IJNRD.ORG ISSN : 2456-4184
INTERNATIONAL JOURNAL OF NOVEL RESEARCH AND DEVELOPMENT (IJNRD) | IJNRD.ORG
An International Open Access, Peer-reviewed, Refereed Journal

BIOABSORPTION, BIOCONCENTRATION, METAL ENRICHMENT AND METAL TRANSFER FACTORS OF TOXIC METALS IN *ARUNDO DONAX* L.

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Abstract : *Arundo donax* L., commonly known as giant reed, is a tall perennial grass belonging to the reed family. It is referred to by various names, including giant cane and elephant grass. In this study, *Arundo donax* macrophytes were acclimatized in synthetic wastewater containing appropriate concentrations of toxic metals such as As, Cd, Cr, Co, Cu, Fe, Mn, Ni, Pb, Sr, and Zn. The experiments were conducted in rectangular test chambers filled with a substrate of washed sand, gravel, and crushed stones, allowing for controlled hydroponic conditions. The research aimed to evaluate the plant's capacity for metal accumulation by examining the bioaccumulation factor (BAF), bioconcentration factor (BCF), metal enrichment factor (MEF), and metal transfer factor (MTF). The findings indicate that *Arundo donax* L. macrophytes play a significant role in the uptake of heavy metals from contaminated growth media into their roots and various plant structures. The highest concentration of iron (Fe) recorded was 4245 µg/g in the roots, 1705 µg/g in the shoots, and 943 µg/g in the aerial parts. In contrast, *Arundo donax* exhibited low concentrations of strontium (Sr) and arsenic (As), with Sr levels at 239 µg/g in the roots, and As concentrations measuring 76 µg/g in the shoots and 53 µg/g in the aerial parts. Evaluations of several factors, including Bioaccumulation Factor (BAF), Bioconcentration Factor (BCF), Metal Extraction Factor (MEF), and Translocation Factor (MTF) associated with *Arundo donax*, demonstrate that the values for As, Cr, Co, Cu, Fe, Mn, Ni, Pb, Sr, and Zn follow the order BCF > MEF > BAF > MTF. However, for cadmium (Cd), the sequence is BCF > MEF > MTF > BAF. This study concludes that *Arundo donax* is a highly effective macrophyte for the phytoremediation of contaminated wastewater, particularly in the removal of heavy metals.

Key words: *Arundo donax* L., macrophytes, phytoremediation, heavy metals, bioaccumulation factor, bioabsorption factor.

INTRODUCTION

The discharge of millions of liters of untreated domestic wastewater results in the depletion of vital nutrients. This practice worsens soil and water pollution, highlighting the urgent need for efficient treatment methods, which are often both energy-consuming and costly. Urban sewage encompasses wastewater produced from residential, commercial, and market activities, in addition to surface runoff and stormwater. The process of biologically eliminating contaminants from polluted environments is termed bioremediation. When plants are employed to extract metals or other pollutants from soil or water, this specific approach is known as 'phytoremediation.'

Wastewater from diverse sources, including industrial effluents, commercial discharges, and municipal sewage, introduces a variety of pollutants into aquatic ecosystems. Both organic and inorganic pollutants among these present significant threats to aquatic organisms and human health, as they can accumulate in the food chain. Elevated concentrations of trace metals in plant tissues can have detrimental toxic effects on animals, especially when ingested. For instance, zinc and copper are trace metals essential in small quantities for healthy growth. While they are crucial for the development of plants and the nutrition of animals and humans, excessive levels can lead to phytotoxicity and zootoxicity (Osundiya et al., 2014).

