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The Assessment of Floating Wetlands in Removing Nutrient from Semi-Synthetic Domestic Wastewater

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Domestic wastewater contains significant concentrations of nutrients such as nitrogen and phosphorus, which can contribute to eutrophication, algal blooms, oxygen depletion, and the deterioration of aquatic ecosystems if discharged without adequate treatment. Although conventional wastewater treatment systems are effective, they often require high energy input, large infrastructure investment, and continuous maintenance. Floating Treatment Wetlands (FTWs) have emerged as a sustainable, nature-based alternative that uses aquatic plants, substrates, and microbial communities to remove pollutants through plant uptake, biofilm activity, sedimentation, and microbial transformation processes. This study assessed the effectiveness of a single-cell FTW system in capturing nutrients from domestic wastewater using different macrophytes and substrate materials. The objectives of this research were to investigate the performance of FTWs under various macrophyte configurations and to examine the roles of plants and substrates in nutrient removal. The experimental setup involved FTW cells planted with *Chrysopogon zizanioides* known as Vetiver plant, *Chlorophytum comosum* known as Spider Plant, and *Canna Indica*, supported by substrate materials such as soil and gravel. Domestic wastewater samples were treated over a 10-day period, and key water quality parameters, including Total Nitrogen (TN), Total Phosphorus (TP), ammonia nitrogen (NH_3-N), and nitrate nitrogen (NO_3-N), were monitored. Energy Dispersive Spectroscopy (EDS) and Scanning Electron Microscopy (SEM) were also used to evaluate nutrient accumulation in plant tissues and substrate materials. The results showed that FTWs were effective in reducing nutrient concentrations in domestic wastewater. Vetiver plant demonstrated the most stable and consistently high nitrogen removal performance, achieving an average TN reduction of more than 94%. Spider Plant showed the highest phosphorus removal efficiency, particularly during the early treatment period, although its performance declined over time. *Canna Indica* exhibited strong nitrate removal capability, reaching more than 97% removal efficiency by the end of the experiment. The findings also confirmed that microbial activity in the root zone and the presence of substrates enhanced nutrient removal by supporting microbial colonisation and pollutant breakdown. Overall, this study demonstrates that FTWs are a practical, low-cost, and environmentally friendly option for domestic wastewater treatment, particularly for decentralised and small-scale applications. The integration of suitable macrophytes and substrates can improve nutrient removal efficiency and reduce the risk of eutrophication in receiving water bodies. With further optimisation and field-scale testing, FTWs have strong potential to complement or enhance existing wastewater treatment systems.

Keywords: Phytoremediation, Eutrophication, Macrophytes, Nature-based solution, Sustainable solution

1. Introduction

Domestic wastewater is a major source of nutrient pollution, particularly nitrogen and phosphorus, which can accelerate eutrophication, stimulate algal blooms, reduce dissolved oxygen, and degrade aquatic ecosystems when discharged without adequate treatment. Conventional wastewater treatment systems are commonly applied to reduce organic and nutrient loads; however, these systems often require high construction costs, continuous energy input, skilled operation, and regular maintenance. Their performance may also fluctuate under varying influent conditions, especially when the treatment process is not specifically designed for effective nitrogen and phosphorus removal (Ishak et al., 2022).

Nature-based Solutions (NbS) have gained increasing attention as sustainable alternatives for wastewater management because they rely on natural physical, chemical,

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and biological processes to improve water quality. Constructed Treatment Wetlands (CTWs), for example, have been widely studied for their ability to remove pollutants through plant uptake, microbial degradation, sedimentation, and filtration (Vymazal, 2014). However, CTWs often require large land areas, substantial substrate materials, excavation works, and long-term maintenance to prevent clogging caused by sediment accumulation and root growth. These limitations reduce their practicality for decentralized wastewater treatment, particularly in areas with limited land availability or financial resources.

FTWs offer a more flexible nature-based approach because they can be installed directly on existing water bodies or treatment tanks without major excavation. In FTWs, macrophytes are supported by floating platforms, allowing their roots to extend into wastewater and provide surfaces for biofilm development. Nutrient removal occurs through plant assimilation, microbial nitrification and denitrification, sedimentation, filtration, and adsorption within the root zone (Colares et al., 2020; Oliveira et al., 2021). Previous studies have reported that FTWs can effectively reduce nitrogen, phosphorus, ammonia, and other pollutants from wastewater, while requiring lower energy and infrastructure inputs compared with conventional treatment systems (Afzal et al., 2019; Zhang et al., 2015).

