Phytoremediation potential, plant yield and bio-oil productivity of *Hibiscus cannabinus* grown in sludge amended soil

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Anita

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SUPERVISOR

Prof. Narendra Kumar

DEPARTMENT OF ENERGY & ENVIRONMENT
SCHOOL OF ENVIRONMENTAL SCIENCES
BABASAHEB BHIMRAO AMBEDKAR UNIVERSITY
(A Central University) (NAAC A++ Accredited)
RAEBARELI ROAD, LUCKNOW, UTTAR PRADESH-226025, INDIA

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Summary

Introduction

Leather is a popular and traded product globally, with tanning industries playing a significant role in economic development. The leather industry is dominated by China, India, Brazil, and the USA, with export earnings quadrupling from 1987-88 to 2020-21. However, the industry generates significant amounts of solid waste and effluents, which pose significant human and environmental concerns. India, the 6th top producer of finished leather, has over 3000 tanneries, primarily using goat or sheep skins and cow or buffalo hides. The production process produces 50-100 m^3 of wastewater and 45-150 kg of solid waste, with 50% used by manufacturers of poultry feed, gelatine, glue, fish meal, and soap. Chromium tanning is the most common method, absorbing 70% of the available amount, with the remaining 30% going into solid waste and effluent wastewater. Sewage Treatment Plants (STPs) are crucial in reducing water and soil pollution in India, where wastewater is produced by class I and class II municipalities. By 2050, India is predicted to generate 132 billion litters of wastewater daily. STPs separate solid wastes into sewage sludge, which undergoes mechanical, biological, and chemical processes. Industrial wastes contain toxic chemicals, with tanneries having the highest concentration of pollutants. Heavy metals, such as lead, mercury, cadmium, arsenic, chromium, nickel, copper, and zinc, are widely used in various industries due to their unique properties. These heavy metals contribute to environmental pollution and the need for effective treatment methods.

Heavy metal contamination poses a significant threat to both the environment and humanity. These metals accumulate in plant and animal bodies over time, entering the food chain and causing mutagenic, teratogenic, endocrine abnormalities, and neurological problems in infants and children. In water bodies, they are absorbed by aquatic organisms, making them available to humans. Heavy metals released into the atmosphere can settle on crops and water bodies, entering the food chain. Soil contamination due to heavy metals has increased due to global industrialization. Remediation technologies are crucial for decontamination and management of impacted sites, involving physical, chemical, and biological methods. Physical remediation methods include soil washing, thermal desorption, chemical remediation, biological remediation, and phytoremediation. Physical methods involve removing and transporting contaminated soil to a disposal site, while chemical methods include soil stabilization and solidification, chemical oxidation, bio-augmentation, and phytoremediation. Physical methods are expensive and disruptive, while chemical methods involve binding agents to immobilize contaminants and chemical oxidation. Bio-augmentation involves adding microorganisms to contaminated soil to enhance degradation. Phytoremediation, on the other hand, uses plants' natural ability to detoxify heavy metals, reducing environmental impact and improving soil quality. It requires minimal energy input and maintenance, making it a sustainable, eco-friendly solution for remediation projects.

Phytoremediation is a plant-based technology that uses naturally occurring or genetically engineered plants to clean contaminated environments. Originally introduced in 1983, it has been used for over 300 years, particularly in wastewater discharges. The process involves using green plants and their micro-organisms to stabilize or reduce contamination in soils, sludge, sediments, surface water, or ground water. Phyto-extraction and phyto-stabilization techniques are used to extract and accumulate metals from the environment without compromising soil's biological properties. The process is effective at various sites and contaminants, but low concentrations of contaminants and shallow depths provide favourable conditions for testing. Native species are also used in some projects to avoid introducing exotic species into ecosystems, ensuring restoration and benefits without compromising local conditions.

This study evaluates the potential of *Hibiscus cannabinus* for phytoremediation in tannery and sewage sludge. It aims to optimize nutrient and sludge concentrations and examines the relationship between plant growth and metal accumulation in various plant parts. The selection of Kenaf was influenced by its versatility Kenaf, with various applications due to its fibrous stems and environment-friendly properties. It thrives in tropical and temperate environments and can grow up to 5 meters in 6-8 months. The hibiscus genus, which includes over 400 species, is categorized into six sections. Kenaf's leaves, fiber, and seeds have significant industrial significance, offering opportunities for product diversification. It is used in paper and pulp production, ropes, twines, cords, and biodegradable plastic composites. The global market for natural fibres is growing due to the demand for eco-friendly industrial products.

