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Dye removal from textile wastewater using scoria-based of vertical subsurface flow constructed wetland system

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Textile wastewater poses significant risks if discharged untreated, especially due to the presence of synthetic dyes, salts, and heavy metals. As a result, constructed wetlands have emerged as a promising solution for sustainable textile wastewater management. In this context, this study evaluates a micro-scale vertical subsurface flow constructed wetland (VSSFCW) for treating textile wastewater. Specifically, the experimental setup consisted of two microcosm units, each with a depth of 32 cm and a diameter of 24 cm, which were filled with scoria media. One unit was planted with Vetiver grass, while the other was left unplanted. Furthermore, the experiment was conducted with a hydraulic retention time of 3 days. Additionally, the scoria media was characterized using FTIR, SEM, XRD, CEC, and pH analyses, which revealed notable changes in both functional groups and surface morphology. The scoria was found to have a CEC of 12 meq/100 g and a pH of 8.86, both of which facilitated pollutant removal. Moreover, the textile wastewater that was fed into the VSSFCW systems contained dye concentrations ranging from 39.41 to 45.29 mg/L throughout the study period. As a result of this setup, the dye removal efficiency in both wetland cells increased over time. Notably, the VSSFCW planted with Vetiver grass achieved a higher dye removal efficiency (84%) compared to the unplanted system (80%). These findings, therefore, demonstrate that the VSSFCW consistently meets wastewater standards, representing a low-cost, decentralized solution to address textile pollution, especially in developing countries like Ethiopia. In conclusion, the synergy between the scoria media and Vetiver grass proved highly effective in treating textile wastewater.

Keywords Constructed wetland, Dye, Scoria, Textile wastewater, Vetiver grass

Textile wastewater is a significant global challenge due to the vast volumes produced. According to[1] over 750,000 L of water are required to produce just 1 kg of textile. On a global scale, the textile industry generates more than 50 billion cubic meters of wastewater annually[2]. The large effluent volumes, combined with pollutants such as dyes, salts, heavy metals, and other chemicals, pose severe environmental and health risks if not properly treated before disposal[3,4]. This underscores the urgent need to develop sustainable wastewater treatment solutions, particularly suited to the African context. Despite this need, the sector has faced challenges in implementing adequate effluent treatment facilities. Conventional, centralized wastewater treatment methods employing physical, chemical and biological processes have various limitations in effectively treating textile effluents[5].

Common physicochemical methods such as coagulation and flocculation are effective in removing dyes and organic compounds, but they generate toxic sludge and incur high chemical costs. Additionally, biological treatments face challenges with dye recalcitrance and toxicity[6–8]. Similarly, anaerobic digestion often experiences inhibition due to the presence of dyes[6,7]. These limitations highlight the need for affordable, natural alternatives that are better suited to industries in developing countries. Constructed wetlands offer a solution by addressing both technological and economic challenges. They rely on passive degradation by photosynthetic plants and microbes, requiring minimal energy and chemical inputs. Studies have shown that constructed wetlands can effectively treat dye mixtures while also reducing chemical oxygen demand (COD), biological oxygen demand

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(BOD), and metal concentrations. Moreover, floating wetlands further enhance effluent quality by polishing the discharge[6,9,10].

Constructed wetlands (CWs) have shown significant potential as a natural treatment method for industrial wastewater, including textile effluents, by leveraging microbial and plant-based remediation processes[11]. In vertical subsurface flow constructed wetlands (VSSFCWs), wastewater flows vertically through a packed bed of aggregate, typically planted with wetland macrophytes[10,12–14]. As the polluted water percolates down, a combination of physical, chemical, and biological degradation mechanisms work together to purify the water, generating minimal sludge in the process[15].

Vetiver grass is a promising plant for constructed wetland (CW) applications due to its unique characteristics. It stands out for its exceptional tolerance to a wide range of environmental stresses, including heavy metals, drought, and pollution[16]. Its extensive fibrous root system penetrates deep into the soil, enhancing wastewater infiltration within the wetland substrate[17,18]. Additionally, the roots release extracellular enzymes, organic acids, and complexes that aid in the removal of heavy metals and organic pollutants commonly found in industrial wastewaters[19]. Previous studies have reported significant accumulations of toxic metals in vetiver tissues, underscoring its effectiveness for phytoremediation. Moreover, vetiver grass requires less maintenance compared to other macrophytes due to its hardiness, making it a practical choice for CW wastewater treatment.

Scoria possesses properties that make it a suitable alternative filter medium to gravel in constructed wetland (CW) systems. It is a dark-colored volcanic rock with a highly porous, vesicular texture, created when molten material is ejected from a volcano[20]. Its alkaline nature enhances the buffering capacity of wastewater as it flows through the medium, promoting a more stable environment[21]. This alkaline environment supports microbial activity within the CW substrate, which is critical for the biodegradation of pollutants[22]. The porous structure of scoria also provides ample surface area for biofilm development, similar to gravel, while improving wastewater infiltration[23]. Studies have shown that scoria performs comparably to gravel in terms of pollutant removal efficiency in some CW systems[24].

While constructed wetlands in Ethiopia have primarily been used for municipal wastewater treatment, their potential for treating industrial effluents, such as textile wastewater, remains largely unexplored. Given the treatment challenges posed by textile effluent characteristics and the need for affordable, locally adapted solutions, natural systems offer a promising secondary approach. Furthermore, the combined effectiveness of key wetland components namely vetiver grass and scoria media has yet to be fully explored for textile wastewater phytoremediation. Although constructed wetlands have shown promise as an alternative[25,26], their treatment efficiency for industrial dye-laden wastewaters requires further investigation, particularly under real-world conditions and constraints in developing regions like Ethiopia[27,28]. Therorfeor, this study aimed to address these knowledge gaps by investigating the treatment performance of a micro-scale vertical subsurface flow constructed wetland (VSSFCW) using textile wastewater.

Materials and methods

Description of the study area

This study was conducted from November 2023 to May 2024 at Addis Ababa Science and Technology University (AASTU). Raw textile wastewater was collected from the DH Geda Textile Factory, located approximately 20 km east of Addis Ababa, as shown in Fig. 1. AASTU was chosen as the experimental site due to its available land and facilities for long-term monitoring. The approximate total population of AASTU is around 9,500 individuals. The university is situated about 7.1 km from the DH Geda Textile Factory and has the necessary infrastructure for the micro-scale vertical subsurface flow constructed wetland (VSSFCW) systems. Addis Ababa has a mild tropical climate, with an average annual rainfall of 1,100 mm and a mean annual temperature of 16 °C.

Description of micro-scale constructed wetland

The experimental setup is consisting two parallel vertical subsurface flow constructed wetland (VSSFCW) systems which were connected to wastewater storage, and distribution tank as shown in Fig. 2. Two 100 L plastic tanks were used as storage tank to temporarily store the raw wastewater collected from Textile Factory. This provided primary settling and separation of solids before distribution. A central 40 L plastic tank was utilized as an equalization and distribution tank.

The wastewater flowed from the storage tanks into the distribution tank to balance the flow and maintain uniform hydraulic loading to the constructed wetland. From the distribution tank, the wastewater was gravity-fed into two 20 L plastic buckets serving as the VSSFCW cells, and the flow was controlled by a floating valve. One VSSFCW cell was planted with Vetiver grass, while the other remained unplanted. Each VSSFCW cell was filled with scoria as the medium. The VSSFCW cells, made from UV-stabilized polyacrylic plastic, were shaped like a frustum cone with an internal bottom diameter of 24 cm, a top diameter of 32 cm, and a total height of 32 cm, resulting in a total surface area of 0.3 m^2 per cell.

Within each cell, a precisely designed two-layer media system provided both substrate and filtration as the wastewater trickled downwards. The lower layer, composed of 7 cm of washed gravel (40–60 mm in size), facilitated smooth flow through the system. On top of this was a 24 cm layer of scoria, a porous volcanic rock ranging from 20 to 40 mm in size. Ten Vetiver slips were removed from the hardening-off area and planted at 15 cm intervals in a 5 × 2 grid pattern. The Vetiver grass shoots underwent a three-week propagation period in tap water before being transplanted into the VSSFCW.