Environmental pollution, particularly from metallic substances, has escalated due to swift industrial development and urbanization, profoundly impacting aquatic ecosystems. Recent studies (Dhir, 2013; Altnsacl et al., 2014) reveal that metal contamination in water bodies is a significant contributor to ecological degradation. These metals pose risks to human health due to their persistence in the environment and their tendency to bioaccumulate as they move up the food chain (Ali et al., 2019; Dalu and Tavengwa, 2022). Macrophytes, which are aquatic plants that can be found in emergent, submerged, or free-floating forms, flourish in or around aquatic habitats (Dhir, 2013; Piedade et al., 2022). They are crucial in transferring pollutants from sediments to higher trophic levels (Demarco et al., 2022; Piedade et al., 2022). Additionally, macrophytes are vital for providing nourishment, creating microhabitats for diverse organisms, promoting primary production, and facilitating nutrient cycling within aquatic ecosystems (Piedade et al., 2022; Brito et al., 2021). These plants have the ability to accumulate metals in aquatic environments and can act as indicators for examining ecological processes such as nutrient and metal cycling (Xin et al., 2020). Numerous investigations (Venkatewarlu et al., 2020; Queiroz et al., 2020; Dean et al., 2022) have confirmed that macrophytes can absorb metals. Common metallic pollutants found in aquatic ecosystems include manganese (Mn), iron (Fe), copper (Cu), zinc (Zn), and cadmium (Cd), which can reach toxic levels through biomagnification in the food chain, raising significant concerns. As a result, macrophytes can take up these metals and store them in various parts, such as roots, stems, and leaves, eventually releasing them back into the aquatic environment during their decay and decomposition (Anand et al., 2019; Topaldemir et al., 2023).

Different species of macrophytes respond uniquely to varying metal concentrations, which significantly affects their ability to absorb these metals (Prajapati et al., 2017). The application of living organisms for metal extraction has attracted substantial public interest, resulting in increased funding for research and development in this field (Prajapati et al., 2017; Kapahi and Sachdeva, 2019; Netshiongolwe, 2020). As a result, numerous studies have promoted phytoremediation as an environmentally friendly and cost-effective method for removing pollutants from aquatic ecosystems (Haq et al., 2019; Khan et al., 2023). Although research on phytoremediation in aquatic environments is ongoing, several studies have yielded encouraging findings, identifying various aquatic macrophytes, such as duckweed (Ekperusi et al., 2019; Liu et al., 2021) and water hyacinth (Rizania et al., 2015; Ting et al., 2018), as effective agents for metal removal from water and sediments. Current research by some scientists is concentrating on leveraging these plants to remediate specific contaminants, including heavy metals, nutrients, and organic compounds (Prajapati et al., 2017; Yan et al., 2020; Shen et al., 2022; Demarco et al., 2023).

To understand the mechanisms of phytoremediation in aquatic ecosystems, it is crucial to conduct research that assesses the different ways aquatic macrophytes remove pollutants from water. This research should examine the roles of roots, stems, leaves, and microorganisms in the phytoremediation process (Shen et al., 2022; Demarco et al., 2023). Such investigations will aid in developing innovative and improved phytoremediation strategies. As noted by Rai (2009) and Sinclair et al. (2023), biological approaches for metal removal in aquatic environments are generally more economical than conventional methods. Macrophytes such as *Arundo donax* have been identified as effective phytoremediation agents due to their ability to absorb and accumulate toxic metals in various plant tissues. Therefore, this study intends to explore the absorption and enrichment capabilities associated with metal uptake, transfer, and accumulation in Arundo donax macrophytes for the treatment of metal-contaminated wastewater.

MATERIALS AND METHODS:

A. Overview of the Collection of *Arundo donax* Macrophytes:

Field excursions were undertaken to a variety of natural and artificial aquatic environments, including both stagnant and flowing water bodies, as well as reservoirs located in the Chhatrapati Sambhajinagar district of the Marathwada region. During these excursions, macrophytes were meticulously observed, sampled, and collected by hand, ensuring that the plants were not physically damaged. The collection method involved either uprooting or sampling the plants using established scientific techniques, followed by rinsing them with water to remove any excess soil and debris, and then gently wrapping them in paper for transportation.

Upon arrival at the laboratory, the samples were thoroughly washed with running tap water while following safety protocols, air-dried, and identified using various literature references. This identification process emphasized qualitative floristic data, focusing on species and community characteristics rather than merely the physical structures and appearances of the *Arundo donax* species present in the Marathwada region. Photographs and samples were subsequently sent to botanical research specialists for verification and validation of the identified information, ensuring precision and providing a trustworthy second opinion prior to drawing final conclusions. The *Arundo donax* macrophytes, which are abundant in four districts of Marathwada, were collected for further investigation into their metal absorption and enrichment capabilities.