Review literature

Land pollution is a major environmental disaster, with soil hazards increasing due to fast industrialization, economic growth, and improper waste disposal. Heavy metal pollution, which includes elements like Cd, Cr, Cu, Hg, Pb, and Zn, has hazardous impacts on both natural and human wellbeing. These toxic metals inhibit plant development, sustenance quality, and the diversity of microorganisms that work for soil health improvement. Natural sources of heavy metal pollution include soil erosion, rock weathering, and volcanoes activities, while anthropogenic sources include fossil fuel burning, metal refining, paints, rubber, plastic, electronic item production units, military activities, dyes, agricultural synthetic fertilisers, insecticides, land filling, alloy forming units, and metal refining. Human activities contribute more heavy metal pollutants to the environment than natural sources, and smelting and mining in China are major sources of contamination due to large amounts of waste water production.

Heavy metal pollution from agricultural activities, industrialization, waste production, industrial effluents, and mining is a major environmental issue. Natural sources include soil erosion, rock weathering, and volcanoes, while anthropogenic sources include fossil fuel burning, metal refining, paints, rubber, plastic, vehicle emissions, electronic item production units, military activities, dyes, agricultural synthetic fertilizers, insecticides, land filling, alloy forming units, and metal refining. Human activities contribute more heavy metal pollutants than natural sources, and some bacterial activities increase the accumulation of toxic Hg in soil and water, lowering soil and water quality. Non-essential heavy metals like chromium, cadmium, copper, iron, manganese, and nickel are essential soil nutrients but can cause soil pollution, alter plant metabolism, decrease crop yields, and affect microbial populations. Land management is crucial for conserving soil's intrinsic value in urban and rural environments.

India's Supreme Court legislation in 1996 mandated the addition of tanneries to Common Effluent Treatment Plants (CETP) or Individual Effluent Treatment Plants (IETP) for production. The Central Pollution Control Board (CPCB) proposed remedial actions, such as CETP and chrome recovery, to ensure the tanning industries' environmental protection. However, these ordinances focused on water pollution and neglected solid waste issues. Environmental guidelines applied to the leather industry are generally local and weak, leading to inefficient enforcement and accelerated illicit activities. In developing countries like India, geographically remote areas lack sewage networks or centralized wastewater collection facilities equipped with treatment facilities. Sewage sludge, the remaining by-product of waste water treatment, has been applied to agricultural land, resulting in high concentrations of heavy metals. Sewage treatment plants often do not remove heavy metals even after treatment, causing contamination in soil and food chains. Sewage treatment plants in rural-urban areas suffer from under-developed supporting infrastructure or incomplete sewage pipelines. Industrial wastes like tannery and municipal sludge cause environmental problems such as leaching due to rain, chemical deterioration, health problems, dust rise in air, and unpleasant aesthetics. Landfills can release contaminants into groundwater, rivers, oceans, and other running water bodies, affecting downstream water quality, river bed silt deposition, and aquatic life. India generates about 960 million tons of solid waste annually from agriculture, municipal, mining, industrial, and other processes and by products. By 2025, these wastes are expected to reach 19 billion tons annually.

Heavy metals are added to NPK fertilizers for crop growth, which contain impurities not present in plant lifecycles. Pesticides are also a major source of heavy metals into the environment. Tannery sludge, a composting material, has been characterized for its ability to reduce concentrations of heavy metals and improve soil quality. The application of tannery sludge can increase soil microbial biomass and activity, and can improve the fresh and dry weight of vegetables. Assessing threats to human health relies on information about dietary intake, which is often gathered through food survey responses. Surface soil contamination is typically investigated in densely populated urban areas with industrial facilities or high agricultural land usage. However, individuals in less populated and less industrialized areas may also face risks from environmental soil contamination. Surface soil contaminants, such as As, Pb, and Cr, can negatively impact neurological development and can become toxic if consumed or inhaled in high concentrations. The bioavailability of metals is crucial in determining toxicity. Metal poisoning is a "silent epidemic" and should be addressed to protect human health. Heavy metal accumulation in agricultural soils due to wastewater irrigation can lead to soil contamination, affecting food quality and safety, depleting essential nutrients, and causing health risks like malnutrition and cancer. Further research is needed.

