

Research article

# Removal Efficiency of Physicochemical and Microbial Pollutants in Wastewater Using Vertical Flow Constructed Wetlands

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## ABSTRACT

Constructed wetlands are decentralized systems for treating wastewater (WW), yet there is still a wide knowledge gap regarding the potential of some indigenous macrophytes. In this study, two indigenous macrophytes, *Eragrostis curvula* (EC) and *Paspalum dilatatum* (PD), were evaluated for treating municipal wastewater using Vertical Flow Constructed Wetland (VFCW) with shea nut shell biochar (BCH) as a substrate enhancer. EC was represented by two units (ECWW and ECBCH), while PDWW and PDBCH represented the wetlands planted with PD. A hydraulic retention time (HRT) of 5 days was observed with a hydraulic loading rate (HLR) of 24 mm/day. The highest removal efficiencies for physicochemical and microbial parameters were as follows: Total Suspended Solids (TSS) – 94.93±8.43%, Total Dissolved Solids (TDS) – 37.68±16.17%, Turbidity – 100±2.47%, Salinity – 60.39±7.86%, Oxidation-Reduction Potential (ORP) – 91.81±13.96%, Electrical Conductivity (EC) – 41.75±7.17%, Nitrite (NO<sub>2</sub>-N) – 100±26.78%, Nitrate (NO<sub>3</sub>-N) – 100±0%, Ammonium (NH<sub>4</sub>-N) – 92.17±4.78%, Faecal Coliform (FC) – 100±9.03%, and Total Coliform (TC) – 98.71±13.55%. Plant height and number of leaves showed that EC was better established than PD. The HYDRUS-1D software was used to validate the porous media parameters and it was concluded that the retention capacities of the constructed wetlands were optimal, with flow occurring from the residual water content region to saturated water content region. The measured shape factors  $\alpha$  (0.438m<sup>-1</sup>),  $\theta$  (1.0) and  $n$  (2.063) produced a Python-fitted curve comparable to the validation curve obtained from the HYDRUS-1D model.

## Key words:

physicochemical, peri-urban, shea nut shells, macrophytes, biochar, coliforms

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## INTRODUCTION

Managing wastewater is a critical developmental challenge in many cities across Sub-Saharan Africa. In developing nations, three out of every four cities use untreated wastewater (DosSantos et al, 2017). In some of these countries, up to 95% of wastewater is discharged untreated directly into the environment. Globally, wastewater generation is estimated at over 380 billion m<sup>3</sup> annually, and this figure is expected to rise to 470 billion m<sup>3</sup> by 2030 and 574 billion m<sup>3</sup> by 2050 (WHO/UNICEF, 2022). According to Qadir et al. (2020), these estimates reflect an increase of 24% and 51%, respectively.

Macrophytes are a primary biological component of wetlands, which play a dual role as catalysts for purification reactions and pollutant removal through their tissues (Thullen et al., 2005). This fosters a range of chemical and biological reactions, thereby enhancing the treatment processes in wetland systems (Dotro et al., 2017). Plants that thrive in artificial wetlands are an integral part of the design due to their various characteristics relevant to the water

treatment processes. Radial oxygen loss (ROL) in the root zone makes macrophytes the primary source of oxygen in constructed wetlands (CWs) (Lai et al., 2012; Wang et al., 2018), which promotes an aerobic microenvironment and accelerates pollutant removal. In contrast, pollutant removal efficiency is lower in anaerobic conditions, which predominate in CWs. Plants thus play a crucial role in CW systems.

The adsorption capacity of biochar derived from agriculture is primarily contingent upon the characteristics of the feedstock and the pyrolysis process. Produced from biomass, such as nut shells, wood, manure, seeds, husks, or leaves, biochar is a carbon-rich product, frequently heated in a closed vessel with little to no air. Thus, the term "biochar" describes a heterogeneous material rich in aromatic carbon and minerals (Pariyar et al., 2020). Numerous researchers have worked to develop novel, cost-effective adsorbents derived from plant and agricultural wastes (Apaydin-Varol et al., 2007). For example, studies using lettuce as a test crop demonstrated that ground shea nut shells can effectively eliminate harmful metals from soil, specifically Mn, Fe, Zn, and Cu (Quainoo et al., 2015). Shea nuts shells are readily available as a common agricultural residue in Northern Ghana. Furthermore, they are considered to be incredibly affordable and environmentally beneficial as a means of cleaning up contaminated areas (Dwiejuah et al., 2022). However, the removal of heavy metals was not the focus of this study as this aspect was previously investigated by Yakubu et al. (2021) in collaboration with the main author of this research.

In the field of soil hydrology, extensive research has been conducted on the assessment of partially saturated hydraulic properties. However, relatively little research has focused on specific porous media, such as sands and gravels, recovered in Vertical Flow Constructed Wetlands (VFCW) systems (Šimůnek et al., 2016). A laboratory-scale experiment conducted by Giraldi & Iannelli (2009) evaluated the saturated hydraulic conductivity of materials in a VFCW system. By combining these measurements with general approximations of the hydraulic function shape parameters, they modelled the water content distributions observed in a VFCW pot plant and in laboratory columns using capacitance probes. Using these techniques, they were able to efficiently determine the actual configuration of VFCW, which allowed them to identify operational flaws. Organic pollutants such as Biological Oxygen Demand (BOD<sub>5</sub>) and Chemical Oxygen Demand (COD) have previously been tested in wastewater at the same study site (Tamale Metropolis) by Abagale (2021).

*Eragrostis curvula* (Schrud.) Nees and *Paspalum dilatatum* Poir. are both perennial and indigenous grasses found in abundance in Sub-Saharan Africa (SSA), particularly in Ghana. The potential of these grasses for use as constructed wetland macrophytes has not yet been investigated globally. The lack of common wetland macrophytes in SSA, especially in Ghana during the dry season, prompted the need to utilize the indigenous grasses. During the dry season, irrigation becomes impossible for local farmers in peri-urban areas, leading them to rely on wastewater for irrigation. Therefore, to evaluate the treatment of wastewater containing microbial and physicochemical pollutants, PD and EC were employed in this study. For optimal growth, PD requires high temperatures typical of SSA, an adequate water supply, and high nitrogen content in the soil. According to Bilgin and Avcı (2020), PD grows readily in areas with annual temperature variations of 15 to 20°C, as well as under drought or flooding conditions. Originally from Southern Africa, EC is a perennial plant now found all over the world, primarily in arid and semiarid areas. Due to its spring-summer growth and higher biomass production compared to temperate forage species, it is primarily used as fodder (Luciani et al., 2012). Biochar pyrolyzed from shea nut shells was also used as a substrate amendment to further enhance the treatment efficiency of the pilot-scale vertical flow constructed wetlands.

## MATERIAL AND METHODS

### Study Area

Similar to Udoma et al. (2024), the experiment was carried out at the Agricultural Engineering experimental site at the University for Development Studies, Nyankpala Campus, Tamale, Ghana, located at 9° 24' 37" N and 0° 58' 53" E (Figure 1). It is situated 450 kilometres from Accra City and 15 kilometres from Tamale Metropolitan. At the downstream end of Koobilmahago urban gutter channel, there are irrigation points that drain and collect wastewater flowing from the central part of the Tamale metropolitan area (Cangola et al., 2025). The experimental site is located within the Guinea Savannah agro-ecological zone. The region experiences a sub-Saharan climate, with unimodal rainfall occurring from June to November (Gyasi et al., 2014). The region experiences high temperatures, with minimum and maximum values of approximately 22°C and 36°C, respectively. Temperatures can reach up to 45°C, and the dry season typically lasts seven months, from November to June. The rate of evapotranspiration varies from 4.4 to 6.5 mm/day on average. The soils are predominantly alluvial.

