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Towards a Cleaner Yamuna: Evaluating Phytoremediation Efficacy of Lemon Grass, Indian Mustard, and Spinach

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Abstract

The Yamuna, one of the major rivers of India, is almost dying because of substantial pollution due to industrial effluents, agricultural runoff, and domestic waste. This study examines and compares the potential of Lemongrass (Cymbopogon citratus), Indian mustard (Brassica juncea), and Spinach (Spinacia oleracea) in phytoremediation to mitigate the river's contamination by heavy metal. Pot experiment was conducted for the three plants, with four replicates to know the efficiency of these plants. Control experiment was also conducted for comparative study for these three plants. Statistical Analysis was done by one-way Anova. For the Analysis, $p<0.05$ was considered significant. Pot experiments were conducted to evaluated the efficiency of these three plants in absorbing heavy metals such as Lead (Pb), Chromium (Cr), Cadmium (Cd), Iron (Fe) Nikil (Ni) and Zinc (Zn)from the contaminated river. The results confirmed significant reductions in contaminant concentrations, spinach can accumulate Cr, Pb, Zn, and Ni over the course of several seasons, but Indian mustard is a plant that is a hyperaccumulator of zinc. For both sites, mustard exhibits a strong uptake for metal but a lower shoot movement for Cd. Particularly for Fe, Cr, and Cd, bioavailability is greatly decreased by seasonal runoff and monsoonal fluctuations. These results imply that each plant species has unique phytoremediation strengths and that the target metal can determine how best to apply them for environmental cleanup. The implications of these findings advocate for the broader application of phytoremediation in similar environmental contexts worldwide.

Keywords*: Yamuna River, Heavy Metal Contamination, Phytoremediation, Spinach, Lemon Grass, Indian Mustard,*
Bioconcentration factor, Translocation Factor, Bioaccumulation factor

Introduction

Yamuna is a sacred river for Hindus and holy river Ganga's main tributary. The origin of river Yamuna is Yamunotri glacier, located near Bandar Punch of lower Himalayas in the Mussourie range, district Uttarkashi, Uttarakhand at a height of about 6320 metres above mean sea level (TERI 2001). One of the chief causes of metal contamination in Yamuna River is industrial effluents (Ashraf 2006). There are 26 industrial sectors in Delhi that are known to contribute to the Yamuna River's pollution. Although the Yamuna River only makes up 2% of its whole length, the portion that flows through Delhi is responsible for more than 75% of the river's pollution load which is a significant volume of both partially treated and untreated wastewater, particularly between Wazirabad and Okhla (Paliwal and Sharma et al. 2007).
Different organic and inorganic contaminants, including heavy metals, contaminate river water when it gets into it from agricultural, industrial, and municipal waste sources, etc. factors responsible for reduced oxygen level in the river water. Twenty-eight significant drain outfalls into Yamuna are additionally under observation by the (CWC, 2007), DPCC and DSIIDC which carried a survey in 2019, of the industries situated in 17 industrial areas (Bawana, Narela, Rajasthani Udyog Nagar, Shahdara Manufacturing

Association (SMA), Small Scale Industries (SSI), Badli, GTK, Nangloi, Lawrence Road, Mangolpuri, Mayapuri, Udyog Nagar, Naraina, Wazirpur, Okhla Ph-I& II, Jhilmil, and Friends Colony. The Shahdra drain is releasing a large volume of industrial and household wastewater. Steel processing and electroplating industries are the industries which transports wastewater to the river located at Badli , Wazirpur, and Jhilmil areas (Sehgal et al., 2012). According the report from Yamuna monitoring committee (YMC report, June2020), total of 31985 industrial units were surveyed, out of which 1966 units were found as defaulters. Classification of heavy metal is done as essential or non-essential. Essential heavy metals include Zn, Fe, Ni, Cu, and Mn which are required in small amounts for the accurate bio-functioning of organisms. Furthermore, deficiencies of heavy metal like Cr, Cd, Pb, Hg and As are heavy metals whose deficiencies have no effect on an organism's ability to function biochemically (Jadia et. al.,2020). When heavy metal concentrations rise above a certain allowable level, the living system's get disrupted (Wuana et. al.,2011). Soil and water contaminated by heavy metal can be effectively remediated by phytoremediation process, a green method based on plants (Ma et al., 2001). Phytoextraction and phytostabilization are two of the methods used in phytoremediation technology. Phytostabilization stops heavy metals from migrating to groundwater or the food chain by reducing their mobility in the soil as a result of their accumulations in plant roots throughout the rhizosphere (Yong et al., 2006) thereby preventing their migrations to groundwater or food chain. Whereas, the ability of plants to extract heavy metals from the soil and transfer them into biomass above ground is known as phytoextraction (Antosiewicz et al., 2008).

Comparatively speaking to other remediation techniques, the primary benefits of phytoremediation is ecofriendly and its low cost. As per Rascio and Navari-Izzo (2011), several plants species have been recognized as hyperaccumulators of heavy metals. These plants, which are known as hyperaccumator plants are capable of absorbing high concentrations of metals into their tissues.

Plant traits like fast growth, high biomass, ease of harvesting, and tolerance to the accumulation of a variety of heavy metals in their tissues are all important for the effectiveness of phytoremediation (He et al., 2005). Because local plants often do better under stress in terms of survival, development, and reproduction than imported plants from different ecosystems, using them in phytoremediation may thus be more successful (Yoon et al., 2006).

Lemongrass (Cymopogon flexuosus L.) is a perennial grass, which is tall, that can grow up to 3 feet (90 cm) in height. It has green leaves which are narrow that have a lemon-like aroma when crushed.It has a significant commercial value. Its leaves are used to make green tea, and the stems can be consumed (Jasha and Chase, 2014). Lemongrass has antioxidant , anti-inflammatory, anti-cancerous, anti-microbial, and insecticidal qualities as per Anand et al., 2011, Figueirinha et al., 2010, Kumar et al., 2008, Rajeswara et al., 2015 respectively. In addition, as per Verma et al. (2014), its essential oil is utilised in aromatherapy, pharmaceuticals as well as in cosmetic industry. Lemongrass can be used for soil restoration projects to prevent erosion and improve soil structure. Lemongrass's therapeutic benefits are well known and valued around the world; nonetheless, little research has been done on the plant for its use in remediating heavy metal-contaminated soil (Khilji and Sajid (2020). Therefore, the goal of the current study was to assess how and which heavy metals were absorbed and accumulated as it is fast growing plant and later can be used as animal fodder or can be used as biomass for bioenergy.