Research on plant absorbing contaminants reveals their mechanisms, which depend on physiological functions and biochemical compositions. Plants have developed efficient systems to acquire micronutrients, even at trace concentrations. Roots, supported by chelating agents and pH changes, can dissolve and absorb micronutrients from low soil concentrations. Factors affecting heavy metal uptake in plants are also studied. Plants have evolved three fundamental approaches to thrive in heavy metal contaminated soil: metal excluder, metal accumulators, and metal hyperaccumulator plants. Metal excluder plants prevent translocations of metals to their aerial parts, while metal accumulators accumulate metals in their above-ground tissues at higher levels than soil or surrounding non-accumulating plants. Metal hyperaccumulator plants contain more than or up to 0.1% of copper, cadmium, chromium, lead, nickel cobalt, or 1% of zinc or manganese in the dry matter. Hyper-accumulator plants can absorb poisonous metal ions at concentrations reaching thousands of parts per million. Heavy metal stress triggers plant responses, which depend on plant-water relationships, root-shoot elongation, biomass allocation, seed germination, and hydraulic or stomatal conductance. Morphological, anatomical, and physiological responses are important for understanding plants' resistance mechanisms to metal-excess conditions in higher plants.

Remediation techniques are used to restore ecosystems, including physical, chemical, and biological aspects. These techniques can be exsitu or in-situ. Ex-situ methods involve removing contaminated soil or water, such as excavation, disposal, biopiles, thermal desorption, solidification, or incineration. In-situ methods treat contamination without removing soil or water, using methods like bioremediation, phytoremediation, soil vapor extraction, oxidizing agents, electrokinetic remediation, and Permeable Reactive Barriers. Both methods have their benefits and limitations, and the choice depends on factors like pollution type and extent and site conditions.

Kenaf, a dicotyledon annual crop, is known for its rapid growth, large biomass, and adaptability. It can grow up to 5 meters tall in 6-8 months and yield up to 30 tons of dry stem material per hectare. Kenaf is used in various industries, including building materials, absorbents, textiles, paper, pulp, bio-composites, insulation mats, and animal bedding. The increasing demand for wood products has put pressure on global forest reserves, affecting various aspects of life. Kenaf has also been explored for oil production and energy production. Its fiber is rich in cellulose and hemicellulose, making it suitable for second-generation bio-ethanol production. Kenaf has shown potential for phytoremediation in soil contaminated with heavy metals, with a maximum concentration of 50% of the total load. Its roots have a high uptake ability, and its tolerance towards Pb by the exclusion mechanism suggests it could be used for phytoremediation of Pb-contaminated sand tailings.

Organic fertilizer can increase biomass yield and lead (Pb) accumulation capacity in soil. Studies have shown that kenaf, a crop contaminated with heavy metals, can be used for reclamation in soil contaminated with heavy metals. Kenaf has a moderate tolerant nature and can transfer at most 185.3 g.hm-2 Cu, 1 012.9 g.hm-2 Zn, 25.7 g.hm-2 Cd, 40.8 g.hm-2 Cr, and 34.8 g.hm-2 Ni. The efficiency of kenaf in extracting metal ions was highest for chromium (Cr), followed by cobalt (Co), manganese (Mn), and cadmium (Cd). The phytoremediation method involving kenaf resulted in a substantial uptake of Cd in the soil. The phloem and xylem showed a Cd uptake percentage ranging from 47 to 61%, while the xylem showed a range of 38 to 53%.

Kenaf and S. plumbizincicola were used to remediate heavy metal contaminated land, with higher uptake levels in S. plumbizincicola. Rotation of these crops resulted in increased removal of Cd, Cu, Pb, and Zn by Kenaf. The root exhibited bioaccumulation of these metals, but the transfer was limited to aerial sections, indicating the uptake through phytoextraction. H. cannabinus, a promising candidate for phytoextraction, showed significant accumulation of iron and zinc in roots and stem.

Method and methodology

Tannery sludge was collected from Common Effluent Treatment Plant (CETP) in Unnao, and sewage sludge was collected from from Sewage Treatment Plant, Sector 10B, Vrindavan Colony, Lucknow Uttar Pradesh. Collected

- Wastewater sludge samples were homogenized and were subsequently analyzed for the different physico-chemical parameters. Physico-chemical analysis of tannery, sewage sludge and garden soil was investigated to characterise samples by performing following parameters pH, electrical conductivity, organic carbon, total organic matter, nitrogen, available phosphorus, potassium.

