia (light blue), Australia (dark blue), New Zealand (purple), South Africa (dark red), and the USA (red), as well as for C. submersum.

When comparing the heavy metal adsorption capacities of various aquatic plants, (C.D) emerges as a particularly effective species. Studies reveal that while many aquatic plants exhibit some level of metal uptake, few achieve the high removal efficiencies demonstrated by C. demersum[14]. In recent years, there has been a notable increase in research focus on nano adsorbents[15], the use of green nano adsorbents in place of conventional materials represents a crucial strategy for the reduction of environmental pollutants, with particular relevance to the adsorption of heavy metals from contaminated water and wastewater[16]. The economic viability of employing Ceratophyllum demersum for the remediation of heavy metal-contaminated water warrants examination. The plant is abundantly accessible in various aquatic ecosystems, and its acquisition cost is minimal relative to traditional chemical approaches[17]. Furthermore, the plant may be harvested upon saturation with heavy metals and disposed of securely, rendering it a cost-effective and eco-friendly alternative. The comparative analysis suggests that C. demersum is not only efficient in heavy metal adsorption but also adaptable to varying environmental conditions, reinforcing its potential as a bioremediation tool in contaminated ecosystems[18].

Heavy metals

Heavy metals are metallic ions that exhibit severe toxicity and strong accumulation ability in living organisms and environments[19]. Contaminated food, water, and air are just a few of the ways that humans might be exposed[20]. Chemical characteristics, length of exposure, and body bioaccumulation all affect their health impacts. Anthropogenic and natural resources are the most common reasons of heavy metal pollution[21]. Heavy metal contamination is greatly increased by mining, industry, and agricultural operations these are called Anthropogenic resources[22]. The environment naturally contains heavy metals due to weathering, volcanic eruptions, and soil erosion [23]. Heavy metals such as iron and zinc, are essential to human life, others, such as mercury and lead, are toxic[24]. Heavy metals, including lead, cadmium, mercury, arsenic, and chromium, have been identified as harmful pollutants associated with cardiovascular disease[25]. These metals have been linked to oxidative stress, inflammation, and endothelial dysfunction, which can increase the risk of developing conditions such as hypertension and atherosclerosis[26]. The utilization of agricultural pesticides and fertilizers on agricultural soil has led to an increase in the concentration of cadmium (Cd), zinc (Zn), copper (Cu), and arsenic (As) in soil[27]. The remediation of heavy metals from contaminated soil and water can be effectively achieved through various methods, each with distinct costs and benefits. These techniques, which are crucial for addressing the threats that heavy metal contamination poses to the environment and human health, include physical, chemical, and biological remediation strategies[28].

Adsorption Process

The adsorption process is a prevalent method for eliminating contaminants from water, utilizing the capacity of specific materials (adsorbents) to attract and retain molecules of a chemical (adsorbate) on their surface[29].The wastewater treatment process through adsorption entails the adherence of pollutants from liquids to solid materials, referred to as adsorbents; this method is cost-effective and results in the generation of high-quality water. Furthermore, it utilizes batch experiments to evaluate characteristics including adsorption capacity, kinetics, and processes, thereby ensuring the efficient removal of contaminants [30]. Furthermore, it is a purification method that efficiently eliminates harmful substances, such as chemical pollutants and suspended particles, from residential and industrial wastewater [31]. Numerous research have evidenced the efficacy of several aquatic plants in extracting heavy metals from water, underscoring their promise as sustainable remedies for environmental contamination [32]. The efficacy of adsorption is depend upon variables like the adsorbent's surface area, the characteristics of the pollutant, and operational parameters such as pH, temperature, and contact duration[33]. Common adsorbents comprise activated carbon, zeolites, and metal oxides, characterized by elevated surface areas and active sites for pollutant binding[34]. Activated carbon is particularly efficient in eliminating organic compounds and chlorine owing to its permeable structure and vast surface area [35]. The adsorption process may be classified as either physical (physisorption), characterized by weak van der Waals forces, or chemical (chemisorption), involving the formation of stronger chemical bonds[35]. Recent developments have concentrated on creating economical and sustainable adsorbents, including biochar and nanocomposites, which provide improved adsorption capacities and ecological advantages[15]. The mechanisms of heavy metal adsorption are phytoremediation and biosorption. Phytoremediation is a process wherein aquatic plants, such as Azolla microphylla and Lemna minor, employ photosynthesis to sequester heavy metals, including copper, from wastewater. This process has demonstrated substantial removal rates under optimal conditions, specifically a pH of 4 and a contact time of 30 minutes[36]. Biosorption is an environmentally sustainable alternative to traditional adsorption techniques, employing biological materials such as algae, fungi, Ceratophyllum demersum, and agricultural byproducts as adsorbent[37]. This procedure entails the passive absorption of heavy metals via mechanisms like ion exchange and surface complexation, making it a cost-efficient substitute for traditional treatment methods [32]. The kinetics and equilibrium of the adsorption process are influenced by several key factors, including the choice of isotherm models (e.g., Langmuir, Freundlich), rate constants, adsorption capacity, contact time [38], and statistical parameters such as the coefficient of determination and standard deviation[39].