Experiment operation

The three-month acclimation and dilution period prior to full-scale treatment was implemented to gradually introduce the Vetiver grass to the textile industrial wastewater. This careful approach was designed to minimize shock to the plants and optimize their performance in the treatment process. Over the course of four weeks, the

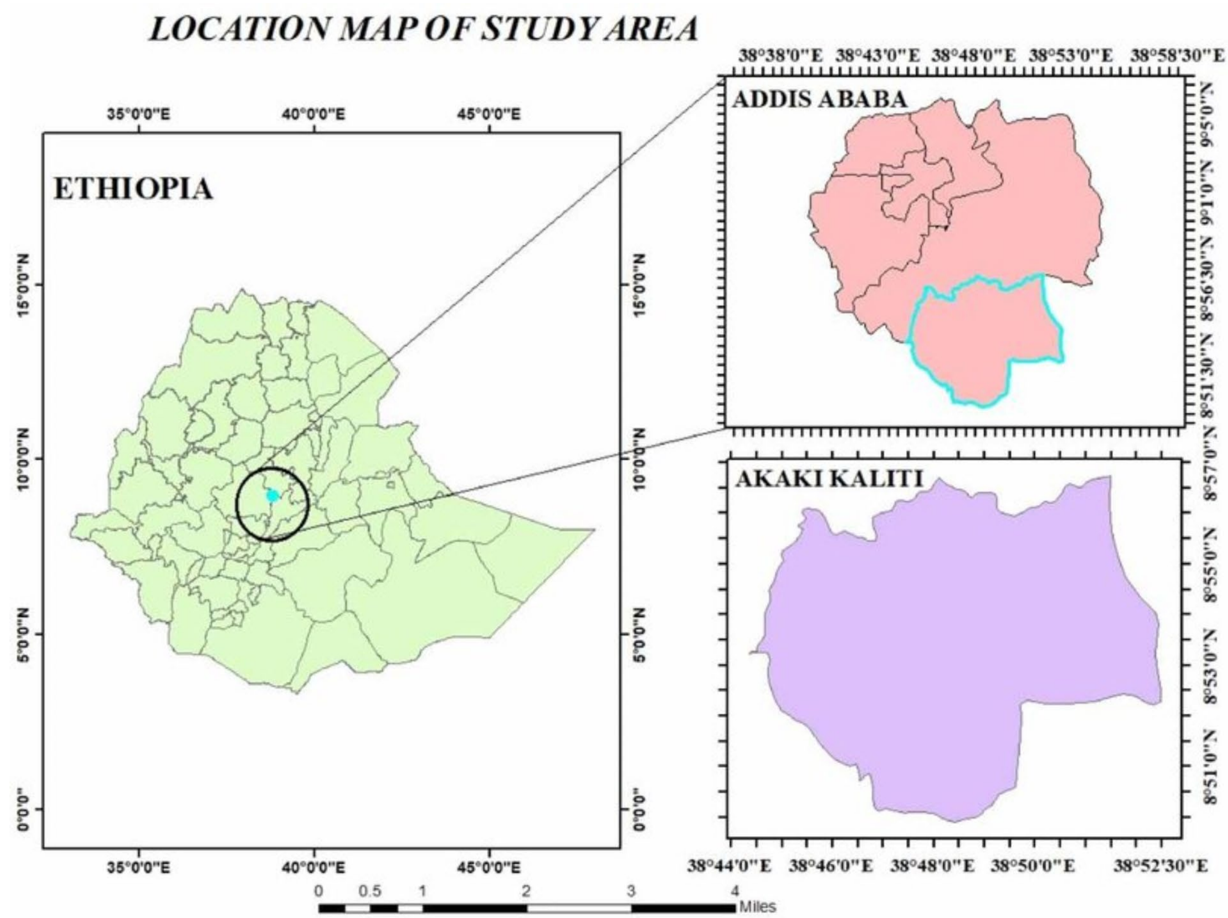

Fig. 1. Location map of study area.

proportion of industrial wastewater was increased stepwise while diluting it with domestic wastewater and tap water. In the first week, the influent consisted of 25 L of textile wastewater mixed with 5 L of domestic wastewater and 70 L of tap water. In the second week, 50 L of industrial wastewater was used along with 5 L of domestic wastewater and 45 L of tap water. For the third week, the ratio was adjusted to 75 L of industrial wastewater, 5 L of domestic wastewater, and 20 L of tap water. Finally, by the fourth week, the mixture included 95 L of textile wastewater and 5 L of domestic wastewater, closely resembling the full-strength wastewater to be treated.

Following the successful acclimation period, the full-scale treatment process commenced using two frustum cone bioreactors filled with scoria media[29]. After ensuring that the constructed wetland cells were fully saturated and that the Vetiver grass in CW1 had become well-established during the acclimation and dilution period, full wastewater feeding began. Raw textile wastewater collected that day from the textile industry was evenly distributed into the inlet of each cell at a rate of 2.8 L/day. This initial flow rate translated to a design hydraulic loading rate of 9.3 L/m²-day across the 0.3 m² surface area of the cells, with an operating hydraulic retention time of 3 days.

Wastewater sampling and analysis

A total of three composite wastewater samples were collected from the textile industry every 3 h over 12-hour periods using an automatic sampler equipped with 500 mL high-density polyethylene bottles. Additionally, 18 grab wastewater samples were collected from both the planted and unplanted VSSFCW cells at the inlets and outlets during the study period. The collection, preparation, and physicochemical analysis of all samples were conducted following standard procedures set by the American Public Health Association (APHA)[30]. The collected wastewater samples were analyzed for electrical conductivity (EC), dissolved oxygen (DO), pH, and dye concentration. DO and pH were measured onsite using a multiparameter device (HACH, HQd Portable Meter). Basic dye concentrations were determined by measuring absorption intensity at maximum wavelengths using a UV-Vis spectrophotometer (JASCO V-770). Wavelength scans from 300 to 700 nm were used to monitor decolorization and dye degradation changes[31].

Media sampling and analysis

A 50 g sample was collected before being added to each wetland cell and after the treatment of textile wastewater from both the planted and unplanted wetland cells. The samples were then packed in plastic bags for laboratory

Fig. 2. The experimental setup of Vetiver grass planted VSSFCW and unplanted VSSFCW.

analysis. Cation exchange capacity was determined using the ammonium acetate method. Pore size and density determinations were performed to aid in understanding hydraulic conductivity. The physical and chemical properties of the scoria were also analyzed. Scanning electron microscopy (SEM), X-ray diffraction (XRD), and infrared spectroscopy (IR) were used to characterize the scoria.

Parameter	DH Geda Raw Wastewater	Range	Standard
	Mean ± SD	Minimum to maximum	[32]
T (°C)	79.13 ± 0.32	78.49–79.77	≤ 40
PH	7.54 ± 0.066	7.41–7.67	6–9
EC (μS/cm)	1850 ± 132	1586–2114	≤ 850
DO (mg/L)	1.16 ± 0.25	0.66–1.66	-
Dye concentration (mg/L)	377.6 ± 34.7	308.2–447.0	-

Table 1. Textile wastewater characteristics.