- Analysis of sludge and sludge-amended soils for the total metal content were undertaken by aqua-regia digestion method and estimation by atomic absorption spectrometer to obtain a metal profile of the wastewater sludge and sludge-soils amendments.
- Sequential Extraction- Sequential extraction were carried out on the principle of selective extraction, proposed by Tessier et. al., in 1979 with the modifications of BCR method.
- TCLP was performed to find out the heavy metals mobility in collected sludge as well as in control, following method given by SW-846, USEPA, 1992 for evaluating physicochemical properties of solid waste.
- Measurements of growth, and productivity of *Hibiscus cannabinus* were analyzed by estimating plant height, number of seed capsule and seeds, fresh and dry shoot length and weight, phytotoxicity of early seeding growth.
- Analysis of bio concentration translocation, and metal tolerance index were done.
- Estimation of biochemical analysis was done by performing chlorophyll, carotenoid, Protein, Ascorbic acid, Proline content, malondialdehyde (mda), catalase, peroxidase, and glutathione reductase activity.
- Extraction of seed oil harvested from soil amendments made by tannery and sewage sludge further the physicochemical analysis of oil was also investigated by performing following parameters: oil content, specific gravity, viscosity, acid value, free fatty acid, saponification value, iodine value and peroxide value.

Result and Discussion

The present study investigated the physio-chemical characteristics of tannery sludge, soil at tannery sludge dumping site, sewage sludge and garden soil as control. Parameters like pH, electric conductivity, organic carbon, total organic matter, NPK, including heavy metals (Cr, Cd, Pb, Ni and Cu) were analysed following standard procedures. The findings showed higher pH value in garden soil whereas, minimum in tannery sludge. Further, pH, electric conductivity, organic carbon, total organic matter, NPK, and heavy metals (Cr, Cd, Pb, Ni and Cu) were found higher in tannery sludge.

Mobility of heavy metals was also investigated by following the European Community Bureau of Reference (BCR, 1992) sequential extraction procedure. Results revealed that nickel was easily bioavailable as the maximum extraction was recorded in exchangeable and reducible fraction of municipal sludge whereas; in tannery sludge, chromium and cadmium was found to be higher in initial two fractions among all the studied metals. Sum of initial two fractions showed the order of mobility and availability of heavy metals as follows: municipal sludge: Ni > Cd > Cr > Cu > Pb and in tannery sludge: Cr > Cd > Pb = Cu > Ni and total recovery of Cr was found to be maximum followed by Cd > Ni > Pb > Cu in tannery sludge contaminated site whereas, in garden soil the order of recovery was found to be Cu > Cr > Ni > Cd > Pb.

Toxicity characteristics leaching procedure (USEPA 2004) was also done to determine the leachability of heavy metals. Trend of leachability of metals was found to be Cd > Cr > Cu > Pb > Ni, Cr> Pb > Cd> Cu > Ni and Ni > Cr > Pb > Cu > Cd in tannery sludge, municipal sludge and garden soil, respectively. Leachable quantity of heavy metals was found higher in tannery sludge against the regulatory limits given by USEPA 2004.

Toxicity assessment of selected sludge extracts was performed during early seedling growth of H. Cannabinnus following the bioassay method given by Hoekstra et al. (2002). Findings revealed insignificant impact of tannery and sewage sludge extracts on the Seed Germination, Root Growth and Germination Index in relation to control.

Total heavy metal uptake in H. cannabinnus plants grown in soil amended with tannery and sewage sludge was also observed after 120 days of cultivation. The trend of heavy metal accumulation in plants grown in tannery sludge amendments was found to be Cr > Cd > Pb> Cu > Ni while, in plants grown in sewage sludge amended soil it was found as Ni > Cd > Cr > Cu > Pb. The Bio-concentration Factor (BCF) is a measure of the ability of a plant to accumulate a substance from its environment relative to the concentration of the substance in the environment. The BCF of H. Cannabinnus was found to be < 0.5 for Cr in all the sludge-soil amendments while, in 100% tannery sludge, it was highest (0.6), followed by 75, 25 & 50% sludge concentrations, respectively, reflecting moderate ability of heavy metal accumulation. While, the BCF of heavy metals in plants grown in sewage sludge-soil amendments was found to be lower in comparison to tannery sludge.