Despite these advantages, FTW performance is strongly influenced by the selected macrophyte species, substrate materials, root structure, microbial activity, and plant–substrate interaction. Different plants may vary in nutrient uptake capacity and ability to support microbial communities, while substrates may enhance plant stability and pollutant removal by providing additional surfaces for microbial attachment. Therefore, further assessment is needed to identify suitable macrophyte–substrate configurations for improving nutrient removal in domestic wastewater treatment.

This study evaluates the performance of a single-cell FTW system using selected macrophytes, namely *Chrysopogon zizanioides* or known as Vetiver plant, *Chlorophytum comosum* known as Spider Plant, and, *Canna indica*, together with selected substrate materials, for the removal of Total Nitrogen, Total Phosphorus, ammonia (NH_3-n), and nitrate (NO_3-N) from domestic wastewater. The findings are expected to support the development of low-cost and sustainable FTW systems for decentralised wastewater treatment applications.

2. Materials and Methods

The experimental setup is shown in the schematic of the FTW systems is illustrated in Fig. 1. Three polyethylene tanks were used for the experiments. The system was designed with a working volume of approximately 0.3 m^3 and operated at a hydraulic retention time (HRT) of 10 days. This corresponds to a design flow rate of 0.03 m^3/day (30 L/day) (Tara et al., 2019). Semi-synthetic wastewater was designed to simulate the nitrogen and phosphorus properties of normal municipal influent to achieve the target concentration of 20-85 mg/L, 4-15 mg/L, 10-20 mg/L and 5-10 mg/L for Total Nitrogen (TN), Total Phosphorus (TP), Ammoniacal Nitrogen (NH_3-N), and Nitrate (NO_3-N), respectively.

The macrophytes listed in Table 1 were purchased fom local nursery and acclimatized for 2 weeks under ambient conditions prior to the experiment. The characteristics of macrophytes are described in Table 1. Each model contained only one plant species, which was planted in the same substrate (black soil) and placed it on the floating platform. The influent was collected at Day 0. The treated samplings were conducted at regular intervals of every two days during the treatment cycle mainly in Day 3, 5, 7 and 10 as described by Tara et al. (2019).

The experiments were conducted in two phases to see the pattern of removal within 10 days duration. All the collected samples were tested in triplicate based on the standard method listed in Table 2.

Plant samples, for example leaves and roots, including black soils, were collected and analyzed at the Centralized Analytical Laboratory (CAL) using cutting-edge techniques mainly Energy Dispersive Spectroscopy (EDS) and Scanning Electron Microscopy (SEM). These methods evaluated the accumulation of nutrients and heavy metals in plant tissues, providing valuable information on each species' phytoremediation potential.

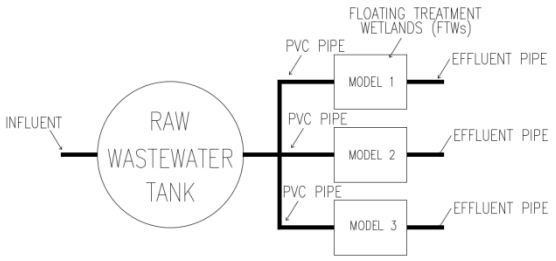

Fig. 1 - Layout plan of experimental setup

Table 1 – The characteristics of selected macrophytes

Macrophytes	Features	Characteristics
Model 1:Vetiver Plant (*Chrysopogon zizanioides)*		• Strong root network, • filtration, • structural stability
Model 2:Spider Plant (*Chlorophytum comosum*)		• Fast growth • nutrient absorption
Model 3*:Canna indica*		• Pollutant removal • aesthetic • biomass contribution

Table 2 - Method Used for Water Quality Analysis

Method Used for Analysis	
Total Nitrogen (TN)	Persulfate Digestion Method (Method 10072)
Total Phosphorus (TP)	Acid Persulfate Digestion Method (Method 8190)
Ammonia (NH_3-N)	Nessler Method (Method 8038)
Nitrate (NO_3-N)	Cadmium Reduction Method (Method 8039)

3. Results

3.1 Water Quality Performance

3.1.1 Total Nitrogen Removal

Figure 3 show the efficacy of floating treatment wetlands (FTWs) planted with *Chrysopogon zizanioides* (Vetiver), *Chlorophytum comosum* (Spider Plant), and *Canna indica* in terms of total nitrogen (TN) removal. The average influent TN concentration was 126.17 ± 45.02 mg/L. Within the first three days, all treatment systems showed a significant reduction in TN concentration, which then remained rather steady until Day 10. For Model 1 (Vetiver), effluent TN concentrations fell from an average of 6.50 mg/L on Day 3 to 5.00 mg/L on Day 10. Similarly, Model 2 (Spider Plant) reduced from 11.75 mg/L to 7.00 mg/L, while Model 3 (*Canna indica*) decreased from 8.00 mg/L to 4.00 mg/L within the same time period.

