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RESEARCH ARTICLE

Physiological insights into the carbon sequestration potential of vetiver grass in effluent-contaminated soil ecosystems

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Abstract

Vetiver grass is one of the best hyperaccumulator plants, widely used for environmental clean-up, therapeutic, and medicinal purposes. A field experiment was conducted with vetiver grass and organic amendments in tannery effluent-contaminated soils of Erode District, Tamil Nadu. Organic amendments *viz*., vermicompost (VC), biocompost (BC), and farmyard manure (FYM), were added to the soil in different proportions according to the treatments. Physiological parameters *viz*., photosynthetic rate, stomatal conductance, and chlorophyll content observed in vetiver grass, recorded 13.53 µmol (CO_2), 0.89 mol (H_2O), and 38.51%, respectively, in vermicompost amended soil followed by the other treatments. Dry matter production and biomass production were positively correlated with the carbon sequestration potential of vetiver grass. The biomass obtained from the treatment T_3 (VC + 100% Soil Test Crop Response (STRC)) recorded the highest carbon dioxide sequestration (33.89 t ha^{-1}). In contrast, the lowest carbon dioxide sequestration (25.42 t ha^{-1}) was recorded in the treatment T_1 (Control). Among the various amendments used in the experiment, the soil amended with vermicompost (5 t ha^{-1}) + 50% STCR (T_3) performed best regarding crop growth, carbon sequestration, and pollutant removal.

Keywords

carbon sequestration; tanneries; vetiver grass; vermicompost

Introduction

Tanneries are classified as "Red-most polluting industries"(1). Tanning is one of the oldest and most rapidly growing industries in India. Over 500,000 tonnes of hides and 314 tonnes of skins per year are processed by tanning industries in India. These industries are concentrated in different states of India *viz*, Maharashtra, Tamil Nadu, Andhra Pradesh, Rajasthan, Karnataka, Uttar Pradesh, West Bengal, Kanpur and Punjab (2). In Tamil Nadu alone, there are over 2500 tanneries, with locations in Vellore, Ranipet, Trichy, Dindigul, Erode and Pallavaram in Chennai (3). Release of untreated tannery effluent to the agricultural land near these industries may pose a threat to soil health and quality. Also, increases in CO_2 levels have provoked a search for management strategies to potentially lower atmospheric carbon levels, especially until new carbon-friendly technologies are developed and adopted.

Vetiver is one of the potential aromatic and medicinal plants with a deep root system to remediate diverse pollutants in soils and can act as a carbon sink. Vetiver is used widely for its medicinal properties and vetiver oil is used for arthritis, stings, and burns. It can store about 100 to 507 million tonnes of carbon (4). Being a graminaceous perennial plant, it is distinguished by its robust and extensive root system, which could reach a depth of 5 m in tropical conditions (5). Vetiver is a potential carbon-sequestering plant because of its deep rooting capability and high biomass production. For 1 square meter of area, vetiver grass can hold up to 1 kg of atmospheric carbon annually in the deep soil pool. Approximately a hedgerow of 8 m of vetiver plant which constitutes 50 to 60 plants would be able to work for one 'carbon footprint' (6). Vetiver grass efficiently increases the level of carbon content in the soil (soil carbon stock). The deep and intervening fibrous root system of the vetiver plant enables it to mitigate global warming impacts by sequestering more carbon than any other grass system (6). Though many studies were carried out using vetiver grass and its phytoremediation potential, the science behind the usage of organic amendments for *in situ* remediation of tannery effluent contaminated soil as well carbon sequestration using vetiver grass and physiological changes occurred were not documented. With this in mind, the present study was carried out in tannery effluent-contaminated soils of Erode district using vetiver grass and organic amendments to assess the phytoremediation ability and carbon sequestration.

Materials and Methods

A field-level experiment was conducted at a tannery effluent contaminated site at Brahma Peria Agraharam, Erode district (11°22'14.897" N, 77°42'27.443" E) using vetiver grass (*Chrysopogon zizanoides*). The field trial was subjected to eight different treatments with randomized block design.