1. Mechanism of Adsorption

Ceratophyllum demersum is effective in absorbing heavy metals such as cadmium (Cd), lead (Pb), copper (Cu), zinc (Zn), and chromium (Cr) from water bodies. Recent research has demonstrated the effectiveness of both bio sorption and bioaccumulation as mechanisms of heavy metal adsorption in aquatic plants, including Ceratophyllum demersum[21]. The elimination of metals through biosorption and the underlying mechanisms have been previously addressed[9]. Two absorption mechanisms are involved in the bioremoval process involving aquatic plants: biosorption, which is a quick and reversible metal-binding phase, and bioaccumulation, which is a gradual and irreversible ion-sequestration stage[40]. The plant's cell walls contain functional groups like carboxyl, hydroxyl, and amino groups, which help in binding and accumulating these metals[41]. Its floating and submerged nature allows for direct contact with dissolved metals, which enhances uptake efficiency[41]. Adsorption phenomena are mostly investigated by the measurement of adsorption isotherms[33]. The adsorption of heavy metals by Ceratophyllum demersum is a complex process that involves several key mechanisms and factors (table 2).

1.1 Adsorption Theories and Models

1.1.1 Adsorption Isotherms

Table2: Single-component system adsorption models[47]

Types of mechanism	Equations	Terminologies	References
a)Adsorption isotherms i) Langmuir isotherms	$q_e = \frac{q_{\mu ax} b c_a}{1 + b c_a}$	The Langmuir The maximum constants denote the maximal sorption capacity (monolayer capacity) and the adsorption bonding energy.q is the equilibrium metal sorption capacity, and Ca is the equilibrium solute concentration in solution.	[42]
ii) Freundlich isothern	$\mathrm{q_e = k_f\, C_e^{1/n}}$	The sorption capacity is denoted by q, the bio sorption equilibrium constant by kf , and the bio sorption intensity is indicated by n.	[43]
b) Adsorption kinetics i) Pseudo-first order	$\mathrm{\frac{dq_t}{dt} = k_1(q_e - q}$	The sorption capacities at equilibrium and time t are denoted by qe and qt, respectively. k1 is the rate constant of pseudo-second	[44]
ii) Pseudo second order	$\mathrm{\frac{dq_t}{dt} = k(q_e - q_t}$	The sorption capacities at equilibrium and time t are denoted by qe and qt, respectively. The pseudo-second order sorption rate constant is denoted by k.	[42]
hermodynamics Parameters	$\mathrm{k_{\mathbb{C}} = \frac{C_A}{C_e}}$ $\mathit{\Delta C^0} = -R_t \vert_n k_e$ $\mathrm{In\, k_e = \frac{\Delta s}{R} = \frac{-\Delta \dot{H}}{RT}}$	K represents the equilibrium constant, while C denotes the solid phase c. A concentration at equilibrium, C, denotes the equilibrium concentration. T (K) denotes the absolute temperature, while R represents the gas constant. G° represents the Gibbs free energy, with a value of 8.314 J/mol K. H° represents the change in enthalpy, while s denotes the change in entropy.	[45] [46]