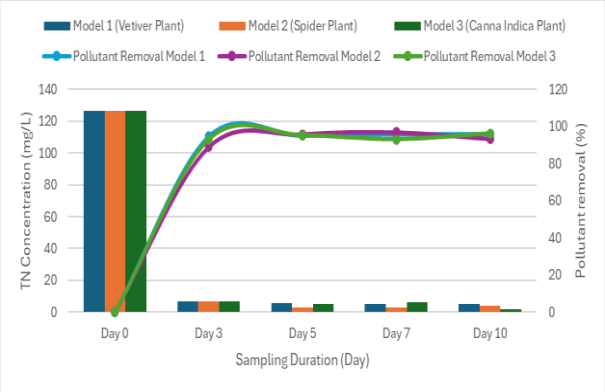

Fig. 3 - Scatter plot indicates efficiency of FTWs with different macrophytes to remove TN while clustered column indicates removal of nutrients in FTWs

The similar removal efficiencies demonstrate excellent treatment performance for all systems. Model 1 demonstrated an increase in TN removal efficiency from 94.60% on Day 0 to 95.77% on Day 10. Model 2 achieved removal efficiencies ranging from 85.04% to 93.43%, despite a transient dip on Day 10. Model 3 showed continuously high removal efficiency, peaking at 96.19% on Day 10 with minor fluctuations on intermediate sample days. Overall, *Canna indica* had the best and most consistent TN removal efficacy, followed closely by Vetiver, but Spider Plant had lower efficiency and greater variability.

The rapid initial decrease in TN content indicates that nitrogen removal activities, such as plant absorption and microbial activity in the rhizosphere, were most active in the early stages of the experiment. The succeeding stability phase suggests that the system was approaching equilibrium, as nitrogen removal rates were more consistent. These findings support the efficacy of FTWs in nitrogen removal and emphasize the impact of plant type on treatment efficiency. In FTWs, nitrogen removal is controlled by several interacting mechanisms, including plant assimilation, microbial nitrification–denitrification, biofilm activity, sedimentation, and filtration within the root zone (Afzal et al., 2019; Colares et al., 2020; Oliveira et al., 2021). The suspended root system of macrophytes plays an important role by increasing root–water contact and providing attachment surfaces for microbial communities responsible for nitrogen transformation (Park et al., 2019; Sharma et al., 2021).

3.1.2 Total Phosphorus Removal

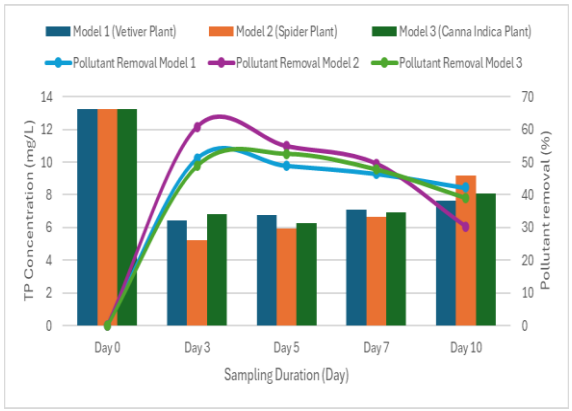

Fig. 4 - Scatter plot indicates efficiency of FTWs with different plant to remove Total Phosphorus (TP) while clustered column indicates removal of nutrients in FTWs

Figure 4 summarizes the total phosphorus (TP) removal performance of the floating treatment wetlands (FTWs). The average influent TP concentration was 13.24 ± 0.27 mg/L. All treatment techniques showed a significant reduction in TP concentrations, while removal effectiveness was lower and more varied than total nitrogen. Model 1 (Vetiver) produced effluent TP concentrations ranging from 6.46 mg/L to 7.66 mg/L, resulting in an average removal efficiency of 46.49 ± 5.66%, which gradually decreased over time. Model 2 (Spider Plant) performed slightly better but fluctuated, with effluent concentrations ranging from 5.20 mg/L to 9.19 mg/L and removal efficiencies varying from 33.43% to 64.35%. In comparison, Model 3 (*Canna indica*) achieved comparable TP concentrations (6.80-8.08 mg/L) with removal efficiencies ranging from 39.03% to 52.53%, indicating moderate but generally steady efficacy.