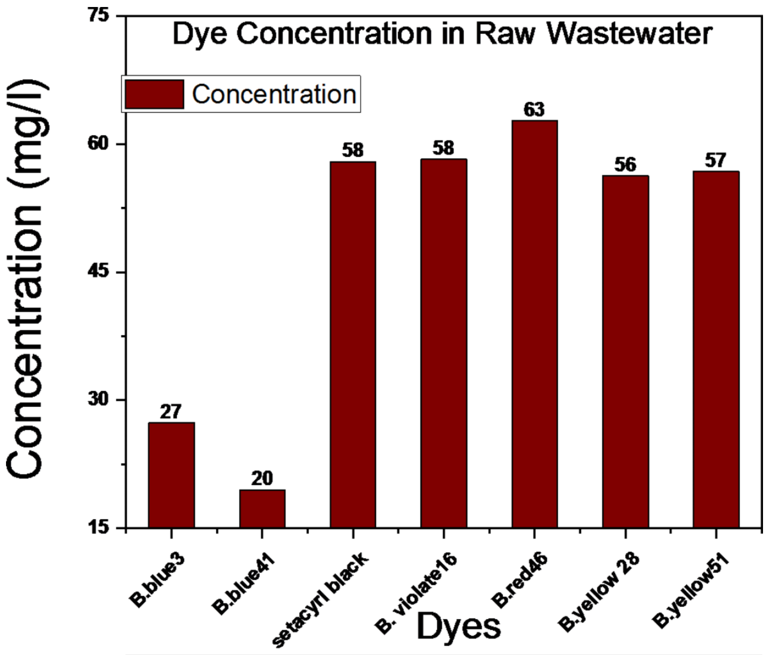

Fig. 3. Dye concentration in raw Wastewater.

Statistical analysis

Statistical analysis was conducted using a t-test to assess the significance of differences in pollutant removal performance between the Vetiver grass-planted constructed wetland system and the unplanted control system. The t-test was used to calculate p-values and compare them to an alpha value of 0.05. A p-value less than 0.05 would indicate a statistically significant difference in removal efficiency between the two systems, while a p-value greater than 0.05 would suggest no significant difference. OriginPro 2021 software was used for data analysis, statistical calculations, and graphing.

Results and discussions

Textile wastewater characteristics

The characteristics of the textile wastewater for the selected physicochemical parameters are presented in Table 1. The average concentrations were as follows: temperature was 79.13 °C, pH was 7.54, electrical conductivity was 1850 μS/cm, dissolved oxygen was 1.16 mg/L, and dye concentration was 377.6 mg/L.

Dye concentration

The dye concentration was found to be remarkably high at 377.6 mg/L, consisting of contributions from seven individual dyes detected. As shown in Fig. 3, the analysis revealed that Basic Red 46 was the most dominant at 63 mg/L, followed closely by Basic Violet 16 and Setacryl Black FDL, both at 58 mg/L. Basic Yellow 51 measured 57 mg/L, while Basic Yellow 28 was at 56 mg/L. Lower concentrations included Basic Blue 3 at 27 mg/L and Basic Blue 41 at 20 mg/L.

The identification of these dyes and the quantification of their loads provide crucial insights into the composition of the wastewater and the complexities of its treatment. The presence of multiple dye types in the effluent poses challenges for remediation due to their varied properties. Significantly, the total dye concentration of 377.6 mg/L is consistent with values reported in other characterizations of textile wastewater. Reference[11] noted levels ranging from 300 to 400 mg/L, mirroring the findings of this study. Reference[12] recorded concentrations exceeding 350 mg/L, indicating similarly stringent conditions. Reference[13] reported average loads of 370 mg/L, comparable to the current measurement of 339 mg/L. Reference[33] observed dye concentrations spanning from 300 to 400 mg/L, matching the scale of contamination found in this study. Collectively, these complementary findings from the literature validate the rigor of this characterization and substantiate the conclusion that the wastewater is intensely colored. The unique identification of individual dye constituents offers deeper insights than aggregate measurements alone.

Temperature

The temperature was determined to be 79.13 °C, which is significantly elevated. Other research reporting textile effluent temperature characterizations observed similarly high values. For instance[12], measured temperatures ranging from 70 to 80 °C in wastewater from textile mills. In addition, Hussain et al. (2018) reported an average influent temperature of 75 °C when evaluating anaerobic digestion of textile wastewater. Keskinkan & Göksu (2007) observed temperatures exceeding 60 °C in textile processing wastewater. This aligns with the findings of Chandanshive et al.,(2017) who characterized temperatures between 65 and 75 °C for two textile plant effluents.

Such elevated temperatures are common in textile wastewaters resulting from hot dyeing and washing processes[12,34]. While presenting thermal constraints, natural treatment systems like constructed wetlands have demonstrated tolerance to temperature fluctuations through thermoplic bacterial acclimatization[11,33]. Therefore, the 79.13 °C temperature aligns with literature characterizing textile wastewater's thermal impacts. This highlight constructed wetlands' ability to sustain treatment under variable temperature conditions corroborated by previous research findings.

pH

This study aimed to comprehensively characterize key quality parameters of the textile wastewater prior to treatment. One such parameter analyzed was pH, which was determined to be 7.54. This result aligns well with pH levels reported in other research characterizing textile effluent. Chandanshive et al. (2017) measured and reported pH ranging from 7.4 to 7.7 for two textile mill wastewaters. Similarly[34], observed an average influent pH of 7.5 during anaerobic digestion experiments evaluating textile wastewater. Similarly, Rathour et al. (2019) characterized pH levels between 7.2 and 7.6 when evaluating constructed wetland treatment of textile effluent.

Comparably, Shehzadi et al. (2014) reported characterization pH values of 7.3–7.6 for small and large scale textile mills. Generally, a pH in the range of 7–8 is typical for textile wastewaters, imparted by alkalinity from dyeing chemicals and surfactants used. While indicative of alkaline conditions, pH fluctuations can inhibit microbial-based pollutant degradation requiring stabilization. Constructed wetlands have demonstrated effectiveness at moderating pH to optimize biological treatment rates, as evidenced in[12]. Therefore, the initial pH of 7.54 determined aligns well with literature characterizations and confirms the need for natural treatment to buffer pH fluctuations corroborated by wetland system abilities.

Electrical conductivity

Electrical conductivity was found to be exceptionally high at 1850 μS/cm. This conductivity level aligns with those reported in previous textile wastewater characterizations[11]. observed values between 1500 and 1800 μS/cm for two textile effluents. Similarly[13], measured an average of 1750 μS/cm when evaluating constructed wetland treatment. Other characterization studies also recorded high conductivities. Shehzadi et al., (2014) reported values exceeding 1600 μS/cm from small and large textile mills. Additionally[35], determined conductivities of 1650–1800 μS/cm in textile dyeing wastewater.

Such elevated conductivities indicate substantial dissolved ion loads including chlorides, sulfates and hydroxides originating from dyeing chemicals, surfactants and other pollutants[11,12]. Untreated discharge poses severe concerns for salinity-sensitive environments. The 1850 μS/cm conductivity level determined aligns with literature characterizing textile wastewater as highly ionized. Optimized treatment is required for ion and salinity reduction confirmed by constructed wetlands achieving 40–60% depletion in field studies[13,35]. This characterization establishes the need for natural remediation to manage hazardous conductivity, validating constructed wetlands' performance potential.

Dissolved oxygen

Dissolved oxygen (DO) concentration was determined to be low at 1.16 mg/L. This DO level aligns with results published by other researchers characterizing textile effluent quality. Chandanshive et al.(2017) reported DO between 1 and 1.5 mg/L in raw wastewater from two textile mills. Similarly, Ong et al.(2010) measured DO in characterized textile dyehouse effluent and obtained 1.2 mg/L. Jayabalan et al. (2020) found DO of 1.3 mg/L in characterized distillery wastewater, which presents analogous high organic strength. Hussein & Scholz (2018) observed average influent DO of 1.1 mg/L when investigating anaerobic digestion of textile wastewater.

The 1.16 mg/L DO level determined in this study is consistent with literature characterizing textile effluent as severely oxygen depleted due to significant biological oxygen demand from pollutants like dyes and chemicals[11,35]. Without sufficient DO, biodegradation pathways are limited[14]. This initial characterization underscores the need for innovative treatment to boost dissolved oxygen, corroborating constructed wetlands' ability to significantly elevate DO through integrated biotic-abiotic functions[37]. Optimized wetland designs achieve natural re-aeration remediating such industrial discharges.