The treatments includes T_1 (Control), T_2 (Soil test crop response (STCR) based application), T_3 (VC @ 5 t ha^{-1} + 100% STCR), T_4 (VC @ 5 t ha^{-1} + 50% STCR), T_5 (BC @ 5 t ha^{-1} + 100% STCR), T_6 (BC @ 5 t ha^{-1} + 50% STCR), T_7 (FYM @ 12.5 t ha^{-1} + 100% STCR), and T_8 (FYM @ 12.5 t ha^{-1} + 50% STCR).

Collection of soil sample

The soil samples were collected from the tannery effluent-contaminated site at B.P. Agraharam, Erode district. Three sets of soil samples were collected from seven different treatment plots laid across the experimental site and were shade-dried and sieved through a 0.02 mm sieve for initial characterization and analyzed by following the standard analytical procedure. The vetiver samples were collected at the initial stage and final stage (180 days). The collected plant samples were oven-dried at a temperature between 60 °C and 70 °C. Then, these samples were powdered, mixed and stored in air-tight containers for further analysis as follows.

Physico-chemical characteristics of tannery-contaminated soil

The physicochemical characteristics of the collected soil sample such as pH and EC available nitrogen, phosphorus, and potassium (7), soil organic carbon (8), and biometric observation were analysed using standard analytical procedures. At the field experiment, biometric observations were obtained by choosing five random vetiver plants from the plots of individual treatments at 60th and 180th days after planting (DAP). Plant height, leaf length, root length, and stem girth were measured, and the mean values were calculated (9).

Carbon Content in Vetiver Grass

The carbon content present in vetiver (Eqn. 1, Eqn. 2) is estimated by a method adapted by Singh (10) and was given as,

$$\text{Total Carbon content in leaf (t ha}^{-1}) = \%\text{ organic carbon in leaf} \times \text{biomass of leaf} \quad \text{.....(Eqn. 1)}$$

$$\text{Total Carbon content in root (t ha}^{-1}) = \%\text{ organic carbon in root} \times \text{biomass of root} \quad \text{.....(Eqn. 2)}$$

Carbon sequestration by vetiver grass

The amount of CO_2 sequestered was calculated by multiplying the carbon stock by 3.6663 as described by Maddhesiya (11). The carbon stock of vetiver grass was calculated by combining both AGC (Eqn. 3) and BGC (Eqn. 4), where,

$$\text{Above ground carbon (AGC) stock} = \text{Biomass (kg ha}^{-1}) \times \text{carbon \% (0.45)} \quad \text{.....(Eqn. 3)}$$

$$\text{Below ground carbon (BGC) stock} = \text{Biomass (kg ha}^{-1}) \times \text{carbon \% (0.48)} \quad \text{.....(Eqn. 4)}$$

With a portable photosynthesis apparatus, transpiration rate (E), net rate of photosynthesis (Pn), intercellular concentration of carbon dioxide (Ci), and stomatal conductance (gs) were assessed. Three replicates were obtained between 9:00 AM and 12:00 PM under the following criteria: photosynthetically active radiation of 1600 μmol m^{-2} s^{-1} through an internal light source, leaf temperature of 35 °C, relative humidity of 60%, and atmospheric CO_2 concentration of 389 μmol^{-1} (Ca).

Stomatal limitation value (L_s) was assessed by (Eqn. 5)

$$L_s = 1 - C_i/C_a \quad \text{.....(Eqn. 5)}$$

Scanning Electron Microscope (SEM)

The surface texture and morphological properties of the plant samples (leaf and root) were recorded using a scanning electron microscope (M/s. FEI – Quanta 250, Czech Republic) (12). The plant roots and leaf materials were ground to nanosize and dispersed on the stub with a double-sided conductive carbon tap. To study theadsorption properties of leaf and roots, the filament was turned on and adjusted to various required parameters such as electron beam, intensity, spot size, voltage and emission current. SEM images were captured and pore space was measured after the filament was turned on and adjusted to various required parameters such as electron beam, intensity, spot size,voltage, and emission current.