Brassica juncea is commonly known as Indian mustard. It belongs to the Brassicaceae (mustard) family, a family that includes many other important crops like cabbage, cauliflower, and radish. It is a fast-growing annual or biennial plant, often reaching up to 1–2 meters in height. It is a versatile plant native to South Asia, primarily grown for its edible seeds, oil, and as a vegetable specially in India. It has high biomass and a rapid growing plant. The leaves are deeply lobed and can be used as a leafy vegetable. The plant produces small, bright yellow flowers, and its seeds, which are the key product, are small and round. So, the present study has been proposed to know the phytoremediation potential of Indian mustard for heavy metal (Cr, Cd, Pb and As) contaminated soil (Cunningham, et.al.,1995). Researchers have also explored the use of Brassica juncea in combination with other plant species or soil amendments to improve the efficiency of phytoremediation, Rahman et al. (2023). Mustard also produces significant biomass and it grows quickly which can be used for bioenergy production or composting. Soil's structure is also improved by organic matter, while the plant itself plays a role in the remediation of pollutants. This was one of the reasons to

use Indian mustard with different crops to know the synergetic effect of intercropping.
Spinach (Spinach Oleracea) is another treasured plant and is widely cultivated leafy green vegetable known for its high nutritional value and health benefits, it is adaptable to diverse environmental conditions and can grow in several soil types. It belongs to the Amaranthaceae family and is native to central and western Asia. Spinach is rich in vitamins (A, C, K), minerals (iron, calcium), and antioxidants, making it a popular food in various diets. However, beyond its nutritional aspects, spinach has gained attention for its role in environmental applications, particularly in phytoremediation. Spinach can tolerate a range of environmental stress, including metal toxicity and soil salinity. This makes it a resilient contender for use in phytoremediation of environment which is contaminated. Singh et al. (2024) presented that spinach could grow in temperately contaminated soils, absorbing heavy metals while maintaining overall plant health, which is crucial for long-term environmental rebuilding efforts.
All three of these plants are edible: spinach, Indian mustard, and lemongrass are popular leafy green vegetables that are used in salads, soups, and other dishes. Lemongrass is frequently used in teas and culinary dishes for its citrus flavour. Indian mustard leaves, seeds, and oils are consumed in various culinary traditions. All of the three edible plants grow rapidly and produces a large biomass, which enhances its capacity to absorb and store contaminants.

This particular study was done with the aim to (i) Assess the phytoextraction potentials of Spinach, Lemon grass and Indian mustard grown on the metal accumulated soils of Shahdra and Okhla Drain, to evaluate the phytoextraction efficiency of Cr, Fe, Cu, Pb and Zn (ii) To compare the local and easily available plant species grown on contaminated soils of the two sites for phytoremediation along with the control soil (iii) To investigate the risk of adverse health effects if banks of Yamuna river are used for growing vegetable

Study Area

Soil sample was collected from 0 to 5 cm deep top layer of soil. Soil sample for control was taken from Biodiversity Park, Sector 137, Noida. Soil samples for control were examined for physical, chemical characteristics, available nutrients and the soil from near Shahdra Drain and Okhla Drain were examined for the Heavy metals and its texture along with other physical characteristics. Water sample form Ohkhla drain(28° 32′ 9.84″N /77° 19′ 29.16″ E), Shahdra drain(28◦31′ 44″ N/ 77◦16′ 57″ E) and tap water was also analyzed for physio- chemical characteristics.

Table 1 Description of sampling sites.

Site	Latitude/Longitude	Description
Okhla Barrage	28° 32′ 9.84″ N Latitude/ 77° 19′ 29.16″ E Longitude	It is the exit point of River Yamuna from Delhi, sampling point is 1.8 km downstream to Okhla.
Shahdara Drain	28◦31′44″N Latitude/) 77◦16′57″ E Longitude	It is the second major polluting drain of River Yamuna in Delhi located in the east of Okhla Barrage (Outlet in the river)
Biodiversity Park Area	28° 51′ 35″ N Latitude/ 77° 39′ 52″ E Longitude	It is in sector 91, Noida

Fig.1 Map of Delhi and the study area

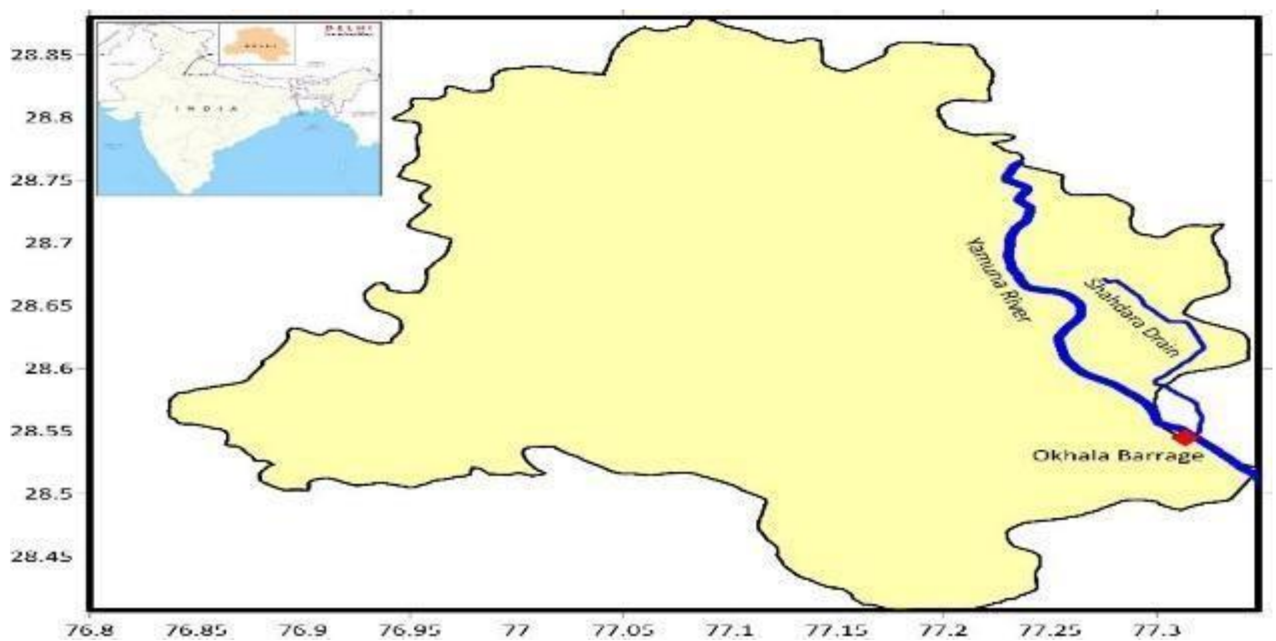

Table1. Physio-chemical properties and Metal ion Concentration of Soil (Control)