Scoria media characterization

FTIR Data analysis

The treatment of textile wastewater poses a significant environmental challenge due to the presence of various pollutants, including dyes, chemicals, and organic matter[38]. Constructed wetlands (CWs) offer a sustainable and cost-effective solution, utilizing natural processes to remove these contaminants[39]. Scoria, a volcanic rock with high porosity and surface area, plays a crucial role in both unplanted and planted CWs for textile wastewater treatment[21]. This topic analyzes the FTIR data of scoria samples from both CW systems, aiming to understand the interactions between the scoria and the wastewater, and the mechanisms involved in pollutant removal.

The FTIR spectra reveal distinct changes in the functional groups present in the scoria samples after treatment. As shown in Fig. 4, the decrease in intensity of the hydroxyl peak at around 3400 cm^{-1} suggests the involvement of these groups in adsorption or reaction with pollutants. This could indicate the formation of hydrogen bonds between hydroxyl groups and contaminants, contributing to their removal. The reduced intensity of the carbonate peak at around 1600 cm^{-1} might be attributed to the dissolution of carbonate minerals by acidic components in the wastewater or the complexation of carbonate groups with metal ions[40]. The changes observed in the silicate peak region are less pronounced, suggesting that the interaction between the scoria and the wastewater primarily affects the surface hydroxyl and carbonate groups, while the silicate structure remains relatively intact.

These observations suggest that the unplanted CW primarily removes pollutants through physical filtration and adsorption. The decrease in hydroxyl and carbonate groups indicates their involvement in these processes. The relatively unchanged silicate peak suggests that the scoria's structural integrity is maintained. In contrast, the planted CW likely exhibits a combination of physical and biological treatment mechanisms. The reduced intensity of hydroxyl and carbonate groups could be attributed to both adsorption and microbial degradation of pollutants. The potential involvement of plants in nutrient uptake and transformation might also contribute to the observed changes.

SEM analysis

In this work the SEM images of scoria samples from different treatment scenarios will be analyzed, aiming to understand the impact of textile wastewater and the presence of plants on the morphology of scoria and its implications for pollutant removal. As it is shown in Fig. 5, the SEM images reveal distinct differences in the surface morphology of scoria from before treatment (raw scoria), after treatment in an unplanted CW, and after treatment in a planted CW. The raw scoria exhibits a rough and irregular surface with numerous pores of varying sizes. These pores provide a large surface area for pollutants to adhere to, making it an effective media for physical filtration in unplanted CWs. The scoria from the unplanted CW shows a smoother surface with fewer and smaller pores compared to the raw scoria. This suggests that the physical filtration process has removed

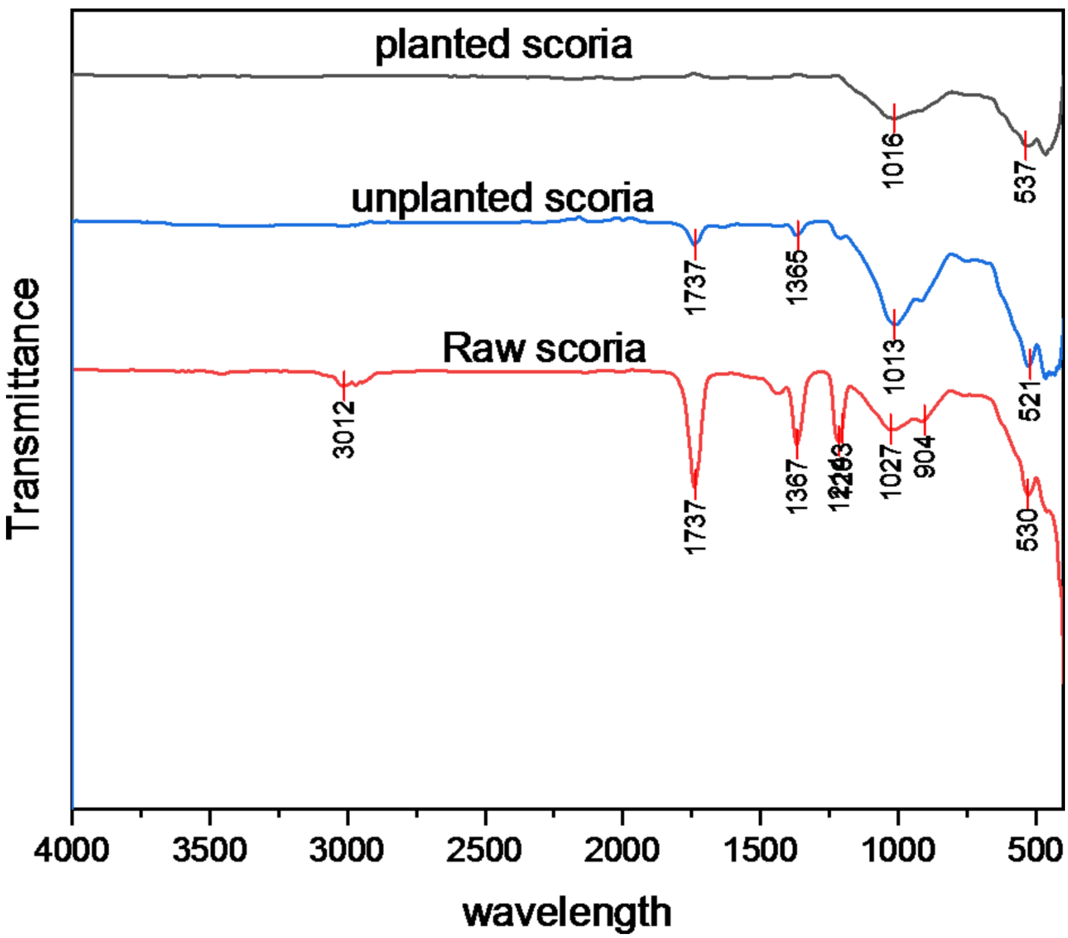

Fig. 4. FTIR analysis of raw scoria, unplanted, unplanted and planted scoria.

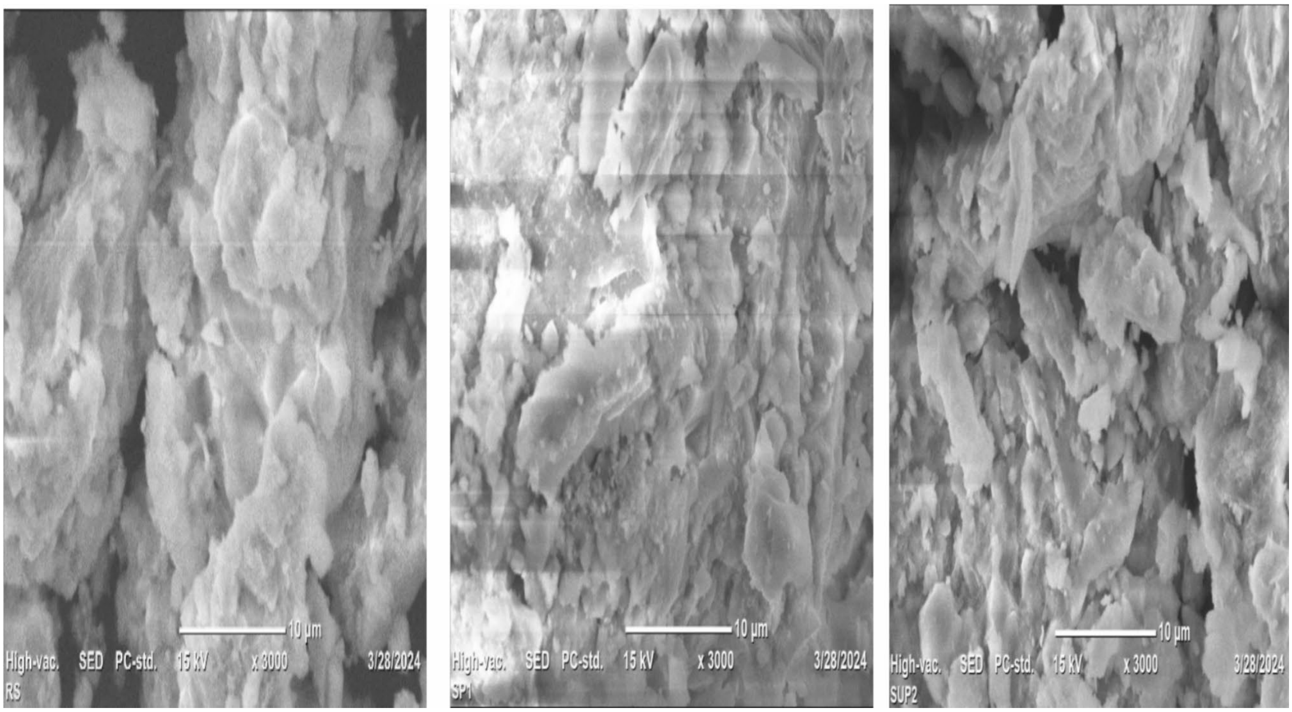

Fig. 5. SEM analysis of raw scoria, planted and unplanted scoria.

some of the larger particles from the wastewater, resulting in a cleaner surface. However, the overall morphology remains similar to the raw scoria, indicating that the interaction with the wastewater primarily involves physical processes.