B. Selected Macrophytes for Study:

The species under investigation is a type of grass from the Poaceae family, recognized for its diverse applications, including traditional and ethnomedicinal uses, bioenergy production, and socio-economic significance. This plant is employed in conventional medicine to address a variety of ailments, including skin disorders, gastrointestinal issues, skeletal conditions, menstrual irregularities, as well as respiratory and urinary diseases. This review consolidates the fragmented information regarding the socio-economic relevance, ethnomedicinal applications, phytochemical properties, and pharmacological characteristics of this species. The current study focuses on the absorption and enrichment factors of toxic metals associated with this emergent plant.

C. Experimental Studies on Phytoremediation Potential for Heavy Metals:

Healthy specimens of *Arundo donax* were collected from the research area, which encompasses Chhatrapati Sambhajinagar and several sites in Naldurga and Dharashiv, located in the Marathwada region. The samples were gathered in optimal green condition and stored in appropriately sized transparent polyethylene bags. A sufficient number of specimens were collected to ensure that each sample included at least ten healthy plants. These specimens were replanted within four to five hours of collection to promote acclimatization in synthetic wastewater containing metals, within rectangular test chambers filled with a substrate of washed sand, gravel, and crushed stones. Each test chamber measured 1 meter by 1 meter, with a depth of 10 cm for the mixed test bath, allowing for a 2 cm freeboard. These hydroponic experiments were conducted in a controlled environment, utilizing *Arundo donax* in specific metal-rich concentrations to evaluate their capacity for metal accumulation.

D. Metal Accumulation Potential Studies:

In this study, the *Arundo donax* macrophytes were refined by eliminating any infected or unhealthy specimens. The healthy plants were then relocated to a laboratory-scale test bath, which consisted of small plastic tanks designed to assess the adaptability of the macrophytes to the new local conditions. The selected healthy macrophytes were subjected to the local climatic environment for a sufficient duration to ensure they adapted and achieved full growth in a synthetic wastewater test bath containing various metals. The acclimatization period specified in this study was one month. Growth continued for an additional month in a metal-mixed synthetic wastewater test bath, utilizing stock solutions with concentrations of 100 ppm. The bath solution was freshly prepared to contaminate tap water, allowing for the periodic creation of the synthetic wastewater test bath, alongside a control set without synthetic wastewater. Metal salts such as $Na_3AsO_4·12H_2O$, $CuSO_4·8H_2O$, PbO, $FeSO_4·7H_2O$, $CdSO_4·8H_2O$, $NH_4SO_4·NiSO_4·6H_2O$, $Co(NO_3)_2·6H_2O$, $ZnSO_4·7H_2O$, $Sr(OH)_2$, and $MnCl_2·4H_2O$ were utilized according to established standard procedures (AOAC, 1975; APHA, 1980; Echem, 2014; Smith, 1983). Following the designated growth period, the *Arundo donax* macrophytes were harvested and analyzed to determine their capacity for metal accumulation, with adjustments made to account for the control samples using normal water. This evaluation aimed to assess their potential and suitability for application in phytoremediation processes. The comprehensive methodology utilized to assess the heavy metal absorption capacity is detailed below:

Initially, the collected plant materials were rinsed with tap water prior to being sent for laboratory analysis. They received an additional wash with gently flowing tap water, followed by a rinse with double distilled water to remove any residual dirt and contaminants. The samples of *Arundo donax* macrophytes were then air-dried and sectioned using stainless steel scissors to isolate the shoots, roots, and aerial components.

Each of these isolated parts was dried in an oven at 60 °C until a stable weight was reached, after which they were ground using a pestle and mortar to form a uniform mixture, which was then stored for subsequent analysis. To determine the metal content, 500 mg of each plant material was digested with H2O2 and H2SO4. The resulting digested aliquot was analyzed for various heavy metals using appropriate methodologies. The heavy metals from the prepared aliquot were examined through Atomic Absorption Spectroscopy (AAS) and Gas Chromatography (GC) in other laboratories, following sample and metal-specific protocols, or through suitable methods cited in reputable literature or research publications, depending on the availability of necessary analytical facilities.