S.no	Parameters	Units	Results
1	Colour		Brown
2	Textural Class		Sandy Loam
3	Bulk Density	gm/cc	1.16
4	WHC	%	35.6
5	Particle Size Distribution	%	
	Sand	%	52.1
	Silt	%	11.5
	Clay	%	36.4
Chemical Analysis			
6	pH		7.4
7	Electrical conductivity	(1:2)	232.6
8	Organic Carbon		0.33

9.	Cation Exchange Capacity	mg/kg	27.2
10.	Sulphate	mg/kg	345.5
11	Chloride		61.25
12	Moisture Content	%w/w	4.42
13	Calcium Carbon	%w/w	12.8
Available Nitrogen (kg/ha)			
14	Nitrogen	kg/ha	328.4
15	Phosphorus	kg/ha	13.5
16	Potassium	kg/ha	322.1
	Heavy Metal		
1	Copper	mg/kg	0.0122
2	Zinc	mg/kg	0.0443
3	Lead	mg/kg	ND
4	Chromium	mg/kg	0.0101
5	Iron	mg/kg	0.61
5	Cadmium	mg/kg	ND

Method

Pot experiment was conducted for control and for both the contaminated sites with three replicates for April 2022 (pre-monsoon), October 2022 (post-monsoon), separate treatments were designed in perforated concrete pots for lemon grass, Indian mustard and Spinach. 5.00 kg of homogenized soil was used in pot in the control treatment and 5.00 kg of homogenized soil from the two-study area was used in each pot in the polluted treatment for Spinach. 5.00 kg of homogenized soil was used in pot in the control treatment and 5.00 kg of homogenized soil from both the study sites was used for the polluted treatment for lemon grass and Indian mustard for premonsoon and postmonsoon. DAP was used a fertilizer for proper growth of the plants. DAP (25 g) was used as a fertilizer for proper growth of the plants. (Géant. Et al. 2022*)* Polluted water from both the drains and tap water were used to moisten the soils in the polluted treatments and control treatment respectively prior to sowing the seeds, amount of water used for irrigation was also noted for later calculations for both the seasons. Seeds for Indian mustard and spinach were brought from the local shops. Seeds were germinated for two days on wet filter paper in dark conditions. Seeds got germinated in 5 days after covering it for maintaining dark condition with enough supply of water while in soil helpful in germination. Old clumps of Lemon grass growing on natural soil were collected and after proper washing and removal of the dried part, seven clump was planted in each of pot. The seeds of Spinach and Indian mustard, germinated well while irrigation was maintained for 40 days until the plants were fully grown and matured. Continuous irrigation with equal volumes of waters was maintained for the optimum germination and growth of the plants. The experiment was protected from invaders (rodents and insects) Plants were harvested, washed with distilled water, air-dried and taken in a newspaper to the laboratory for further treatment and analysis. Experimental pots were then placed in the nearby open area under the natural conditions. The plants germinated within 2 to 3 weeks and continuous irrigation was maintained for 40days until the plants were fully grown and matured and the plants was harvested and the experiment was terminated. Taken in a newspaper to the laboratory for further analysis after cleaning and air drying in shade. Water for irrigation was stored in large plastic containers thoroughly washed with distilled water. Six heavy metals Fe, Cr, Zn Cd, Ni and Pb were studied.

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(a) Day 1 Day 40

(b) Day 1 Day 40

(c) Day 1 Mid Growth

Day 40

Figure 2. (a), (b), (c) Plant Growth in Shahdra drain soil and Okhla drain soil from Day 1 till Day 40 for Lemon Grass, Mustard and Spinach for pre-monsoon respectively

Soil and Plant Analysis

The Indian mustard plant completes its life cycle within 1-2 months. That's why it was also harvested after 40 days. Soil (used in pot experiment) were air-dried separately and then oven dried at 80 ° C for 2 hours and sieved through 2mm mesh and was examined for HM. Sieved samples were used for determination of pH too. Individual plants were divided into two components: root and shoot, carefully washed in distilled water until visual inspection revealed that no solid particles remained adhering to the roots or shoots. Cleaned plant samples were then oven dried at 80 °C overnight. Dried plant samples (shoots and roots) were ground to powder form in a mixer grinder. Each dried sample (50 gm on dry weight basis) was digested with a mixture of nitric acid and hydrogen peroxide followed by addition of hydrochloric acid as suggested by Yang et al.2004. The digested sample was analyzed for heavy metal concentration by using Inductively Coupled Plasma Optical Emission Spectroscopy techniques (ICP-OES) 5800.

To evaluate the ability of plant to accumulate Heavy metal, following three parameters were calculated: Bioconcentration factor (BCF), Bioaccumaltion Factor(BAF),Translocation factor (TF)
BCF is defined as the ratio of concentration of heavy metal in plant to the concentration in the soil.
BCF= C harvested tissues/ C soil (Zhuang et.al.,2007)
Where, C harvested tissue is the concentration of the target metal in the plant harvested tissues (leaves, roots and shoots). C soil is the total concentration of same heavy metal in the soil (Padmavathiamma et.al.,2007).
Translocation Factor is defined as the Concentration of Heavy Metal in the shoot to the concentration of Heavy metal in the roots.
TF = C shoots/C roots (Ali et al., 2013)
Where, C shoots is concentration of target HM in shoot and C roots is concentration of target HM in roots.

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Phytoremediation

The Plants used for phytoremediation should be able to remove a decent amount of heavy metal, bear soil contaminants, and should have good biomass under adverse condition (Ma et al., 2001 McGrath and Zhao, 2003; Doumett et al., 2008). It involves numerous approaches, two of which are phytoextraction and phytostabilization. The ability of a plant to accumulate heavy metals in its shoots is defined as Phytoextraction (Ma et al., 2001; Yong et al., 2006; Usman and Mohamed,2009). On the other hand, Phytostabilization is a process to reduces the mobility of heavy metals in the soil via their accumulation in plant roots with heavy metals being retained in the rhizosphere (Yong et al., 2006; Antosiewicz et al., 2008).

Evaluation of heavy metal removal efficiency was done by calculating values of Bio-accumulation Factor (BAF)of shoot and BAF of root, and Translocation Factor (TF). The plant ability to accumulate metals from soils can be estimated using the BAF and TF (Ma et al., 2001; Yoon et al., 2006), said to be the most reliable criteria for comparing the performance of different plants involved in phytoremediation.

Bioaccumulation factor is defined as the ratio of concentration of metal in the root or shoot to the concentration of HM in the soil. BAF shoots > 1 indicates that the plant is an accumulator, while the values of BAF shoot < 1 indicate that the plant is an excluder (Baker, 1981). Also, if the values of BAF shoot > 10 indicate that the plant has the potential to be a hyperaccumulator (Ma et al.,2001).