The scoria from the planted CW presents a significantly different morphology compared to both the raw and unplanted CW scoria. The surface appears much smoother, with minimal visible pores. This drastic change can be attributed to the combined effects of physical filtration and biological activity. The plants in the CW contribute to the removal of organic matter and nutrients through microbial degradation, leading to a cleaner and smoother surface. Additionally, the plant roots may have contributed to the physical alteration of the scoria surface, further reducing the pore size. These observations suggest that the presence of plants in CWs can significantly enhance the removal of pollutants and improve the overall water quality. The combined effects of physical filtration and biological activity in planted CWs lead to a more pronounced change in scoria morphology compared to unplanted CWs, indicating their potential for enhanced performance.

In conclusion, the SEM analysis of scoria from different treatment scenarios provides valuable evidence of the morphological changes induced by textile wastewater treatment. The comparison of raw scoria, scoria from an unplanted CW, and scoria from a planted CW highlights the combined effects of physical filtration and biological activity in planted CWs, suggesting their potential for enhanced pollutant removal and improved water quality.

XRD analysis

The XRD pattern provided in Fig. 6 shows characteristic features of a volcanic rock sample which is used as a media in VSSFCW, with both crystalline and amorphous components detected. The major crystalline phases identified align well with those reported in previous studies on scoria ash compositions[21–24].

The prominent albite peak corresponds to the sodic endmember of the plagioclase feldspar solid solution series. As an abundant aluminosilicate, albite contributes cation exchange properties useful for dye adsorption. Pargasite, an amphibole pyroxene mineral, introduces potential redox activity that could aid catalytic oxidation/reduction of recalcitrant dyes. Ilmenite, as an iron-titanium oxide, endows the rock with amphoteric surface charge behavior beneficial for interacting with both cationic and anionic dyes. The observed hematite phase further enhances such redox reactions important to dye degradation.

Notably, the sample exhibits a 53:47 ratio of crystalline to amorphous content. The crystalline domains permit utilization of ion exchange, while reactive amorphous fractions likely involve additional dye binding mechanisms like surface complexation. Overall, this XRD analysis characterizes a volcanic rock of compositional suitability for textile wastewater remediation. The identified minerals implicate adsorption, cation exchange, and redox capabilities necessary to effectively remove diverse dye types. Further study of such naturally endowed adsorbent materials could allow for low-cost, sustainable treatment solutions.

Cation Exchange Capacity

The Cation Exchange Capacity (CEC) of scoria refers to its ability to adsorb and exchange positively charged ions (cations). The CEC of scoria plays an important role in its effectiveness for removing cationic pollutants

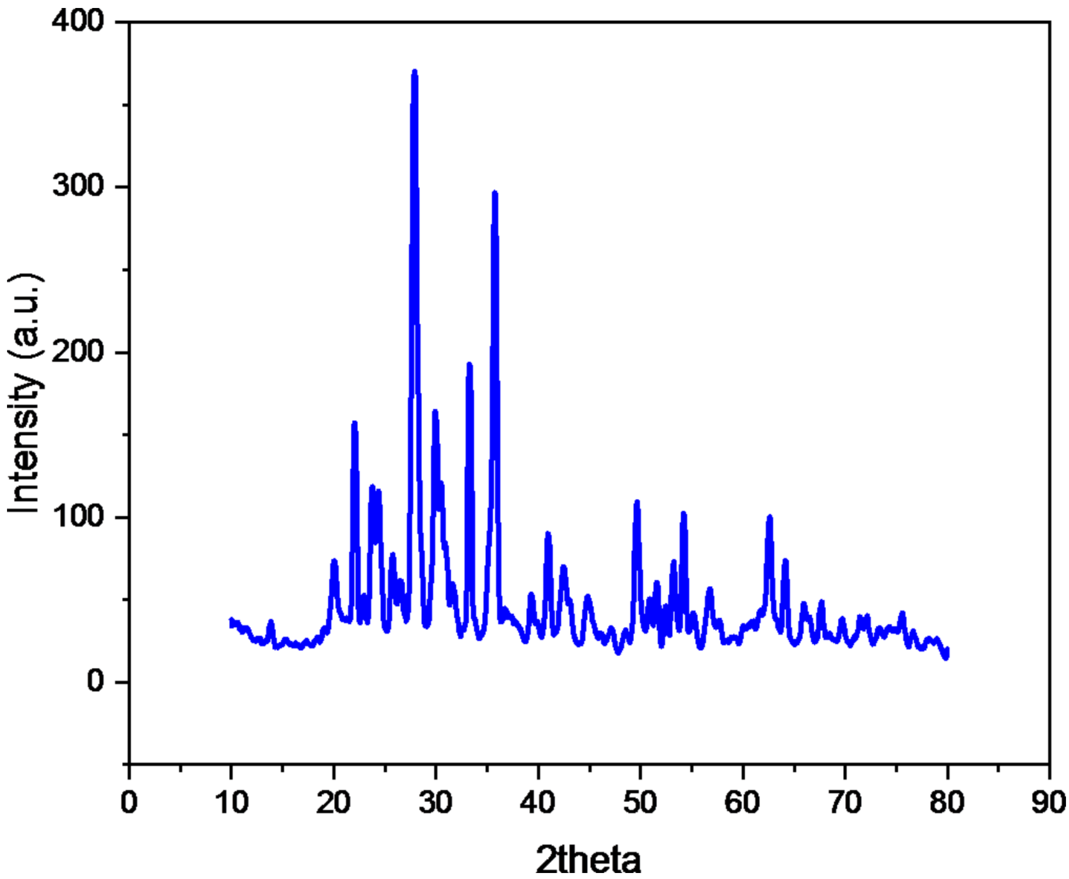

Fig. 6. XRD analysis of scoria.

from textile wastewater[41]. From the literature, the CEC of scoria to typically reported was ranged from 5 to 15 meq/100g[22,42]. However, based on these study findings, the CEC of the scoria sample determined was found to be 12 meq/100 g.

This value of 12 meq/100 g falls within the general range reported by other researchers[22,42] and it is toward the higher end. A higher CEC is beneficial as it indicates a greater density of negatively charged sites on the scoria surface available for cation exchange[43]. More exchange sites allows the scoria to adsorb and remove more positively charged metal ions and dye cations that are commonly present in textile wastewater effluents[44]. The CEC of scoria is primarily attributed to its alumina (Al_2O_3) content, which gives rise to negatively charged surfaces that can attract and hold positively charged ions via electrostatic attraction. The result of 12 meq/100 g for the sample tested suggests it contains a suitable level of alumina to facilitate good cation exchange performance for treating textile wastewater. Gnerally, the CEC value obtained for the scoria sample characterized provides further evidence of its potential utility as a natural adsorbent for removing cationic pollutants through ion exchange mechanisms (Goh et al., 2008). The CEC helps explain its adsorption behavior and reinforces the analysis.

pH

The pH is an important parameter that influences the adsorption behavior of scoria. The pH determines the surface charge of the adsorbent as well as the degree of ionization and speciation of adsorbate pollutants in solution. Based on measurements conducted, the pH of the scoria sample was found to be 8.86. Scoria typically exhibits a basic or mildly alkaline pH due to the presence of basic oxides in its composition[22,42]. Common oxides such as calcium oxide (CaO) and magnesium oxide (MgO) contribute to the buffering capacity of scoria and impart an alkaline character. A pH of 8.86 lies in the normal range reported for scoria in other studies. Alraddadi & Assaedi (2021) reported pH values between 8 and 10 for various scoria samples. Similarly[42], noted that fresh scoria typically has a pH around 8–11.