The analytical methods utilized included a range of techniques: Cobalt was analyzed using the cobaltous pyridine method as described by Nicolaysen (1941), Iron (Fe) was measured through the Dichromate method, and Zinc (Zn) was assessed via the EDTA Complexometry-Back Titration method (Tazul and Ahemad, 2013). Manganese (Mn) was evaluated using Volhard's method, while Copper (Cu) was determined through Sodium Thiosulphate titration, with further confirmation provided by Spectrophotometric analysis (Ahmed and Zannat, 2012). Lead (Pb) was quantified using the EDTA Complexometric method, and Manganese (Mn) was also analyzed by the Periodate Oxidation Method. Chromium was assessed through the Diphenylcarbazide Spectrophotometric method (IBM, 2012), and Cadmium (Cd) was analyzed using a spectrophotometric technique (Ahamed and Chowdhury, 2004). Additionally, Chromium (Cr) underwent further evaluation via the Diphenylcarbazide Method (Yarbro, 1976), while Cobalt (Co) was analyzed through a colorimetric approach (Hobart, 1920).

A series of samples were processed and digested using the Ultra Microwave Digestion Extraction System. These samples were then analyzed for metal content, including As, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, Sr, and Zn, in a separate laboratory employing the Shimadzu Atomic Absorption Spectrometer 6300 model and the Agilent 725 ICP-OES instrument for confirmation as necessary. The majority of results were corroborated through random cross-checks against established standard methods to ensure analytical accuracy and simplicity, as referenced in numerous studies (Bendix and Grabenstetter, 1943; Kimura and Murakani, 1951; Sandall, 1965; Hackley et al., 1968; Loftberg, 1969; Rubeska, 1969; Baker et al., 1971; James and MacMohan, 1971; Song et al., 1976; Sarma et al., 2005; Soomro and Menon, 2009; Ahemad and Roy, 1969; Soomro and Shar, 2014; Wei, 2014).

E. Chemicals and Reagents

All chemicals, reagents, and solvents used in this study were of analytical reagent grade or exhibited the highest purity levels, and they were freshly prepared prior to use. Doubly distilled water was consistently utilized throughout the procedures. The glassware underwent thorough cleaning by soaking in acidified solutions of potassium permanganate (KMnO4) or potassium dichromate (K2Cr2O7), followed by treatment with concentrated nitric acid (HNO3) and multiple rinses with doubly distilled water. Calibration curves, which served as standard references for solutions with known concentrations of the respective metals, were created. These curves were then employed to determine the concentrations of substances in unknown samples. The calibration curves for heavy metals were specifically used in analyzing the concentrations within the test samples.

F. Evaluation of Factors Influencing Heavy Metal Mobility Potential:

The ability of *Arundo donax* macrophytes to promote the transfer of heavy metals from contaminated growth media into their roots, as well as their capacity to accumulate these metals in different parts of the plant, was evaluated. This assessment included the translocation of metals from the roots to the harvestable aerial sections and the potential for metal enrichment. The evaluation utilized several metrics, including the bio-concentration factor (BCF), bioaccumulation factor (BAF), metal translocation factor (MTF), and metal enrichment factor (MEF). These indicators were used to assess the feasibility of employing *Arundo donax* macrophytes for phytoremediation, providing valuable insights into their potential for remediating metal-contaminated environments.

i. Bioaccumulation Factor (BAF):

The bioaccumulation factor (BAF) measures the extent to which a chemical, particularly a heavy metal, accumulates in an organism or biological system. For heavy metals, the BAF is expressed as the ratio of the concentration of the heavy metal found in the organism to its concentration in the surrounding environment.

The Bioaccumulation Factor (BAF) was determined using the following formula:
BAF = [Concentration of heavy metal in aerial parts] / [Concentration of heavy metal in the source]
For specific metal, it can be expressed as;

$$BAF_{Metal} = \frac{[\text{Metal content in aerial parts}]}{}$$

[Metal Concentration in Source]

$= C_{AP}/C_{WW}$

Where BAF_{Metal} stands for bioaccumulation factor for a specified metal, C_{AP} represents specific Metal Concentration in aerial parts expressed in mg/kg and C_{WW} represents Metal Concentration in growth environment-source like wastewater expressed in mg/kg.

ii. Bioconcentration Factor (BCF):

The bioconcentration factor (BCF) measures the extent to which a chemical, such as heavy metals, accumulates in an organism or biological system from its surrounding environment. This factor reflects the capacity of plants to uptake metals from the soil (Kamari et al., 2014). The BCF is calculated using the following formula:

BCF = [Concentration of heavy metal in the organism] / [Concentration of heavy metal in water]

The BCF for macrophytes was assessed using the equation established by Demina et al. (2009).

$$\text{B.C.F} = \frac{\text{Conc. of element in plant}}{\text{Conc. of element in water}}$$

For a specific metal, the bio-concentration of a specified metal is calculated using the following equation;

$$BCF_{\text{Metal}} = \frac{[\text{Metal Concentration in root}]}{[\text{Metal Concentration in Source}]}$$

$= C_R/C_{WW}$

Where BCF_{Metal} stands for bio-concentration factor for a specified metal, C_R represents specified Metal Concentration in root expressed in mg/kg and C_{WW} represents Metal Concentration in growth environment-source like wastewater expressed in mg/kg.

iii. Metal Enrichment Factors (MEF)

Metal Enrichment Factors (MEF) were employed to assess the degree of metal contamination in sediment, adhering to the methodology outlined by Buat-Menard and Chesselet (1979). A common approach for estimating anthropogenic impact involves the calculation of a normalized enrichment factor (EF), which is based on metal concentrations found in uncontaminated background levels, as indicated by Salomons and Forstner (1984), Dickinson et al. (1996), and Hornung et al. (1989). The purpose of calculating the EF is to reduce the variability in metal concentrations that may result from differences in source ratios, thereby serving as an effective analytical tool. This technique normalizes the observed concentrations of heavy metals against a reference metal, such as iron (Fe) or aluminum (Al), as detailed by Ravichandran et al. (1995).

$$MEF_{\text{Metal}} = \frac{[\text{Metal content in only shoot}]}{[\text{Metal Concentration in Source}]}$$

$= C_{OS}/C_{WW}$

Where MEF_{Metal} stands for specific metal enrichment factor, C_{OS} represents specified Metal content in only shoot expressed in mg/kg and C_{ww} represents Metal Concentration in growth environment-sources like wastewater expressed in mg/kg.

iv. Metal Translocation Factor (MTF):

The translocation factor indicates the proportion of metal concentration present in the shoot relative to that in the root. An MTF value exceeding 1 demonstrates the plant's ability to efficiently move metals from the root system to the shoot (Rezvani and Zaefarian, 2011). The metal transfer factor serves as a metric for assessing the mobility of metals from their origin to macrophytes. The MTF for particular metals can differ considerably depending on the species of macrophytes and the surrounding environmental conditions. Significant factors that affect MTF include the physical and chemical characteristics of the source, the behavior of trace metals in both the source and the macrophytes, as well as environmental fluctuations. The transfer factor from soil to plants is calculated by determining the ratio of metal concentration in the plants to that in the source (Kumar et al., 2015; Akande and Ajayi, 2017; Ogoko, 2015).

$$MTF_{\text{Metal}} = \frac{[\text{Metal Content in only shoot}]}{[\text{Metal Concentration in root}]}$$

$$= C_{OS}/C_R$$

Where MTF_{Metal} stands for specific metal translocation factor, C_s represents_Metal content in aerial parts expressed in mg/kg and C_r represents Metal Concentration in root expressed in mg/kg. It is also called as shoot-root quotient and may be denoted as MTF in general.

RESULTS AND DISCUSSION

Bioconcentration is the process by which organisms absorb and retain toxic substances, including metals, from their environment through respiration. This environment may consist of water in aquatic systems or air in terrestrial systems. Such accumulation can lead to biomagnification, where the concentration of these toxic chemicals increases as they ascend the food chain, resulting in higher levels in predators than would normally be expected. This phenomenon disrupts the balance between the organism and its environment. In essence, bioconcentration indicates the increasing levels of harmful chemicals within an organism's tissues, which can be further amplified through the food chain.

The metal enrichment factor (MEF) serves to measure the degree of metal transfer from growth media, such as wastewater or water, into plant tissues. Meanwhile, the metal translocation factor (MTF) assesses the movement of these accumulated metals from the roots to the leaves of plants. This study seeks to evaluate the Bioaccumulation Factor (BAF), Bioconcentration Factor (BCF), Metal Enrichment Factor (MEF), and Metal Translocation Factor (MTF) using data previously published by researchers associated with the current authors [Shingadgaon et al., 2018].