FTIR analysis

Fourier Transform Infrared (FTIR) is generally used to assess the chemical composition of organic as well as inorganic materials. FTIR spectrum (model 8400S of Shimadzu, Japan) was used in determining the functional groups present on the surface of carbon. The spectrum was recorded for the sample taken in a small amount of 0.5 mg entrenched with 0.1% potassium bromide solution. Generation of the curve with wavenumber (400-4000cm^{-1}) in the x-axis and recording of the y-axis, the percent transmittance indicates the peaks of compounds vibrating at a specific frequency (13).

Results and Discussion

Initial characteristics of the tannery effluent contaminated soil

The initial characteristics of the tannery effluent-contaminated soils are displayed in Table 1. The pH was 8.30 with an EC of 3.30 dS m^{-1}. The available nitrogen was in the medium range whereas the available phosphorus and potassium were in the high range of soil fertility rating. Tannery effluent discharged without treatment due to its highly saline nature causes salinization of soil (acidification, reduction in soil fertility) (14). Alkaline wastewater from beam house operations is high in decomposable organic matter, hair, lime, solids, sulphides and biologicaloxygen demand. This is primarily due to low-quality calcium hydroxide and other chemicals used in large quantities without sufficient monitoring (15).

Table 1. Initial characteristics of the experimental soil

S. No	Parameters	Values (0th day)
1.	pH	8.30
2.	Electrical conductivity (dS m^{-1})	3.30
3.	Available N (kg ha^{-1})	305
4.	Available P (kg ha^{-1})	23.9
5.	Available K (kg ha^{-1})	426
6.	Organic carbon (%)	0.32

Influence of vetiver and organic amendments in soil characteristics

The pH of the experimental soil was analysed during the 60th and 180th day after the application of the organic amendments (VC, BC and FYM) and the reduction in pH was noticed. The pH of the soil ranged from 8.10 to 8.20 on the 60th day and 7.40 to .68 on the 180th day. Among treatments, T_3 (VC + 100% STCR) showed a better reduction in pH with 8.10 (60th day) and 7.40 (180th day) followed by T_4 (VC + 50% STCR) with 8.12 (60th day) and 7.43 (180th day) and T_6 (BC + 50% STCR) with 8.17 (60th day) and 7.49 (180th day). A least reduction of pH was observed with 8.19 (60th day) and 7.59 (180th day). The EC was analyzed on the 60th and 180th day after the application of the organic amendments (VC, BC and FYM). Initially EC of the soil was 3.30 dS m^{-1} which indicated a higher salinity level in the tannery-contaminated soil and after organic amendment application a reduction in EC was noticed. The initial organic carbon (OC) in the soil was 0.32% and increased with the application of organic amendments (VC, BC and FYM). During the 60th day after treatment application, the OC varied between 0.23% and 0.29%. The OC of T_3 (VC + 100% STCR) was higher (0.36%) followed by T_8 (FYM + 50% STCR) with 0.35% and 0.34% for T4 (VC + 50% STCR) as well as T_6 (BC + 50% STCR) during 180th day after treatment application.

Physiological traits

The values of photosynthesis rate, stomatal conductance, and chlorophyll content were found to be significantly higher in organic inputs amended soils (T_3-T_8) whereas it was decreased in the control soil (T_1), (Table 2). Higher N availability of vermicompost would have possibly boosted photosynthesis and carboxylation efficiency by Rubisco to remain high (16). For both the chlorophyll and the Rubisco enzyme activities, soil N content is an essential component (17).

Inappropriate photosynthetic apparatus function could result in lower chlorophyll concentration (18-20),

Table 2. Changes in physiological parameters of Vetiver grass grown in tannery effluent contaminated soil

