



Phytoextraction Potential of Chrysanthemum and Cumbu Napier Hybrid Grass to Remediate Chromium-Contaminated Soils Using Bioamendments

Murugaiyan Sinduja¹ · Velusamy Sathya² · Muthunalliappan Maheswari¹ · Govindaraj Kamalam Dinesh³ · Periyasamy Dhevagi¹ · Shiv Prasad³ · Kovilpillai Boomiraj¹ · Palani Kalpana⁴

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Abstract

Chromium is one of the most toxic heavy metals impacting soil quality and human health. However, remediating Cr from contaminated environments and soil by the chemical method is uneconomic and unsustainable. Phytoremediation is a potential, eco-friendly and cost-effective technique to decontaminate Cr from the soil. In this study, chrysanthemum and Cumbu Napier hybrid grass were grown with various amendments in the pots to evaluate their phytoextraction potential to remediate Cr-polluted soil. In the treatment (T₃-composted poultry manure), Cr concentration above 300 ppm was slightly toxic to the chrysanthemum, resulting in the reduction of flowers. Cumbu Napier grass had good growth in all the treatments. The productivity of Cumbu Napier grass was excellent, and 80% of Cr accumulation was in the T₄ treatment (Cr + 5 t ha⁻¹ of press mud compost) compared to other treatments. Cr removal was maximum with Cumbu Napier, followed by chrysanthemum because of its higher biomass. According to Cr partitioning, a high concentration was found in the roots, followed by shoots and flowers. Thus, both crops with added bioamendments are excellent options for phytoremediation. Results suggest that plants grown with bioamendments pose a promising future for developing a sustainable, cost-effective methodology for chromium removal from the soil.

Highlights

- **Phytoremediation is a potential, eco-friendly and cost-effective technique to decontaminate Cr from the soil.**
- **Cr content ranged from 92.39 to 298.29 mg Kg⁻¹; a high concentration was found in the roots, followed by shoots and flowers.**
- **Poultry manure shows the highest reduction in total Cr content in chrysanthemum.**

✉ Velusamy Sathya
sathyavelu1987@gmail.com

Murugaiyan Sinduja
seethasinduja@gmail.com

Muthunalliappan Maheswari
maheswarisekar2004@yahoo.com

Govindaraj Kamalam Dinesh
gkdineshiari@gmail.com

Periyasamy Dhevagi
devagisivaraj@gmail.com

Shiv Prasad
shiv_drprasad@yahoo.co.in

Kovilpillai Boomiraj
kb78@tnau.ac.in

Palani Kalpana
kalpana.rajesh@nationalagro.org

¹ Department of Environmental Sciences, Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu 641 003, India

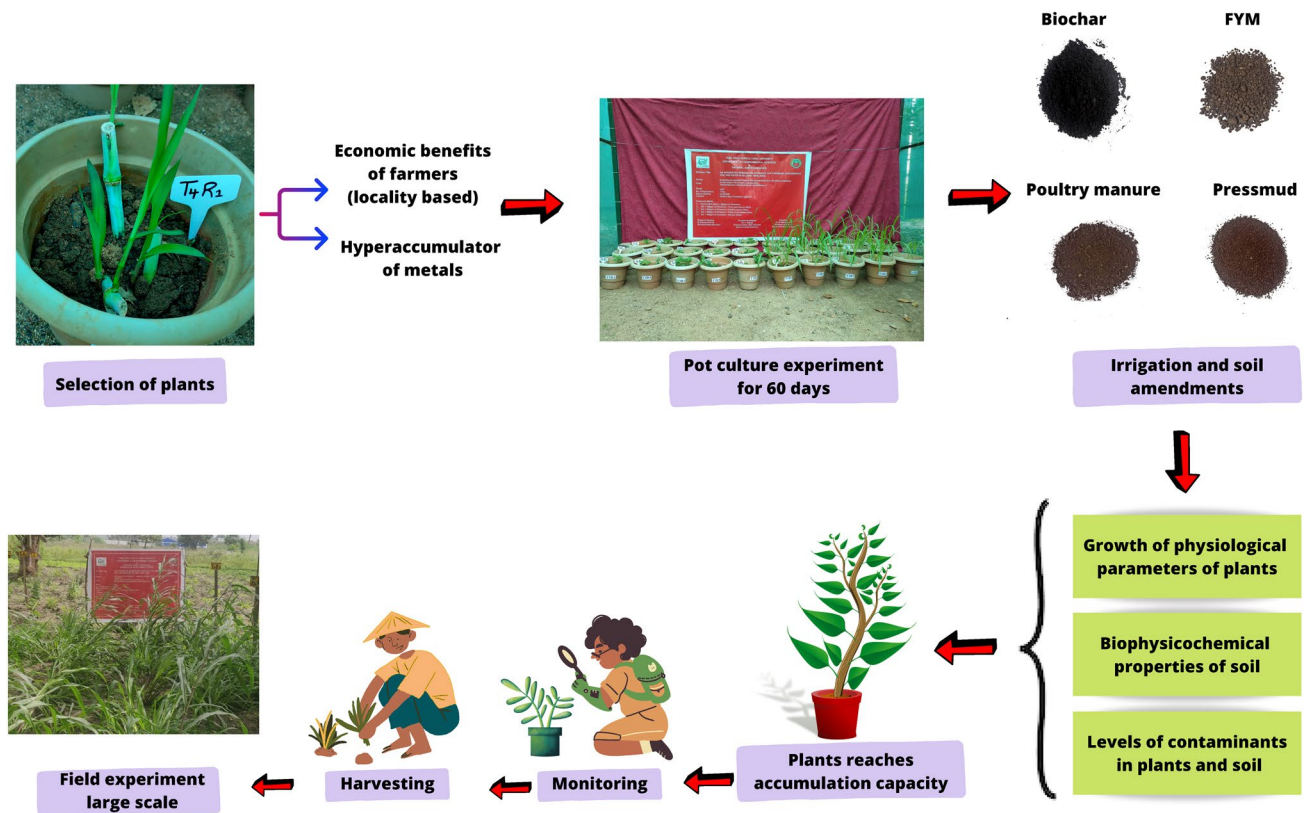
² Tamil Nadu Pollution Control Board, Chennai, Tamil Nadu 600 032, India

³ Division of Environment Science, ICAR-Indian Agricultural Research Institute, New Delhi 110 012, India

⁴ National Agro Foundation, Research and Development Centre, Anna University Taramani Campus, Taramani, Chennai, Tamil Nadu 600 113, India

- **Chrysanthemum can tolerate high levels of chromium (and accumulate it to about 40% in leaves) and can thus be grown on chromium-contaminated sites, which could aid in the reclamation and remediation of chromium-contaminated soil and land.**

Graphical abstract



Keywords Chromium · Phytoremediation · Chrysanthemum · Cumbu Napier hybrid grass · Bioamendments · Hyperaccumulators

Introduction

Chromium (Cr) is one of the environment's most toxic and hazardous metals. Cr is released into the environment through various industrial processes, including electroplating, tanning, polishing, painting, pigment manufacture, and wood preservation, in addition to its natural occurrence (Sinduja et al. 2022). The primary source of chromium is high influx into the biosphere (Ahirwar et al. 2018). In most plant species, higher concentrations of these metals can cause metabolic disturbances and growth inhibition, both of which can result in death (Gill 2014; Sinduja et al. 2018; Suganthi et al. 2020). The degree of metal absorption by plants varies substantially between species and plant areas (Baker et al. 2020). Several investigations have indicated that arsenic and chromium levels in roots are greater than in leaves or stems.

However, soil microbes and organic waste additives, on the other hand, play an essential role in improving plant development and metal tolerance (Shukla et al. 2009). Though phytoremediation, with bioamendments that employ harvestable sections of plants to remove contaminants, offers a green and environmentally acceptable method for cleaning metal-contaminated soils and rivers, if edible crops are used for the purpose, there is a risk of food chain contamination (Madanan et al. 2021).