The findings show that phosphorus removal in FTWs was less efficient than nitrogen removal, most likely due to the limited mechanisms available, including plant uptake, adsorption to suspended particles, and microbial digestion. The initial increase in removal efficiency, notably around Day 3, indicates quick uptake and sorption processes, followed by a steady reduction or stabilization, possibly due to adsorption site saturation or decreased plant demand. Among the investigated species, Spider Plant had the highest peak removal efficiency, whereas Vetiver performed more consistently throughout time. Overall, the findings indicate that, while FTWs can help with phosphorus reduction, optimizing system conditions or incorporating other removal mechanisms may be required to obtain higher TP removal efficiency.

This reduction may be attributed to the saturation of phosphorus adsorption sites on plant roots, substrate surfaces, and microbial biofilms. Unlike nitrogen, phosphorus is not removed through gaseous transformation; therefore, its removal depends mainly on plant assimilation, adsorption, sedimentation, filtration, and microbial immobilisation. Once the available uptake and adsorption capacity becomes limited, phosphorus removal efficiency may decline over time. FTWs have been reported to provide larger root–water contact areas and greater biofilm surfaces, which improve nutrient removal compared with some conventional wetland configurations (Colares et al., 2020; Oliveira et al., 2021).

Previous studies have also shown that FTWs can achieve considerable TP removal depending on plant species, system design, hydraulic retention time, and wastewater characteristics. For example, studies summarised in the thesis reported TP removal efficiencies of 84.53% in Kampala,

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Uganda, and 31.75% in Bangkok, Thailand, demonstrating that phosphorus removal performance can vary significantly across FTW systems (Zhang et al., 2015). Other studies on domestic wastewater treatment using FTWs also reported TP removal values such as 91.5%, 82.7%, greater than 90%, 66.2%, 53.1%, and 19.6%, depending on plant species, treatment configuration, and operating conditions (Zhang et al., 2015; Colares et al., 2019). These variations support the finding that phosphorus removal is highly system-specific and depends on the interaction between macrophytes, microbial communities, and substrate or root-zone surfaces.

3.1.3 Ammonia (NH_3-N) Removal

Figure 5 shows how ammoniacal nitrogen (NH_3-N) concentrations and removal efficiency vary in floating treatment wetlands (FTWs). The average influent NH_3-N concentration was 11.39 ± 3.41 mg/L. Within the first three days, all models showed a rapid reduction in NH_3-N content, indicating effective initial removal. The effluent content in Model 1 (Vetiver) dropped dramatically to around 1.01 mg/L on Day 3 and then to 0.37 mg/L by Day 10. Similarly, Model 2 (Spider Plant) and Model 3 (*Canna indica*) had considerable reductions, with average concentrations of 0.40 mg/L and 0.67 mg/L, respectively, at the end of the trial.

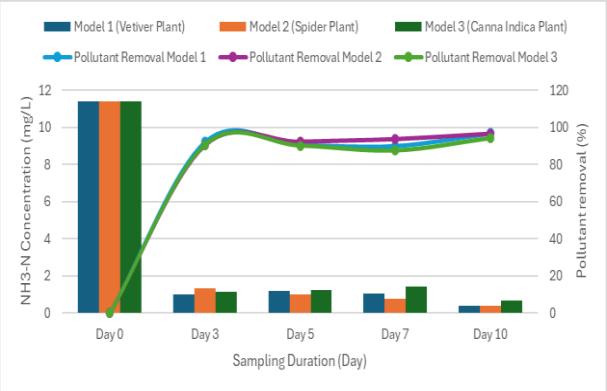

Fig. 5 - Scatter plot indicates efficiency of FTWs with different macrophytes to remove Ammonia (NH_3-N) while clustered column indicates removal of nutrients in FTWs