Treatments	Photosynthetic rate (μmol (CO_2) m^{-2} s^{-1})	Stomatal conductance (mol (H_2O) m^{-2} s^{-1})	Chlorophyll content (%)
T_1 – Control	7.74	0.33	22.57
T_2 – STCR Recommendation	8.22	0.41	24.45
T_3 – Vermicompost + 100% STCR	13.53	0.89	38.51
T_4 - Vermicompost + 50% STCR	12.28	0.78	34.22
T_5 – Biocompost + 100% STCR	11.80	0.71	33.15
T_6 – Biocompost + 50% STCR	10.41	0.65	31.05
T_7 – FYM + 100% STCR	9.66	0.61	30.58
T_8 – FYM + 50% STCR	9.09	0.54	29.77
Mean	10.34	0.61	30.53
SEd	0.23	0.02	0.65
CD (0.05)	0.51	0.04	1.40

and the utilization of VC and FYM enhanced photosynthetic parameters in the current study. Various earthworm species can consume the decaying organic materials and transform them into nutrient-rich components, which would help the plants for their vegetative and reproductive growth (21). The results of this study are also in line with the previous findings (22, 23) suggesting that vermicomposting significantly augments chlorophyll levels and the rate of photosynthesis.

The increase in the photosynthetic rate of vetiver could be due to the sequestration of more CO_2 from the ambient atmosphere. The concentration of chlorophyll was highest in VC-applied soil (38.51%), compared to the control (22.57). This may be attributed to the enhanced shoot length resulting from the application of organic amendments. Stomatal conductance (gs) implies both the water state of the plant and its photosynthetic activity. Plants typically maintain a balanced ratio between intercellular CO_2 (Ci) and atmospheric CO_2 (Ca), with carbon metabolism also being linked to stomatal conductance (24). The stomatal conductance of the vetiver is shown in Table 2. It was noticed that the chlorophyll content of the vetiver grasses grown in treatments T_2 to T_8 were 7.68, 41.39, 34.04, 31.91, 27.31, 26.19, and 22.18 respectively higher than control (T_1) soil.

In contrast, heavy metal stress impairs the absorption of essential minerals and photosynthetic pigments (chlorophyll, carotenoid) (25-27). Cadmium inhibited the uptake of copper and iron in the growth medium, limiting *R. communis* growth (25). Increasing concentration of lead inhibits the leaf CO_2 absorption rate and stomatal conductance of *R. communis* and *Brachiaria mutica* respectively (28). The above studies signify that metal toxicity and its impact on nutrient uptake and photosynthetic pigments vary among plant species and the type of metal concentration.

Biomass production and carbon sequestration potential of vetiver

Shoot and root biomass of vetiver were recorded and are presented in Table 3. The average aboveground (shoot) and belowground (roots) biomass of 29.85 t ha^{-1} and 20.47 t ha^{-1}, respectively, were recorded for vetiver. The total dry matter production of vetiver ranged from 15.03 to 20.03 t ha^{-1}. The application of organic amendments (BC and FYM) had a significant effect on the biomass production of vetiver. In tannery effluent-contaminated soils, the highest aboveground biomass production (33.88 t ha^{-1}) and belowground biomass production (23.36 t ha^{-1}) were recorded in T_3, applied with VC +100% STCR. Conversely, the lowest aboveground biomass production (25.92 t ha^{-1}) and belowground biomass production (17.04 t ha^{-1}) were recorded in T_1 (control). Similarly, T_3 exhibited the highest aboveground dry matter production (11.85 t ha^{-1}), below-ground dry matter production (8.17 t ha^{-1}), and the total dry matter production (20.03 t ha^{-1}). In contrast, T_1 recorded the lowest aboveground dry matter production (9.07 t ha^{-1}), belowground dry matter production (5.96 kg ha^{-1}), and total dry matter production (15.04 kg ha^{-1}).

The highest vetiver growth and improved biomass resulted in higher sequestration of carbon dioxide. The highest carbon assimilation in plant biomass was observed in VC + 100% STCR (T_3) and VC + 50% STCR (T_4) applications. The carbon sequestration potential of vetiver under the influence of different organic amendments was calculated and assessed (Table 4). It was found that the cultivation of vetiver has the potential to create a carbon sink of 33.80 t ha$^{-1,}$ which was the highest among all the treatments with organic amendments (T_4- T_8). In the tannery effluent irrigated soils, the highest aboveground carbon stock of vetiver grass (5.33 t ha^{-1}) and belowground carbon stock (3.92 t ha^{-1}) was recorded in T_3 i.e. VC + 100% STCR and the lowest aboveground carbon stock of vetiver grass (4.08 t ha^{-1}) and belowground carbon stock (2.86 t ha^{-1}) was recorded in T_1 (control). The biomass obtained from treatment T_3 (VC + 100% STCR) recorded the highest CO_2 sequestration (33.89 t ha^{-1}), while the lowest CO_2 sequestration (25.42 t ha^{-1}) was recorded in treatment T_1 (control).