Bioamendments such as farmyard manure, composted poultry manure, press mud compost, and biochar have been reported to reduce toxic contaminants from soil environments (Sathya et al. 2021). These bioamendments offer the opportunity to improve pH, specific surface area, porous structure, surface functional groups, and the ability to be employed as an adsorbent to immobilize heavy metals in soil (Rieuwerts

2007). Furthermore, bioamendments incorporated into the soil can be used as a natural fertilizer because it improves soil fertility due to its high organic carbon content and high water and nutrient sorptive capacity (Amoah-Antwi et al. 2020; Sathya and Mahimairaja 2016). In addition, many authors hypothesized that the high pH of the biochar produced at high temperatures prevents heavy metal leaching (Raj et al. 2021). Among non-edible crops, floriculture plants are a form of higher plant that can help with soil remediation (Lajayer et al. 2019). Phytoextraction is the process by which pollutants are removed from plant roots and transferred to shoots or other aboveground biomass including stems, leaves, and fruits. Phytoaccumulation and phytosequestration are other terms. Previous phytoremediation studies (Ramana et al. 2013) have investigated the viability of remediation of Cr-contaminated soil and other heavy metals with tuberose, marigold, amaranthus, and mesta. The tanning industry is a major source of pollution in Tamil Nadu, India, because it disposes of large amounts of chromium (Cr) and salt-rich effluents and sludge. The indiscriminate discharge of such pollutants into rivers and on land has severely deteriorated productive agricultural land and water sources. Hence, overcoming phytoremediation is a new approach that involves using metal-accumulating or metal-tolerant plants to remediate metal-contaminated soils. Some plants have an inherent ability to absorb and hyperaccumulate heavy metals in their tissues, which can be used to remove hazardous heavy metals from contaminated soils. Bioremediation of chromium-contaminated soils is a widely established process that uses biological wastes to detoxify or change harmful Cr into less hazardous forms. Though it has several limitations, this technology holds continuing interest because of its cost-effectiveness. We examined the potential of certain crops (flower and fodder crops) and biological wastes (poultry manure, press mud compost, farmyard manure, and poultry biochar) in remediating the Cr-contaminated soil.

The objective of the present study was to investigate the phytoextraction potential of chrysanthemum and Cumbu Napier hybrid grass with various bioamendments such as FYM, poultry manure, press mud compost, and biochar to remediate the Cr from contaminated soil. In addition, this study also aimed to restore contaminated sites by identifying acceptable phytotolerance amendments, Cr accumulation, and translocation potential to aerial parts of chrysanthemum and Cumbu Napier hybrid grass.

Materials and Methods

Description of the Study Area and Initial Soil Characteristics

The effect of various bioamendments and the plants on the bioavailability of Cr were studied by performing a pot culture

Table 1 Characteristics of the experimental soil

Parameter	Unit	Value
Soil type	–	Clay loam
As per USDA classification	–	Vertisols
Bulk density	Mg m ⁻³	1.09
pH	–	7.30 ± 0.11
Electrical conductivity	dSm ⁻¹	0.542 ± 0.01
Organic matter	%	0.96 ± 0.02
Nitrate nitrogen	mg kg ⁻¹	63.7 ± 1.06
Available phosphorus	mg kg ⁻¹	23.72 ± 0.20
Exchangeable potassium	mg kg ⁻¹	428 ± 4.90
Exchangeable calcium	mg kg ⁻¹	2601 ± 5.41
Exchangeable magnesium	mg kg ⁻¹	815 ± 4.66
Available sulfur	mg kg ⁻¹	44.0 ± 0.89
Available manganese	mg kg ⁻¹	9.38 ± 0.20
Available copper	mg kg ⁻¹	2.34 ± 0.04
Available boron	mg kg ⁻¹	0.5 ± 0.006
Total chromium	mg kg ⁻¹	BDL
Cation exchange capacity	Cmol (p+) kg ⁻¹	22.40 ± 0.33

BDL below detectable limit (below 0.1 ppm)

experiment at the National Agro Foundation Research and Development Centre, Chennai, India (12° 98'84.01" N, 80° 22'26.4" E). Two plant species, i.e., chrysanthemum and Cumbu Napier hybrid grass, were grown to screen metal accumulation and phytoremediation of Cr-contaminated soils. The farmyard manure, composted poultry manure, press mud compost, and biochar were applied and uniformly mixed according to the treatment schedule (crop production guide, 2005). To compensate for moisture loss, a known amount of water was added to each pot regularly. At the end of the experiment, soil and plant samples were collected for various analyses.

Soil Sample Collection and Analysis

Soil samples from the pot culture experiment were collected at fortnightly intervals on the 0th, 15th, 30th, 45th, and 60th days. Soil samples were collected and dried for 2–3 days, ground, sieved (2 mm sieve), packed in polyethylene cover, and used for further analysis. pH was measured with a pH meter (Jackson 1973), EC with a conductivity meter (Jackson 1973), organic carbon with a wet digestion method (Walkley and Black 1934), total Cr content digestion with aqua regia (USEPA 1979), and speciation of Cr by the sequential extraction method (Noble and Hughes 1991). The important characteristics of these bioamendments are presented in Table 1. First, 4.0 kg soil was taken in plastic pots, amendments were added according to treatment and uniformly mixed. Then, 5 kg plastic pots were taken and the soil was transferred to it. 2.83 g K₂Cr₂O₇ was added in

1000 mL distilled water and dissolved to make a Cr stock solution of 1000 ppm. The soil in the pot was then treated with an aqueous solution of $K_2Cr_2O_7$ to get 300 ppm. After that, both seedlings of local varieties collected from the local nursery were transplanted into each pot. Finally, watering and weeding were done on an as-needed basis. The experiment was replicated three times with a completely randomized block design with the treatments of T_1 —control (soil alone) + 300 ppm of Cr, T_2 —soil + 300 ppm of Cr + 12.5 t ha^{-1} of farmyard manure, T_3 —soil + 300 ppm of Cr + 5 t ha^{-1} of composted poultry manure, T_4 —soil + 300 ppm of Cr + 5 t ha^{-1} of press mud compost, T_5 —soil + 300 ppm of Cr + 5 t ha^{-1} of biochar. For all four treatments, control pots containing no heavy metals were kept.

Plant Harvest and Sample Analysis

For the determination of the Cr accumulation in the plants, on the 60th day of the flowering stage, the plants were harvested and separated into roots, shoots, and leaves; then, the samples were dried in a 65 °C oven to achieve constant weight, and the dry weight of each component was recorded. Finally, the dried plant samples were crushed and digested with a di-acid mixture (9 HNO_3 :4 $HClO_4$) in 10 mL, and the Cr concentration was determined using an atomic absorption spectrophotometer (Varian Spectra AA220). The data on plant height (cm), root, and shoot length (cm) were recorded.

Bioconcentration Factor (BCF) and Translocation Factor (TF)

BCF is the ratio of concentration of Cr in plant tissue to its concentration in soil. BCF is the plant's ability to accumulate heavy metals. $BCF > 1$ indicates heavy metal accumulation in the shoot. TF is the ratio of a plant's ability to extract heavy metals from the root to shoot; TF indicates heavy metal accumulation in the root and vice versa (Zhang et al. 2014).

$$BCF = \text{Cr in the roots (mg kg}^{-1}\text{)}/\text{Cr in the soil (mg kg}^{-1}\text{)}$$

$$TF = \text{Cr in stover/stalks (mg kg}^{-1}\text{)}/\text{Cr in roots (mg kg}^{-1}\text{)}$$

$$EF = \text{Cr in stover/stalk (mg kg}^{-1}\text{)}/\text{Cr in soil (mg kg}^{-1}\text{)}$$

Statistical Analysis

Statistical analysis of experimental data from the experiment was carried out to determine the effect of treatments and factorial completely randomized design (pot culture experiment) by statistical software SPSS Version 22. The *F* test used a 0.05 probability level of significance. The analysis of variance was suggested and calculated by Panse and Sukhatme (1967). A simple Pearson correlation analysis was also carried out to determine the relationship between the soil parameters and crop yield under the impact of treated tannery effluent at different dilutions in combination with amendments (Blyth 1994).

Results and Discussion

Characteristics of Soil and Bioamendments

The pH of the experimental soil was 7.30 with an EC of 0.542 $dS m^{-1}$, and other parameters are given in Table 2. Four bioamendments were chosen: farmyard manure, composted poultry manure, press mud compost, and biochar. The pH varied between 6.23 (composted poultry manure), 6.27 (press mud compost), 7.25 (farmyard manure), and 7.86 (biochar). The electrical conductivity (EC) was 2.35 $dS m^{-1}$ (composted poultry manure), 2.28 $dS m^{-1}$ (press mud compost), 3.08 $dS m^{-1}$ (farmyard manure) and 3.19 $dS m^{-1}$ (biochar). The farmyard manure has an organic carbon content of 24.12%, which is higher than others when compared to composted poultry manure (20.42%), press mud compost (16.80%), and biochar (5.16%).