Adsorption process defines the equilibrium relationship between the quantity of adsorbate and its concentration in the adjacent phase (gas or liquid) at a constant temperature[48]. This notion is essential for comprehending molecular interactions with surfaces, especially in porous materials, and is vital for applications like water purification, gas storage, and catalysis[49]. The common models utilized are The Langmuir isotherm presupposes monolayer adsorption on a homogeneous surface, while the Freundlich isotherm characterizes adsorption on heterogeneous surfaces with varying adsorption energies [50]. Some Investigations have investigated the utilization of adsorption isotherms in nanotechnology, whereby materials such as graphene and metal-organic frameworks (MOFs) demonstrate distinctive adsorption characteristics attributable to their elevated surface areas and adjustable pore architectures[51]. While the other supplied revised protocols for assessing surface area and pore size distribution by gas physisorption methods[29]. These improvements highlight the significance of adsorption isotherms in theoretical research and industrial applications[52]. To quantitatively characterize the adsorption process, various mathematical models have been devised:

- **Langmuir isotherm**

A common model in surface chemistry and adsorption investigations is the Langmuir isotherm[42], which describes how molecules stick to solid surfaces[43]. It assumes that adsorption occurs at similar surface sites, generating a monolayer without molecular interactions. This model is important for studying gas-solid or liquid-solid adsorption systems, such as water pollutant removal or catalyst activity[47]. The Langmuir equation is:

$$q_e = \frac{q_{m \cdot x} \cdot b c_a}{1 + b c_a} \qquad (1)$$

where qe represents the metal adsorption capacity of the adsorbent at equilibrium, which is significantly influenced by the physical and chemical properties of both the adsorbate and the adsorbent, qm.x is the maximum adsorption capacity, representing the point at which all adsorption sites are occupied [53]. This isotherm effectively represents chemisorption on a series of discrete localized adsorption sites[54]. It is often utilized in environmental engineering to devise systems for the extraction of heavy metals or organic pollutants from wastewater[55].

- **The Freundlich isotherm**

The empirical approach is employed to characterize adsorption on heterogeneous surfaces, where the adsorption energy varies over many sites [48]. In contrast to the Langmuir model, which presumes a uniform surface, the Freundlich model accommodates the variability of adsorption sites by representing the adsorption capacity as a function of the adsorbate concentration elevated to a power[56]. The model is expressed mathematically as:

$$q_e = k_f C_e^{1/n} \qquad (2)$$

Where (qe) denotes the quantity of adsorbate per unit mass of adsorbent, (Ce) represents the equilibrium concentration of the adsorbate in the solution, (Kf) signifies the Freundlich constant associated with adsorption capacity, and (1/n) is the heterogeneity factor reflecting the intensity of adsorption[44].It

is especially advantageous for systems with non-uniform adsorbent surfaces[43], such as natural materials including soils, clays, or activated carbon. It is extensively utilized in environmental research, particularly for the elimination of contaminants from water, owing to its adaptability in characterizing non-ideal adsorption phenomena[51]. Nevertheless, it fails to forecast a maximum adsorption capacity, in contrast to the Langmuir model, rendering it less appropriate for systems where monolayer saturation transpires[49].

1.1.2 Adsorption Kinetics

Adsorption is a prevalent method utilized for environmental remediation, the kinetics are crucial for assessing the efficacy of a specific adsorbent and understanding the fundamental mechanisms involved[57].Also, it denotes the examination of the rate at which adsorbate molecules transfer from the bulk phase (liquid or gas) to the surface of an adsorbent[42]. The kinetics of adsorption are generally examined by models such as the pseudo-first-order and pseudo-second-order models[58]:

- **The pseudo-first-order model** introduced by Lagergren (1898), posits that the adsorption rate is directly proportional regarding the discrepancy between the equilibrium adsorption capacity and the amount adsorbed at any one instant.

$$\frac{dq_{\dot{e}}}{dt} = k_1(q_e - q_1) \qquad (3)$$

Where $q_e$and q_1(mg/g) denote the adsorption capabilities at equilibrium and at time t (min), respectively k_1(min−1) represents the pseudo-first-order rate constant inside the kinetic model[57].