The biomass production dry matter production and carbon dioxide sequestration by the vetiver grass grown in tannery effluent contaminated soil revealed that vetiver grown in VC-treated soil (T_3) has a better potential to ab-

Table 3. Carbon dioxide and dry matter production of Vetiver grass in tannery effluent contaminated soils (180th day)

Treatments	Biomass production (t ha^{-1})		Dry matter production (t ha^{-1})		Total Dry matter production (t ha^{-1})
	Shoot (Above ground)	Root (Below ground)	Shoot (Above ground)	Root (Below ground)	
T_1 - Control	25.92	17.04	9.07	5.96	15.04
T_2 – STCR recommendation	26.88	19.44	9.41	6.80	16.21
T_3– Vermicompost + 100% STCR	33.88	23.36	11.86	8.18	20.03
T_4 - Vermicompost + 50% STCR	32.48	22.48	11.37	7.87	19.24
T_5 – Biocompost + 100% STCR	31.32	21.96	10.96	7.69	18.65
T_6 – Biocompost + 50% STCR	30.72	21.08	10.75	7.38	18.13
T_7 – FYM + 100% STCR	29.68	19.92	10.39	6.97	17.36
T_8 – FYM + 50% STCR	27.92	18.48	9.77	6.47	16.24
Mean	29.85	20.47	10.45	7.16	17.61
SEd	0.50	0.31	0.25	0.15	0.24
CD (0.05)	1.08	0.67	0.54	0.33	0.51

Table 4. Carbon dioxide sequestration potential of Vetiver grass in tannery effluent contaminated soils (180th day)

Treatments	Carbon stock (t ha^{-1})		Total carbon stock (t ha^{-1})	Carbon dioxide sequesteration (t ha^{-1})
	Above ground	Below ground		
T_1 – Control	4.08	2.86	6.95	25.42
T_2 – STCR Recommendation	4.23	3.27	7.50	27.45
T_3 – Vermicompost + 100% STCR	5.34	3.92	9.26	33.89
T_4 - Vermicompost + 50% STCR	5.12	3.78	8.89	32.55
T_5 – Biocompost + 100% STCR	4.93	3.70	8.62	31.56
T_6 – Biocompost + 50% STCR	4.84	3.54	8.38	30.67
T_7 – FYM + 100% STCR	4.68	3.35	8.02	29.36
T_8 – FYM + 50% STCR	4.40	3.11	7.50	27.46
Mean	4.70	3.44	8.14	29.795
SEd	0.10	0.05	0.14	0.5060
CD (0.05)	0.22	0.12	0.31	1.0855

sorb CO_2 than vetiver grown in BC and FYM treated soil (Table 3). Vetiver, in particular, has a higher root biomass, making it a larger carbon reservoir (6). The growth of vetiver grasses indicated that vetiver accumulates biomass at a faster pace, indicating that it can sequester more carbon (Table 3). Total C sequestered in its shoots and roots of vetiver grown under T_3 (24.99%) more than control soil (Table 4). In addition, the total carbon stock of T_3 is 24.94% higher than control (T_1).