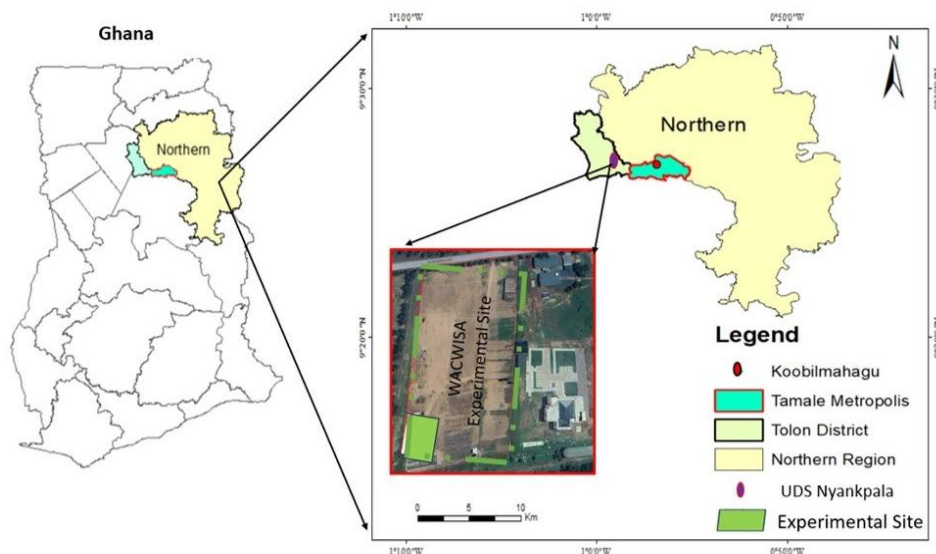


Figure 1. Geographical location map of the experimental site (Udoma et al., 2024)

### Criteria for Selecting Macrophytes

The study was carried out during the dry season, from January to May 2024. During this period, commonly used macrophytes such as Cattails (*Typha latifolia*) and Vertiva (*Chrysopogon zizaniodes*) are usually not obtainable in the study area (Cangola et al., 2025). Hence, macrophytes EC and PD were selected based on their abundance around the farming sites in Tamale. The macrophytes were harvested from their natural habitat, trimmed to 10 cm shoot length and transplanted into the wetlands at a density of 6 plants per pilot for PD and 4 tufts per pilot for EC. On the other hand, during the wet season, which spans from June to December, rainfall is generally sufficient for cultivation, hence, farmers do not rely on wastewater for vegetable production.

### Experimental Design

The experimental design involved six treatments in triplicates and two controls in duplicates. The treatments, in no particular order, were *Paspalum dilatatum* Poir (PD) planted with biochar (PDBCH), PD without biochar (PDWW), unplanted beds with biochar (UPBBCH) and without biochar (UPBWW), and *Eragrostis curvula* (Schrud.) Nees (EC) planted with biochar (ECBCH) and without biochar (ECWW). Lastly, the overall control treatments consisted of freshwater units, one set planted with PD and the other set with EC (PDFW and ECFW, respectively). Schematic diagrams of the constructed wetland field layout and each wetland are presented in Figures 2 and 3. Table 1 presents the materials used for constructing the treatment wetlands.

Table 1. Wetland construction materials

| Construction Materials |                    |                  |                                   |
|------------------------|--------------------|------------------|-----------------------------------|
| Section                | Materials          | Composition      | Properties                        |
| Wetland                | CW                 | Plastic Pots     | 0.3x0.2x0.4 m                     |
|                        | Ground Support     | Cement Blocks    | 0.5x0.05x0.2 m                    |
|                        | Aeration Tube      | PVC Pipe         | Ø: 0.06 m                         |
|                        | Effluent Collector | Plastic Bottles  | 1 litre                           |
|                        | Effluent Outlet    | Taps with Valves | ¾ inch Pipes                      |
|                        |                    |                  | ES = 0.28                         |
| Bedding Media          |                    |                  | UC = 2.21                         |
|                        | Filter Media       | Coarse Sand      | P (%) = 40                        |
|                        |                    |                  | BD (g/cm <sup>3</sup> ) = 0.00128 |
|                        | Middle Layer       | Biochar          | Ø = 0.08 – 4.0 mm                 |
|                        | Base Layer         | Gravel           | Ø = 4.0 – 12.0 mm                 |
|                        |                    |                  | Ø = 9.5 – 19 mm                   |

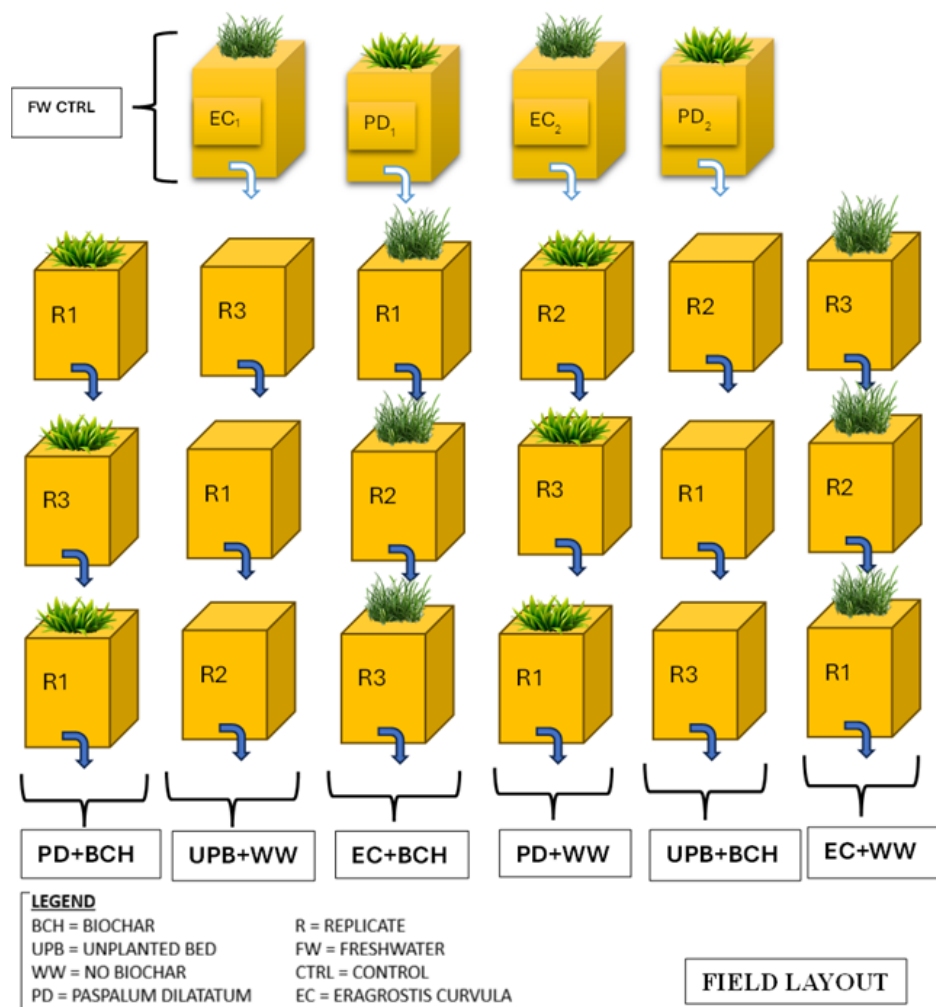


Figure 2. Schematic representation of the field layout (Udoma et al., 2024)