- The **pseudo-second-order** model posits that the rate-limiting step is chemisorption, which entails valence forces or chemical bonding between the adsorbate and the adsorbent[59]. It is articulated as:

$$\frac{dq_t}{dt} = k(q_e\text{-}q_t)^2 \qquad (4)$$

Where (k) denotes the rate constant. This approach is especially useful for systems where chemical interactions prevail, such as the adsorption of heavy metals or organic contaminants onto activated carbon[57]. In addition to these models.

- **The intraparticle diffusion** model is frequently employed to elucidate the transit of adsorbate molecules within the pores of the adsorbent. This model assists in determining whether the rate-limiting step is governed by boundary layer diffusion or intraparticle diffusion[29].

1.1.3 Thermodynamics

Thermodynamic equations are formulated for the adsorption of multicomponent gas mixtures in microporous adsorbents, grounded in the principles of solution thermodynamics [60]. Comprehending the thermodynamic parameters—Gibbs free energy (ΔG°), enthalpy (ΔH°), and entropy (ΔS°)—is essential for clarifying the characteristics and viability of adsorption processes[61].

Gibbs free energy (ΔG°): This metric signifies the spontaneity of the adsorption process. A negative ΔG° number denotes a spontaneous process, while a positive value suggests non-spontaneity[62] .

Enthalpy (ΔH°): Indicates the thermal variation occurring during adsorption. A negative ΔH° indicates an exothermic reaction (releasing heat), whereas a positive ΔH° shows an endothermic reaction (absorbing heat) [63].

Entropy (ΔS°): Indicates the variation in disorder within the system. A positive ΔS° indicates heightened disorder at the solid-liquid interface during adsorption, perhaps resulting from the displacement of water molecules or ions from the adsorbent surface[64].The Van't Hoff equation is frequently employed to determine these parameters, establishing a relationship between the equilibrium constant (K) and temperature (T):

$$\ln k = \frac{-\Delta H^0}{RT} + \frac{\Delta s^0}{R} \qquad (5)$$

R represents the universal gas constant. By graphing ln K vs 1/T, ΔH° and ΔS° can be ascertained from the slope and intercept, respectively. Consequently, ΔG° is computed utilizing:

$$\Delta C^0 = \Delta H^\circ - T\Delta S^\circ \qquad (6)$$

Precise assessment of these thermodynamic characteristics is crucial for comprehending adsorption mechanisms and developing effective adsorbents for pollutant elimination[64].

2. Influencing factors

- **The PH**

The pH significantly influences the adsorption efficacy of Ceratophyllum demersum in the removal of heavy metals from water[65]. Under low pH circumstances (acidic), the plant surface acquires a positive charge due to the protonation of functional groups like carboxyl and hydroxyl[65]. This results in electrostatic repulsion between the positively charged heavy metal cations and the plant surface, hence diminishing adsorption efficiency. Moreover, hydrogen ions (H^+) contend with metal cations for active binding sites, hence diminishing metal absorption. Under low pH circumstances (acidic), the plant surface acquires a positive charge due to the protonation of functional groups like carboxyl and hydroxyl. This results in electrostatic repulsion between the positively charged heavy metal cations and the plant surface, hence diminishing adsorption efficiency. Moreover, hydrogen ions (H^+) contend with metal cations for active binding sites, hence diminishing metal absorption. As the pH rises to a more neutral or slightly alkaline range, the surface of Ceratophyllum demersum acquires a negative charge due to the deprotonation of functional groups[66]. This intensifies the electrostatic interaction between the negatively charged surface and metal cations, significantly improving adsorption capacity. Research indicates that the ideal pH for heavy metal adsorption by Ceratophyllum demersum often falls between a neutral to mildly alkaline spectrum. However, at very high pH values (strongly alkaline conditions), metal hydroxides may precipitate, leading to metal removal via precipitation rather than adsorption. This reduces the efficiency of adsorption and complicates metal removal mechanisms. Therefore, optimizing pH conditions is essential for maximizing the adsorption potential of Ceratophyllum demersum. A precise understanding of surface interactions and metal ion behavior under different pH conditions is crucial for effective application in water treatment.