C_4 plants in general have inherent higher photosynthetic and growth rates, vetiver being a C_4 plant to exhibits this property which might be the reason for higher biomass & dry matter production. The increase in root biomass of vetiver grass indicates its high carbon sequestration in soil which was also evident from the increase of soil organic carbon levels of the experiment. Photosynthetically fixed carbon in grass species is quickly transported to the root portion and its rhizosphere environment, accounting for nearly 5 to 21% of all photosynthetically fixed carbon through root exudates. This can vary between 20 to 50% of the biomass of the plant (29). The loss of photosynthates synthesized in plant parts through the root system is influenced by various factors, including the age of the plant, and biotic or abiotic stresses. Roots release CO_2 into the soil environment from carbohydrate respiration and stimulation by lumichrome. Plant roots exude a range of compounds from simple and complex sugars, vitamins, and organic acids to mucilage and nitrogenous macromolecules such as purines and nucleosides. The depth and architecture of plant roots also play a crucial role in determining carbon sequestration (30). Vetiver grass, with its dense fibrous root system, enhances the carbon sequestration in soil, which was evident from the increase in shoot and root biomass (aboveground and belowground biomass). Photosynthetic carbon capture and the translocation of photosynthates to the rhizosphere through root exudation are key processes contributing to this effect.

Carbon sequestration involves the absorption of carbon dioxide from the atmosphere during the process of photosynthesis and sending that fixed carbon into the vegetative part of plants and also into the soil pools for storage (31). This implies carbon capture and storage which is an effective strategy for the mitigation of climate change. Vetiver total biomass output (above and underground) for four ecotypes ranges from 84.4 to 114.7 t C/ha (6). In comparison to non-vetiver grass cultivation, vetiver-cultivated regions increase soil carbon stock by 16.35 t C/ha on average, whereas this parameter fell by 12.3 t C/ha in non-vetiver grass cultivation areas. As a result, vetiver significantly increases carbon sequestration by increasing soil organic carbon, resulting in a reduction of CO_2 in the atmosphere.

In various parts of India and abroad, a comparative examination of diverse plant systems for carbon sequestration has revealed that vetiver has a higher C sequestration capability than other systems. Vetiver grass is a perennial, fast-growing plant that can withstand a wide range of climatic conditions, including protracted drought, flooding, submergence, high salinity, sodicity, high levels of Al, Mn, and heavy metals, extreme temperature (14–55 °C), and soil pH (3.3–9.5). It has been demonstrated to thrive in soils containing high concentrations of heavy metals and other pollutants (32). Vetiver's vast root system allows it to absorb heavy metals and establish itself in polluted soils. This plant is good for extraction because of its high shoot biomass, metal tolerance, and metal accumulating capacity (33). Vetiver can be used in agroforestry and social forestry systems, as well as on degraded soils. Vetiver wastes can be recycled by converting them to vermicompost, and one field estimation revealed that 18 Mg of vermicompost from vetiver could add 4.7 Mg C per hectare. Another long-term field study with vetiver grass found to have soil organic carbon of 1.39% in the 0–15 cm depth and 1.12% in the 15–30 cm depth in vetiver grown soil, compared to 0.70 and 0.64 %, respectively, in cultivable soil without any crop at the end of 5 years (6). According to our calculations, if 107.83 million hectares of degraded lands in India (10%) are converted to vetiver systems, almost 150 Tg C year^{-1} can be sequestered, accounting for about 46% of the country's total carbon emissions. Additionally, China, also has substantial land regions where vetiver could be grown and contribute to mitigation (34). Our research has found that vetiver systems have a high potential for sequestering carbon while also providing a long-term solution for farmers' livelihoods.

Scanning Electron Microscope (SEM) analysis

SEM Scanning electron micrograph analysis was carried out in the vetiver plant samples of the experimental study to assess the distribution pattern of heavy metals and their translocation pattern. The SEM of the stomata on the leaf skin layer of the plants grown under Cr contaminated site, salt stress condition, and control soil are shown in Fig. 1. In comparison to the control, the stomata on the leaves of plants grown in Cr contaminated site appeared to be slightly smaller and closed. Stomata closure in the leaves of plants exposed to high metal concentrations agrees well with a prior report showing stomata closure in the leaves of *Helianthus annuus* L. growing on soil modified with tannery sludge containing high metal concentrations (35). In addition, stomata closure in pea leaves has been documented as a result of Cd-induced stress (36). Plants constrict their stomata in response to metal-induced stress as a mechanism to reduce water loss through transpiration. The rateof translocation of water and mineral solutes is disrupted in the presence ofmetals, affecting normal metabolic and growth processes (37, 38). During response to metal-induced stress, the plant would regulate the stomatal aperture so that water loss is not intensified (38).