Table 2 Physicochemical characteristics of bioamendments used

Parameter	Unit	Farmyard manure	Composted poultry manure	Press mud compost	Biochar
pH		7.25 ± 0.009	6.23 ± 0.07	6.27 ± 0.13	7.86 ± 0.19
EC	dSm^{-1}	3.08 ± 0.02	2.35 ± 0.003	2.28 ± 0.03	3.19 ± 0.06
Total Nitrogen	%	1.85 ± 0.04	2.75 ± 0.04	2.29 ± 0.04	1.19 ± 0.02
Total phosphorous	%	7.54 ± 0.003	1.44 ± 0.03	10.18 ± 0.08	10.35 ± 0.21
Total Potassium	%	0.13 ± 0.001	0.86 ± 0.01	0.62 ± 0.01	0.76 ± 0.005
Nickel	$mg kg^{-1}$	16.01 ± 0.39	16.26 ± 0.25	13.50 ± 0.29	18.07 ± 0.23
Lead	$mg kg^{-1}$	19.65 ± 0.15	24.07 ± 0.26	21.05 ± 0.15	24.00 ± 0.53
Chromium	$mg kg^{-1}$	BDL	0.47 ± 0.001	0.33 ± 0.007	BDL
Cadmium	$mg kg^{-1}$	3.69 ± 0.08	3.14 ± 0.02	3.07 ± 0.07	3.86 ± 0.04

BDL below detectable limit (below 0.1 ppm)

Changes in Soil pH After Bioamendments Addition

The adsorbent characteristics and the metal ion's ionization level in the aqueous solution depend on the solution's pH (Puentes-Cárdenas et al. 2012). Due to the application of bioamendments, the pH of the soil was changed significantly (Fig. 1). The pH varied between 7.34–8.18 and 7.06–8.21 in soil with chrysanthemum and Cumbu Napier hybrid, respectively. Soil pH is the most critical factor influencing the plant's heavy metal uptake (Eriksson and Weeks 1994). According to this study, the pH of the soil was alkaline in control soil and soils with lower concentrations of heavy metals in all four treatments. The pH increased as the metal concentration increased. The soil pH gradually increased from 0 to the 60th day in the crops. The bioamendments had a marked influence on soil pH. Initially, in chrysanthemum, the pH of the soil was found to be maximum (7.82) in the treatment that had composted poultry manure (T₃), followed by farmyard manure, and minimum (7.34) in the control soil (T₁). Alkali salts release from feedstock during pyrolysis may affect the alkaline pH of biochar (Ahmad et al. 2012). At the final stage, a significantly higher pH (8.18) was observed in the control soil (T₁), and lower pH (8.05) was obtained in the soil amended with farmyard manure (T₂) in chrysanthemum. In addition, lower adsorption of cations Cr at low pH might be due to the competition of H⁺ and metal ions (Banat et al. 2003) and electrostatic repulsion (Jeon and Höll 2003).

The soil becomes alkaline as the pH rises, and metal ion bioavailability decreases. Lower pH is ideal for metal availability, but is detrimental to vegetation (Hutchinson et al. 2007). Initially, in Cumbu Napier hybrid grass, the pH of the soil was found to be maximum (7.19) in the treatment that had farmyard manure (T₂) and minimum in the composted poultry manure soil (T₃). After that, a gradual increase was observed throughout the experiment. At lower pH levels, the surface functional groups (mostly

oxygen-containing groups) bind to the H⁺, rendering them inaccessible to Cr ions, according to Liu et al. (2016). As a result, the CEC of biochar was higher, and the reason for the high CEC in biochar could be the increase in surface area after pyrolysis and surface charge density (Tomczyk et al. 2020).

Changes in Soil Electrical Conductivity (EC) After Bioamendments Addition

Electrical Conductivity (EC) ranged from 0.59 to 1.32 in the soil during the experiment with chrysanthemum. EC was found to increase with the advancement of time. On the 0th day, it was found to be a maximum (0.93) in the soil amended with press mud compost (T₃) and a minimum (0.74) in farmyard manure (T₂) initially. Alternatively, conductivity increased as metal content increased because conductivity indicates the concentration of soluble salts in the soil (Rhoades 1996). At a later stage, the maximum (1.32) value was recorded in the soil added with composted poultry manure (T₃) and the minimum (1.07) in control (T₁). The EC ranged from 0.44 to 1.18 in the soil with Cumbu Napier hybrid grass in the chrysanthemum. In general, EC increased with the advancement of time. On the 0th day, it was found to be maximum (0.86) in the soil amended with biochar (T₅) and minimum (0.44) in farmyard manure (T₂) initially. Biochar also had a significant effect on soil EC. In support of the results obtained, Mueguet et al. (2017) reported an increase in soil EC when the biochar dose was increased from 5 to 10%. At a later stage, the maximum (1.18) value was observed in the soil added with composted poultry manure (T₃) and minimum (1.01) in control (T₁) shown in Fig. 2. This is correlated with the findings of Souza et al. (2018), who reported the severity associated with salinization of soil by utilizing water enriched with salts like NaCl.

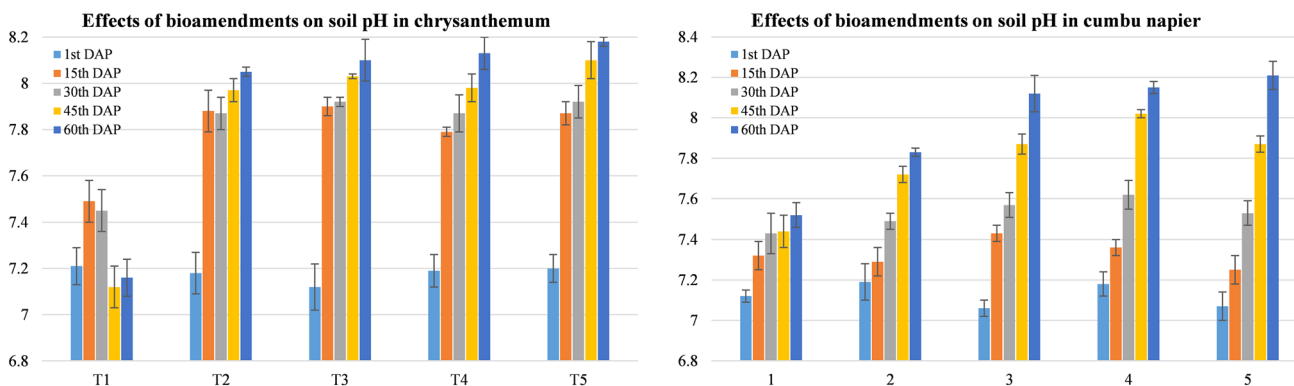


Fig. 1 Effect of bioamendments on pH of chromium-contaminated pot experiment with chrysanthemum and Cumbu Napier

Changes in Soil Organic Carbon (SOC) After Bioamendments

Soil Organic Carbon (SOC) in soil bioamendments has shown a marked influence on SOC. Initially, the SOC was found at maximum (0.26%) in the soil amended with biochar (T₅) and minimum (0.13%) in the control soil (T₁), followed by the soil amended with farmyard manure (T₂). Organic carbon bioamendments are introduced into the soil, interacting with microorganisms to supplement other nutrients and make them available to plants (Barajas-Aceves 2005). However, at a later stage, the maximum SOC was (0.71%) recorded in the soil amended with farmyard manure (T₂) and the minimum (0.46%) in the control soil (T₁) in the chrysanthemum. With increasing heavy metal concentrations, biomass carbon decreases as a percentage of soil organic carbon (Al-Wabel et al. 2019). The SOC ranged from 0.18 to 0.69% during 60 days in Cumbu Napier hybrid grass (Fig. 3), and there was a gradual increase from the 0th day to the 60th day.

The bioamendments have shown a marked influence on SOC. Initially, the SOC was found to be maximum (0.51%) in the soil amended with biochar (T₅) and minimum (0.18 percent) in the (T₂). Applying FYM @ 12.5 t ha⁻¹ also improves the soil organic carbon content due to the contribution of C and synergistic effect on soil physical, chemical, and biological properties. This is in line with the findings of Saha et al. (2021). As a result, biochar is more likely to serve as a soil conditioner and nutrient transformation catalyst than as a predominant source of nutrients (Lehmann et al. 2003). It collaborates with the findings of Wiesmeier et al. (2015), who reported a substantial decline in SOC of the organic manure-amended soils due to the C mineralization and its respective losses.

Biotransformation and Bioavailability of Cr in Contaminated Soil

Chemical bioavailability is today's thought to mitigate chemical availability even though it is in contact with soil.