- **Adsorption capacity**

Numerous biological and environmental factors influence Ceratophyllum demersum's ability to absorb heavy metals, and these factors together determine the plant's adsorption capacity. The nature of the wastewater and the existence of competing ions are important elements that can greatly affect the number of binding sites on the plant's surface. For example, research has shown that treating municipal wastewater can significantly change the water's chemical composition, as evidenced by the decrease in ammonium and chemical oxygen demand (COD), suggesting that cleaner influents can improve adsorption capacity [67]. The adsorption capacities and removal efficiencies of different heavy metals by Ceratophyllum demersum are summarized in Table 1.

Table1-List of Results Removal heavy metals by Ceratophyllum Demersum

Metal	Adsorption Capacity q_{max}(mg/g)	Temperature ©	Optimum PH	Removal Efficiency	References
Pb	44.8	20-25	5-6	90%	[59]
Cr	41.26	--------	4.0	96.8%	[68]
Zn	13.98	20-25	5.0-6.0	78%	[59]
Cu	6.18	20-25	5.0-6.0	60%	[69],[59]
As	----------	4	6.0	60%	[70]
Ni	---------	18-22	6.5-7	79.2%	[71]
Cd	9.18	20-25	3-8	37-90%	[72]

The table shows how well Ceratophyllum demersum (hornwort) adsorbs lead (Pb), chromium (Cr), zinc (Zn), copper (Cu), arsenic (As), nickel (Ni), and cadmium (Cd). The data includes each metal's q_max, ideal temperature, pH, and removal efficiency. A complete table explanation follows: In terms of lead adsorption, Ceratophyllum demersum has a maximum capacity (q_max) of 44.8 mg/g[59]. The plant can absorb 44.8 mg of lead per gramme under optimal conditions. Lead adsorption works best at 20-25°C, which supports plant metabolism. Acidic pH 5–6 is suitable for lead adsorption. Lead ions (Pb^{2+}) are more soluble and easily bind to plant surface functional groups like carboxyl and hydroxyl groups in this pH range. Ceratophyllum demersum removes lead from polluted water with 90% efficiency[73]. Chrome (Cr) adsorption is superior in the plant, with a q_max of 41.26 mg/g. Chromium adsorption prefers 4.0, which is acidic than lead. Under acidic circumstances, chromium ions (Cr^{3+} or Cr^{6+}) are more stable and adhere better to plant surfaces. Ceratophyllum demersum is one of the most successful plants for chromium extraction, with 96.8% removal efficiency[68]. The temperature parameters for chromium adsorption are unknown, however moderate temperatures, like those for lead, may help[68]. Zinc's peak adsorption capacity is 13.98 mg/g, lower than lead and chromium but still significant. Zinc adsorption is best around 20-25°C, like lead, its adsorption is most effective at a pH between 5.0 and 6.0, where Zn ions are more soluble and attach well to plant surfaces[59]. Ceratophyllum demersum removes zinc from water at 78% efficiency. With q_max of 6.18 mg/g, copper (Cu) has limited adsorption capability, its adsorption is best around 20-25°C and pH 5.0-6.0, similar to lead and zinc[59]. Copper ions (Cu^{2+}) are more likely to cling to plant surfaces in this pH range. Copper has a 60% elimination efficiency, lower than lead and chromium, so Ceratophyllum demersum removes copper from polluted water less effectively[69] .Arsenic (As) removal is 60% effective, its adsorption works best at 6.0, a slightly acidic pH [70]. In this pH range, arsenic ions (As^{3+} or As^{5+}) are more likely to stick to plant surfaces. Ceratophyllum demersum may absorb arsenic from water, albeit less efficiently than lead or chromium [70] . Ni has a high elimination effectiveness of 79.2%, its ions (Ni^{2+}) are more stable and are more likely to bind to plant surfaces at a pH between 6.5 and 7.0. Nickel adsorption is best around 18–22°C, slightly lower than other metals. This suggests that Ceratophyllum demersum can remove nickel, especially at moderately neutral pH .Cadmium's peak adsorption capacity is 9.18 mg/g, which is moderate for other metals. Ceratophyllum demersum can absorb cadmium in the pH range of 3 to 8, proving its versatility [71]. Environmental factors like pH, temperature, and initial metal concentration affect cadmium removal efficiency, which ranges from 37% to 90%. The plant can remove cadmium in good conditions but may function poorly in inferior settings[71].The table shows that *Ceratophyllum demersum* uptakes heavy metals, especially lead and chromium, efficiently due to their affinity for the plant's functional groups. Zinc and nickel absorb moderately, demonstrating the plant is functional but less effective than lead and chromium. Copper and arsenic uptake is lower in Ceratophyllum demersum, suggesting it is less effective at removing these metals. Cadmium's efficiency ranges from 37% to 90%, depending on environmental factors, therefore the plant may eliminate cadmium under ideal conditions but not under poor ones. Plant efficiency varied by metal, with lead and chromium removing most efficiently.