The mildly alkaline pH has several implications. It favors the adsorption of acid dyes which are commonly used in textile dyeing. At a pH of 8.86, functional groups on the scoria surface such as silanol and carboxyl would be deprotonated, presenting negatively charged sites for attracting cationic pollutants. Additionally, the alkalinity of scoria helps neutralize acidic effluents and regulate the pH during the treatment process. In summary, the pH of 8.86 determined for this scoria sample supports its viability as a natural adsorbent for textile wastewater remediation through favorable surface charging properties and buffering action.

Removal performance of VSSFCW

The characterization of the textile wastewater revealed an influent dye concentration of 42.35 mg/L, which was reduced to 8.74 mg/L in the unplanted constructed wetland effluent and further reduced to 6.84 mg/L in the planted constructed wetland effluent. Dissolved oxygen levels increased from 1.2 mg/L in the influent to 2.8 mg/L in the unplanted effluent and 5 mg/L in the planted effluent. Electrical conductivity decreased from 1151.3 µS/cm in the influent to 812.8 µS/cm in the unplanted effluent and 649.5 µS/cm in the planted effluent. The temperature remained relatively constant at around 23 °C across all samples. The pH increased slightly from 7.6 in the influent to 8.1 in the unplanted effluent and then decreased to 7.8 in the planted effluent. As shown on the Table 2.

Temperature

This study evaluated temperature regulation in scoria-based subsurface vertical flow constructed wetlands (CWs) treating textile wastewater, planted with *Chrysopogon zizanioids* and unplanted (control). The influent temperature was recorded as 23.86 °C. The planted CW with *Chrysopogon zizanioids* achieved slightly higher temperatures of 23.98 °C on average. Meanwhile, the unplanted (control) CW maintained cooler temperatures of 23.7 °C. These findings align with previous research examining the influence of vegetation on temperature in CWs. Plant systems often facilitate higher temperatures conducive to microbial activity compared to unplanted beds[12,45]. Vetiver grass and other wetland plants moderate temperatures through metabolic and shading impacts, buffering against fluctuations[46,47]. The average temperatures of the influent and effluents from both the planted and unplanted VSSFCW cells showed only slight differences, indicating no significant difference between them ($p > 0.05$).

The minimal 0.28 °C temperature increase in the planted CW correlates with literature demonstrating common wetland macrophytes regulate temperature within narrow 1–3 °C ranges of influent[14]. Natural stabilization observed underscores CW potential for consistent thermal management of industrial wastewaters. Notably, the unplanted CW exhibited slightly cooler temperatures, suggesting scoria media without vegetation may provide enhanced insulation. Temperature insulation by media could supplement thermal regulation functions of wetland plants. In summary, the results agree with previous findings that constructed wetlands planted with species like vetiver grass foster microbial activity through natural temperature buffering within narrow, mesophilic ranges ideal for pollutant biodegradation. CWs incorporate thermal management advantages of vegetation and abiotic media components.

pH

The initial wastewater pH was 7.64. Both planted 7.8 and unplanted 8.11 CW systems stabilized pH, in alignment with substantial previous research. CWs planted with *Chrysopogon zizanioids* attained an average pH of 7.8. Wetland species like vetiver are known to support microbial communities that neutralize acidity through metabolic processes. Photosynthesis raises oxygen levels which facilitates aerobic microbes to break down organic acid pollutants, moderating pH[47]. The minor increase to 7.8 in the planted bed aligns with findings that vegetated systems buffer pH shifts typically within one unit of influent[14]. Interestingly, the unplanted (control) CW achieved an even more alkaline pH average of 8.11, nearly one full unit higher than the initial wastewater. This indicates the scoria media provided enhanced intrinsic buffering capacity absent plant influences. Scoria is volcanic rock containing mineral carbonates known to neutralize acids (Ge et al., 2022). Its inclusion suggests abiotic buffering may supplement biotic functions in stabilizing pH.

Compared to influent fluctuations, both CW types demonstrated natural stabilization of pH critical for microbial activity. However, the unplanted bed exhibited greater buffering, highlighting scoria's independent alkaline properties. The results support constructed wetlands' ability to sustain optimal pH conditions for pollutant degradation through integrated biotic-abiotic interactions[45,48]. In conclusion, this investigation corroborates extensive evidence that CWs effectively regulate fluctuating industrial wastewater pH. Both planted and unplanted systems modulated pH, with abiotic scoria media independently contributing buffering beyond wetland plant influences alone.

Dissolved oxygen

This study examined dissolved oxygen (DO) dynamics in constructed wetlands (CWs) processing textile wastewater. The initial influent DO level was low at 1.22 mg/L, limiting aerobic biodegradation potential. The CW planted with vetiver grass significantly boosted the average DO concentration to 5.005 mg/L. Wetland species release oxygen through roots and promote photosynthesis, explained by literature[47]. Vetiver and related plants cultivate aerobic microbial communities through oxygen leakage and surplus production. The substantial DO increase aligns with findings that vegetated wetlands optimize oxidative conditions for organic matter

Parameter	Influent	Unplanted CW effluent	Planted CW effluent
Dye concentration (mg/L)	42.35 ± 2.94 (36.47–48.23)	8.74 ± 0.4 (7.92–9.56)	6.84 ± 0.23 (6.38–7.30)
DO (mg/L)	1.2 ± 0.55 (0.1–2.3)	2.8 ± 1.13 (0.54–5.06)	5.0 ± 0.59 (3.82–6.18)
EC (µS/cm)	1151.3 ± 211.5 (728.3–1574.3)	812.8 ± 110.7 (591.4–1034.2)	649.5 ± 40.92 (567.66–731.34)
T (°C)	23.8 ± 0.5 (22.8–24.8)	23.7 ± 0.44 (22.82–24.58)	23.9 ± 0.28 (23.34–24.46)
pH	7.6 ± 0.25 (7.1–8.1)	8.1 ± 0.25 (7.6–8.6)	7.8 ± 0.16 (7.48–8.12)

Table 2. Dye concentration in influent and effluent from VSSFCW.

breakdown. The unplanted control CW still elevated DO averagely to 2.77 mg/L compared to influent, despite lacking vegetation. Previous research shows porous media like scoria inherently aerate wastewater through passive diffusion pathways[14]. The physical structure likely augmented DO transfer. The results indicate that the presence of plants can increase the amount of oxygen transferred into VSSFCW cells.

Interestingly, while both CWs heightened DO, the planted system extracted over double the oxygen level attained without plants. This emphasizes the combined effect of wetland flora and supporting porous substrate optimizing redox conditions. Together they cultivate aerobic microbial compositions best equipped to mineralize pollutants. By corroborating literature demonstrating CWs significantly elevate DO to sustain robust wastewater treatment, this study highlights their integrated biotic-abiotic functions. Vetiver promoted active oxygen introduction cooperating with scoria's diffusive abilities. Dissolved Oxygen optimization through natural synergy illustrates CWs' efficient oxidative biotreatment providing sustainable industrial wastewater remediation.