Fourier Transform Infrared (FTIR) analysis

Fourier Transform Infrared (FTIR) analysis was carried out in the root samples of vetiver to evaluate the chemical composition and distribution of functional groups which play a crucial role in phyto and carbon sequestration. Vetiver roots were analysed directly with FTIR on post-heavy metal exposure and spectra are provided in Fig. 2. After exposure to heavy metal, functional groups for treated soil were identified and peaks were assigned after analysing

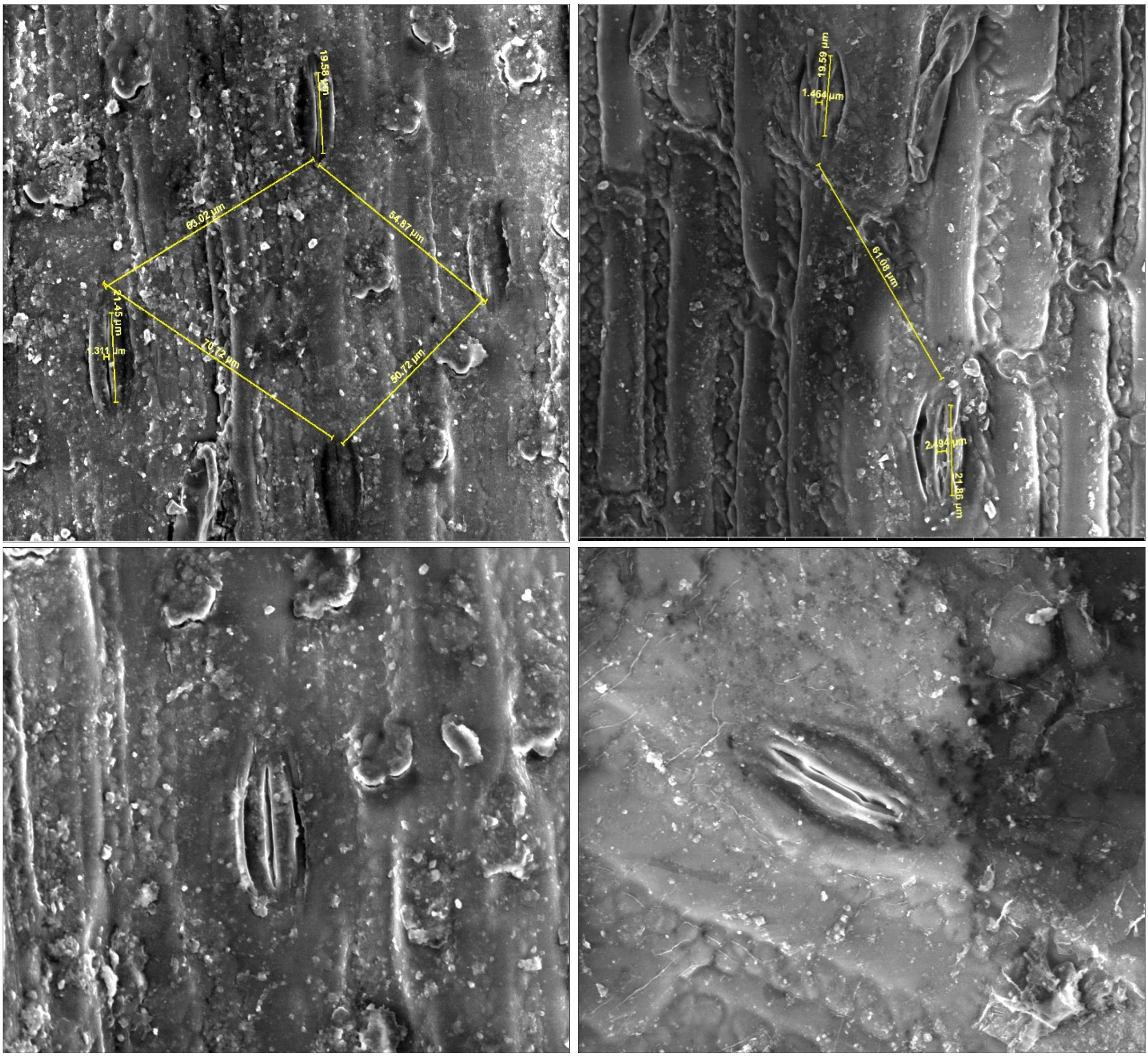

Fig. 1. Scanning electron micrographs (SEM) image of Vetiver leaf.

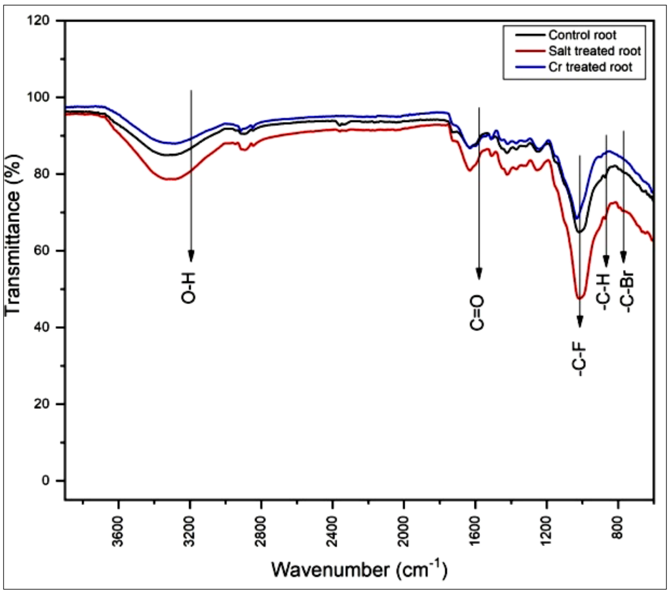

Fig. 2. FTIR spectrum of vetiver root under different conditions.

other reports (38). The wide band around 3,455 cm^{-1} was accorded O–H vibrations of cellulose, 1,625 to 1,633 cm^{-1} was assigned C¼ O stretching of proteins amide component, 1,216–1,228 cm^{-1} was assigned to C-C and C-O vibrations of lignin and cellulose, 1,003–1,092 cm^{-1} was corresponding to C-O bonds of carbohydrate and 778 cm^{-1} was accorded to C-H cellulose bending.

Peaks observed in contaminated and control soils (39) indicate important differences. A peak at1092 cm^{-1} corresponds to the C–F stretch of alkyl halide. Narrow peaks at 535 and 469 $cm^{-1}$are attributed to metal oxide hydroxide. On the other hand, absorption peaks of control soils, specifically salt-affected and chromium-contaminated soils, showed significant differences in peak intensities, thus authenticating the effective remediation by vetiver grass.

Conclusion

The current findings suggest that vetiver grass planted in tannery-contaminated soil treated with vermicompost (T_3) demonstrated superior growth compared to plants treated with farmyard compost and bio manure. This result highlights the plant's strong salt tolerance capacity. They also acquired a large amount of nutrients and salts due to their unique physiological and morphological characteristics, such as vetiver plants (T_3) containing high shoot and root biomass. Based on the experiment, it was also evident that the carbon sequestration potential of vetiver grass was higher in vermicompost-treated soil compared to the control. Soil health and quality were also improved with vetiver grass. As a result, vetiver grass, an exceptionally effective medicinal plant, can be employed to successfully treat tannery-contaminated soils, providing a sustainable solution for environmental cleanup and improving soil quality.

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Authors' contributions

All the authors have contributed to the conceptualization of research work and designing of experiments, execution of field/lab experiments and data collection, analysis of data, and interpretation and preparation of the manuscript.

Compliance with ethical standards

Conflict of interest: The research is original and the findings are neither published nor under consideration elsewhere. All the authors that have contributed to the preparation of this manuscript do not have any conflict of interest.

Ethical issues: None

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