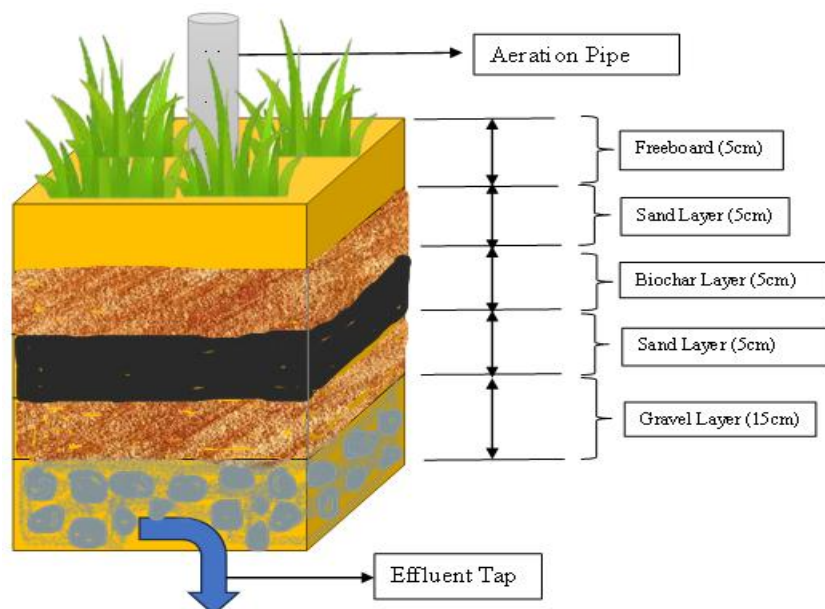


Figure 3. Schematic representation of a wetland (Udoma et al., 2024)

### Characterization of Raw Influent and Effluent Wastewater Quality

Raw wastewater was analyzed for physicochemical parameters and microbial pathogens before (influent) and after (effluent) treatment. The effluents were sampled into sterilized bottles and transported in ice chests to the laboratory. Wastewater characterization was conducted in-situ with the AQUAProbe AP 5000 meter for physical parameters, including Electrical Conductivity (EC), pH, Temperature (Temp.), Oxidation-Reduction Potential (ORP), and Salinity (Sal). LAQUA WQ-330 Horiba was used for measuring solids, including Turbidity (NTU), Total Dissolved Solids (TDS), and Total Suspended Solids (TSS). Laboratory tests were also conducted to estimate faecal pollutants, namely Total Coliform (TC) and Faecal Coliform (FC), using the AQUASafe WSL50 Pro. Nutrient analysis (NO<sub>2</sub>-N, NO<sub>3</sub>-N, NH<sub>4</sub>-N) was performed using the HYDROTEST Meter HT 1000, in accordance with the Standard Methods for the Examination of Water and Wastewater (APHA, 2023), as detailed in Table 2.

Table 2. Instruments used and their details

| Instrument Model       | AP-5000<br>Aquaprobe | LAQUA WQ-330                  | AQUASafe WSL50<br>Pro             | HydroTest HT1000<br>Photometer    |
|------------------------|----------------------|-------------------------------|-----------------------------------|-----------------------------------|
| Manufacturer           | Aquaread Ltd         | HORIBA Advanced<br>Techno Ltd | Trace2o / Wagtech<br>Projects Ltd | Trace2o / Wagtech<br>Projects Ltd |
| City                   | Broadstairs          | Minami-ku, Kyoto              | Thatcham                          | Thatcham                          |
| Country (State)        | Kent                 | Kyoto                         | Berkshire                         | Berkshire                         |
| Country of Manufacture | United Kingdom       | Japan                         | United Kingdom                    | United Kingdom                    |

### Macrophyte Acclimatization

Morphological growth, comprising plant height and number of plants, was monitored, and data was collected every 48 hours (2 days). Macrophytes were allowed to establish and acclimatize for a period of 4 weeks before wastewater was introduced. A standard engineer's metre rule was used to measure plant height in centimetres (cm), while a manual counting method was employed to determine the number of plants. During the acclimatization stage, irrigation was carried out with freshwater twice daily (morning and evening) to promote rapid establishment of the grasses. Six plants were transplanted into each wetland containing PD, while four tufts were transplanted for EC. Before transplanting, the macrophytes were trimmed to a uniform height of 10cm to prevent leaf wilting at the initial stage.

### Wastewater Flow Rate and Loading Rate

Optimal moisture conditions for each wetland required the application of 3 litres of wastewater every 48 hours, resulting in a flow rate (Q) of 0.0015 m<sup>3</sup>/day, with a uniform surface area (A) of 0.0624 m<sup>2</sup> for all the pilot-scale wetlands. A hydraulic retention time (HRT) of 5 days and a hydraulic loading rate (HLR) of 24 mm/day were applied to each CW.

The hydraulic loading rate (HLR) was estimated using Equation (1) (Kadlec and Wallace, 2009), expressed as:

$$HLR = \frac{Q}{A} \quad (1)$$

Where:

HLR = hydraulic loading rate (m/day)

Q = flow rate (m<sup>3</sup>/day)

A = surface area of wetland (m<sup>2</sup>).

### Pollutant Removal Efficiency

The efficiencies of the VFCWs were estimated using water quality parameters measured before and after treatment. Percentage removal efficiency was estimated as the percentage of pollutant removal (R) for influent and effluent concentrations using Equation (2) (Kadlec and Wallace, 2009).

$$\%R = \frac{C_{in} - C_{eff}}{C_{in}} \times 100 \quad (2)$$

Where:

R = pollutant removal efficiency (%); C<sub>in</sub> and C<sub>eff</sub> = influent and effluent concentrations (mg/L).

### The HYDRUS Model

This study utilized the HYDRUS-1D model, developed by Langergraber and Šimůnek (Šimůnek et al., 2016), to simulate water movement within vertical flow constructed wetlands (VFCWs). The modelling process involved several essential steps, including configuration, calibration, validation, and application, to predict VFCW performance under various treatment conditions.

**Substrate Properties:** The HYDRUS-1D model requires detailed substrate characteristics such as porosity, bulk density, and soil water retention properties. These parameters were obtained through laboratory analysis of substrate samples from the constructed wetlands.

**Initial Conditions:** The initial moisture content of the substrate layers was measured and used as input data for the model to ensure an accurate representation of the system's starting state.

**Boundary Conditions:** The upper boundary condition accounted for wastewater infiltration, including inflow rate and influent quality. The lower boundary condition represented drainage and the outflow of treated effluent.

**Domain Discretization:** The vertical profile of the wetland was divided into multiple layers to capture variations in substrate properties and moisture content. A finer discretization was applied near the surface to enhance the accuracy of infiltration and evapotranspiration simulations.

**Time Discretization:** The simulation period was segmented into appropriate time intervals to reflect dynamic water flow changes, with shorter time steps applied during rapid infiltration events.

**Calibration Data:** Initial experiments provided data on water levels, flow rates, and effluent concentrations, which were used to calibrate model parameters.

**Validation Data:** Independent datasets, collected under different experimental conditions, were employed to validate the model. The accuracy of the model was assessed by comparing simulated outputs with observed data, ensuring a reliable representation of VFCW processes.

**Water Flow Dynamics:** The HYDRUS-1D model simulated water movement within the VFCWs, capturing infiltration and drainage processes. By integrating experimental data with the model, the study provided a comprehensive understanding of hydraulic retention time and wetland performance. These insights contribute to optimizing the design and operation of constructed wetlands for sustainable wastewater treatment and irrigation reuse.

### Curve Fitting with Machine Learning

The study employed a machine learning algorithm within Python's Jupyter environment to fit the water content curve for hydraulic dynamics in the wetlands. The shape parameters for the Van Genuchten and Mualem equation were derived through curve fitting, using experimental residual and saturated water content values as inputs.

Applying the Van Genuchten and Mualem (Cao and Yue, 2014) closed-form equation, the hydraulic properties of the gravel and sand layers in the VFCWs were modelled to enhance understanding of their water retention behaviour, as expressed in Equation (3).