Likewise, TF values is used to evaluate the capacity of a plant to transfer a heavy metal from the root to the shoot. TF is defined as the ratio of the metal concentration in the shoot to that in the root of plants. TF > 1 indicates that the plant is effective in translocation of metal from its root to shoot (Ma et al., 2001).

Statistical analysis

Statistical analysis was done to determine the significance between the means and draw a valid conclusion. “Analysis of Variance” (One Way) method was adopted as the statistical tool for the raw data observed during the whole experiment. Significant difference between three different crops for root and shoot for Shahdara Drain, Okhla Drain and Control was calculated. In all, $p<0.05$ was considered significant. Data are presented as mean± standard deviation. Post hoc (Tukey T-test) were used to analyze the significant variation in heavy metal concentration among different sampling sites and different seasons for all studied heavy metals (normally distributed).

Result and Discussion

The phytoremediation potential of Indian mustard, lemon grass depends on the biomass of shoot, roots and its accumulation concentration where as potential of Spinach depends on its fast growth, bioconcentration factor (BCF) translocation factor (TF). absorb heavy metals from the soil and ability to store them in its tissues. It is the ratio of the concentration of heavy metals in the soil to that in the plant tissues (leaf, stem, and roots) (Zhuang et.al.,2007). A plant's BCF must be greater than 1 in order for it to be instrumental in the phytoremediation of contaminated soil.

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Table 2 Species surveyed with potential for phytoremediation (Post-monsoon)

Heavy Metal	**Potential phyto-stabilizers (BCF > 1 > TF)**			
	Site(Post)	***Plants***	***BCF***	***TF***
Zn	Shahdra	Spinach	1.93	0.60
Ni	Shahdra	Spinach	5.32	0.12
Zn	Shahdra	Lemon grass	1.50	1.42
Cd	Shahdra	Mustard	2.58	0.25
Ni	Okhla	Spinach	2.59	0.33
Cd	Okhla	Mustard	1.53	0.35
Ni	Okhla	Mustard	2.25	0.40
Cr	Okhla	Mustard	1.366409	0.257271

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Table 2.1 Species surveyed with potential for phytoremediation(Pre-monsoon)

Heavy Metal	**Potential phytoextractors(BAC > 1 < TF)**				**Heavy Metal**	**Potential phytostabilizers (BCF > 1 > TF)**			
	Site (Pre)	***Plants***	***BAC***	***TF***		***Site(Pre)***	***Plants***	***BCF***	***TF***
Pb	Shahdra	Spinach	1.78	2.53	Cr	Shahdra	Spinach	1.44	0.14
Zn	Shahdra	Spinach	2.48	0.56	Zn	Shahdra	spinach	6.86	0.56
Zn	Shahdra	Lemon Grass	1.80	3.59	Ni	Shahdra	Lemon grass	2.41	0.46
Zn	Shahdra	Mustard	1.00	1.69	Zn	Shahdra	Lemon grass	5.58	1.80
Cr	Okhla	Lemon grass	1.56	2.84	Pb	Okhla	Spinach	2.09	1.34
Cd	Okhla	Mustard	1.11	1.22	Cr	Okhla	Spinach	2.10	2.84
					Zn	Okhla	Mustard	1.33	0.16
					Ni	Okhla	Mustard	1.93	0.23
					Cd	Okhla	Mustard	1.53	1.27

BCF > 1 for spinach (1.44 pre, 1.42 post) for Cr, lemon grass and mustard had BCF<1. With mustard (0.35). pre-monsoon BCF values decreased significantly, with Lemongrass dropping to 0 and mustard reducing to 0.10 post monsoon. Seasonal runoff may reduce Cr bioavailability. BCF >1 for Mustard (2.48 pre-monsoon) showed the maximum Pb uptake, tailed by Spinach (1.08) post monsoon. In Mustard (0.61 to 0.09) and lemon grass (0.93 pre to 0.29 post) BCF values were less than 1 for both the seasons, showing a sharp decline in accumulation. Spinach is effective Pb accumulator, providing potential hyperaccumulator plants to remediate soil contaminated by Lead.

Spinach showed highest Zn with BCF>1 (6.87 pre-monsoon, 1.93 post), demonstrating decent Zn uptake in both seasons. Mustard also showed BCF <1 (5.58 pre, 1.51 post) and had BCF>1(1.60 pre) but post monsoon it decreased for Zn. Spinach consistently accumulates Zn and could be used for Zn removal in phytoremediation. BCF <1 for Fe post-monsoon, with Lemongrass (0.05-0.14), Spinach (0.06-0.74), and with mustard TF>1 (1.29) pre-monsoon but decreased post monsoon. BCF value for Ni is high (BCF >1) with spinach pre-monsoon (2.41), and further increasing to 5.32 post-monsoon. Lemongrass had low Ni accumulation in both seasons. BCF>1 for Cd with mustard pre and post-monsoon (1.49 and 2.59 respectively). Lemongrass showed consistent but lower Cd uptake (0.86 pre, 0.95 post).

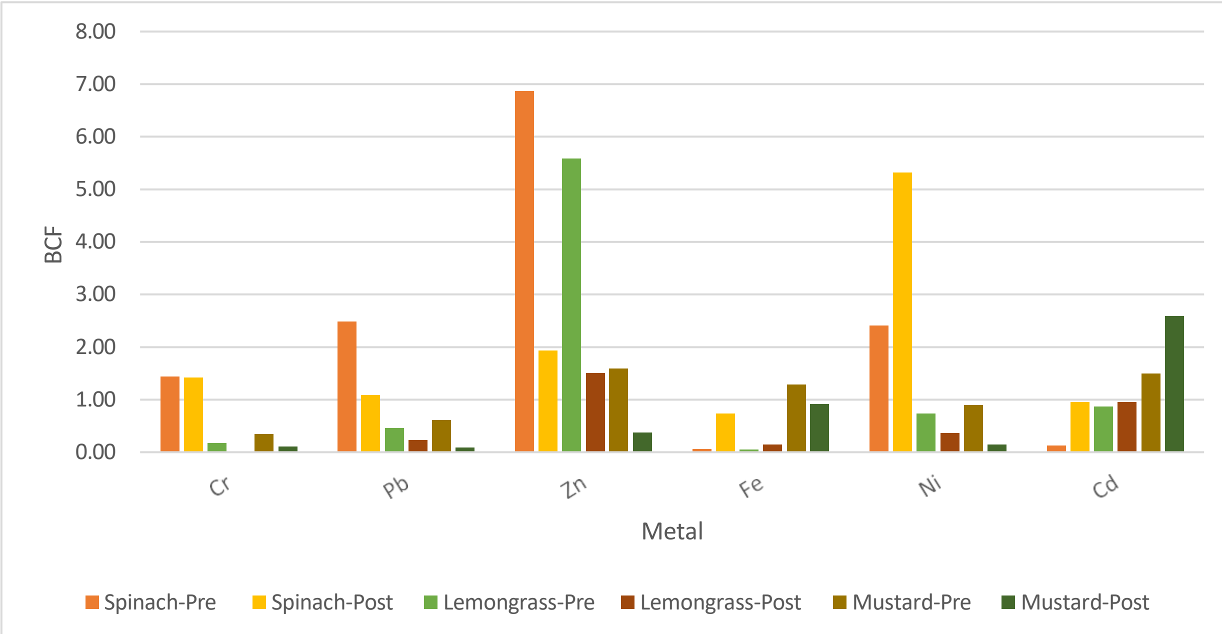

Fig. 1 Bioconcentration factors for three plants for Shahdra Drain for pre and post monsoon