Metal transfer factors indicated that the movement of metals in macrophyte plants is most pronounced between the roots and stems, whereas the least movement occurs between the stems and inflorescences. Among the fifty mobility factors assessed, the highest values were found in the stems-leaves relationship, while the roots-stems relationship exhibited the lowest values. The presence of high bioconcentration factor (BCF) values, along with low metal transfer factor (MTF) and bioaccumulation factor (BAF) values, implies that these macrophytes are effective for the phytostabilization of metals, and the reverse is also true.

Table 1: Concentrations of metals in the roots, shoots, and aerial components of *Arundo donax* recorded during phytoremediation bioassays.

Macrophyte species	Metal	Conc. in roots in µg/g (C_{R})	Conc. in shoots in µg/g (C_S)	Conc. in Aerial parts in µg/g (C_{AP})
Arundo donax	As	425	76	53
	Cd	1289	442	293
	Cr	1292	371	145
	Co	459	137	69
	Cu	2126	828	512
	Fe	4245	1705	943
	Mn	1740	967	657
	Ni	417	134	35
	Pb	2675	921	512
	Sr	239	86	51
	Zn	3147	1342	531

A bioaccumulation factor (BAF) of less than 1 indicates that the organism is not accumulating the heavy metal, resulting in a concentration lower than that of the surrounding environment. When the BAF is equal to 1, it implies that the organism is accumulating the heavy metal at a rate that corresponds to the environmental concentration. In contrast, a BAF greater than 1 indicates that the organism is accumulating the heavy metal, with its concentration surpassing that of the environment. Similarly, a bioconcentration factor (BCF) of less than 1 signifies that the organism is not concentrating the heavy metal. A BCF of 1 indicates that the organism is concentrating the heavy metal at the same rate as the surrounding water. A BCF greater than 1 suggests that the organism is indeed concentrating the heavy metal. In terms of the metal enrichment factor (MEF), a value below 1 indicates that the organism is not enriching the specific heavy metal. An MEF of 1 suggests that the organism is enriching the specific heavy metal, while an MEF greater than 1 indicates that the organism is actively enriching that heavy metal. For the metal transfer factor (MTF), a value under 1 indicates that the plant is not translocating the specific heavy metal. If the MTF is equal to 1, it suggests that the organism is enriching the specific heavy metal, and an MTF greater than 1 implies that the organism is indeed enriching that specific heavy metal.