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{[1 + [\alpha h]^n]^m} \quad h < 0 \quad (3)$$

Where:

$h < 0$  and  $m = 1 - 1/n$

$h(L)$  is the actual pressure head

$\theta(h) (L^3 L^{-3})$  is the actual water content dependent on  $h$

$\theta_r$  and  $\theta_s (L^3 L^{-3})$  are the residual and volumetric water contents, respectively

$\alpha (L^{-1})$  and  $n (-)$  are shape parameters.

### Statistical Analysis

The variation among species in average plant height and number of plants was analyzed for statistical significance. Macrophyte morphological parameters were subjected to trend analysis and plotted with Microsoft EXCEL. Additionally, the statistical significance of macrophyte, biochar and their interactive effect on pollutant removal was also evaluated. These were determined using analysis of variance (ANOVA) at 5% significance level, with the 12th edition of GENSTAT software (Hemel Hempstead, Hertfordshire, England, United Kingdom).

## RESULTS AND DISCUSSION

### Raw and Treated Wastewater Analysis

The raw (influent) wastewater used in this study was characterized based on its physical properties, solid content, nutrients, and bacterial coliform levels (Table 3). The quality parameters were compared with existing literature values. Additionally, treated wastewater samples were characterized and compared with the Ghana Environmental Protection Agency (EPA) limits for irrigation (Table 4).

Table 3. Characteristics of raw wastewater used in this study

| Parameter                 | n  | Mean                 | (Cangola et al., 2025) | (García-Pérez et al., 2011) | (Apuseyine, 2021) |
|---------------------------|----|----------------------|------------------------|-----------------------------|-------------------|
| TDS (mg/L)                | 30 | 1235.27(±470.6)      | 1073(±424.4)           | -                           | 469.5(±78.06)     |
| TSS (mg/L)                | 19 | 51.00(±72.49)        | 2.78(±0.833)           | 52                          | 715(±230.68)      |
| Turbidity (NTU)           | 27 | 23.72(±42.46)        | 3.0(±1.414)            | -                           | 163.75(±77.41)    |
| pH                        | 30 | 8.18(±0.61)          | 7.91(±0.43)            | 6.9-7.1                     | 7.57(±0.46)       |
| TEMP (°C)                 | 30 | 29.35(±3.83)         | 32.76(±2.30)           | 17.4                        | 31.91(±2.05)      |
| Sal (PSU)                 | 30 | 1.02(±0.34)          | NA                     | -                           | NA                |
| ORP (mV)                  | 30 | -77.00(±70.86)       | -62.31(±21.53)         | -199                        | -124.45(±50.82)   |
| EC (µS/cm)                | 30 | 1928.73(±583.99)     | 2021(±139.2)           | -                           | 1130(±0.4)        |
| DO (mg/L)                 | 18 | 1.81(±1.12)          | 0.83(±0.253)           | -                           | 0.9(±0)           |
| NO <sub>2</sub> -N (mg/L) | 16 | 2.35(±3.77)          | 0.294(±0.05)           | -                           | 1.97(±3.18)       |
| NO <sub>3</sub> -N (mg/L) | 16 | 7.47(±12.92)         | 0.198(±0.05)           | 0.5                         | 18.3(±29.77)      |
| NH <sub>4</sub> -N (mg/L) | 19 | 1.07(±1.91)          | 14.67(±4.06)           | 80                          | 89.9(±0)          |
| FC (Log CFU/100mL)        | 30 | 1.18×10 <sup>1</sup> | NA                     | 3.0×10 <sup>6</sup>         | NA                |
| TC (Log CFU/100mL)        | 30 | 2.31×10 <sup>2</sup> | NA                     | -                           | NA                |

Legend: n - number of samples; NA – not applicable; TDS - Total Dissolved Solids; TSS - Total Suspended Solids; Sal - Salinity; ORP - Oxidation-Reduction Potential; EC - Electrical Conductivity; DO - Dissolved Oxygen; NO<sub>2</sub>-N - Nitrite-Nitrogen; NO<sub>3</sub>-N - Nitrate-Nitrogen; NH<sub>4</sub>-N - Ammonium-Nitrogen; FC - Faecal Coliform; TC - Total Coliform

Table 3 presents the results of a detailed analysis of untreated wastewater samples collected from the study site. The raw wastewater had slightly higher values compared to those reported in previous studies presented in the table. These discrepancies suggest the presence of dissolved organic substances such as salts, minerals, or domestic effluents, including detergents and household chemicals. Another possible explanation is seasonal variation, as sampling was conducted during the dry season, when evaporation concentrates dissolved substances, thereby increasing TDS, which is proportionally linked to EC and Salinity (Sal). The higher TSS and Turbidity values compared with those reported by Cangola et al. (2025) were attributed to the presence of unsettled heavy particles prior to sampling, as well as disturbances during the sampling process. Reduced surface run-off during the dry season also resulted in lower TSS and Turbidity values compared with those reported by García-Pérez et al. (2011) and Apuseyine (2021). The critical parameters examined included TDS, TSS, Turbidity, EC, Sal, ORP, Nutrients, and Coliforms.

Table 4 outlines findings from a similar analysis to that presented in Table 3, but this time for treated wastewater samples in comparison with the untreated values. The Ghana Environmental Protection Agency pollutant limits for irrigation water were used to determine the suitability of the treated samples for irrigation. The treatments included PD, EC, and UPB, with and without biochar (BCH). All the results obtained after treatment were suitably reduced below EPA standards, except for TDS, Electrical Conductivity, and Salinity. The TDS value of the raw (untreated) wastewater was 1235.27 mg/L, exceeding the EPA guideline of 1000 mg/L, as indicated in Table 4. TDS values in the treated wastewater showed a higher increase in the BCH-amended treatments, suggesting that while particulate matter was removed, the ionic content increased as a result of biochar solubilization. The same results were observed for Electrical Conductivity and Salinity, which confirms the relationship among the three measured parameters, as previously discussed. NO<sub>2</sub>-N, NO<sub>3</sub>-N, and NH<sub>4</sub>-N concentrations decreased significantly across all treatments, indicating effective removal of excess nutrient. Faecal and total coliforms were also significantly reduced, particularly in PDBCH and UPBBCH wetlands.

Table 4. Effluent concentrations from treatment wetlands

| TRT                            | RAW                  | ECWW                  | ECBCH                 | UPBWW                 | UPBBCH                | PDWW                  | PDBCH                 | P-value Biochar | P-value Macrophyte | LSD   | Ghana EPA Limit |
|--------------------------------|----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------|--------------------|-------|-----------------|
| <b>TDS (mg/L)</b>              | 1235.27              | 1725.50               | 2267.25               | 1499.33               | 1961.58               | 1745.17               | 2127.25               | 0.006           | 0.007              | 148   | 1000            |
| <b>TSS (mg/L)</b>              | 51.00                | 6.92                  | 12.42                 | 7.50                  | 8.42                  | 2.58                  | 14.75                 | 0.005           | 0.869              | 1.9   | 50              |
| <b>Turbidity (NTU)</b>         | 23.72                | 2.67                  | 13.00                 | 4.50                  | 14.58                 | 2.42                  | 16.25                 | 0.03            | 0.842              | 8.7   | -               |
| <b>pH</b>                      | 8.18                 | 7.97                  | 7.71                  | 8.86                  | 8.76                  | 8.05                  | 7.68                  | 0.132           | <0.001             | 0.421 | 6.0-9.0         |
| <b>Sal (ppt)</b>               | 1.02                 | 1.83                  | 2.49                  | 1.60                  | 2.19                  | 1.81                  | 2.46                  | 0.012           | 0.044              | 0.298 | <0.7            |
| <b>ORP (mV)</b>                | -77.00               | -65.63                | -47.95                | -117.22               | -112.19               | -70.86                | -49.31                | 0.083           | <0.001             | 19.4  | -               |
| <b>EC (µS/cm)</b>              | 1928.73              | 3445.83               | 4534.17               | 2991.75               | 3927.00               | 3486.75               | 4255.00               | 0.005           | 0.007              | 276.9 | -               |
| <b>NO<sub>2</sub>-N (mg/L)</b> | 2.35                 | 0.01                  | 0.01                  | 0.01                  | 0.01                  | 0.00                  | 0.03                  | 0.147           | 0.724              | 0.019 | 1               |
| <b>NO<sub>3</sub>-N(mg/L)</b>  | 7.47                 | 0.03                  | 0.12                  | 0.76                  | 0.17                  | 0.04                  | 0.06                  | 0.131           | 0.006              | 0.273 | 50              |
| <b>NH<sub>4</sub>-N(mg/L)</b>  | 1.07                 | 0.23                  | 0.12                  | 0.08                  | 0.15                  | 0.12                  | 0.14                  | 0.741           | 0.315              | 0.095 | 1               |
| <b>FC (cfu/100mL)</b>          | 1.18×10 <sup>1</sup> | 5.93×10 <sup>-1</sup> | 5.99×10 <sup>-1</sup> | 3.52×10 <sup>-1</sup> | 1.00×10 <sup>0</sup>  | 4.65×10 <sup>-1</sup> | 2.81×10 <sup>-1</sup> | 0.358           | 0.213              | 5.0   | 0-10*           |
| <b>TC (cfu/100mL)</b>          | 2.31×10 <sup>2</sup> | 9.54×10 <sup>-1</sup> | 9.62×10 <sup>-1</sup> | 6.20×10 <sup>-1</sup> | 6.28×10 <sup>-1</sup> | 8.50×10 <sup>-1</sup> | 8.75×10 <sup>-1</sup> | 0.897           | 0.049              | 6.5   | 0-100*          |