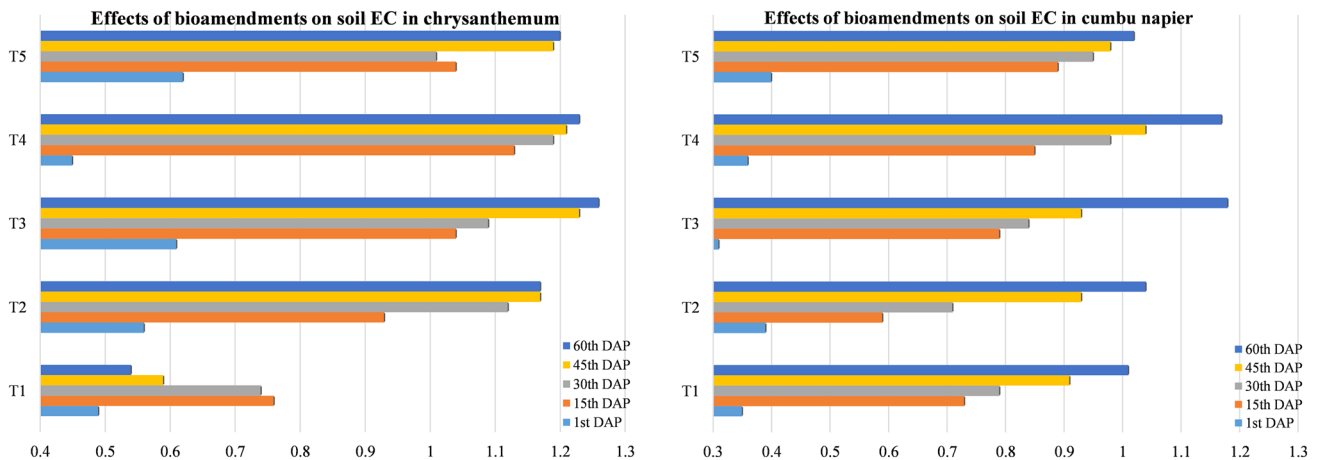


Fig. 2 Effect of bioamendments on EC (dS m⁻¹) of chromium-contaminated pot experiment with chrysanthemum and Cumbu Napier

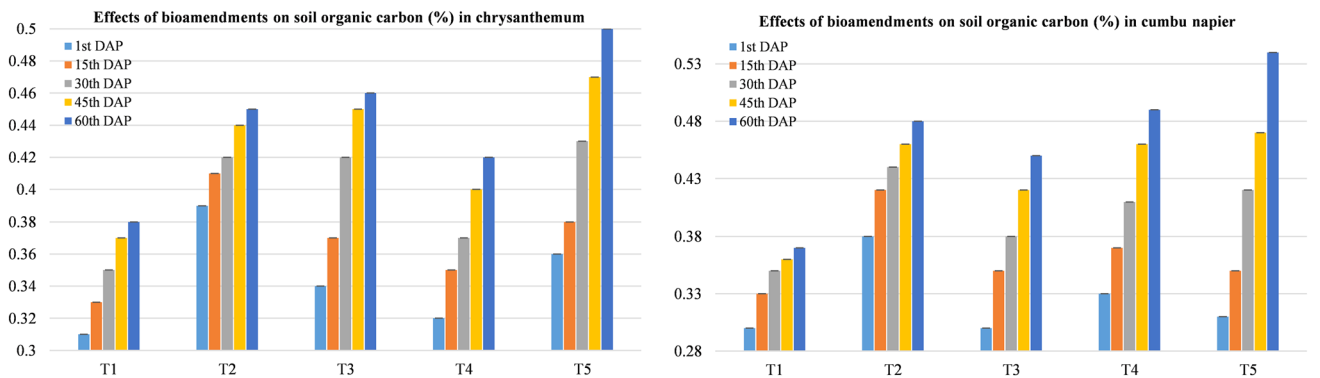


Fig. 3 Effect of bioamendments on organic carbon (%) in chromium-contaminated pot experiment with chrysanthemum and Cumbu Napier

Favas et al. (2011) reported that availability depends on soil's origin, mineralogy, properties (physical and chemical), and edaphic factors. Metal speciation defines the forms in which an element occurs. Therefore, the knowledge of metal speciation in soils is much needed to understand its transport and interaction better. In the current study, diverse water sources and amendments influence Cr speciation via changes in soil chemical characteristics and metal adsorption, complexation, and chelation. Chop-pala et al. (2016) reported transforming the water-soluble fraction into fractions of lower solubility through surface complexation or adsorption onto the soil particles.

Changes in Water-Soluble Chromium: Chrysanthemum

Chromium is water soluble, and the application of bioamendments resulted in drastic changes in the concentration of water-soluble Cr. Water-soluble Cr concentrations ranged from 14.94 to 37.25 mg kg⁻¹. From the 0th day to the 60th day, the concentration of H₂O-soluble Cr decreased gradually. Initially, the concentration of H₂O-soluble Cr in the control soil (T₁) was found to be significantly higher (37.25 mg kg⁻¹) and lower (26.21 mg kg⁻¹) in the soil amended with composted poultry manure (T₃). The highest value (21.27 mg kg⁻¹) was recorded in the soil amended with biochar (T₅) at the final stage (60th day), and the lowest in the soil amended with farmyard manure control (14.27 mg kg⁻¹). The possible mechanism involved includes the release of soluble salts from organic manure and dissolving salts from the soil on decomposition. This conforms to the findings of Mokolobate and Haynes (2002).

Changes in Water-Soluble Chromium: Cumbu Napier Hybrid Grass

The application of bioamendments resulted in remarkable changes in the concentration of water-soluble Cr. The H₂O-soluble Cr concentration ranged from 18.27 to 38.21 mg kg⁻¹. The water-soluble Cr was found to increase slightly from the 0th day to the 15th day and then gradually decrease up to the 60th day of the experiment. Initially, the H₂O-soluble Cr concentration was found to be significantly higher (38.21 mg kg⁻¹) in the soil amended with composted poultry manure (T₃) and lower (35.25 mg kg⁻¹) in the control soil (T₁). However, the highest value (22.34 mg kg⁻¹) was recorded in the soil amended with press mud compost (T₄) at the final stage (60th day) and the lowest in press mud compost (18.27 mg kg⁻¹).

Changes in Exchangeable Chromium: Chrysanthemum

The exchangeable Cr showed marked changes as the concentrations ranged between 15.94 and 34.56 mg kg⁻¹. The concentration was found to decrease gradually from the 0th day to the 15th day, and after that, it increased rapidly up to the 60th day. Initially, the soil was amended with composted poultry manure (T₃) and had the highest concentration of exchangeable Cr (28.21 mg kg⁻¹), and the biochar-amended soil had the lowest (21.94 mg kg⁻¹) (T₅). In the end, the highest value was recorded in the treatment (T₃) with composted poultry manure (34.56 mg kg⁻¹), and the lowest value was recorded in control (T₁) (24.28 mg kg⁻¹). The reduced exchangeable fraction in biochar-amended soils might be due to Cr ions in pore spaces present in the biochar, as Beesley et al. (2011) reported. However, this fraction remained more or less similar to the water-soluble fraction.

Changes in Exchangeable Chromium: Cumbu Napier Hybrid Grass

The exchangeable Cr showed marked changes as the concentrations ranged between 31.45 and 57.64 mg kg⁻¹. The concentration was found to decrease gradually from the 0th day to the 30th day; and after that, it increased rapidly up to the 60th day. Initially, the highest concentration of exchangeable Cr (39.34 mg kg⁻¹) was reported in control soil (T₁), while the lowest (31.45 mg kg⁻¹) was noticed in biochar-amended soil (T₅). In the end, the highest value was recorded in the treatment (T₃) with composted poultry manure (57.64 mg kg⁻¹), and the lowest value was recorded in control (57.64 mg kg⁻¹) (50.37 mg kg⁻¹).

Changes in Organic Chromium: Chrysanthemum

The organic Cr in soil ranged from 51.67 and 91.43 mg kg⁻¹. During the experimental period, the concentration of organic Cr gradually increased from the 0th day to the 30th day. After that, it showed a slight decrease on the 45th day and a sudden increase on the 60th day. Thus, there were marked changes in the concentration of organic Cr due to the application of bioamendments. Initially, the concentration of organic Cr was found high in the treatment (T₄) with press mud compost (81.23 mg kg⁻¹) and low in the control soil (51.67 mg kg⁻¹). Because of adsorption, complexation, and precipitation, the inorganic salts in the soil make phytoextraction difficult (Zaier et al. 2014). The concentration of organic Cr was found to increase over time, and finally, the highest value of 75.32 mg kg⁻¹ was recorded in the treatment that had composted poultry manure (T₃). The lowest value of 60.61 mg kg⁻¹ was observed in the control soil (T₁). A negative charge on the biochar's surface could explain why

substrates have a higher adsorptive capacity. The charges and functional groups in the biochar increased its ability to adsorb metal cations.

Changes in Organic Chromium: Cumbu Napier Hybrid Grass

The organic Cr in soil ranged from 51.82 to 88.31 mg kg⁻¹. During the experimental period, the concentration of organic Cr gradually decreased from the 0th day to the 15th day, and there was a sudden increase from the 30th day after that. It showed a slight decrease on the 45th day and a sudden increase on the 60th day. There were marked changes in the concentration of organic Cr due to the application of bioamendments. Initially, the concentration of organic Cr was found high in the treatment (T₄) with press mud compost (84.34 mg kg⁻¹) and low in the control soil (54.39 mg kg⁻¹). The concentration of organic Cr increased over the 30th day, and finally, it increased up to the 60th day. The highest value of 84.54 mg kg⁻¹ was recorded in the treatment with press mud compost (T₄). The lowest value of 51.82 mg kg⁻¹ was observed in the biochar (T₅). The results relating biochar addition and organic Cr fraction contradict the findings of Herath et al. (2015), which followed a decrease in an organic heavy metal fraction on biochar application.