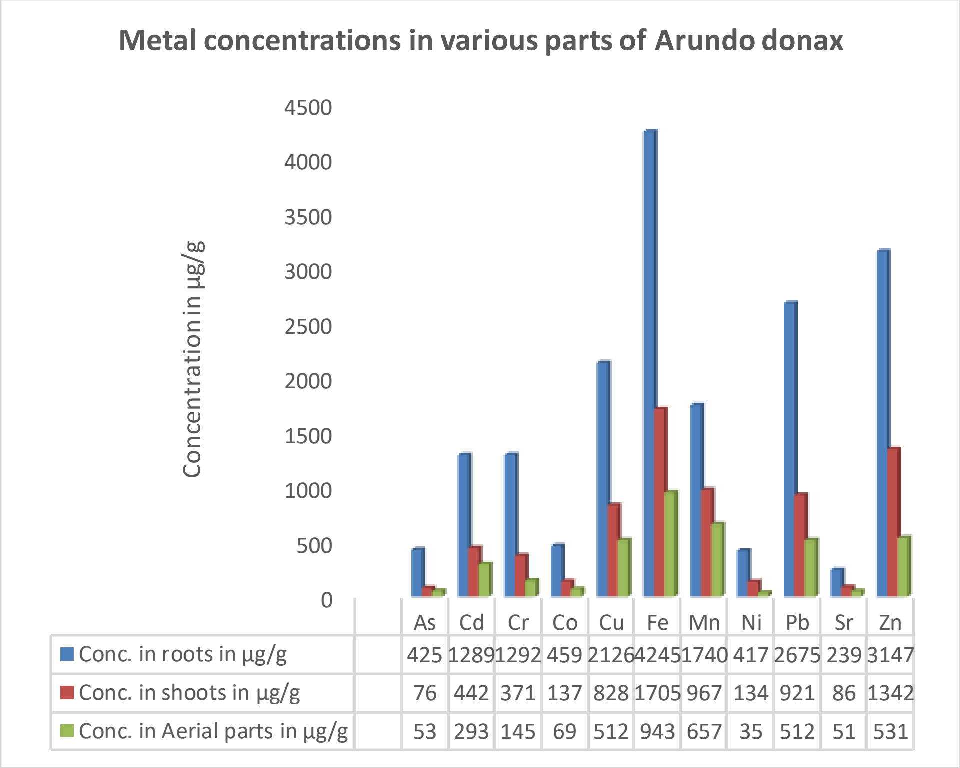
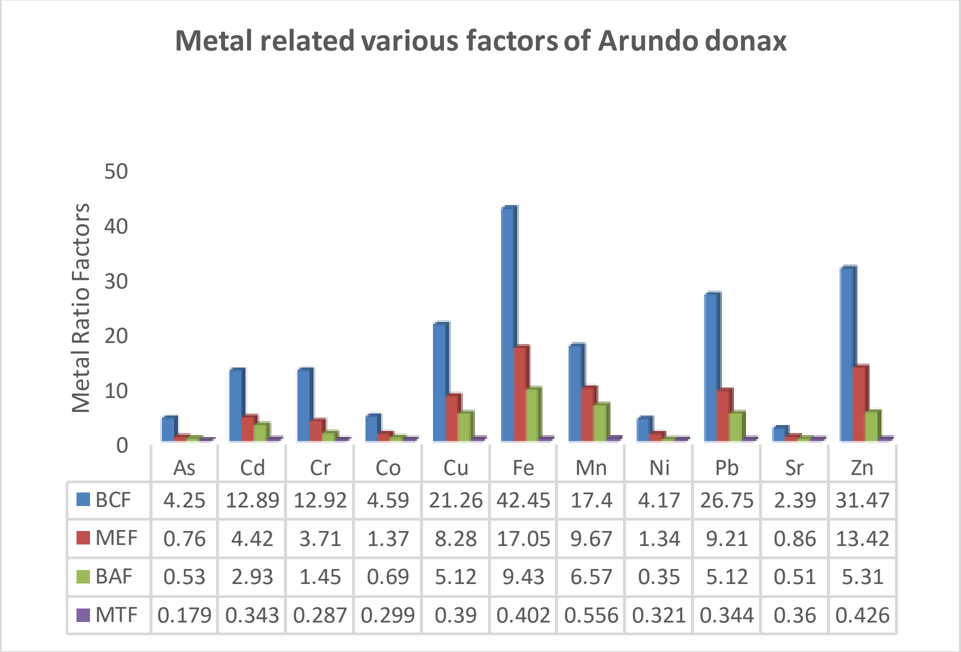


Figure 1: Levels of metal concentration in the roots, shoots, and aerial components of *Arundo donax* evaluated during phytoremediation bioassays.

Table 2: Assessment of the Bioconcentration Factor (BCF), Bioaccumulation Factor (BAF), Metal Enrichment Factor (MEF), and Metal Translocation Factor (MTF) for the *Arundo donax* species during phytoremediation bioassays.

Metal	**BCF**	**MEF**	**BAF**	**MTF**
As	4.25	0.76	0.53	0.1788
Cd	12.89	4.42	2.93	0.3429
Cr	12.92	3.71	1.45	0.2872
Co	4.59	1.37	0.69	0.2985
Cu	21.26	8.28	5.12	0.3895
Fe	42.45	17.05	9.43	0.4016
Mn	17.40	9.67	6.57	0.5557
Ni	4.17	1.34	0.35	0.3213
Pb	26.75	9.21	5.12	0.3443
Sr	2.39	0.86	0.51	0.3598
Zn	31.47	13.42	5.31	0.4264



	As	Cd	Cr	Co	Cu	Fe	Mn	Ni	Pb	Sr	Zn
BCF	4.25	12.89	12.92	4.59	21.26	42.45	17.4	4.17	26.75	2.39	31.47
MEF	0.76	4.42	3.71	1.37	8.28	17.05	9.67	1.34	9.21	0.86	13.42
BAF	0.53	2.93	1.45	0.69	5.12	9.43	6.57	0.35	5.12	0.51	5.31
MTF	0.179	0.343	0.287	0.299	0.39	0.402	0.556	0.321	0.344	0.36	0.426

Figure 2: Assessment of the Bioconcentration Factor (BCF), Bioaccumulation Factor (BAF), Metal Enrichment Factor (MEF), and Metal Translocation Factor (MTF) for the *Arundo donax* species during phytoremediation bioassays.