The translocation factor (TF) is a metric employed to measure the capacity of a plant to facilitate the transfer of heavy metals or other pollutants from its root system to its aboveground components, such as stems and leaves. The calculation involves determining the ratio between the amount of metal in the aerial section (shoot) and the concentration in the root.The translocation factor (TF) was found to be higher in plants cultivated in tannery sludge in comparison to control soil i.e. Cr > Cd > Cu > Pb > Ni whereas, the trend of accumulation of metals in sewage sludge amendment was found to be as follows: Ni > Cd > Cr > Cu > Pb. The trend of distribution of heavy metals in plant parts is noticed to be root > shoot > leaves in almost all the sludge-soil amendments.

Plant growth parameters (root, shoot length, fresh and dry weight) were periodically investigated in H. cannabinnus grown in various sludge amendments at 30, 60 and 120 days time intervals. The plants grown in the sewage sludge amended soil exhibited profound growth, root and shoot length compared to tannery sludge amended soil. Further, a gradual decrease in growth of plants was observed in tannery sludge amendments with the increase of proportion of tannery sludge in prepared amendments.

Various biochemical parameters (Photosynthetic pigments; chlorophyll a, b and carotenoid, proline, malondialdehyde, catalase, superoxide dismutase and ascorbate peroxidase) were also investigated in H.cannabinus plants grown in various sludge amendments to study the impact on metabolic and enzymatic activities arose due to exposure to tannery and sewage sludge amendments. Results showed a decrease in photosynthetic pigments with increase of tannery sludge concentration in amendments, whereas in sewage sludge it increased with increase of sewage sludge. On the other hand, carotenoids tend to increase with the increase of tannery sludge concentration in amendments.

Proline accumulates in plants as response to various stress conditions. On investigation, total proline content was found to increase with increase in tannery sludge proportion in sludge-soil amendments. Proline content was found to be higher in plants grown in 100 and 75% concentration of tannery sludge i.e. 1.02 and 0.84, 1.12, 0.89 and 1.8, 1.58 mg/g at 30, 60 and 120 days time intervals. While, the proline content in plant grown in sewage sludge demonstrated a negligible increase in proline content with increase of sewage sludge concentration.

Protein content was seen to be decreased with increase in tannery sludge concentration. Maximum protein content (27.57±0.66 mg/g) was obtained in plants grown in 25% sludge treatment followed by 50, 75 and 100% as 25.06±0.98, 20.10±0.52 and 18.82±0.26 mg/g, respectively. While, with sewage sludge an increase in sewage sludge levels in soil resulted in increased protein content.

Chemical composition of plants grown in tannery and sewage sludge amendments was also investigated in terms of lipid, fat, carbohydrate and crude fiber. The plants grown in tannery sludge exhibited the decrease in fat, lipid carbohydrate and crude fiber percentage. Maximum levels of these parameters were obtained in 25% tannery sludge concentration whereas, minimum in 100% sludge treatment. These parameters were found to increase with increase in sewage sludge concentration; highest levels were recorded with 100% sewage sludge combination, while lowest levels were obtained in 25% sludge strength yet the difference was not much distinct.

Antioxidant responses on exposure to heavy metal pollution and other environmental stresses were also observed in Hibiscus cannabinnus grown in various tannery and sewage sludge amendments. Results revealed that high toxicity exhibit in 100% sludge as ascorbic acid found to decrease, while it was found higher in 75% concentration of tannery sludge (64.43±3.36 mg/g). Similarly ascorbic acid content in plants grown in sewage sludge amendment revealed the increase of ascorbic acid with the increase of sewage sludge concentration. Glutathione is a crucial antioxidant, according to results maximum glutathione was recorded in pure tannery and sewage sludge, whereas, minimum was found in 25% sludge-soil amendments. Oxidative stress caused by heavy metals was analyzed with the help of Superoxide dismutase (SOD), Peroxidase (POD) and Catalase (CAT), enzymes that protect plant during stress conditions. A significant increase in SOD was recorded at 100% tannery sludge exposure, whereas it decreased at lower sludge levels in soil. Similarly, higher levels of POD were seen in plants grown in 100% whereas, minimum was observed in 25% tannery sludge amendment. High POD levels was obtained in 100% and lowest was found in 25% sewage sludge amendment yet the levels were found to be lower than those found in plants grown in tannery sludge amendments. Likewise, plants grown in 100% concentration of sewage and tannery sludge showed highest CAT activity whereas, it was found minimum in 25% sludge amendment.