Changes in Organic Plus Iron Oxide: Chrysanthemum.

The organic plus iron oxide fraction of Cr was influenced significantly by different bioamendments. The concentration of organic plus iron oxide bound Cr ranged from 97.58 to 175.29 mg kg⁻¹, and it was increased up to the 60th day of the experiment with chrysanthemum. Due to various treatments, there were significant changes in organic plus iron oxide bound Cr in soil. The organic plus iron oxide bound Cr was found to be high (115.98 mg kg⁻¹) in the control soil (T₁) and low (97.58 mg kg⁻¹) in the soil amended with press mud compost during the initial stage of the experiment (T₄). Finally, it was high (175.29 mg kg⁻¹) in the control soil (T₁) and low (138.61 mg kg⁻¹) in the biochar-added soil (T₂) (T₅). This fraction's increase could be attributed to Cr complexation or chelation with organic matter.

Changes in Organic Plus Iron Oxide: Cumbu Napier Hybrid Grass

The organic plus iron oxide fraction of Cr was influenced significantly by different bioamendments. The concentration of organic plus iron oxide bound Cr ranged from 95.83 to 179.59 mg kg⁻¹, decreased up to the 30th day, and then increased slightly during the 45th and 60th day of the experiment with Cumbu Napier hybrid grass. Due to

various treatments, there was a significant change in soil's organic plus iron oxide bound Cr. During the initial stage of the experiment, the organic plus iron oxide bound Cr was found high (141.09 mg kg⁻¹) in soil amended with farmyard manure (T₂) and low (108.23 mg kg⁻¹) in the composted poultry manure. Finally, it was high (179.59 mg kg⁻¹) in the treatment that had farmyard manure (T₂) and low (129.64 mg kg⁻¹) in the soil amended with biochar (T₅).

Changes in Residual Chromium: Chrysanthemum

The residual fraction of Cr in soil ranged from 109.38 to 181.23 mg kg⁻¹. The concentration of residual Cr increased gradually from the 0th day to the 15th day and then decreased on the 60th day in soil with chrysanthemum. Initially, the highest value (145.24 mg kg⁻¹) of residual Cr was obtained in the control soil (T₁), and the lowest value (118.29 mg kg⁻¹) in the biochar-amended soil. However, during the final stage of the experiment, the highest concentration of residual Cr (153.79 mg kg⁻¹) was recorded in the press mud-amended soil (T₄), and the lowest residual Cr (109.38 mg kg⁻¹) in the biochar-amended soil (T₅). Comparing other Cr fractions, the residual fraction is the most stable and the least bioavailable found within the crystal lattice of soil silicate minerals. This might be due to the sorption of Cr. These results are in line with the findings of Zhang et al. (2013), and Zhu et al. (2015) reported a positive relationship between the biochar dosage and residual fraction of heavy metals.

Changes in Residual Chromium: Cumbu Napier Hybrid Grass

The residual fraction of Cr in soil ranged from 101.72 to 175.29 mg kg⁻¹. The concentration of residual Cr increased gradually from the 0th day to the 30th day and then decreased on the 60th day in soil with Cumbu Napier hybrid grass. Initially, the highest value (139.56 mg kg⁻¹) of residual Cr was found in the control soil (T₁), and the treatment with biochar yielded the lowest value (101.72 mg kg⁻¹). However, during the final phase of the experiment, the highest residual Cr concentration (127.25 mg kg⁻¹) was found in farmyard manure (T₂), and the lowest residual Cr (102.15 mg kg⁻¹) in biochar-amended soil (T₅).

Phytoextraction Potential of Cumbu Napier Hybrid Grass and Chrysanthemum

The phytoextraction potential of Cumbu Napier hybrid grass and chrysanthemum with various bioamendments to remediate the Cr from contaminated soil is presented in Fig. 4. Total chromium content in both the chrysanthemum and Cumbu Napier hybrid grass significantly

showed a decreasing trend throughout the experiment. The total Cr content ranged from 92.39 to 298.29 mg kg⁻¹. As time progress, metal ion adsorption decreases gradually because ions must transfer through the deeper surface of the pores, where they face significant resistance, resulting in lower adsorption during the later phase of the study (Srivastava et al. 2020). Among all the treatments, T₃ (soil + composted poultry manure @ 5 t ha⁻¹) has the highest total Cr content of 298.89 mg kg⁻¹ during the first days, followed by T₁ (297.29 mg Kg⁻¹) (control soil without amendment) in chrysanthemum. Evidently, none of the crops showed any toxicity symptoms at high Cr concentrations in the study. Alternatively, conductivity increased as metal content increased, which might be explained because conductivity indicates the concentration of soluble salts in the soil. At the same time, the lowest total Cr content of 92.39 mg kg⁻¹ was recorded in T₃ (soil + composted poultry manure @ 5 t ha⁻¹). Among all the treatments, T₃ (soil + poultry manure @ 5 t ha⁻¹) with 92.39 mg kg⁻¹ shows the highest reduction in total Cr content in chrysanthemum. A decrease in Cr concentration in wheat plants with bioamendments application might be due to the complexation of Cr with amendments in the outer part of the root cell wall (Siebers et al. 2013). Several studies showed that the organic amendments resulted in the successful revegetation of metal-contaminated soil (Ortiz and Alcaniz 2006; Kumar et al. 2008). The total Cr content in the Cumbu Napier hybrid grass ranged from 72.97 to 299.82 mg kg⁻¹. They determined that as contact time and agitation speed increase, so does Cr adsorption by biological amendments (Priyanka and Venkatachalam 2020). In the treatments, the highest total Cr content was recorded at 299.82 mg kg⁻¹ in T₃ (soil + composted poultry manure @ 5 t ha⁻¹) during the initial days, followed by 294.23 mg kg⁻¹ in T₅ (soil + biochar @ 5 t ha⁻¹), whereas

on the 60th day of the experiment, the lowest total Cr content of 72.97 mg kg⁻¹ was recorded in T₅ (soil + biochar @ 12.5 t ha⁻¹).

Furthermore, the adsorption rate of the later phase is determined by the rate of ion transport from the exterior to the interior sites of the adsorbent particles (Shafaghat et al. 2012). Among all the treatments, T₅ (soil + biochar @ 5 t ha⁻¹) shows the highest reduction in total Cr content in Cumbu Napier hybrid grass, followed by T₂ (soil + farmyard manure 12.5 t ha⁻¹). Therefore, such Cr-tolerant crops can be used for phytoremediation of soil contaminated with Cr.

Effect of Cr on Chrysanthemum and Cumbu Napier Height and Root Length

The major limiting factors for plant growth were heavy metal phytotoxicity and severe infertility of contaminated soils (Rotkittikhun et al. 2007; Norwood et al. 2013). The plant height ranges from 19.92 to 22.21 cm in chrysanthemum (Fig. 5). At the final stage (60th day), the highest plant height was recorded, 22.21 cm at T₂ (farmyard manure @ 12.5 t ha⁻¹), followed by the control and the lowest plant height, 19.92 cm, was recorded in T₅ (Prosopis biochar @ 5 t ha⁻¹) in chrysanthemum. Cr's adverse effects on different plants have been reported to affect plant height and shoot growth (Joseph et al. 2008). At the final stage (60th day), the highest plant height was recorded, 51.53 cm, at T₁ (control), followed by T₃ (composted poultry manure), and the lowest plant height, 42.30 cm, was recorded in T₂ (farmyard manure), followed by T₅ (biochar) in Cumbu Napier hybrid grass. The decrease in plant height may be attributed primarily to decreased root growth and less nutrient and water transport to the plant's upper parts (Zurayk et al. 2001). Supporting this, Chahal et al. (2017) reported a negative relationship between organic carbon content and salt