The corresponding removal efficiencies perform consistently well throughout the trial. Model 1 had the highest and most consistent removal efficiency, ranging from 92.19% on Day 3 to 96.77% on Day 10. Model 2 had somewhat lower efficiency, ranging from 90.19% to 96.46%, whereas Model 3 performed similarly, with values ranging from 87.39% to 94.03%, despite minor changes over intermediate sample days. The significant increase in removal efficiency during the early stages indicates that active nitrification and assimilation processes are encouraged by plant absorption and microbial activity in the rhizosphere. The subsequent stabilization phase indicates that the system has attained a steady state in which nitrogen removal activities are continuously effective. Vetiver outperformed Spider Plant and *Canna indica* in removing NH_3-N from household wastewater, indicating the efficiency of FTWs. Similar findings have been reported in FTW systems treating domestic and decentralised wastewater, where ammonia removal improved after root-zone microbial communities became established (Oliveira et al., 2021; Park et al., 2019).

The root zone of macrophytes is important in this process because plant roots provide attachment surfaces for nitrifying microorganisms and may release oxygen into the surrounding rhizosphere, thereby enhancing aerobic microbial activity. This mechanism is consistent with previous FTW studies, which reported that nutrient reduction occurs through plant absorption, microbial activity, biofilm development, sedimentation, and root-zone filtration (Colares et al., 2020; Oliveira et al., 2021). Previous FTW studies have reported effective nutrient removal using *Canna* species due to their tolerance to wastewater conditions, biomass production, and ability to support microbial processes in the rhizosphere (Zhang et al., 2015; Colares et al., 2020).

3.1.4 Nitrate (NO_3-N) Removal

Over a 10-day sampling period, Figure 6 shows the variation of influent and effluent nitrate nitrogen (NO_3^--N) concentrations and pollutant removal efficiencies for three different planted treatment models: Model 1 (Vetiver plant), Model 2 (Spider plant), and Model 3 (*Canna indica* plant). The influent concentration remains rather stable, with mean values of roughly 11.39 mg/L, demonstrating that the loading condition is consistent throughout all three systems. This establishes a realistic baseline for comparing treatment performance among models.

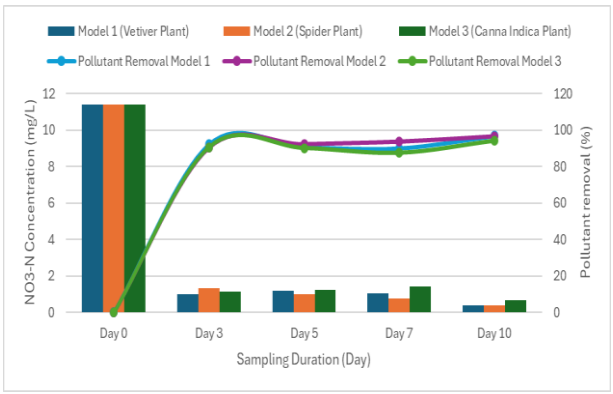

Fig. 6 - Scatter plot indicates efficiency of FTWs with different macrophytes to remove Nitrate (NO_3-N) while clustered column indicates removal of nutrients in FTWs

Immediately following treatment, all three models show a considerable drop in NO_3^--N concentration. By Day 3, effluent concentrations have dropped significantly from the influent level to low levels. Model 1 shows a drop of around 1.01 mg/L, Model 2 to about 0.97 mg/L, and Model 3 to about 1.14 mg/L. This rapid decrease shows that the treatment systems are extremely effective at eliminating nitrate within a short amount of time, most likely due to active biological processes and plant uptake. Following this initial reduction, effluent concentrations stay quite low and consistent from Day 5 to Day 10, with only modest variations. Model 1 maintains levels ranging from 1.01 to 1.18 mg/L, Model 2 has slightly lower concentrations ranging from 0.40 to 0.97 mg/L, and Model 3 takes place from 0.67 to 1.42 mg/L.

In terms of treatment efficiency, all three systems achieve high nitrate removal rates. After Day 0, removal efficiency steadily increases, often topping 90% by Day 3. Model 1 had efficiencies ranging from 90.68% to 92.19%, suggesting consistent performance during the research period. Model 2 had comparable efficiency, ranging between 90.19% and 92.14%, with somewhat lower values found on Day 10. Model 3 likewise performs well, with removal efficiencies ranging from 87.39% to 92.14%, gradually improving after the initial stage and then stabilizing. Previous studies have similarly reported that FTWs enhance nitrogen removal through root-zone biofilm development, plant assimilation, nitrification–denitrification, and microbial transformation processes

(Colares et al., 2020; Oliveira et al., 2021; Afzal et al., 2019; Park et al., 2019).