Legend: \* - restricted; TDS - Total Dissolved Solids; TSS - Total Suspended Solids; Sal - Salinity; ORP - Oxidation-Reduction Potential; EC - Electrical Conductivity; DO - Dissolved Oxygen; NO<sub>2</sub>-N - Nitrite-Nitrogen; NO<sub>3</sub>-N - Nitrate-Nitrogen; NH<sub>4</sub>-N - Ammonium-Nitrogen; FC - Faecal Coliform; TC - Total Coliform; TRT - Treatment; RAW - Untreated Wastewater (influent); ECWW - *Eragrostis curvula* (without Biochar); ECBCH - *Eragrostis curvula* (with Biochar); UPBWW - Unplanted Bed (without Biochar); UPBBCH - Unplanted Bed (with Biochar); PDWW - *Paspalum dilatatum* (without Biochar); PDBCH - *Paspalum dilatatum* (with Biochar); LSD - Least Significant Difference; EPA - Environmental Protection Agency

Source: Udoma et al. (2024)

### Biochar Characterization

Shea nut shells were pyrolyzed at 450<sup>0</sup>C using a locally fabricated cone-shaped “Kuntan” equipped with a detachable chimney at the top. Table 5 shows the proximate analysis results obtained from the produced biochar. The results were compared with values in existing literature and found to be within standard ranges.

Table 5. Biochar proximate analysis characteristics

| Parameter                              | Current Study   | Reference           |                        |                    |                     |                     |
|----------------------------------------|-----------------|---------------------|------------------------|--------------------|---------------------|---------------------|
|                                        |                 | Zhang et al. (2020) | Christou et al. (2022) | Chen et al. (2014) | Ahmad et al. (2012) | Zhang et al. (2020) |
| <b>Biochar Feedstock</b>               | Shea nut shells | Sewage Sludge       | Poultry Litter         | Orange Peels       | Peanut Shells       | Rice Straw          |
| <b>pH</b>                              | 8.74            | 7.98                | 10.43                  | N/A                | 10.57               | 10.3                |
| <b>EC (mS/cm)</b>                      | 0               | N/A                 | 4123                   | N/A                | N/A                 | N/A                 |
| <b>MC (%)</b>                          | 7.28            | -                   | -                      | -                  | -                   | -                   |
| <b>VM (%)</b>                          | 72.238          | -                   | -                      | -                  | -                   | -                   |
| <b>FC (%)</b>                          | 17.23           | -                   | -                      | -                  | -                   | -                   |
| <b>Particle Size (mm)</b>              | N/A             | 13.4                | 3.94                   | 1.6                | N/A                 | 7.85                |
| <b>Ash Content (%)</b>                 | 10.54           | 76.6                | N/A                    | 14.9               | 8.91                | 42.9                |
| <b>Sulphur (%)</b>                     | 0.76            | -                   | -                      | -                  | -                   | -                   |
| <b>Oxygen (%)</b>                      | 35.82           | -                   | -                      | -                  | -                   | -                   |
| <b>Nitrogen (%)</b>                    | 8.65            | -                   | -                      | -                  | -                   | -                   |
| <b>Carbon (%)</b>                      | 76.0            | -                   | -                      | -                  | -                   | -                   |
| <b>Temp (<sup>0</sup>C)</b>            | 450             | 550                 | 550                    | 700                | 700                 | 550                 |
| <b>Porosity (%)</b>                    | 60              | N/A                 | N/A                    | N/A                | N/A                 | N/A                 |
| <b>Bulk Density (g/cm<sup>3</sup>)</b> | 0.48            | -                   | -                      | -                  | -                   | -                   |
| <b>Surface Area (m<sup>2</sup>/g)</b>  | N/A             | 12.0                | 14.03                  | 501                | 448.2               | 4.15                |

Legend: pH - Power of Hydrogen; EC - Electrical Conductivity; MC - Moisture Content; VM - Volatile Matter; FC - Fixed Carbon; Temp - Temperature

Tables 5 and 6 are interrelated. Table 6 highlights all the pyrolysis results and their benefits in the wetland substrate/porous media. All the results showed positive effects of shea nut shell biochar application in the wetlands. Irrespective of the values of the pyrolysis parameters, the biochar displayed the most favorable properties compared to those reported in existing studies by other scholars. From its pH to its temperature, ash content, porosity and several other important features, the biochar exhibited excellent properties.

Table 6. Biochar pyrolysis benefits and properties

| Parameter                              | Current Study | Lowest/Best in Lit.                 | Benefits of Current Study                  |
|----------------------------------------|---------------|-------------------------------------|--------------------------------------------|
| <b>pH</b>                              | 8.74          | Above neutral, ideal for acid soils | Good                                       |
| <b>EC (mS/cm)</b>                      | 0             | Lowest                              | Excellent for Salinity Control             |
| <b>MC (%)</b>                          | 7.28          | N/A                                 | Good Storage/ Combustion                   |
| <b>VM (%)</b>                          | 72.23         | High                                | High Reactivity                            |
| <b>FC (%)</b>                          | 17.23         | Moderate                            | Some Carbon Sequestration                  |
| <b>Ash Content (%)</b>                 | 10.54         | Moderate                            | Nutrient Balance                           |
| <b>Sulphur (%)</b>                     | 0.76          | Low                                 | Minimal Pollutant Risk                     |
| <b>Oxygen (%)</b>                      | 35.82         | Medium                              | Adsorptive Capacity/ Structural Reactivity |
| <b>Nitrogen (%)</b>                    | 8.65          | High                                | Soil Fertility                             |
| <b>Carbon (%)</b>                      | 76.08         | High                                | Sequestration & Energy                     |
| <b>Temp (<sup>0</sup>C)</b>            | 450           | Low                                 | Nutrient Retention/Microbial Compatibility |
| <b>Porosity (%)</b>                    | 60            | High                                | Water/Nutrient Retention                   |
| <b>Bulk Density (g/cm<sup>3</sup>)</b> | 0.48          | Low                                 | Easy Handling                              |

Legend: pH - Power of Hydrogen; EC - Electrical Conductivity; MC - Moisture Content; VM - Volatile Matter; FC - Fixed Carbon; Temp - Temperature

## Development of Macrophytes

### Plant Height

Plant selection in constructed wetlands is crucial for nutrient removal. EC and PD heights were measured every 48 hours after 4 weeks of freshwater acclimatization (FW Acclim.), with initial shoot lengths of 10 cm. PD showed signs of stress but recovered without wilting. ANOVA showed a significant difference between planted and unplanted beds ( $p < 0.001$ ). At week 2, EC had an average height of 74.83 cm, while PD reached 50.33 cm. Both macrophytes grew over the 14-week period, with EC showing 20% higher growth than PD in the ECBCH treatment (Figure 4). Similarly, Ni et al. (2020) reported a 25% increase in plant height with biochar treatments. By week 14, EC reached 149.50 cm, while PD reached 73.50 cm, with significant differences ( $p < 0.001$ ) observed among the different pilots. Control units (CTRL) showed higher shoot lengths for both macrophytes compared to freshwater with fertilizers (Figure 4).