Translocation Factor : A method efficient for computing the metal phytoextraction from soils. TF classifies plants by their TF as Indicator (TF near 1), Excluder (TF<1), and Accumulator (TF>1) (Baker 1981, Ghosh et.al.,2005). Furthermore, the stronger the phytoextraction ability, the higher the TF value.

Translocation Factor for heavy metals (Cr, Pb, Zn, Mg, Fe, Ni, Cd) for Spinach, Lemongrass, and Mustard for pre-monsoon and post-monsoon for Shahdra Drain. The TF values, indicating the ability of plants to accumulate metals from soil, varied significantly among the three vegetations, metal types, and seasons. For chromium, TF <1 for spinach and lemon, whereas TF> 1 for Cr with mustard (1.54) post-monsoon. Post-monsoon Cr accumulation dropped to zero in Lemongrass and Mustard, and was reduced to 0.14 in Spinach. Cr uptake is strongly influenced by seasonal changes, possibly due to leaching or reduced bioavailability post-monsoon. Spinach showed TF < 1 for Pb (2.53 and 1.77) in pre-monsoon and post-monsoon respectively and it is followed by Lemongrass (1.67pre and 1.22post) and Mustard (1.11). Spinach showed moderate uptake of Zn (0.28–0.60). Spinach proves to be potential phytoextractor of Pb. Mustard showed TF<1for Zn (3.68 pre-monsoon, 2.60 post), while Lemongrass had negligible.Mustard validates effective uptake of Zn form root to shoot, maintaining high TF even post-monsoon, due to high root absorption. Spinach exhibited the highest TF for Mg during pre-monsoon its 8.19, significantly higher than Lemon grass and mustard. All plant species showed reduced TF for Mg in post-monsoon.Mg uptake is highly seasonal and plant-dependent; waterlogging or dilution during monsoon may reduce Mg bioavailability .Iron uptake in Spinach was 1.61 in pre-monsoon which is higher compared to other plants. Seasonal saturation and redox changes post-monsoon likely impact Fe solubility and uptake.Post-monsoon Lemongrass had TF>1 for Ni (3.30), indicating enhanced phytoextraction under wet conditions. Mustard and Spinach showed reasonable Ni uptake, with post-monsoon increases. With lemongrass TF>1 (1.61 pre-monsoon) for Cd.Post-monsoon TF decreased in all plants, with the most significant drop in Lemongrass (to 0.16).Cd is readily accumulated by all plants, especially pre-monsoon, but its mobility and availability may reduce with seasonal rainfall.

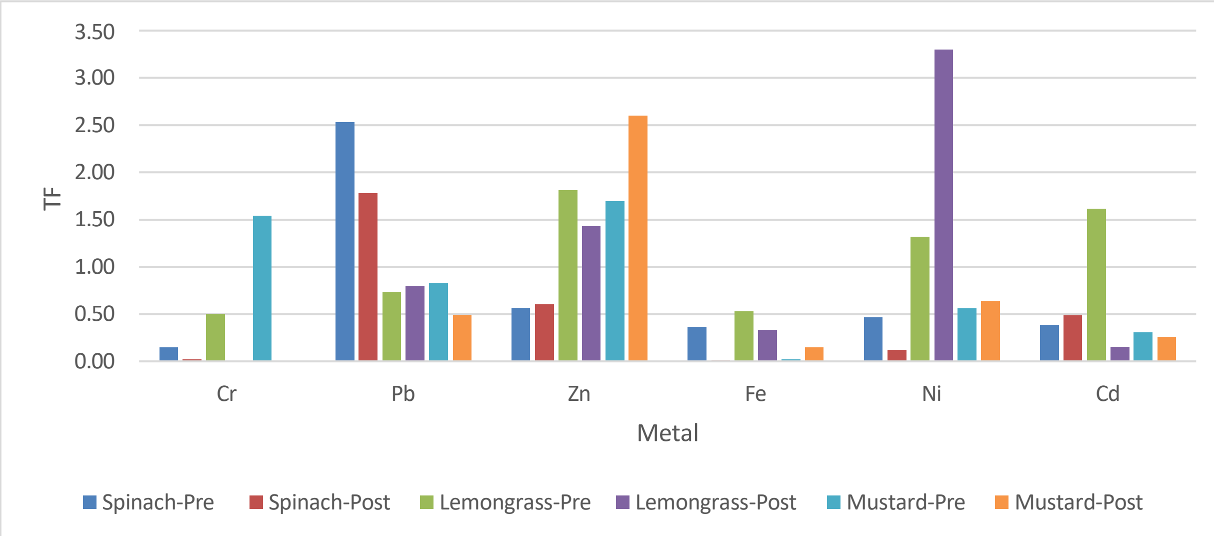

Fig. 2 Translocation factors for three plants for Shahdra Drain for pre and post monsoon

BCF and TF for Okhla Drain:

The **Bio-Concentration Factor (BCF)** of **Cr, Pb, Zn, Mg, Fe, Ni, and Cd**, in **Spinach, Lemongrass, and Mustard**, in **pre- and post-monsoon seasons for Okhla drain** are shown below

BCF>1 was observed for chromium (2.1) pre-monsoon was observed in lemon grass. BCF for mustard is 1.37 for Cr, post monsoon, Spinach shows poor Cr uptake post-monsoon (0.01). Seemingly Mustard is the best post-monsoon Cr accumulator. BCF>1 for Pb during pre- monsoon (2.09) and post- monsoon respectively (1.18) with spinach. Mustard and lemongrass have BCF < 1 consistently for Pb. With spinach BCF >1 post-monsoon for Zn values ranging from 1.84 to 7.98, which validates a potential hyperaccumulator plant. All three plant species shows, but for mustard plant it dropped post monsoon(0.30).All the three vegetations had BCF<1 in both seasons , with lemongrass(Pre:0.98) and Mustard (pre: 0.92).Pre-monsoon , BCF >1 for lemongrass (4.49), spinach (3.03), mustard (1.94) for Nickel. In post-monsoon season mustard (2.26) and spinach (2.60) have BCF>1 for Ni. For pre-monsoon and post monsoon, BCF>1 for lemongrass for Cd. With mustard BCF>1 post monsoon for Cd and BCF<1 for Cd with spinach.