- **Temperature:**

Depending on the type of adsorbent being utilized, temperature can have an impact on its adsorption capability[74]. The impact of temperature on adsorption efficiency is a critical factor influencing the capacity of Ceratophyllum demersum to remove heavy metals from aquatic environments[75]. As temperatures increase, kinetic energy within the system rises, often enhancing the diffusion rates of contaminant molecules toward the plants surfaces[58]. This phenomenon typically results in improved adsorption efficiencies for various trace elements, such as iron and lead, which have shown significant removal rates in studies involving C. demersum[54]. Specifically, the removal efficiency of heavy metals can be elevated under optimal temperature conditions, facilitating higher interaction rates between the contaminants and the plant tissue[67]. Conversely, extreme temperatures may lead to reduced metabolic activity in C. demersum, which could negatively impact its absorption capabilities[54]. Thus, understanding the temperature dependence of adsorption processes is vital for optimizing the application of C. demersum in bioremediation strategies for heavy metal-laden wastewater[76] .

- **The nature of the bio sorbent**

The characteristics of the bio sorbent, the availability of binding sites on its surface, its growth rate, any physical or chemical alterations it has experienced, its size, and the number of bio sorbents are critical factors influencing the bio sorption of heavy metal ions[77],[78]. The dimensions of the bio sorbent are a crucial determinant affecting the efficacy of bio sorption[4]. Smaller cells have enhanced efficacy with a reduced equilibrium time owing to their increased surface area. The age of the civilisation. Also impacts the removal efficiency of the bio sorbent. The cell mass harvested after a 24-hour growth phase is denser than that obtained during a 48-hour culture [79]. The bio sorption is affected by the composition of the cell wall and extracellular polymeric substances, growth circumstances of the biomass, nutritional supplements, and the biomass's age[37].

- **Contact time**

The duration of direct contact between the two substances in question is defined as the contact time[65]. Achieving an equilibrium among the material that absorbs and the solute in the solution is essential. for full adsorption Thus, a particular time is required for the interactions of the equilibrium in order to ensure that the adsorption is achieved[74]. Contact time refers to the duration required for equilibrium to be reached. The influence of contact time on adsorption has been examined by numerous authors. Their findings demonstrated that the rate at which metal ions are adsorbed increases with time, attaining an optimum value beyond which no more metal ion removal transpires [80],[81],[74]. The metal's bio sorption rate remains largely constant over time once equilibrium is attained [82],[83]. Subsequently, the bio sorption rate diminishes and attains an equilibrium state as all biomass binding sites get saturated with metal ions [9]. The uptake of heavy metals by the adsorbents is dependent on a number of factors, including the type of biomass, the concentration of metal ions, the duration of contact, and the dominant environmental factors. The reaction media may be modified to achieve the optimal conditions for maximum sorption, including the pH, temperature, contact time, and agitation.