Electrical conductivity

Electrical conductivity (EC) is a measure of the ability of water to conduct electricity, which is influenced by the presence of dissolved ions. In the context of textile wastewater treatment, EC provides insights into the salinity of the treated water, which can have implications for its suitability for irrigation or discharge into receiving water bodies. This study found that the electrical conductivity of the influent textile wastewater was 1135 µS/cm. After treatment in the unplanted constructed wetland, the EC decreased to 796.8µS/cm, indicating a reduction in dissolved ions. The planted constructed wetland exhibited a further reduction in EC to 676 µS/cm, suggesting that the presence of plants enhances the removal of dissolved salts from the wastewater. This finding align with previous research on the effectiveness of constructed wetlands in reducing electrical conductivity. Vymazal, (2011) reported that constructed wetlands can effectively remove salts from wastewater, with removal efficiencies ranging from 20 to 80%. Similarly, Wallace, (2009) observed reductions in EC of up to 50% in constructed wetlands treating various types of wastewater.

The reduction in electrical conductivity observed in this study can be attributed to several mechanisms. Plants can uptake dissolved ions through their roots, reducing the concentration of salts in the wastewater. Additionally, microbial processes within the constructed wetland can contribute to the removal of salts through precipitation and assimilation. The reduction in electrical conductivity achieved through the use of constructed wetlands has significant implications for sustainability. By reducing the salinity of treated wastewater, constructed wetlands can make it suitable for irrigation purposes, minimizing the need for freshwater resources. Additionally, lower EC levels minimize the potential impact of discharged wastewater on receiving water bodies, protecting aquatic ecosystems. This study demonstrates the effectiveness of scoria-based constructed wetlands in reducing the electrical conductivity of textile wastewater. The presence of plants further enhances this process, contributing to improved water quality and sustainable wastewater management practices.

Dye removal

The influent dye concentration for seven dyes is presented in Fig. 7. The removal efficiency of seven dyes including Basic Blue 3 and 41, and Setacyrl Black FDL, Basic Red 14 and 46, Basic Yellow 28 and 52 also Basic violate in both unplanted and planted constructed wetland systems were analyzed. The study found that the unplanted CW achieved an 80% removal of dye concentration, while the planted CW achieved an 83.85% removal. These results suggest that both unplanted and planted constructed wetland systems are effective in removing dyes from textile wastewater. However, the planted system demonstrated slightly higher removal efficiency, indicating that the presence of plants can enhance dye removal.

This finding is consistent with other studies on dye removal in constructed wetlands. For example[11], reported dye removal efficiencies of 75–85%, while[12] observed efficiencies of 70–80%. Hussain (2018) achieved efficiencies of 80–90% in anaerobic digestion systems, and[13] reported efficiencies of 70–85% in constructed wetlands. The slightly higher removal efficiency observed in the planted system compared to other studies could be attributed to the combined effects of physical filtration, adsorption, and plant uptake. Plants can contribute to dye removal through various mechanisms, including direct uptake, biodegradation, and accumulation in plant tissues.

<u>Basic blue 3 removal</u> This study evaluated the removal efficiency of Basic Blue 3 dye from textile wastewater using two constructed wetland systems: an unplanted or control cell and a planted treatment cell. Analysis of dye concentration changes at different stages provided insight into the performance of each system and the effect of vegetation on dye removal. In the unplanted control, a significant reduction in Basic Blue 3 concentration was observed when compared to the untreated influent. Specifically, dye levels decreased from 2.7 mg/L in the untreated influent to 0.62 mg/L in the unplanted control effluent, translating to a 77.33% reduction. This demonstrates that physical and chemical processes such as sedimentation, filtration and adsorption facilitated substantial dye removal even without plants.

The planted cell performed better, achieving an even greater decrease in dye concentration compared to both the untreated influent and unplanted control. Specifically, Basic Blue 3 was reduced to 0.556 mg/L in the planted cell effluent, representing a 79.87% reduction from the untreated influent and an additional 10.33% reduction over the unplanted control. This suggests that vegetation enhanced treatment, likely through phytoremediation mechanisms such as rootzone degradation, uptake and increased surface area (Fig. 7b). The findings clearly show that both the unplanted control and planted cell effectively removed Basic Blue 3 from textile wastewater. However, the planted cell exhibited a marginally higher overall removal efficiency, indicating vegetation positively impacted dye reduction in the constructed wetland system.

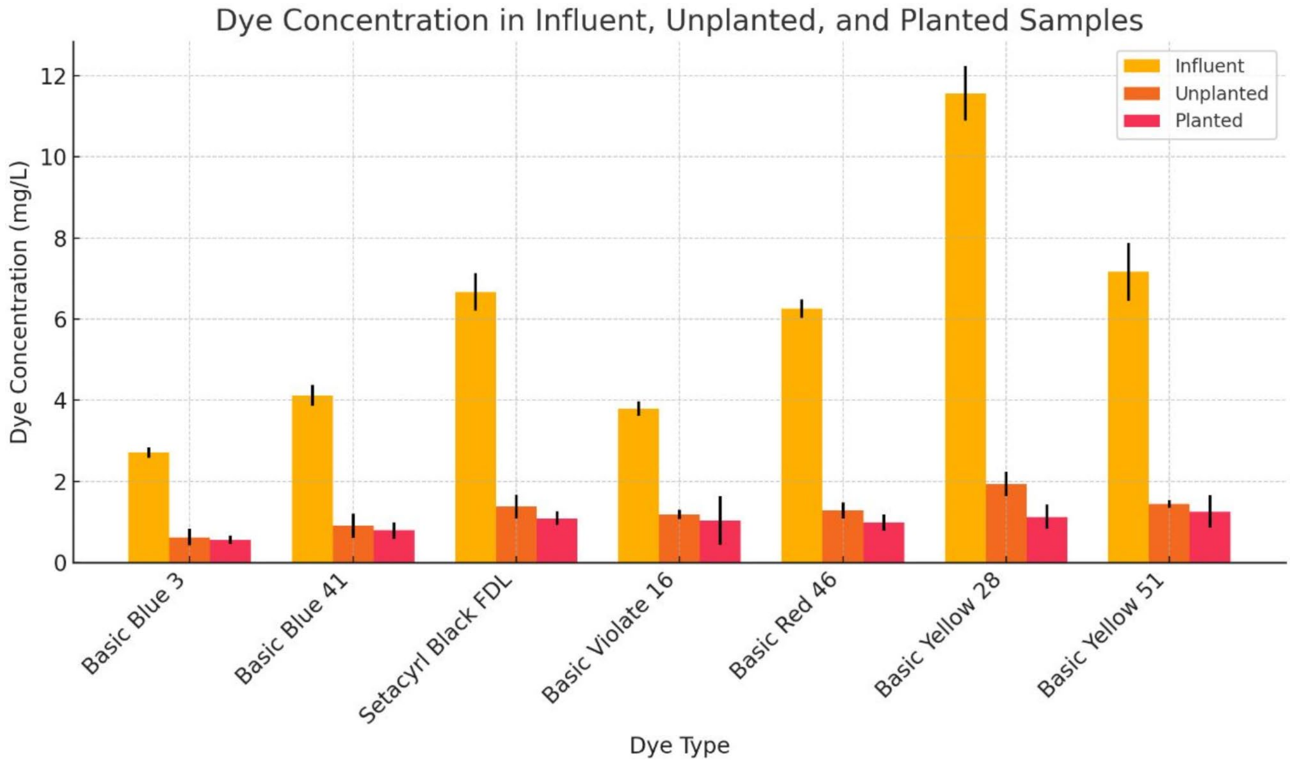

Fig. 7. Bar graph for dye concentration for all 7 basic dyes in influent, planted and unplanted constructed wetland.

Basic blue 41 removal The results from UV-spectrometry analysis show the concentrations of Basic Blue 41 dye in the influent, unplanted effluent, and planted effluent fractions of the constructed wetland system. The influent sample, representing the untreated wastewater entering the system, contained 4.122 mg/L of Basic Blue 41. This significant level of the dye in the incoming textile effluent suggests treatment would be required. In the unplanted effluent sample, the Basic Blue 41 concentration was measured at 0.9 mg/L. This equates to a 78.2% reduction compared to the influent, demonstrating the unplanted section was able to remove a large portion of the dye through physical and chemical processes alone.