Overall, the figure shows that all three planted systems can achieve high nitrate removal under the testing conditions. The rapid fall in concentration within the first few days demonstrates the treatment process's efficiency, while the stable performance over time indicates that the systems achieve a steady operational state soon. Although there are modest discrepancies between the models, particularly in early-stage performance and variability, all three show equal success in nitrate removal, with efficiencies usually around or over 90%.

3.2 Macrophytes Photo

Table 3 depicts a visual comparison of three macrophyte species employed in floating treatment wetlands (FTWs): Vetiver plant, Spider plant, and *Canna indica*, before and after a 10-day treatment of semi-synthetic residential wastewater. Prior to treatment, all plants appear to be in good health, with intact roots and upright foliage. The Vetiver plant has solid roots and firm green shoots, while the Spider plant has long, arching leaves and a reasonably large root mass. The *Canna indica* plant has broad leaves and a well-developed root base.

Table 3 - Macrophytes Photo Before and After 10-Day Treatment

Before Treatment	After 10-Day Treatment
Chrysopogon zizanioides (Vetiver Plant)	
	
Chlorophytum comosum (Spider Plant)	
	
Canna Indica Plant	
	

After 10 days of treatment, there are visible changes in plant morphology and growth. The Vetiver plant shows improved root development and maintained shoot growth, showing a good adaptability to the wastewater environment. The Spider plant has a modest decline in leaf vigor, with some leaves seeming less upright, but the root system is still viable. In comparison, the *Canna indica* plant shows evident growth, enhanced leaf expansion, and a healthy overall structure, indicating high tolerance and adaptability to the treatment conditions.

3.3 Findings from Energy Dispersive Spectroscopy (EDS) and Scanning Electron Microscopy (SEM)

Table 4 represents an Energy-Dispersive X-ray Spectroscopy (EDS) testing was conducted to assess changes in nitrogen (N) and phosphorus (P) compounds in the vetiver plant and substrate (black soil) before and after treatment. The findings show a considerable increase in nitrogen accumulation inside plant tissue, with the nitrogen weight percentage increasing from 9.02% (0.23 mg) before treatment to 13.86% (0.42 mg) after treatment. This rise demonstrates that the macrophyte can effectively absorb and assimilate nitrogen. In contrast, the nitrogen concentration of the black soil reduced from 15.63% (2.45 mg) to 11.73% (1.69 mg), indicating that nitrogen was either absorbed by the plant or changed by microbial processes such as nitrification and denitrification.

Table 4 – The presence of nitrogen and phosphorus in selected macrophyte and substrate (a) before treatment (b) after treatment

Macrophytes/Substrates Samples	Before treatment			
	Nitrogen		Phosphorus	
	Weight (%)	Weight of Element (mg)	Weight (%)	Weight of Element (mg)
Vetiver Plant	9.02	0.23	8.01	0.2
Black Soil	15.63	2.45	7.75	1.22

(a)

Macrophytes/Substrates Samples	After treatment			
	Nitrogen		Phosphorus	
	Weight (%)	Weight of Element (mg)	Weight (%)	Weight of Element (mg)
Vetiver Plant	13.86	0.42	5.56	0.17
Black Soil	11.73	1.69	11.2	1.61

(b)

For phosphorus, a different pattern was seen. The phosphorus concentration of the vetiver plant fell marginally, from 8.01% (0.20 mg) to 5.56% (0.17 mg), indicating little accumulation within the plant biomass. In contrast, phosphorus content in black soil increased significantly from 7.75% (1.22 mg) to 11.20% (1.61 mg), indicating that the substrate played a prominent role in phosphorus retention. This result indicates that phosphorus removal was predominantly controlled by adsorption and precipitation mechanisms within the substrate matrix, rather than plant uptake.

3.3.1 Findings from Scanning Electron Microscopy (SEM)

SEM, when paired with Energy-Dispersive X-ray Spectroscopy (EDS or EDX), is an effective method for determining the surface composition of materials that absorb phosphorus (P) and nitrogen (N) from residential wastewater. EDS identifies and maps these components on the material's surface, with EDS peaks at certain energy levels indicating nutritional adsorption. Comparing pre- and post-adsorption spectra indicates the amount of phosphorus and nitrogen absorbed.