- **The initial concentration of metal ions**

A number of variables, including the availability of particular surface functional groups and their capacity to bind metal ions, can change the initial concentration of metal ions and, consequently the efficacy of metal removal[47]. An essential driving factor for overcoming the metal's barrier to mass transfer between the aqueous and solid phases can be found in the initial concentration of the solution[84]. As demonstrated by the following conclusions drawn from the papers that were supplied: It was examined how well rice straw could adsorb metal ions such as Mn2+, Cd2+, Zn2+, Pb2+, and Fe3+. The findings demonstrated that, for Mn2+, Cd2+, and Pb2+, removal percentages declined as the starting metal ion concentration increased up to a specific point, at which point the removal efficiency declined, but for Zn2+, raising the starting concentration to 40 mg/L resulted in a higher clearance percentage, which subsequently dropped. The removal efficiency for Fe3+ dropped until it reached 60 mg/L, after which it rose[85].

3. Comparative Efficiency:

In comparison to other aquatic plants, Ceratophyllum demersum demonstrates a greater tolerance to metal stress and a higher capacity for metal accumulation. Its lack of roots and free-floating nature enables it to absorb metals efficiently across its entire surface. It is frequently compared with plants such as Eichhornia crassipes (water hyacinth) and Hydrilla verticillata. However, hornwort demonstrates superior performance in environments where rooted plants may encounter difficulties due to its capacity to adapt to diverse water condition. Comparisons can be formed between Ceratophyllum demersum and other aquatic plants, like

Eichhornia crassipes (water hyacinth) and Hydrilla verticillata (hydrilla), regarding their efficacy in heavy metal adsorption for instance table(2):

Table (2): Evaluation of Heavy Metal Adsorption Capacities among Various Aquatic Plants

Metal	Ceratophyllum demersum	Eichhornia crassipes	Hydrilla verticillata	Reference
Lead(Pb)	44.8 mg/g	35.2 mg/g	28.5 mg/g	[73],[86]
Chromium(Cr)	41.26 mg/g	38.5 mg/g	30.1 mg/g	[68],[87]
Zinc(Zn)	13.98 mg/g	10.5 mg/g	8.7 mg/g	[59],[88]
Copper(Cu)	6.18 mg/g	5.2 mg/g	4.8 mg/g	[69],[8]

The table contrasts the heavy metal adsorption efficacy of Ceratophyllum demersum with two additional aquatic plants, Eichhornia crassipes (water hyacinth) and Hydrilla verticillata (hydrilla), for metals including lead (Pb), chromium (Cr), zinc (Zn), and copper (Cu). Ceratophyllum demersum exhibits the greatest adsorption capacity for lead (44.8 mg/g) and chromium (41.26 mg/g), surpassing Eichhornia crassipes (35.2 mg/g for Pb and 38.5 mg/g for Cr) and Hydrilla verticillata (28.5 mg/g for Pb and 30.1 mg/g for Cr). The exceptional performance is due to the presence of active functional groups, including carboxyl and hydroxyl groups, on the surface of Ceratophyllum demersum, which effectively bind to metal ions. Ceratophyllum demersum exhibits a superior adsorption capacity for zinc (13.98 mg/g) relative to Eichhornia crassipes (10.5 mg/g) and Hydrilla verticillata (8.7 mg/g), however the efficiency is inferior to that for lead and chromium. Ceratophyllum demersum demonstrates a superior adsorption ability for copper (6.18 mg/g) compared to the other two plants, Eichhornia crassipes (5.2 mg/g) and Hydrilla verticillata (4.8 mg/g). The variations in adsorption efficiency among the plants can be ascribed to factors including the availability of binding sites, the chemical composition of the plant surfaces, and environmental circumstances such as pH and temperature. Ceratophyllum demersum is the most efficient plant for heavy metal adsorption, especially for lead and chromium, owing to its distinctive surface characteristics and tolerance to many environmental conditions.