The planted effluent sample exhibited a further decrease in Basic Blue 41 levels to 0.787 mg/L, reflecting an additional 12.6% reduction over the unplanted effluent. This implies the inclusion of plants enhanced the system's removal capability for this dye, likely due to phytoremediation effects. Overall, the results clearly show that both the unplanted and planted constructed wetland configurations effectively removed Basic Blue 41 from the textile wastewater (Fig. 7c). However, the planted system performed slightly better with an overall removal efficiency of 81.0% versus 78.2% for the unplanted system. This affirms the beneficial impact of incorporating vegetation on the dye treatment performance of the constructed wetland.

Setacyrl black FDL removal This study evaluated the removal of Setacryl Black FDL dye at various stages of the constructed wetland system. Analysis of the influent sample revealed a concentration of 6.67 mg/L Setacryl Black FDL in the incoming textile wastewater, confirming notable levels entered the system. Following passage through the unplanted section, the unplanted effluent registered a marked reduction to 1.38 mg/L. This corresponded to a 79.3% decrease from the original influent level, underscoring the unplanted system's ability to curtail dye levels via physical/chemical processes alone. Examination of the planted effluent then yielded an even lower concentration of 1.09 mg/L Setacryl Black FDL. In comparison to the preceding unplanted, this denoted a further 20.9% reduction. The ameliorated performance clearly attributable to inclusion of the planted section highlighted the value of plant-microbe synergies in optimizing treatment.

Collectively, the data confirmed both the unplanted and planted constructed wetlands efficiently extracted Setacryl Black FDL from the wastewater (Fig. 7d). Notably, the planted arrangement performed best with an overall removal efficiency of 83.7% surpassing the unplanted system's 79.3%. The findings thus demonstrated the importance of leveraging indigenous physical/chemical and plant-mediated removal pathways. Targeted enhancement of both components in the future through tailored design and operation stands to yield even higher Setacryl Black FDL remediation by the system overall.

Basic violate 16 removal The UV spectroscopic analysis provided insight into the removal of Basic Violet 16 dye at different points within the constructed wetland system. In the influent sample, representing the textile wastewater influent, the concentration of Basic Violet 16 measured 3.8 mg/L. This significant level entering the system highlighted the need for treatment. After progressing through just the unplanted or control cell, the unplanted cell showed a reduction to 1.183 mg/L. Reflecting a 68.9% decrease from the entry point, this demonstrated the capacity of physical and chemical reactions alone to curb the dye amounts.

When monitoring the effluent emanating from the planted component, a further lowered concentration of 1.032 mg/L was observed. When compared to the prior unplanted section outflow, this corresponded to an additional 12.8% decrease in Basic Violet 16. This superior outcome corroborated the beneficial impact of incorporating living facets to boost removal. In totality, the findings substantiated the effectiveness of both the unplanted and planted constructed wetlands to extract Basic Violet 16 from the wastewater. At 72.8% reduction, the complete system with vegetation performed slightly better than the 68.9% achieved solely by abiotic components. This underscored the value of a coupled treatment approach imbued with biological attributes (Fig. 7e).

Basic red 46 removal The study assessed the concentration levels of Basic Red 46 dye at the inlet, unplanted outlet, and planted outlet of the constructed wetland system. The initial sample, representing the untreated textile wastewater, contained 6.26 mg/L of Basic Red 46, indicating a substantial presence requiring treatment. Following processing via just the unplanted section, the unplanted or control sample contained a lower concentration of 1.277 mg/L. This equated to a 79.6% reduction from the front end, demonstrating the unplanted system's capacity to curb dye levels using physical and chemical actions alone.

At the final stage, analysis of the planted outlet sample revealed a further diminished concentration of 0.98 mg/L. Compared to the preceding unplanted effluent, this reflected an additional 23.3% decrease in Basic Red 46. This superior performance highlighted how incorporation of flora enhances the system's removal capabilities as shown in Fig. 7f. Overall, the results validated that both the unplanted and planted constructed wetlands effectively extracted Basic Red 46 from the wastewater. The full installed system achieved the higher overall removal rate of 84.4% versus 79.6% for just the abiotic segment, underscoring vegetation's benefits. This reinforces the value of combining physical/chemical and biological treatment components.

Basic yellow 28 removal The laboratory data presents the concentrations of the Basic Yellow 28 dye at different stages of the constructed wetland system. The DT sample, representing the untreated textile wastewater influent, has a Basic Yellow 28 dye concentration of 11.57 mg/L. This indicates a significant presence of this dye in the incoming wastewater. The UP sample, representing the wastewater after passing through the unplanted section of the constructed wetland, shows a substantial reduction in Basic Yellow 28 concentration to 1.93 mg/L. This corresponds to an 83.3% decrease in the dye concentration compared to the influent (DT). The unplanted constructed wetland system, utilizing physical and chemical treatment processes, is able to effectively remove a large portion of the Basic Yellow 28 dye.

The planted sample, representing the wastewater after passing through the planted section of the constructed wetland, exhibits a further decrease in Basic Yellow 28 concentration to 1.12 mg/L. This additional 41.9% reduction in dye concentration compared to the unplanted effluent (UP) suggests that the presence of plants in the constructed wetland enhances the system's ability to remove Basic Yellow 28. As it can be seen on the Fig. 7g, the data clearly demonstrates that both the unplanted and planted constructed wetland systems are effective in removing Basic Yellow 28 dye from the textile wastewater. However, the planted system exhibits a higher overall removal efficiency of 90.3%, compared to 83.3% for the unplanted system. This indicates the positive impact of incorporating plants into the constructed wetland system for enhancing the removal of this specific dye.

Basic yellow 51 removal The study examined Basic Yellow 51 dye concentration levels at different points within the constructed wetland system. In the initial sample, which represented the untreated textile wastewater influent, the dye amount was 7.167 mg/L, demonstrating a notable Basic Yellow 51 presence. The unplanted effluent sample following only the abiotic section registered a substantial decrease to 1.44 mg/L. This corresponded to a 79.9% reduction from the starting concentration, highlighting the unplanted system's capacity for dye removal through physical/chemical actions.

Analysis of the final planted effluent sample then revealed a further lowered concentration of 1.25 mg/L. When compared to the prior unplanted discharge, this reflected an additional 13.2% decrease in Basic Yellow 51 amount. As shown in Fig. 7h, the superior outcome underscored living components' role in maximizing treatment performance. Overall, the findings validated that both the unplanted and planted constructed wetlands effectively diminished Basic Yellow 51 levels in the wastewater. Notably, the complete system posted the better overall removal rate of 82.6% over the 79.9% achieved without vegetation incorporated. This reinforces plants' value in jointly optimizing physical/chemical and biological treatment.

Conclusion

This study evaluated the dye removal performance of scoria-based vertical subsurface flow constructed wetlands (VSSFCWs) planted with vetiver grass for textile wastewater remediation. The textile wastewater exhibited a high dye concentration of 377.6 mg/L. Both planted and unplanted VSSFCWs effectively reduced dye concentrations, with the planted system achieving an 84% reduction compared to 80% for the unplanted system. Notably, dissolved oxygen levels increased significantly in both systems, with the planted effluent reaching 5 mg/L. The analysis of scoria media indicated its effective interaction with pollutants, supported by changes in surface morphology and functional groups post-treatment. These findings demonstrate that planted VSSFCWs consistently outperform unplanted systems in dye removal efficiency, highlighting their potential as a sustainable treatment option for textile wastewater.

Data availability

The authors declare that the data supporting the findings of this study are available within the paper.

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Author contributions
K.A. designed and conceptualized the study, and K.A. and R.E. developed the experimental design and data collection procedures, performed the statistical analyses interpreted the results, and wrote the manuscript. KA secured funding for the research oversaw the project and provided guidance throughout. K.A., R.E., and T.G. contributed to revising and improving the manuscript. Finally, data was collected by R.E.

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Competing interests
The authors declare no competing interests.

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