Sample 1 and 3

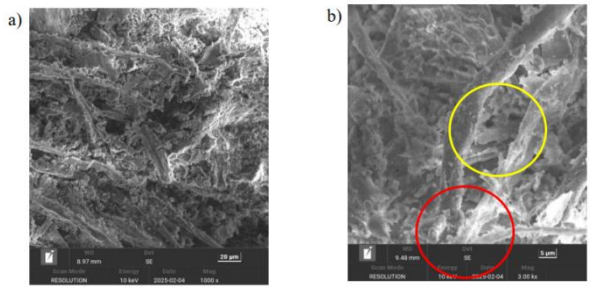

Fig. 11 - Sample 1 (a) and Sample 3 (b) under microscope. Red circle indicates the presence of Phosphorus in the sample after treatment while yellow circle indicates presence of Nitrogen in the sample after treatment

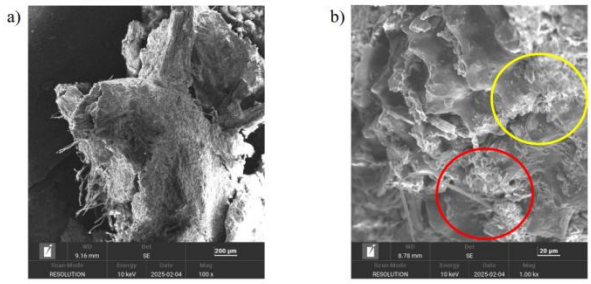

Fig. 12 - Sample 1 (a) and Sample 3 (b) under microscope. Red circle indicates that presence of Phosphorus in the sample after treatment while yellow circle indicates presence of Nitrogen in the sample after treatment

A piece from the entire sample of the Vetiver Plant is presented in Sample 1 prior to its exposure to synthetic wastewater. The nitrogen content, represented by the yellow circle in figures 11 and 12, was measured at 9.02%. The phosphorus content, indicated by the red circle in figures 11 and 12, was recorded at 8.01%. After the analysis, Sample 3 of the Vetiver Plant demonstrated a nitrogen content of 13.86% and a phosphorus content of 5.56%, as indicated by the red circle in figures 11 and 12. The Vetiver Plant demonstrated an enhanced capacity to absorb 4.84% more nitrogen and 2.45% more phosphorus. The plant absorbs nutrients from the surrounding soil or water through its roots, utilizing these resources for its growth and development. Conversely, as a natural outcome of its metabolic processes, it is also able to release any excess nutrients back into the surrounding environment. The plant may excrete or release certain nutrients back into the synthetic wastewater when it absorbs more than necessary or when there is an excess of nutrients present. The Vetiver Plant likely absorbed both nitrogen and phosphorus in this case; however, it is also possible that some of the phosphorus and nitrogen were released back into the synthetic wastewater due to the plant's natural growth processes or the management of excess nutrients.

Sample 2 and 4

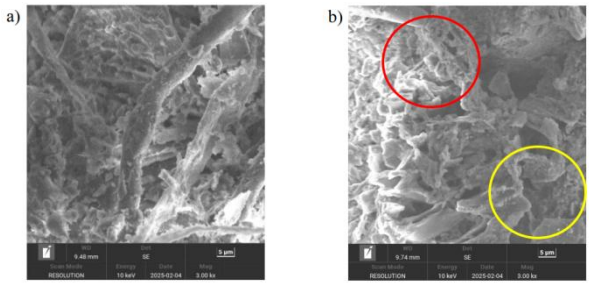

Fig. 13 - Sample 2 (a) and Sample 4 (b) under microscope. Red circle indicates that presence of Phosphorus in the sample after treatment while yellow circle indicates presence of Nitrogen in the sample after treatment

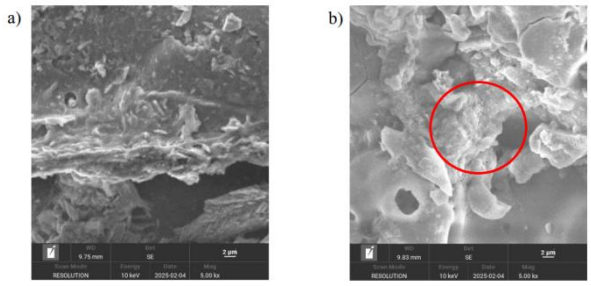

Fig. 14 - Sample 2 (a) and Sample 4 (b) under microscope. Red circle indicates that presence of Phosphorus in the sample after treatment