Bio-oil obtained from seeds of H. cannabinus grown in various tannery and sewage sludge amendments were subjected to productivity assessment and quality characterization. Results revealed the decrease in production of seed capsule with increase in tannery sludge strength in prepared soil-sludge amendments. The data obtained from investigation suggested that average capsule production was approx. 49 capsules per plant. Likewise seed number and weight of seed per plant also got affected at various sludge amendments. Maximum number of seeds production and weight was observed in plants grown in 25 and 50% tannery sludge amendment, however, it decreased with increase in tannery sludge proportion. Whereas, with various sewage sludge amendments the number of seeds and weight was found to increase with increase in sludge.

Heavy metal accumulation in seeds was also analysed and results revealed that Pb was maximum (4.34±0.36 µg/g) accumulated among the studied heavy metals in plants grown in 100% sludge followed by 1.87±0.14 and 2.56±0.16 µg/g at 25 and 75% sludge-soil amendments, respectively. Cr was observed least accumulated among the studied heavy metals. The accumulation of Cr was found to be higher in 100% (571.81±4.02 µg/g) concentration whereas, insignificant difference in other three amendments.

Quality of bio-oil was analysed with the help of various primary fuel parameters such as acid value, iodine number, specific gravity, free fatty acid, peroxide value, saponification value, and viscosity. Results revealed that the average oil content obtained from the seed of control plants was 26%; whereas in the seeds of plants grown in tannery sludge-soil amendments, the oil content was found to decrease with increase of tannery sludge concentration while increases with the increase of sewage sludge. Specific gravity was found to be higher in oil obtained from the seeds of plant harvested in tannery sludge amended soil. Highest specific gravity (0.99) of oil was observed in plants grown in 100% tannery sludge. Similarly Viscosity of obtained oil was found to increase in plants grown in higher concentration of tannery sludge in prepared soil amendments. Highest viscosity was recorded in 100% sludge concentration i.e. 57.08 mPas. Whereas, plants grown in sewage sludge amendment showed a slight increase in viscosity on increasing sludge content.

Acid value of the bio-oil obtained from the plants grown in tannery sludge amendments was found to increase with increase in sludge. Maximum acid value was found in plants grown in 100% tannery and sewage sludge concentration whereas, minimum in 25% sludge concentration. Similarly, free fatty acid and peroxide were also found to increase with increase of sludge concentration in soil amendments. Maximum free fatty acid and peroxide were found in plants grown in 100% in tannery and sewage sludge, while minimum in 25%.

The degree of unsaturation in the oil was measured by iodine value (IV). Results showed a higher iodine value in 25% tannery and sewage sludge amendments i.e. 135 and 138 gI/100g, respectively. Whereas, lowest value was found in 100% concentration i.e. 127 and 132 gI/100g in tannery and sewage sludge, respectively.

The saponification value gives an idea of the fatty acid chain length. Results showed the increase of saponification value with increase of sludge concentration in amendments i.e. maximum was found in plants grown in 100% amendment and lowest in 25% sludge amendment.

Present study also investigated the metal accumulation and translocation of heavy metals in indigenous plant species growing naturally around sludge dumping site. Eighteen plants species were collected from the vicinity of tannery sludge dumping site. Simultaneously, soil samples were also collected from the rhizospheric zone of the selected plants and subjected to physic-chemical characterization. Results revealed that the level of heavy metals was higher in soil samples collected tannery sludge dumping site in comparison with sewage sludge and garden soil. Geo-accumulation index (Igeo) is a mathematical model to determine the heavy metal pollution levels at contaminated site. Igeo of Cd was obtained as 7.9849 and 8.2041 at tannery sludge dumping site and tannery sludge, respectively and can be classified as ‘extremely polluted’ whereas, in terms of Cu and Cr, Igeo reflects moderate pollution level.