Plants that demonstrate both high bio-concentration and translocation factors are considered strong candidates for phytoextraction. Furthermore, species with elevated bioconcentration factors and reduced metal translocation factors are expected to be effective for phytostabilization [Yoon et al., 2006]. Elevated metal transfer factor (MTF) values indicate a significant ability to transport metals from the roots to the shoots, which may imply the existence of tolerance mechanisms in macrophyte plants to cope with high metal concentrations [McGrath and Zhao, 2003]. As a result, the rankings of bioaccumulation factor, bioconcentration factor, metal enrichment factor, and metal transfer factors evaluated in the current studies are summarized below for the metals analyzed (Table 3).

Table 3: The sequences of the bioaccumulation factor, bioconcentration factor, metal enrichment factor, and metal transfer factor for the heavy metals analyzed in *Arundo donax*.

Metal	Order of factors
As	BCF>MEF>BAF>MTF
Cd	BCF>MEF>MTF>BAF
Cr	BCF>MEF>BAF>MTF
Co	BCF>MEF>BAF>MTF
Cu	BCF>MEF>BAF>MTF
Fe	BCF>MEF>BAF>MTF
Mn	BCF>MEF>BAF>MTF
Ni	BCF>MEF>BAF>MTF
Pb	BCF>MEF>BAF>MTF
Sr	BCF>MEF>BAF>MTF
Zn	BCF>MEF>BAF>MTF

In the realm of macrophytes and metal contamination, it is essential to comprehend the significance of the Bioconcentration Factor (BCF), Metal Enrichment Factor (MEF), Bioaccumulation Factor (BAF), and Metal Transfer Factor (MTF). These metrics are vital for evaluating a plant's capacity to absorb and transport metals, which is critical for phytoremediation efforts and assessing ecological risks. A high BCF indicates a plant's remarkable ability to take up metals from its environment, making it a key indicator for identifying potential hyper-accumulator species that can be utilized in phytoremediation initiatives. The BAF is important for measuring the overall metal accumulation within a plant, which aids in understanding the potential for biomagnification and the risks it poses to higher trophic levels. The MEF evaluates whether a plant has elevated metal concentrations compared to background levels, while the MTF assesses how effectively a plant can transfer metals from its roots to its above-ground parts. By understanding these factors, researchers and environmental managers can evaluate the suitability of different plant species for phytoremediation, predict the risks of metal biomagnification in food webs, and develop strategies to mitigate metal pollution in contaminated areas. Investigations into various factors associated with *Arundo donax* indicate that the concentrations of As, Cr, Co, Cu, Fe, Mn, Ni, Pb, Sr, and Zn follow the order BCF>MEF>BAF>MTF. In contrast, for Cd, the sequence is BCF>MEF>MTF>BAF. This suggests that *Arundo donax* is an effective macrophyte for the removal of these heavy metals from polluted wastewater.

Arundo donax serves as a promising macrophyte for the phytoremediation of wastewater contaminated with heavy metals. Employing *Arundo donax* for the rehabilitation of polluted aquatic ecosystems offers an effective and sustainable strategy to mitigate toxic metal pollution. This widely distributed aquatic macrophyte has shown capability in extracting harmful metals from contaminated water. However, the processes involved in the absorption and accumulation of these toxic metals within *Arundo donax* remain inadequately understood.

Conclusion:

The current research on the absorption and accumulation properties of toxic metals in *Arundo donax* has provided significant insights into its potential application in phytoremediation. This study has contributed to the development of sustainable and economically feasible methods to combat toxic metal pollution in aquatic environments.

ACKNOWLEDGMENT

Authors are thankful to Prof. Dr. B.L.Chavan, Professor and Head, Department of Environmental Science, Dr. Babasaheb Ambedkar Marathwada University, Chhatrapati Sambhajinagar for his fruitful discussions and help in the present research work.

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