Sample 2 illustrates Black Soil with a nitrogen content of 15.63%, represented by a yellow circle in the figure, and a phosphorus content of 7.75%, indicated by a red circle in figures 13 and 14, prior to exposure to synthetic wastewater. Sample 4 demonstrates black soil with nitrogen levels of 11.73%, represented by a yellow circle in figures 13 and 14, and phosphorus levels of 11.2%, indicated by a red circle in figures 13 and 14, following environmental exposure. Black Soil demonstrated an increase in nitrogen absorption by 3.9%, while experiencing a reduction of 3.45% in its phosphorus content. Black soil possesses the capacity to absorb nutrients from wastewater; however, it also has the capability to release certain nutrients, particularly phosphorus, back into the environment through natural processes. Phosphorus may be diminished through leaching, a process that removes excess nutrients, or via microbial activity, which alters the soil's nutritional composition. These processes exemplify the loss of phosphorus. The soil may not retain all of the nutrients it absorbs. This is especially relevant when the ability to retain nutrients is exceeded or when microbial activities occur, both of which may account for the decrease in phosphorus levels. Consequently, although Black Soil has the ability to absorb nitrogen, it appears to be experiencing a decline in phosphorus levels over time, likely due to the natural processes occurring within the soil.

4. Conclusion

This study successfully achieved its two main objectives: to evaluate the performance of a single-cell FTW system using selected macrophytes and substrate materials, and to determine the role of plants and substrates in nutrient removal from wastewater. The FTW models were planted with *Canna indica*, Spider Plant and Vetiver Plant, while soil and gravel

were used as supporting substrates to stabilise the plants and enhance microbial activity.

The results showed that FTWs were effective in reducing nutrient concentrations, particularly Total Nitrogen (TN), Total Phosphorus (TP), ammoniacal nitrogen (NH_3-N), and nitrate (NO_3-N). For TN removal, Vetiver Plant showed stable performance in the first phase, with removal efficiency increasing from 86.04% on Day 3 to 94.70% on Day 10. In the second phase, *Canna indica* achieved the highest final TN removal efficiency of approximately 99%, while Spider Plant showed rapid initial TN removal of approximately 98.5%. These findings indicate that the FTW system was able to support effective nitrogen removal through plant uptake and microbial nitrogen transformation.

For TP removal, Spider Plant recorded the highest efficiency among the selected plants, particularly during the early treatment period. It achieved 66.31% TP removal on Day 3, although the efficiency decreased to 50.78% by Day 10. Meanwhile, Vetiver Plant and *Canna indica* recorded lower TP removal efficiencies of 38.20% and 35.15%, respectively, by Day 10. This shows that phosphorus removal was effective during the early stage but became less stable over time, possibly due to saturation of plant roots, substrate surfaces, and biofilm adsorption sites.

The FTW system also showed strong performance in removing NH_3-N and NO_3-N. In the second phase, Vetiver Plant achieved the highest NH_3-N removal efficiency of approximately 98% on Day 10, followed by Spider Plant at 96% and *Canna indica* at 94%. For NO_3-N, all three plant species reached nearly 100% removal efficiency by Day 7 in the second phase. These results suggest that the root zones of the macrophytes provided suitable conditions for microbial nitrification and denitrification, which are important processes in nitrogen removal.

The substrates also contributed to the overall treatment performance by supporting plant growth and providing surfaces for microbial colonisation. Soil and gravel helped improve pollutant breakdown and nutrient transformation within the FTW system. In addition, the Energy Dispersive Spectroscopy (EDS) and Scanning Electron Microscopy (SEM) analyses showed nutrient accumulation in plant and substrate samples after treatment, further confirming the role of macrophytes and substrates in capturing nutrients from wastewater.

This study concludes that FTWs are a practical, low-cost, and environmentally friendly alternative for wastewater treatment, especially for decentralised and small-scale applications. Among the tested plants, Vetiver Plant provided stable nitrogen and ammonia removal, Spider Plant was most effective for early phosphorus removal, and *Canna indica* showed strong final-stage nitrogen removal. However, the decline in phosphorus removal over time indicates that long-term FTW operation may require regular plant harvesting, substrate maintenance, and proper system management. With further optimisation, FTWs have strong potential to complement existing wastewater treatment systems and reduce nutrient pollution in receiving water bodies.

5. Acknowledgement

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