Plants uprooted from the vicinity of tannery sludge dumping site were subjected to heavy metal analysis to evaluate the respective potential of each plant for the purpose of phytoremediation. The phytoremediation potential of indigenous plant species growing naturally in the vicinity of tannery sludge dumping site was found to be in the order of C. procera > A. aspera, > Amaranthus spinosus > Parthenium hysterophorus, > Commelina benghalensis > Dolichos lablab > Ctnadon Dactylon > Croton bonplandianum > Luffa aegyptica > Euphorbia hirta > Datura stramonium > Solanum nigram > Solanum Xanthocarpum > Chenopodium album > Coriandrum sativum > Cyprus rotundus > Spinacea oleracia > Brassica compestris. Highest TF was exhibited by Luffa aegyptica; >1 for Cr, Cu and Ni whereas, Pb and Cd were moderately translocated (TF >0.5). Further, TF of Ni and Cd in Spinacea oleracia was observed as >1 and for Cr, Cu and Cd it was found to be >0.5. Datura stramonium efficiently translocated Cu and Cd as the TF was found to be >1 whereas, other metals were moderately translocated as the TF for rest of the metal was found to be > 0.5 but < 1. TF of Ni in Solanum nigram, Chenopodium album and Brassica compestris, Cr in Solanum Xanthocarpum, Cu in Euphorbia hirta, and Cd, Ni & Pb in Cyprus rotundus was found to be < 0.5 that indicates slow uptake of these metals by plants.

Conclusion

Effective and eco-friendly management of industrial and sewage sludge is essentially required to avoid the any possible environmental and public health concerns. When erroneously handled, tannery sludge, which is rich in hazardous heavy metals particularly chromium, and sewage sludge, which frequently contains microorganisms, organic pollutants, and heavy metals have the potential to pollute terrestrial and aquatic environments. Environmental contamination due to heavy metals has the potential to adversely impact ecological systems, diminish soil fertility, and pose health hazards to human populations via contaminated water sources and food chain. Ecological impacts and health risks posed by these sludges requires urgent attention for their proper management.

The application of phytoremediation as a means for tackling heavy metal contamination is justified due to its environmentally sustainable and economically viable nature. Plants can absorb, collect, and partially detoxify heavy metals present in polluted soils and water, thereby mitigating pollution levels and reinstating the overall well-being of the ecological system. The proposed approach exhibits reduced disruption compared to conventional cleanup methods and possesses the capability to be implemented across expansive regions, rendering it a viable and sustainable alternative for the management of heavy metal contamination in diverse settings.

Phytoremediation is an eco-friendly, economic, efficient and user friendly technique which utilizes plants for the restoration of contaminated sites. Hibiscus cannabinus, commonly known as kenaf, is successfully employed in the field of phytoremediation due to its notable characteristics such as quick growth, substantial biomass generation, and enhanced capacity to endure and retrieve heavy metals. The plant possesses a deep and dense root system that augments its ability to effectively extract and eliminate pollutants from the soil, while its adaptability enables it to thrive in diverse soil environments. Moreover, the biomass generated by kenaf provides options for industrial applications, rendering it a highly efficient and economically feasible alternative for the remediation of contaminated soil.

Characterization of sludge by various methods revealed the potential hazards associated with tannery sludge and sewage sludge. Chromium present in the tannery sludge was found to be most problematic due to its high concentration and mobility. Bioavailability and leachability of heavy metals assessed by the application of sequential extraction procedure revealed that the initial fractions primarily govern the bio-availability and subsequent toxicity of the metals to the plants. Concentration of Cr and Cd was found higher in the initial and most labile phases compared to other metals. Germination and early seedling growth studies performed on Hibiscus cannabinus against the sludge extracts exhibited its tolerance towards tannery sludge leachate and consequently was subjected to various pot studies. Insignificant impact on growth and productivity of Hibiscus cannabinus were seen in 25 and 50% tannery sludge amendments and effective bioaccumulation and translocation of toxic metals from sludge-amended soil to roots and subsequently to aerial parts was encountered. Further, study on heavy accumulation and translocation patterns in indigenous plant species identified natural hyper-accumulator plants. Findings of the present study gives direction for the effective application of *H. cannabinus* for reclamation of land contaminated with industrial waste/heavy metals.

Future recommendation

- For a comprehensive understanding of the effects of heavy metals in natural environments, it is imperative to undertake large scale field experiments
- It is required to conduct an exhaustive investigation on the quality of bio-oil and explore its potential as a biodiesel feedstock.
- In order to facilitate its subsequent industrial application, it is warranted to conduct fibres quality inspections on plants cultivated in soil that has been altered.