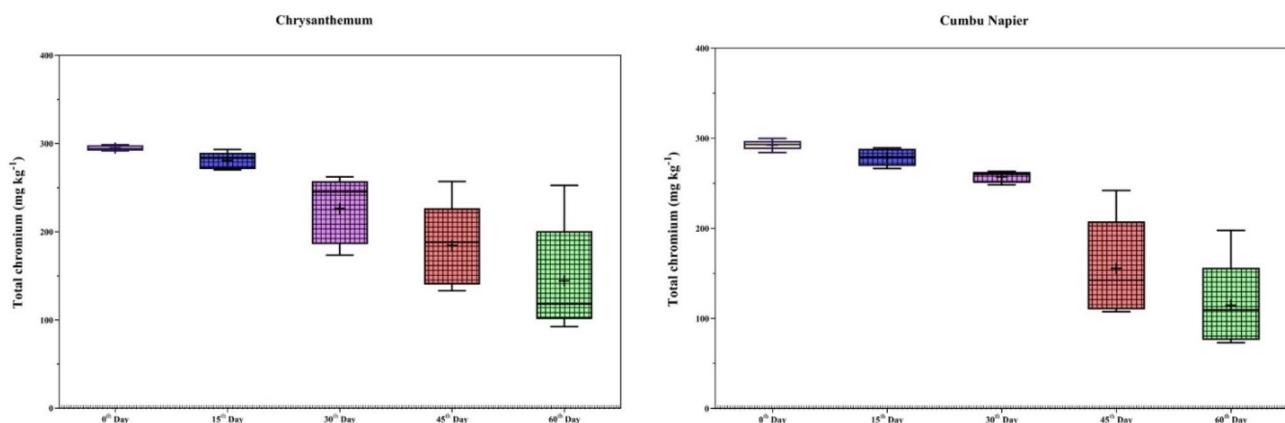


Fig. 4 Effect of bioamendments on total chromium (mg Kg⁻¹) in chromium-contaminated pot experiment with chrysanthemum and Cumbu Napier

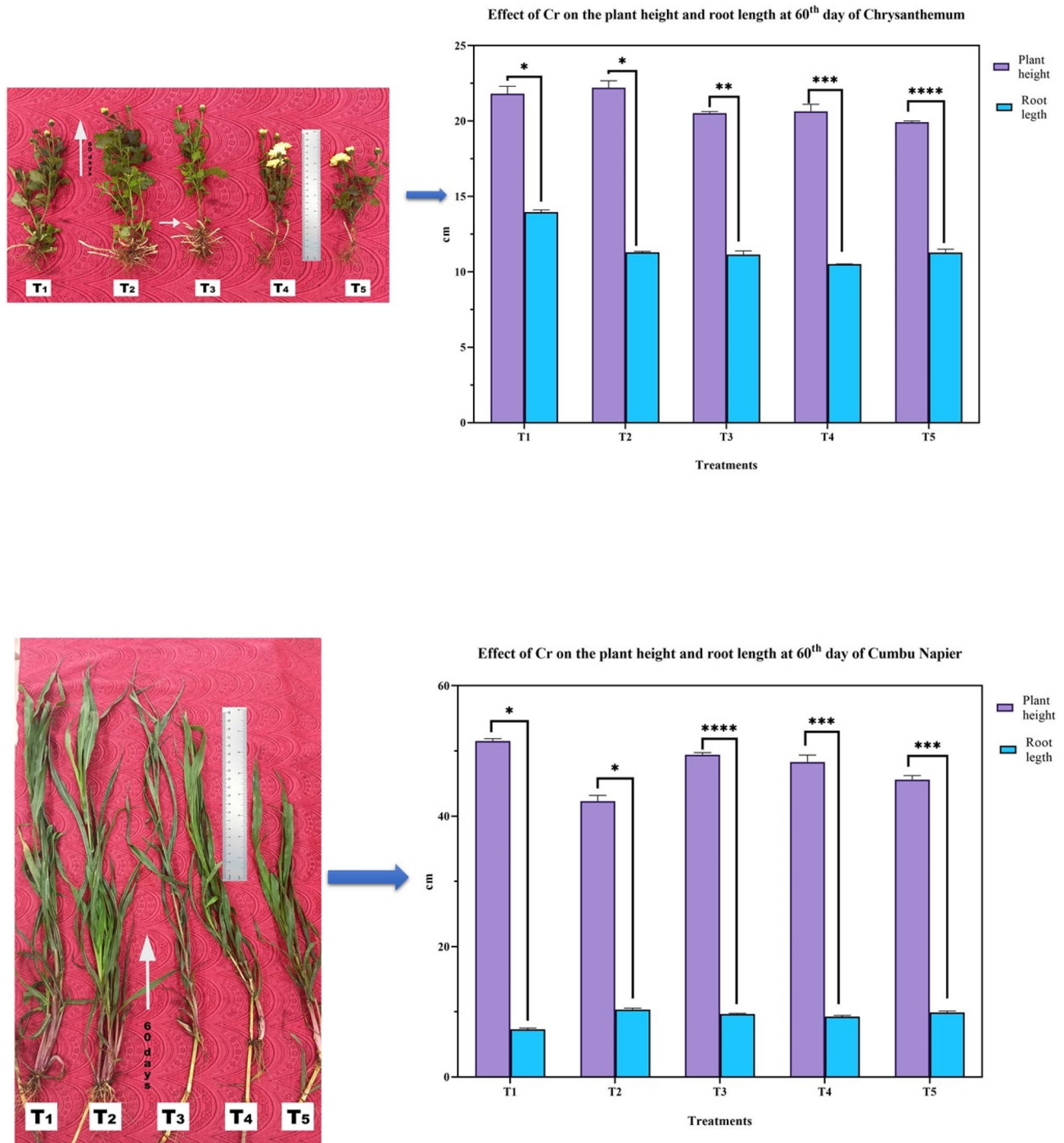


Fig. 5 Effect of Cr on the plant height and root length at 60th day of chrysanthemum and Cumbu Napier

concentration in soils amended with animal manure. Adding this, Verma et al. (2010) reported a decline in soil respiration rate (index to assess the microbial activity) in the soils contaminated with heavy metals (Cr, Cd, Ni, etc.), thereby reducing the soil organic carbon content.

The root length of the chrysanthemum ranges from 10.52 to 13.96 cm. The highest root length of 13.96 cm was

recorded in control soil, followed by T₂ (composted poultry manure @ 12.5 t ha⁻¹), and the lowest root length of 10.52 cm was recorded in T₄ (press mud compost), followed by T₂ (farmyard manure) in chrysanthemum. Heavy metals have been shown to inhibit root growth in trees and crops (Godbold and Kettner 1991), and a similar reduction in total root weight and length was observed in wheat at 20 ppm Cr

(Chen et al. 2015). The root length of the chrysanthemum ranges from 7.31 to 10.32 cm. The highest root length of 10.32 cm was recorded in composted poultry manure (T_2), followed by T_5 (biochar @ 5 t ha⁻¹), and the lowest root length of 7.31 cm was recorded in T_1 (control), followed by T_4 (press mud compost) in Cumbu Napier hybrid grass. A decrease in plant height to increasing soil salt concentration might reduce cell division, elongation, and cell wall rigidity. An excessive quantity of specific salts injures the plant cells, affecting plant growth. These obtained findings are in accordance with Heidari and Golpayegani (2012). This result also showed the beneficial effect of FYM in soils having a higher concentration of soluble salts. The reduction in the yield attributes and yield under higher soluble salt concentration might be due to (1) reduced supply of water and (2) nutrient imbalance which inhibits the diversion of photosynthetic to sink.

Identifying Phytotolerance Amendments Based on Chromium Uptake and Bioconcentration Factor (BCF)

Chromium Uptake by Chrysanthemum

Plant biomass and growth rate are two critical factors when selecting plant species for phytoremediation. Phytoextraction is regarded as the best phytoremediation method for removing contamination primarily from the soil without destroying its structure and fertility (Ghosh and Singh 2005). The Cr content in aboveground biomass and belowground biomass of chrysanthemum was calculated. However, most of the Cr concentrated in the roots of both crops did not move to the plant's upper part. Noticeably, in the treatments with lower Cr concentrations, accumulation was retained entirely in the roots (T_5). The application of different bioamendments significantly influenced the Cr content of the chrysanthemum. In the aboveground biomass, the Cr content varied between 35.17 and 196.28 $\mu\text{g g}^{-1}$. While plants grown on control soil (T_1) had the lowest Cr content, plants grown on soil amended with press mud compost @ 5 t ha⁻¹ had the highest Cr content (196 g g^{-1}) (T_4).

Cr concentrations in the roots were higher than in other plant parts, indicating that Cr is not readily translocated within plants. The Cr content of root biomass showed a differential pattern varying from 74.60 to 219.70 $\mu\text{g g}^{-1}$. This poses a higher risk of Cr in the roots due to Cr being immobilized in the vacuoles of the root cells, making it non-toxic, which could be a natural plant toxicity response (Das et al. 2020). The plants grown on the control soil had the lowest Cr content in root biomass, whereas the highest Cr content in root biomass was observed in plants grown on soil amended with composted poultry manure @ 12.5 t ha⁻¹. The Cr uptake by chrysanthemum varied between 308.90 and

858.66 $\mu\text{g plant}^{-1}$. The Cr concentration and accumulation in root and shoot of chrysanthemum increased with increasing Cr (VI) concentrations in soil.