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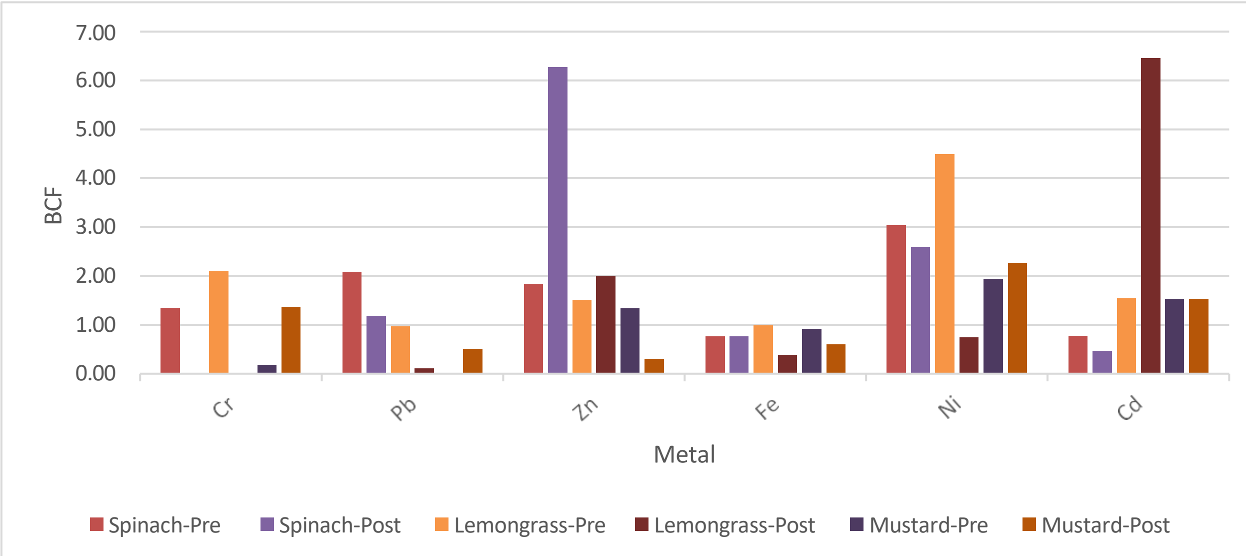

Fig. 3 Bioconcentration factors for three plants for Okhla Drain for pre and post monsoon

The TF values for seven metals (Cr, Pb, Zn, Mg, Fe, Ni, Cd) across three plants (Spinach, Lemongrass, Mustard) during pre- and post-monsoon periods from Okhla drain are shown in Fig 4.
Lemon grass shows TF >1 (2.85 pre-monsoon) for Cr, for other TF<1 for Cr .Lemongrass is an effective Cr phytoextractor. Seasonal reduction post-monsoon may be due to Cr leaching or immobilization in soil. Spinach(1.35 pre,1.18 post) had TF>1 indicating high Pb accumulation. Mustard post-monsoon (4.04) showed a remarkable Zn TF, significantly higher than other plants. Spinach (1.49), lemon grass (1.56) post monsoon as well as pre monsoon also TF>1 (1.26) with lemon grass.
TF<1 for Fe for all the three vegetations.TF<1 for Spinach and mustard for Ni across both seasons. For mustard TF>1 pre-monsoon (1.28) lemongrass post-monsoon (1.32) for Cd.Cd uptake is highly variable and plant-specific. Mustard and Lemon grass shows potential for phytoremediation of Cd-contaminated soils.

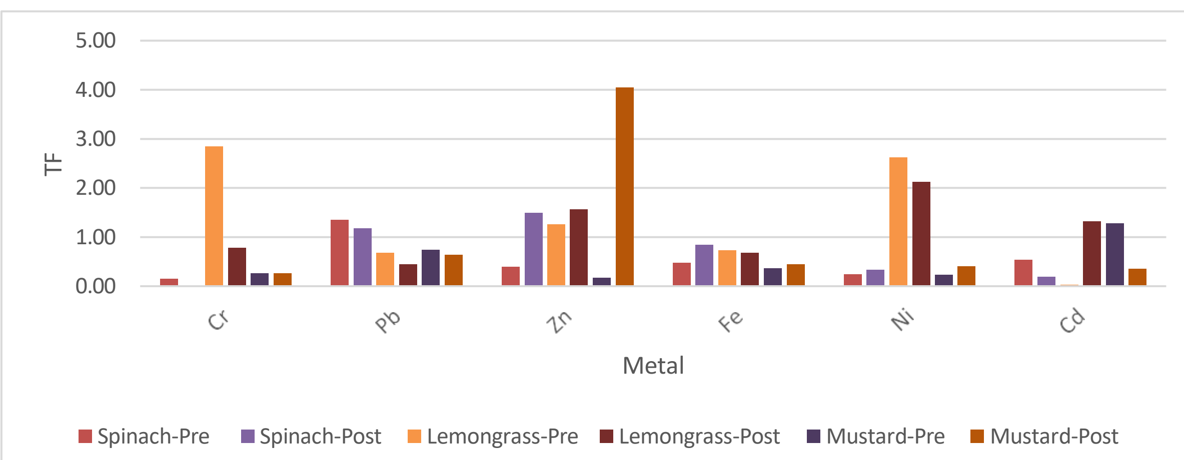

Fig. 4 Translocation factors for three plants for Okhla Drain for pre and post monsoon