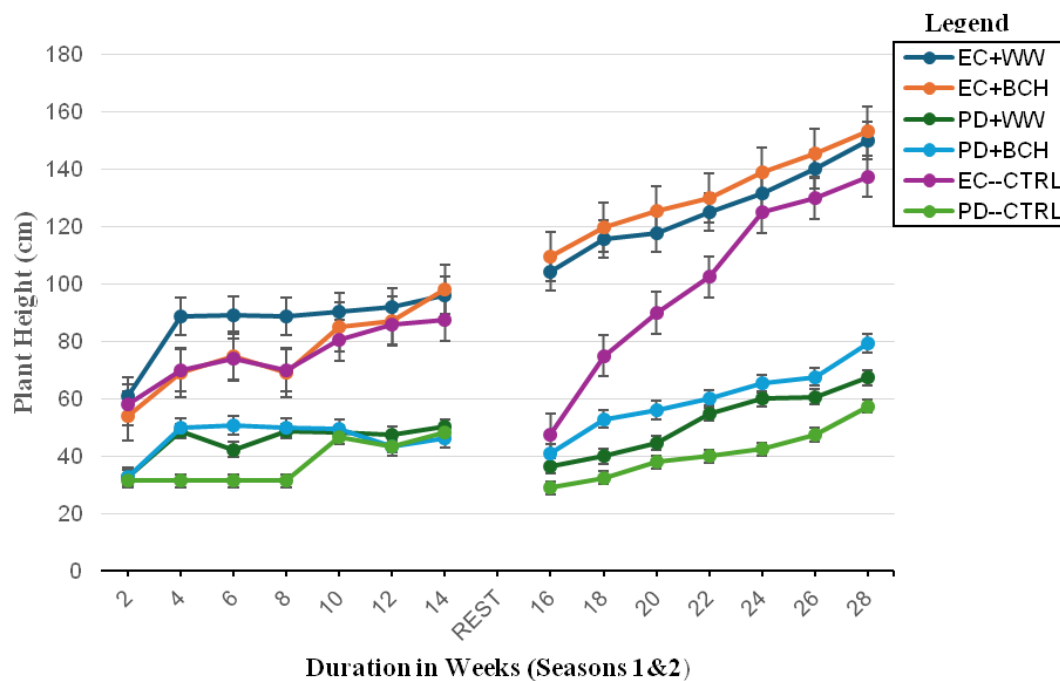


Figure 4. Average plant height per pilot across 14 weeks

### Number of Plants

During the acclimatization stage (Figure 5), both macrophytes had a low number of plants before transplanting in 4th week. A uniform increase in plant numbers continued until 10th week, when EC surpassed PD. Initial mean values were around 21 plants for EC and 12 plants for PD. Over time, EC increased significantly, surpassing PD by approximately 20%. ANOVA results at 14 weeks showed a significant difference ( $p < 0.001$ ) among treatments. Both biochar and non-biochar pilots showed a notable increase in plant numbers towards the harvest stage. By the end of the dry season, the ECBCH treatments had the highest number of plants, reaching approximately 148 stalks.

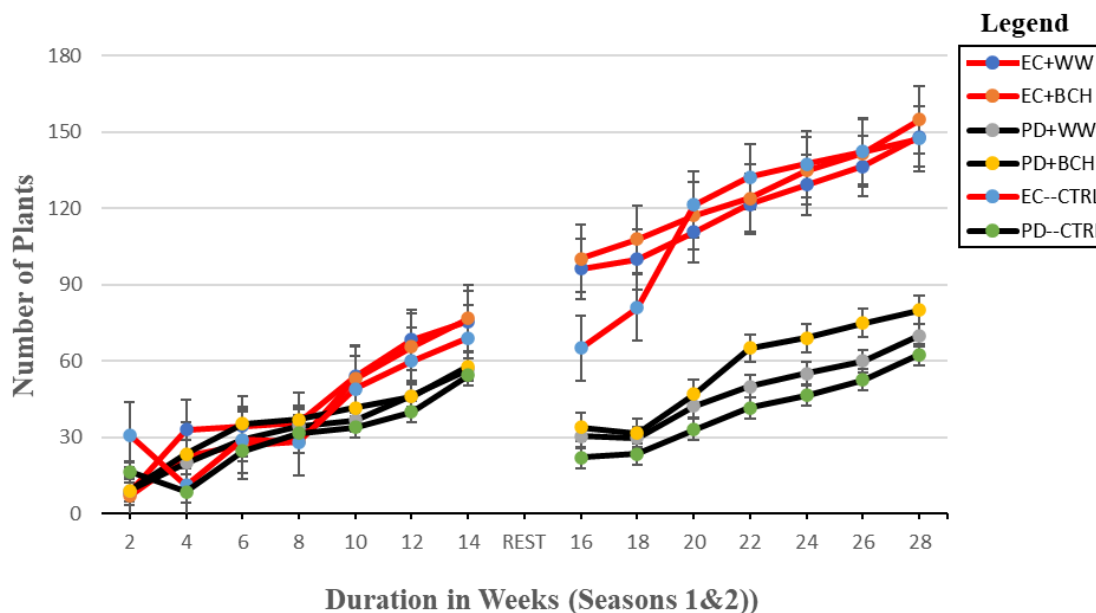


Figure 5. Average number of plants across 14 weeks

## Physicochemical Parameters Removal

### Redox Potential, pH, and Electrical Conductivity

Oxidation-Reduction Potential (ORP) measures the electron availability or electrochemical potential (Eh) in biological and chemical systems (Stefanakis, 2020). ORP values ranged from  $-117.22 \pm 4.8$  to  $-47.95 \pm 6.3$  across all treatments (Table 4). While unplanted beds showed a reduction in ORP from the raw influent concentration, other treatment wetlands exhibited a negative increase. A significant difference in average ORP was observed among treatments, with a significant difference ( $p < 0.001$ ). ORP values became less negative in almost all the treatments, especially ECBCH at  $-47.95$  mV, indicating a shift towards more oxidizing conditions. This is favorable for pathogen inactivation and improved water quality. Treatments like UPBWW and UPBBCH showed more reducing conditions, possibly enhancing denitrification but requiring cautious monitoring for anaerobic byproducts. Tanaka et al. (2006) noted that temperature, redox potential, and pH significantly influence denitrification and nitrification reaction rates in wetlands.

pH is an abiotic factor that influences wetland performance (Kadlec and Wallace, 2009). The raw influent had a slightly alkaline pH ( $8.18 \pm 0.6$ ), which decreased in all wetlands except for the unplanted beds. The treated effluents showed a moderate increase in pH (Table 4), ranging from slightly alkaline ( $7.68 \pm 0.1$ ) in the PD with biochar (PDBCH) to alkaline ( $8.86 \pm 0.1$ ) in the unplanted bed without biochar (UPBWW). Biochar-amended wetlands had lower pH values ( $7.71 \pm 0.1$ ,  $7.68 \pm 0.1$ , and  $8.76 \pm 0.1$  for ECBCH, PDBCH, and UPBBCH, respectively) compared to their no-biochar counterparts ( $7.97 \pm 0.2$ ,  $8.05 \pm 0.2$ , and  $8.86 \pm 0.1$  for ECWW, PDWW, and UPBWW, respectively). The observed decrease in pH may be attributed to nitrification, the oxidation of ammonium to nitrate. Effluents from planted CWs with biochar showed lower pH values, consistent with findings reported by Apuseyine (2021) in the same geographical area. Vymazal (2011) suggests that a pH range of 6.5–8.5 is optimal for ammonification. Analysis of variance revealed a significant difference ( $p < 0.001$ ) among the various CW treatments.