Because the plants absorb, concentrate, and potentially cause toxic metals from contaminated soils to accumulate in their biomass, they are better suited to the remediation of diffusely contaminated environments where contaminants are only present in trace amounts and tangentially (Tiwari et al. 2019). This might be due to the higher amount of Cr added through water source, higher metal solubility under high salt concentration, and reduced microbial activity under high salt concentration affecting Cr transformation, keeping a higher proportion under water-soluble form. These results are in accordance with the findings of Navarro-Pedreño et al. (2003). Furthermore, as the above conditions improved the Cr availability, Cr uptake was higher under high salt concentration. This corroborates the conclusion drawn by Ali et al. (2015).

Chromium Uptake by Cumbu Napier Hybrid Grass

The application of different bioamendments significantly influenced the Cr content of Cumbu Napier hybrid grass. In the aboveground biomass, the Cr content varied between 56.55 and 241.60 $\mu\text{g g}^{-1}$. Furthermore, pollutant phytoavailability is influenced by soil physicochemical properties and plant physiological characteristics (Ren et al. 2018). The findings on tuberose showed reduced biomass production in all four plant species (Ramana et al. 2015). Heavy metal toxicity is usually determined by the amount of metal accumulated by plants (Sevik et al. 2019), while the lowest Cr content was found in plants grown on control soil (T_1), and the highest Cr content (241.60 $\mu\text{g g}^{-1}$) was observed in plants that grew on soil amended with press mud compost @ 5 t ha⁻¹ (T_4). All the bioamendments had a significant influence on Cr content. The application of different bioamendments significantly influenced the Cr content of Cumbu Napier hybrid grass-root biomass. The Cr content of root biomass showed a differential pattern varying from 46.87 to 171.70 $\mu\text{g g}^{-1}$. Cumbu Napier hybrid grass biomass ranged from 6.80 to 11.02 g. The plant grown on soil amended with press mud compost (T_4) was found to have the highest biomass (11.02 g), followed by Prosopis biochar (T_5), whereas the lowest biomass (6.80 g) was recorded in plants grown on control soil (T_1). The application of different bioamendments significantly influenced the uptake of Cr by Cumbu Napier hybrid grass. The Cr uptake by Cumbu Napier hybrid grass varied between 765.46 $\mu\text{g plant}^{-1}$ and 1356.51 $\mu\text{g plant}^{-1}$. According to Santiago and Shenbagavalli (2010), the threshold for defining Cr hyperaccumulation is 1000 mg kg^{-1} of Cr in the dry matter of aboveground tissues (0.1%).

The applied Cr significantly reduced the plant's total dry weight compared to the control. Cumbu Napier hybrid grass, commonly known as CO₄, is one of both plants' best-known hyperaccumulators; without visible injury, it has been shown to accumulate up to 1200 mg kg⁻¹ Cr and up to 40% of soil-exchangeable Cr from contaminated sites. So far, no research on the phytoremediation effectiveness and phytoaccumulation potential of Cumbu Napier hybrid grass to chromium has been authored. As a result, many methods for increasing pollutant phytoavailability have been proposed, including agricultural management (e.g., fertilization), treatment with added chemicals (e.g., chelating agent), inoculation of rhizospheric microorganisms, and genetic engineering (Song et al. 2019). Increasing the phytoavailability of pollutants has been shown to improve the phytoremediation efficiency.

Bioconcentration Factor (BCF) and Translocation Factor (TF)

Bioconcentration Factor (BCF) is used to classify plants as excluders (BCF value less than 1), accumulators (BCF value 1 to 10) or hyperaccumulators (BCF greater than 10) based on their BCF value (Lam et al. 2018). Brassicaceae, Fabaceae, Euphorbiaceae, Asteraceae, Lamiaceae, and Scrophulariaceae are the 45 families identified as hyperaccumulator plants (Ghosh and Singh 2005). The capacity of chrysanthemum and Cumbu Napier hybrid grass to tolerate and accumulate Cr is advantageous for phytoextraction and, thus, phytoremediation. Plants with more than one BCF and TF may be suitable for phytoextraction. Plants with a BCF greater than one and a TF less than one have the potential to maintain the environment. The lower BCF values could indicate a restriction in soil–root transfer at this Cr concentration in the soil. The hyperaccumulator plant's EF or TF should be greater than one. The results of the pot experiments revealed that the BCF and EF for both chrysanthemum and Cumbu Napier hybrid grass were less than one, but the TF was greater than one in plants grown on soil amended with bioamendments (Tables 3, 4). The proportion of heavy metal translocation to harvestable parts is important when selecting a phytoremediation plant (Pulford and Watson 2003). As a result, they may be classified as Cr hyperaccumulators. Heavy metal tolerance was proposed as a phytoaccumulator for polluted soil with a high TF and low BCF value.

On the other hand, these plants showed a more remarkable ability to tolerate and accumulate higher concentrations of Cr and thus could be used in conjunction with bioamendments for phytoextraction and phytoremediation of Cr-contaminated soil. The TF value represents the plant's ability to translocate pollutants to the harvestable part, whereas the TF value is used to assess phytoextraction capacity for soil amendment.

Table 3 Bioconcentration factor (BCF), translocation factor (TF) and enrichment factor (EF) for chrysanthemum

Treatments	Bioconcentration factor (BCF)	Translocation factor (TF)	Enrichment factor (EF)
T ₁	0.14	0.47	0.07
T ₂	0.31	1.13	0.35
T ₃	0.43	0.84	0.37
T ₄	0.39	1.02	0.39
T ₅	0.40	0.81	0.33

Table 4 Bioconcentration factor (BCF), translocation factor (TF) and enrichment factor (EF) for Cumbu Napier

Treatments	Bioconcentration factor (BCF)	Translocation factor (TF)	Enrichment factor (EF)
T ₁	0.09	1.02	0.11
T ₂	0.21	1.55	0.34
T ₃	0.34	1.17	0.40
T ₄	0.32	2.05	0.48
T ₅	0.21	1.87	0.40

Relationship Between Various Plant Parameters and Chromium Accumulation by Plants

Pearson's Correlation Analysis in Chrysanthemum

Pearson's correlation relationship between chromium and chrysanthemum is shown in Fig. 6. The correlation analysis uses the r software program (Zhu et al. 2016). Root length is highly negatively correlated with aboveground chromium (shoot) concentration (−0.99), the biomass of the plant (−0.94), chromium root concentration (−0.91), and chromium uptake (−0.93). Cr uptake by the plant is highly positively correlated with aboveground chromium concentration (0.93), plant biomass (0.86), and chromium concentration in roots (0.91); as a result, a large amount of soil Cr (60%) and uptake was higher in the aboveground concentration and these findings are in line (Rajaie et al. 2008). Chromium concentration in roots positively correlates with aboveground chromium concentration (0.92) and plant biomass (0.91). The positive correlation was mainly detected between the roots and ground chromium concentration, because of more available and mobile fractions of Cr from soil to roots (Barman et al. 2019). Root length has a strong level of significance (** $p \leq 0.01$) with aboveground chromium (shoot) concentration and a good level of significance with (* $p \leq 0.05$) biomass of the plant, chromium root concentration, and chromium uptake the good level correlation is mainly due to the Cr fraction concentration. It was also more significant when the soil was used as the source

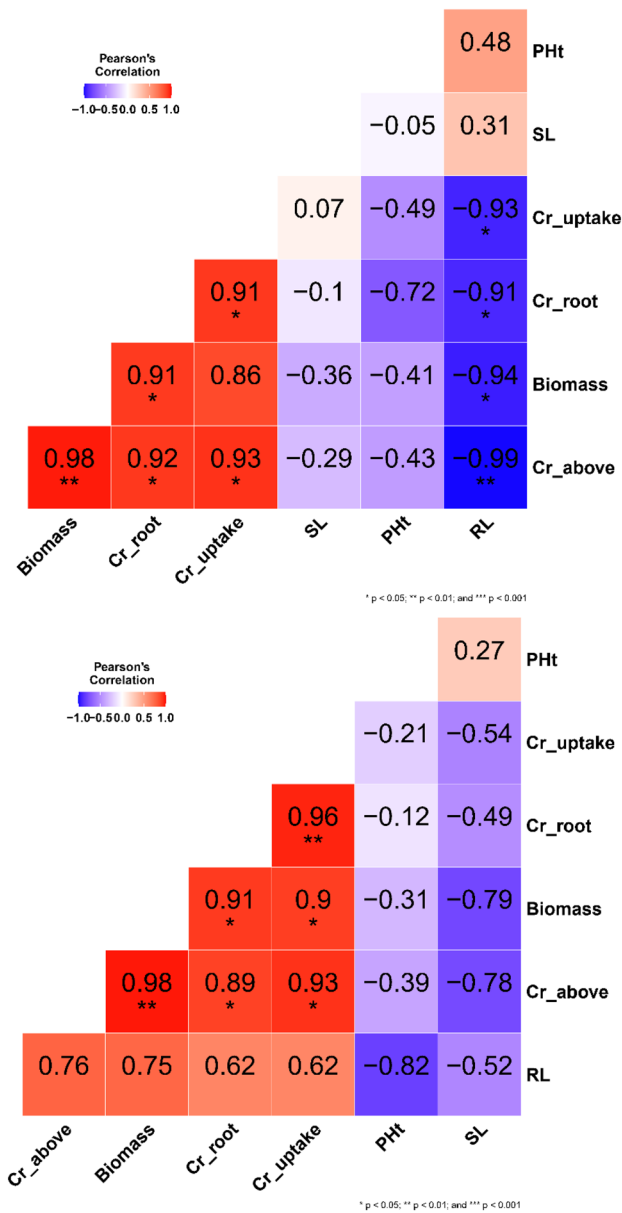


Fig. 6 Relationship between various plant parameters and chromium concentration in chrysanthemum and Cumbu Napier by Pearson's correlation analysis