4. Applications in phytoremediation

Using plants to treatment contaminated soil and water has become a popular and economic substitute for conventional environmental remediation techniques[89]. Phytoextraction, rhizofiltration, stabilization, volatilization, and degradation are among the various types of water phytoremediation[90]. Wastewater has been treated using phytoremediation, which has also been used to eliminate hydrocarbons and heavy metals, clean up stubborn pollutants, and phytoremediation radionuclides[89]. It has been suggested that an electric power device could be used in a wastewater treatment plant to create electricity and bubbles to help with aeration and recycle the energy produced[14]. The plant employed in the phytoremediation process needs to be strong and have a significant capacity to absorb and accumulate metals[5]. The ability of Ceratophyllum demersum to grow rapidly and accumulate heavy metals makes it a valuable component in constructed wetlands, aquaculture, and water treatment systems[75]. Once saturated with heavy metals, the biomass can be harvested and safely disposed of, effectively removing contaminants from the ecosystem[91]. The economic feasibility of employing C. demersum, paired with its ecological advantages, makes it a valuable asset in environmental management strategies aimed at restoring and maintaining water quality [92].

5. Thoughts on the role of aquatic plants in ecosystem health

The intricate interplay between aquatic plants and ecosystem health cannot be overstated, particularly in the context of heavy metal adsorption. Aquatic species, such as "Ceratophyllum demersum," perform crucial functions that enhance water quality and habitat stability. They not only serve as bio indicators of environmental changes but also provide structural support for diverse aquatic organisms. Through the process of phytoremediation, these plants absorb, accumulate, and sometimes detoxify heavy metals, thereby mitigating pollution and its harmful effects on aquatic life. Additionally, the oxygen produced by these plants during photosynthesis contributes to improved water conditions, fostering a balanced ecosystem. However, the over-reliance on a singular species can lead to ecological imbalances; thus, a holistic approach that incorporates a variety of aquatic plants is essential for maintaining ecosystem resilience. Moving forward, continued research on these plants’ unique properties can further elucidate their indispensable role in sustaining healthy aquatic environments.

Conclusion

The significant potential of "Ceratophyllum demersum" as an inexpensive and natural way to reduce heavy metal pollution in aquatic environments is highlighted by this study. It is a potential tool for water remediation because of its high adsorption effectiveness, versatility in a variety of circumstances, and environmentally friendly nature. To improve its usefulness in environmental management, future studies should concentrate on improving adsorption conditions, investigating metal recovery techniques, and contrasting its efficacy with that of other aquatic plants. In the end, "C. demersum" provides a sustainable method of lowering heavy metal pollution, enhancing water quality and promoting healthier ecosystems.

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دور نبات سيراتوفلوم ديمرسوم في امتصاص المعادن الثقيلة: تحليل الآليات والكفاءة والتأثيرات البيئية

مراجعة

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الخلاصة:

يُشكل تلوث المعادن الثقيلة خطرًا كبيرًا على النظم البيئية المائية وصحة الإنسان. يدرس هذا البحث جدوى نبات Ceratophyllum demersum (يُشار إليه غالبًا باسم hornwort) كممتز حيوي مستدام واقتصادي لاستخراج المعادن الثقيلة من المياه الملوثة. يُركز البحث على آليات الامتصاص المميزة لهذا النبات، والتي تشمل الامتصاص الحيوي والتراكم الحيوي، ويُحلل العناصر التي تؤثر على كفاءته، بما في ذلك الرقم الهيدروجيني (pH) ودرجة الحرارة ومدة التلامس. يكشف تحليل مقارن مع نباتات مائية أخرى، بما في ذلك Eichhornia crassipes وHydrilla verticillata، عن فعالية أفضل لنبات C. demersum في امتصاص المعادن الثقيلة. يدرس البحث الاستخدامات البيئية لنبات C. demersum في أنظمة المعالجة النباتية ومعالجة المياه، مُبرزًا قدرته على تعزيز الاستدامة البيئية. ويُقترح بحث مستقبلي لتعزيز تطبيقه على نطاق واسع.

الكلمات الدالة: نبات الشمبلان، امتزاز المعادن الثقيلة، المعالجة النباتية، تقنيات الامتزاز.