Electrical conductivity (EC) values of the effluents ranged from  $2991.75 \pm 242.3$  to  $4534.17 \pm 45.0$   $\mu\text{S}/\text{cm}$ . The relatively high effluent values may be attributed to incomplete washing of saline sand and gravel filter materials. The experimental site is known for its highly saline soils, due to excessively alkaline groundwater in the Tamale metropolis. The biochar-amended wetlands exhibited even higher EC values, indicating the presence of salt in the pyrolyzed shea nut shells. Since biochar contains ash derived from charring agricultural residues, extra care should be taken to wash off a considerable amount of salt (ash) before use.

### Nitrite-N, Nitrate-N, and Ammonium-N

In this study, Nitrite-N ( $\text{NO}_2\text{-N}$ ) in the influent recorded a higher concentration of  $2.35 \pm 3.77$  (Table 4), while Nitrate-N ( $\text{NO}_3\text{-N}$ ) was observed at  $7.47 \pm 12.92$ . The treated effluents showed very high removal efficiencies across all wetlands, with the highest concentration being  $0.03$  mg/L for  $\text{NO}_2\text{-N}$  and  $0.76$  mg/L for  $\text{NO}_3\text{-N}$ . The safe

irrigation or discharge limits for nitrite-N (0.9 mg/L) and nitrate-N (11.4 mg/L) reported by Acquah et al. (2025) align with the effluent concentrations found in this study. For faecal sludge dewatering in constructed wetlands, Uggetti et al. (2009) reported higher effluent concentrations, similar to those obtained by Osei et al. (2022). This increase was attributed to the growth of aerobic nitrifying bacteria in the wetlands (Uggetti et al., 2009). Kadlec and Wallace (2009) noted that nitrification in wetlands is not primarily considered a nitrogen removal mechanism. In this study, ANOVA results showed a significant difference for  $\text{NO}_3\text{-N}$ , with  $p = 0.006$  for macrophytes and  $p = 0.019$  for the interactive effect of biochar and macrophyte.

This study recorded a  $\text{NH}_4\text{-N}$  treated effluent concentration of 0.23 mg/L in the (ECWW) treatment. The removal of  $\text{NH}_4\text{-N}$  occurs through volatilization, nitrification, plant uptake, and adsorption (Gupta et al., 2016). Gupta et al. (2016) reported  $\text{NH}_4\text{-N}$  removal efficiencies between 30-81%, while Ajibade and Adewumi (2017) recorded values between 50.01-58.3%.  $\text{NH}_4\text{-N}$  effluent concentrations reported by Kengne et al. (2014) were  $38.70 \pm 20$  mg/L, while Andrade et al. (2017) recorded a high value of  $29 \pm 23$  mg/L. In the same geographical area, Apuseyine (2021) found a high influent concentration of  $89.9 \pm 0$  mg/L and a similarly high effluent concentration of  $31.3 \pm 32.53$  mg/L. These values were higher than those typically observed in medium-strength domestic wastewater (approx. 20 mg/L), likely due to the runoff of ammonium-based fertilizers from agricultural lands into the raw wastewater through open ditches.

#### **Total Dissolved Solids, Total Suspended Solids and Turbidity**

The minimum recorded influent TDS value was 607 mg/L (Table 4), which is higher than the minimum of 340 mg/L reported by Apuseyine (2021) in the same area. The observed increase in effluent TDS in some beds was attributed to incomplete washing of the bed materials before CW assembly. Effluent TDS in this study increased above the mean influent value ( $1235.27 \pm 470.60$  mg/L). This increase, noted by Coleman et al. (2001), was linked to the decomposition of dead plants or evapotranspiration processes. Tanaka et al. (2006) observed that biofilm growth on wetland filter beds can trap micro-particles in wastewater. ANOVA analysis showed a significant difference in TDS among the treatments with a p-value of 0.007. Werner and Kadlec (2000) explained that solid removal in wetlands occurs through filtration mechanisms, including mechanical straining and sedimentation of heavier particles. Soluble ions such as calcium, sodium, nitrate, and magnesium contribute to TDS levels.

The mean influent TSS in this study was  $51 \pm 72.49$  mg/L, with a maximum value of 232 mg/L. Higher TSS removal efficiencies were observed in the effluents of treatments planted without biochar compared to biochar-amended wetlands. The PDWW treatment exhibited the highest TSS removal efficiency at 94.93%, followed by ECWW at 86.44%, and UPBWW at 85.29% (Figure 6). The corresponding biochar-amended wetlands recorded 71.08%, 75.65%, and 83.50%, respectively. This suggests that TSS removal was primarily driven by physical processes and plant activity. A TSS removal efficiency of 83.73% was obtained by Ahmed and Kareem (2025) using *Lemna minor* in constructed wetlands for treating wastewater. Vymazal (2011) noted that abiotic processes play a significant role in TSS removal in constructed wetlands. According to Kadlec and Wallace (2009), TSS affects both effluent quality and wetland system operation. Sedimentation, filtration, and interception within the filter media are key mechanisms for TSS removal (Tilak et al., 2016).

The maximum influent turbidity value in this study was 162 NTU, similar to the mean of  $163.75 \pm 77.41$  NTU reported by Apuseyine (2021). The PDWW treatment recorded 89.81% turbidity removal efficiency, while the biochar-amended treatment PDBCH had a lower removal efficiency of 31.49%. Gupta et al. (2016) reported a turbidity removal efficiency of 99.33% using biochar, but this study observed lower efficiencies in biochar-amended treatments. Nevertheless, ANOVA results showed significant effects of biochar among treatments, with a p-value of 0.03.

#### **Total Coliform (TC) and Faecal Coliform (FC)**

This study achieved 100% removal efficiency in one of the wetlands for faecal coliform (FC). Similarly, total coliform (TC) showed removal efficiencies above 95% (Figure 6). The higher efficiencies were attributed to natural die-off rates, as noted by Kadlec and Wallace (2009). Total coliform averages ranged from 4.17 to 9.17 log cfu/100m (Table 4), while faecal coliform recorded means of between 0.00 and 3.92 log cfu/100mL.

The ANOVA results for TC revealed a significant effect in planted beds ( $p = 0.049$ ), which aligns with findings reported by Osei et al. (2022). Kadlec and Wallace (2009) highlighted the potential health risks of faecal contamination. In this study, significant removal rates of total and faecal coliforms were observed in the effluents of all treatments compared to the raw wastewater. Tunçsiper et al. (2012) reported that coliform removal efficiencies in wetland systems range from 34% to 99.9%.