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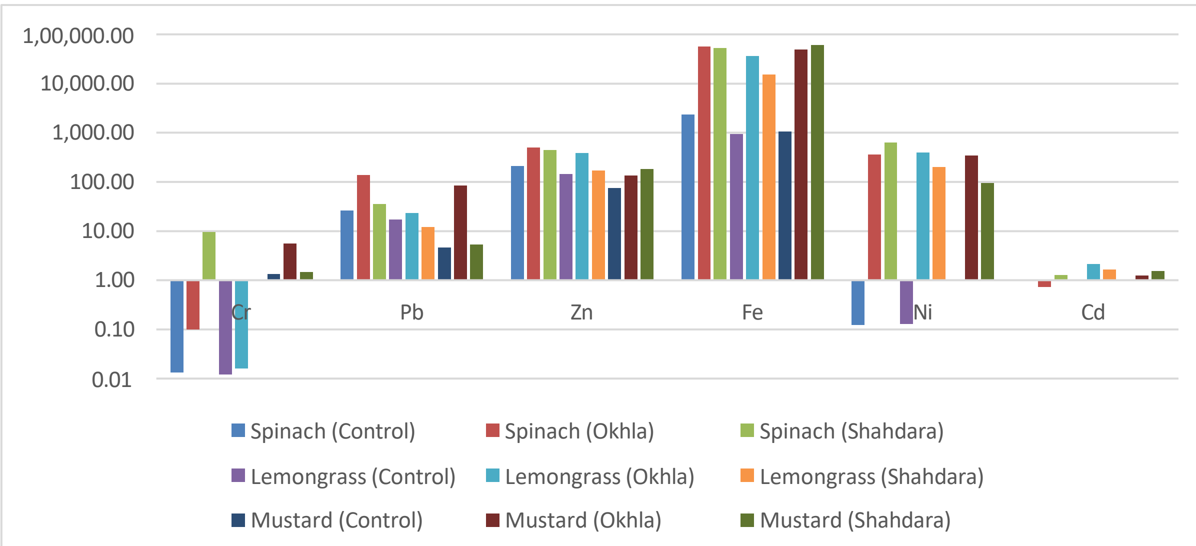
The Fig no.5 and 6, below compares the efficiency of three vegetations for pre-monsoon and post-monsoon separately with Control, and this clear that concentration of heavy metal concentrations (Cr, Pb, Zn, Fe, Ni, Cd) are significantly higher in spinach, lemongrass, and mustard collected from both the sites compared to control samples. The highest iron (Fe) accumulation was observed in mustard from Shahdara (65,308.92 mg/kg), whereas Pb and Ni has high level for spinach in polluted areas. Cadmium (Cd) was absent in all control samples for pre and post- monsoon seasons but present in Okhla and Shahdara, indicating contamination. In graph no.6 all the value for Cr are negative for Lemon grass for Control, while for Fe the values are too high for all three vegetations for Okhla and Shahdra.

Fig 5. Comparative graph for metals with Control for pre-monsoon



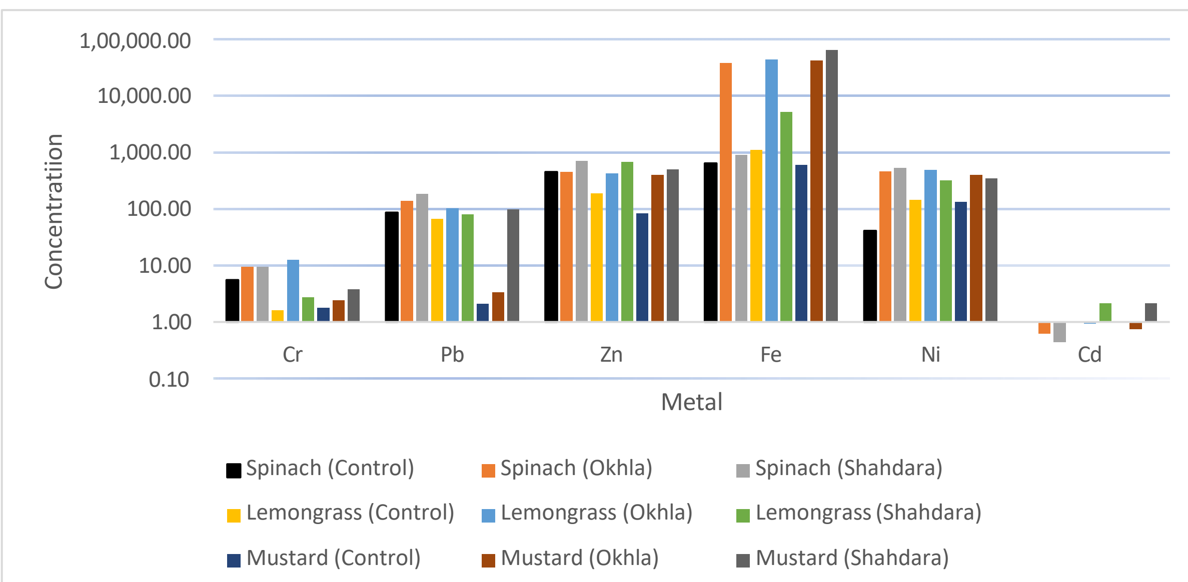


Fig 6. Comparative graph for metals with Control for post- monsoon

To conclude, the Bioconcentration Factor (BCF), Bioaccumulation coefficient (BAC) and Translocation

Factor (TF), which quantify the effectiveness of phytoremediation, exhibit distinct differences among three plant species, 6 metals, and seasons.

Spinach has high BAC (BAC>1<TF) for Pb, means high uptake and high translocation (TF, 2.58- BAC, 1.78) which implies a phytoextractor for lead. Whereas for Zn, spinach accumulates it in roots with BCF 6.87, acting as a phyto-stabilizer for Zn. Spinach also has a good ability to absorb Ni and Cd with (BCF>1> TF), making it the most adaptable and versatile plant. To conclude , Spinach has a potential for accumulation of Cr, Pb, Zn, Ni, across seasons.

Lemon grass is efficient for Zn uptake and it is translocated to shoots. Lemon grass acts as a phytoextractor for Cr and Cd predominantly in premonsoon. Lemongrass has limited root uptake but can exhibit higher TF for Ni. Mustard acts as a phytoextractor for Zn and Ni whereas phyto-stabilizor for Cd.Hence,mustard displays sturdy Pb and Cd , Zn and Ni uptake but performance varies by season.

Mustard shows high uptake for metal but shoot movement if less for Cd for both the sites. Seasonal runoff and monsoonal changes significantly reduce bioavailability, especially for Fe, Cr and Cd. These findings suggest that each plant species has specific strengths in phytoremediation, and their application can be tailored based on the target metal for effective environmental cleanup.