of inorganic salt, particularly in neutral or acidic soils. This could be due to the soil's significantly higher uptake and amendments in the field capacity moisture regime. Chromium concentration in roots has a good significance level ($*p \leq 0.05$) with aboveground chromium concentration and plant biomass. Plant biomass has a strong level of significance ($**p \leq 0.01$) with aboveground chromium concentration based on the findings of this investigation, and it was discovered that stronger plant biomass had a significant impact on the binding of chromium heavy metals in various forms. The parameters other than those mentioned above

have no statistically significant differences ($p \geq 0.05$) and have a very weak or low relationship (< 0.90) between the parameters.

Pearson's Correlation Analysis in Cumbu Napier Grass

Chromium uptake in plants is highly positively correlated with chromium aboveground concentration (0.93), plant biomass (0.90), and chromium concentration in roots (0.96). Chromium concentration in roots is highly positively correlated with chromium aboveground concentration (0.89) and plant biomass (0.91). Hence, the chromium uptake was higher in the uptake of the plant. Plant biomass is positively correlated with chromium aboveground concentration (0.98). Chromium uptake in plants has a good level of significance ($*p \leq 0.05$) with chromium aboveground concentration, and plant biomass has a strong level of significance ($**p \leq 0.01$) with chromium concentration in roots. Based on this investigation's findings, plant biomass had a stronger correlation with the above, and SOM concentration significantly impacted the binding of heavy metals in various forms (Huang et al. 2020). The very weak correlation was that the residual chromium fractions do not correlate with water-soluble organic carbon and soil organic carbon (Zhu et al. 2015). These results by Neina (2019) suggested a negative relationship between soil pH and the availability and mobility of metal ions in the soil solution.

Principal Component Analysis (PCA) in Chrysanthemum

All the observations were clustered into five principal components from the PCA analysis. The principal component 1 and 2 contributed more than 89% of variances, and the eigenvalue of PC 1 and PC 2 was 5.07 and 1.17, respectively. Therefore, PC 1 and PC 2 were considered the best components and taken for further analysis. Scree plot analysis also confirmed that PC 1 and PC 2 contributed 72.5 and 16.8%, respectively. From the loadings (Fig. 7) of PC1, the parameters such as chromium uptake in plants and chromium in roots contributed to the positive responses, but plant height contributed to strong negative responses. The first two factorial axes represent 52.63% of the variance of the data. The biplot analysis revealed that the treatments T₁, T₂, and T₅ were toward mild negative dispersions, explaining that they performed poorly. On the other hand, the treatments T₃ and T₄ were toward positive dispersions, which performed well.

Principal Component Analysis (PCA) in Cumbu Napier Grass

The PC analysis clustered all the observations of Cumbu Napier grass into five principal components (PC). The principal components 1 and 2 contributed more than 89% of variances, and the eigenvalue of PC 1 and PC 2 was 5.03 and

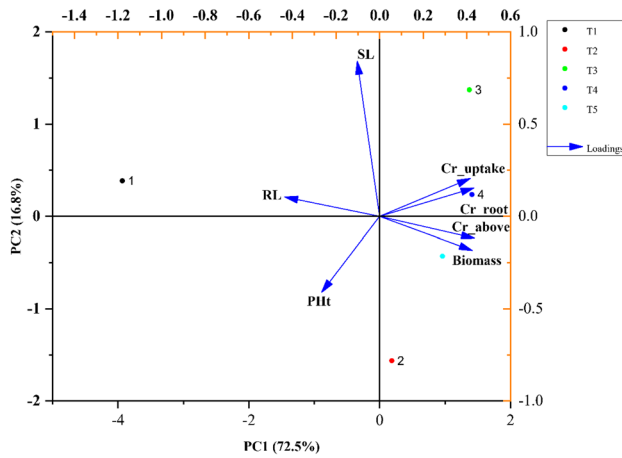


Fig. 7 Biplot analysis of chrysanthemum parameters

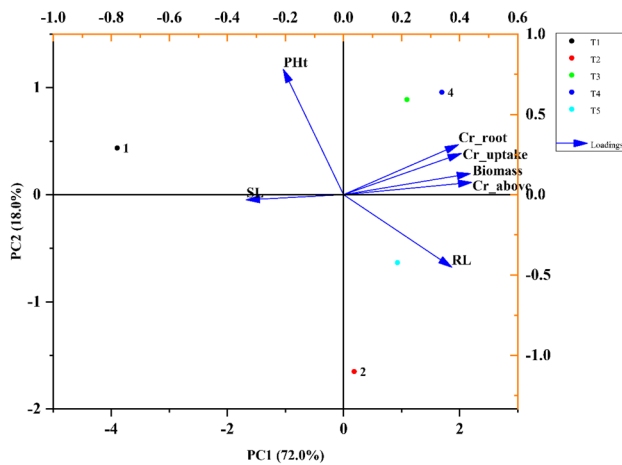


Fig. 8 Biplot analysis of Cumbu Napier grass parameters

1.25, respectively. Therefore, PC 1 and PC 2 were considered the best components and were taken for further analysis. Scree plot analysis also confirmed that PC 1 and PC 2 contributed 72 and 18%, respectively. From the loadings (Fig. 8) of PC1, the parameters such as chromium uptake in plants, chromium in roots, biomass, and chromium in above-ground contributed to the positive responses, but stem length contributed to strong negative responses. The biplot analysis revealed that the treatments T_1 , T_2 , and T_5 were toward mild negative dispersions explaining that they performed poorly; the same results were observed for the chrysanthemum. On the other hand, the treatments T_3 and T_4 were toward positive dispersions, which performed well.

Limitations

Certain factors must be considered in the search for hyper-accumulator species, such as the species being non-edible

plants, the greatest concentration that plants can tolerate (maximum acceptable concentration), the smallest concentration of heavy metals that begins to restrict the plant's development (minimum inhibitory concentration), and perennial plant type indicated to limit harvesting, which can raise the operation and maintenance costs (Ekperusi et al. 2019; Shahid et al. 2020; Imron et al. 2021). Because there is little existing study on biomass usage following treatment of heavy metal-contaminated medium, post-treatment also becomes a problem that has to be further investigated. Biomass from harvested phytoremediation plants is frequently sent to incineration or secure landfills rather than being used any more (Abhilash and Yunus 2011). Selecting an appropriate action for future processing may be made possible by analysis of heavy metal components inside plants following treatment (Alskehli et al. 2020).

Conclusion

The ability of chrysanthemum and Cumbu Napier hybrid grass to take up Cr from the soil has been established through screening the plants and studying the phytoremediation of Cr at various concentrations using eco-friendly, solar energy-driven in situ remediation technology that utilizes the inherent ability of live plants to clean up the environment. Our results show that chrysanthemum can tolerate high levels of chromium (and accumulate it to about 40% in leaves) and can thus be grown on chromium-contaminated sites with low chromium contamination, which could aid in the reclamation and remediation of chromium-contaminated soil and land. As a result of the growth and uptake, it was determined that Cumbu Napier hybrid grass and chrysanthemum could be appropriate for the phytoremediation of soils contaminated with extremely high levels of chromium. Furthermore, manure addition was the most effective method for reducing the toxic effects of added Cr(VI) on chrysanthemum and Cumbu Napier hybrid grass plants. The test plant may be a good candidate for large-scale phytoremediation management when considering the phytoremediating potential for phytoremediation. As a result, further investigation in the field is required.

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project administration, funding acquisition, supervision; GKD: writing—review and editing, data visualization, statistical analysis, language editing; SP: manuscript technical corrections and suggestion, English language editing; KB: manuscript technical corrections and suggestion, review and editing; MM: supervision, review and editing, review and editing; PK: resources, laboratory accommodation, review and editing.

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Availability of Data and Materials The authors confirm that the data supporting the findings of this study are available in the article.

Code Availability Not applicable.

Declarations

Conflict of Interest The authors declare that they have no competing interests.

Ethics Approval and Consent to Participate Not applicable.

Consent for Publishing Not applicable.

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