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Table no.3 Concentrations in mass balance (mg dry weight) of 6 heavy metals in roots and shoots of three plants for Shahdra/Okhla/Control Area

		Heavy Metal	**Cr**	**Pb**	**Zn**	**Fe**	**Ni**	**Cd**
Pre-Okhla	Spinach	Root	8.335±0.0129	59.75±0.129	324.15±0.129	25785.25±0.129	368.675±0.170	0.415±0.0129
		Shoot	1.26±0.0129	80.45±0.129	127.40±1.49	12575.15±0.129	86.7±0.182	0.215±0.0129
	Lemon Grass	Root	3.24±0.0129	61.25±0.129	186.25±0.129	25573.15±0.129	136.65±0.129	0.915±0.0129
		Shoot	9.25±0.0129	41.3±0.0816	234.45±0.129	18634.15±0.129	358.45±0.3109	0.0215±0.00129
	Mustard	Root	1.89±0.0081	1.91±0.012	342.8±0.163	31375.18±0.095	323.45±0.129	0.3325±0.0170
		Shoot	0.5±0.00816	1.41±0.0129	56.1±0.637	11254.38±0.262	75.55±0.129	0.425±0.0129
Post-Okhla	Spinach	Root	0.1±0.0082	62.9±0.386	200.25±0.129	30785.25±0.129	267.15±0.129	0.615±0.0129
		Shoot	0.0±0.0	73.52±0.171	297.45±0.129	25875.25±0.129	89.5±0.129	0.12±0.0182
	Lemon Grass	Root	0.009±0.00017	16.3±0.216	150.25±0.129	21834.15±0.129	126.42±0.095	0.922±0.022
		Shoot	.0071±0.00012	7.15±0.129	234.25±0.129	14673.35±0.129	267.65±0.129	1.22±0.0129
	Mustard	Root	4.47±0.0182	51.35±0.129	26.6±0.0816	37375.18±0.125	243.55±0.129	0.915±0.0129
		Shoot	1.15±0.129	32.75±0.129	107.52±0.170	11379.25±0.129	98.55±0.129	0.325±0.0129
Pre-Shahdra	Spinach	Root	8.25±0.129	52.3±0.163	452.325±0.206	2412±0.208	358.35±0.129	0.315±0.0129
		Shoot	1.21±0.0095	132.35±0.311	256.35±0.129	874.25±0.208	167.25±0.129	0.1225±0.01707
	Lemon Grass	Root	1.815±0.0129	46.75±0.129	245.55±0.129	3387.25±0.208	136.45±0.129	0.815±0.0129
		Shoot	0.915±0.0129	34.35±0.129	443.555±0.129	1789.77±0.25	179.65±0.129	1.315±0.0129
	Mustard	Root	1.49±0.017	53.45±0.129	185.25±0.129	63876.35±0.129	224.35±0.129	1.622±0.0170
		Shoot	2.305±0.129	44.35±0.129	313.65±0.129	1432.57±0.095	125.35±0.129	0.517±0.0170
Post-Shahdra	Spinach	Root	9.42±0.0129	12.6±0.0816	272.65±0.129	51874.25±0.129	558.375±0.1707	0.8515±0.00129
		Shoot	0.2±0.00816	22.37±0.171	164.25±0.3109	1012.4±0.1825	67.15±0.129	0.415±0.0129
	Lemon Grass	Root	0.00±0.00	6.8±0.129	164.27±0.129	11482.25±0.129	46.55±0.129	1.415±0.0129
		Shoot	0.00±0.00	5.31±0.0129	5.315±0.129	3934.25±0.129	153.65±0.129	0.2225±0.0170
	Mustard	Root	1.45±0.129	3.55±0.129	50.25±0.129	51972.25±0.129	58.35±0.129	1.225±0.0170
		Shoot	0.0±0.0	1.75±0.129	130.575±0.095	7638.5±0.129	37.25±0.129	0.315±0.0129
		Heavy Metal	**Cr**	**Pb**	**Zn**	**Fe**	**Ni**	**Cd**
Pre-Control	Spinach	Root	1.22±0.0182	12.55±0.129	222.35±0.129	387.35±0.129	24.62±0.125	0.0±0.0
		Shoot	4.322±0.0171	73.65±0.129	128.55±1.49	257.25±0.129	16.35±0.129	0.0±0.0
	Lemon Grass	Root	1.35±0.129	46.35±0.129	122.25±0.129	834.25.1±0.129	85.25±0.129	0.0±0.0
		Shoot	0.25±0.129	10.6±0.182	67.45±0.129	273.25±0.129	59.35±0.129	0.0±0.0
	Mustard	Root	1.25±0.129	1.75±0.129	40.75±0.129	278.45±0.129	156.65±0.129	0.0±0.0
		Shoot	0.522±0.0170	0.35±0.0129	42.47±0.1707	324.65±0.129	56.35±0.129	0.0±0.0
Post-Control	Spinach	Root	0.012±0.00182	8.7±0.129	122.23±0.0216	1598.22±0.0182	0.1225±0.0170	0.0±0.0
		Shoot	.00122±0.00017	17.65±0.129	88.54±0.309	757.15±0.129	0.0±0.0	0.0±0.0
	Lemon Grass	Root	0.01±0.0017	11.65±0.129	89.42±0.170	647.25±0.129	0.129±0.0129	0.0±0.0
		Shoot	0.0±0.0	5.25±0.0129	55.12±0.0170	289.21±0.0170	0.0±0.0	0.0±0.0
	Mustard	Root	1.1±0.0170	3.25±0.129	27.55±0.129	438.35±0.129	0.0±0.0	0.0±0.0
		Shoot	0.2155±0.0129	1.35±0.129	17.425±0.0208	624.65±0.129	0.0±0.0	0.0±0.0

Conclusion and Discussion

To conclude, the Bioconcentration Factor (BCF), Bioaccumulation coefficient (BAC) and Translocation Factor (TF), which quantify the effectiveness of phytoremediation, exhibit distinct differences among three plant species, 6 metals, and seasons.

Spinach has high BAC (BAC>1<TF) for Pb, means high uptake and high translocation (TF, 2.58- BAC, 1.78) which implies a phytoextractor for lead. Whereas for Zn, spinach accumulates it in roots with BCF 6.87, acting as a phyto-stabilizer for Zn. Spinach also has a good ability to absorb Ni and Cd with (BCF>1> TF), making it the most adaptable and versatile plant. To conclude, Spinach has a potential for accumulation of Cr, Pb, Zn, Ni, across seasons.

Lemon grass is efficient for Zn uptake and it is translocated to shoots. Lemon grass acts as a phytoextractor for Cr and Cd predominantly in premonsoon. Lemongrass has limited root uptake but can exhibit higher TF for Ni. Mustard acts as a phytoextractor for Zn and Ni whereas phyto-stabilizor for Cd.Hence,mustard displays sturdy Pb and Cd, Zn and Ni uptake but performance varies by season. Whereas we can conclude that Indian Mustard is a hyperaccumulator plant for Zn removal, is similar to the findings by (D. R. Parkinson ,2012).

Mustard shows high uptake for metal but shoot movement if less for Cd for both the sites. Seasonal runoff and monsoonal changes significantly reduce bioavailability, especially for Fe, Cr and Cd. These findings suggest that each plant species has specific strengths in phytoremediation, and their application can be tailored based on the target metal for effective environmental cleanup.

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