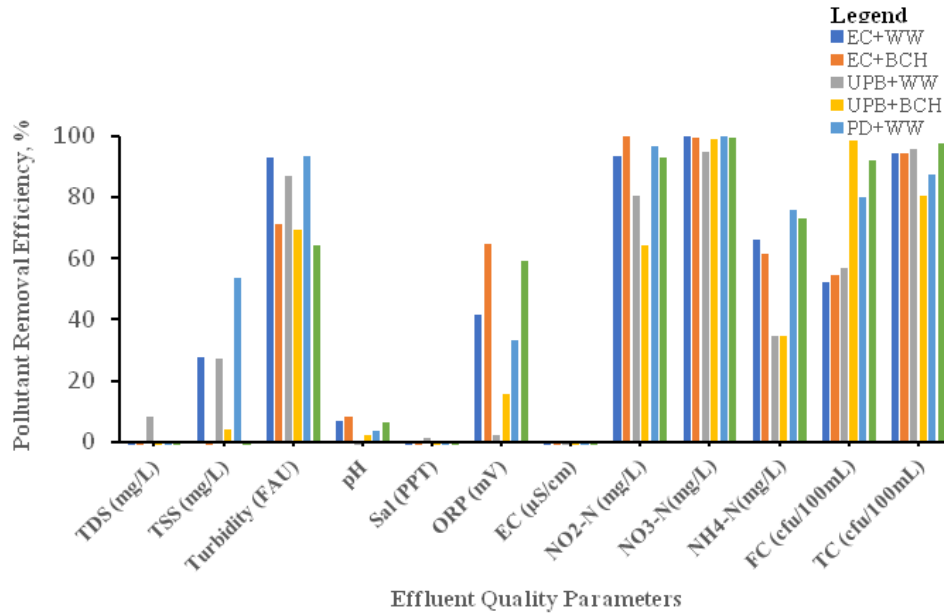


Figure 6. Average pollutant removal efficiencies for seasons 1 & 2 (Udoma et al., 2024)

### Model Configuration Output

Table 7 displays the wetland substrate characteristics measured by sampling quantities of the three substrates (gravel, sand, and biochar). These measured values were used to calibrate the HYDRUS-1D model which was subsequently validated using independent experimental data. The particle size retained on the sieve was plotted on a graph (Figure 9) to illustrate the distribution of D10, D30, and D60, respectively.

Table 7. Substrate characteristics

| Substrate Type    | Layer Depth (cm) | Layer Position/Function | Diameter (mm) | Porosity (%) | D10<br>D30<br>D60    | Bulk Density (g/cm <sup>3</sup> ) |
|-------------------|------------------|-------------------------|---------------|--------------|----------------------|-----------------------------------|
| Gravel            | 5                | Bottom Layer 1          | 9.5-19.0      | 42           | NA                   | 1.54                              |
| Sand              | 10               | Layers 2 and 4          | 0.08-4.0      | 40           | 0.28<br>0.39<br>0.62 | 1.59                              |
| Biochar Feedstock |                  |                         | NA            | 72           | NA                   | 0.74                              |
| Biochar           | 5                | Layer 3 (Sandwiched)    | NA            | 60           | NA                   | 1.06                              |

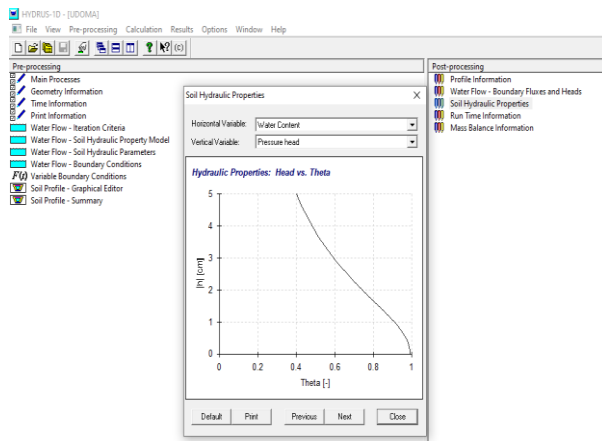


Figure 7. Fitted curve with measured Values

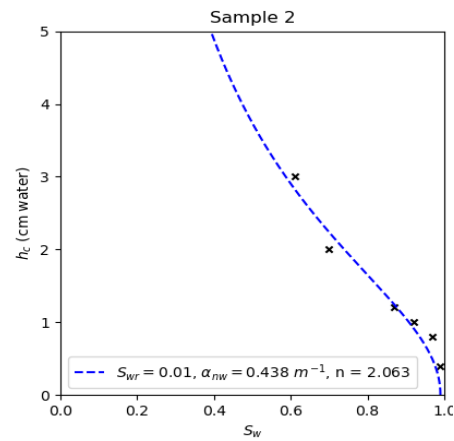


Figure 8. Simulated curve from model

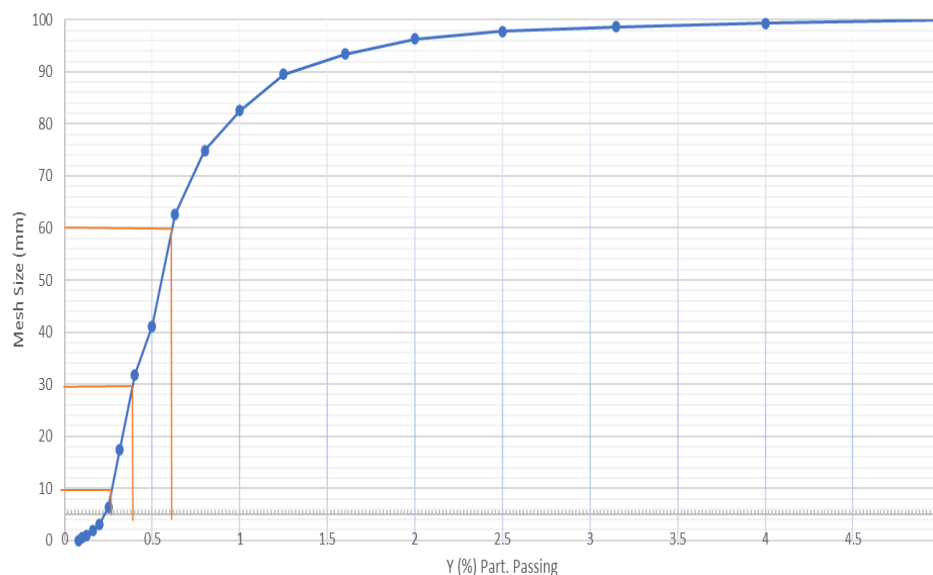


Figure 9. D10, D30, and D60 values of substrate particles

#### Hydraulic Head versus Saturation

At full saturation level (100%), the pressure head required to pull water from the wetland is relatively negligible (zero). In contrast, when the water content is at its residual stage, the required pressure head increases to 5cm. The measured and simulated curves clearly illustrate these conditions.

#### Validating Van Genuchten & Mualem Curve with the HYDRUS Model

From the developed code, the fitted curve for the ordinate ( $h_c$ ) and abscissa ( $S_w$ ) values is shown in Figure 7, while the HYDRUS-1D model simulation is seen in Figure 8. The linear similarity of the curves in both figures validates the authenticity of the developed code. This confirms the goal of investigating the water flow and retention capacities of the wetland substrates (gravel, biochar, and sand) in the engineered ecosystem. Flow was observed to occur from a region of residual water content to saturated water content. This indicates that water flow in VFCWs occurs from the surface downwards to the outlet at the bottom of the wetlands.

### CONCLUSION

The constructed wetlands demonstrated significant pollutant removal efficiencies, with most of treated effluents falling below the permissible limits for irrigation. Considering suitability for reuse in irrigation, the treated wastewater is suitable for irrigating salt-tolerant crops (e.g. spinach, okra, and barley) and for restricted irrigation practices (such as drip irrigation systems or irrigation of non-edible parts of vegetables). As for treatment efficiencies of the wetlands, biochar-amended treatments, especially ECBCH and UPBBCH, exhibited the most effective nutrient and microbial reduction, with PDWW showing similar traits. However, these treatments also resulted in higher salinity and variations in ORP conditions. Furthermore, the morphological growth and development of both macrophytes showed consistent improvement from week 2 to week 14. While EC demonstrated better morphological establishment compared to PD, both grasses contributed significantly to excess nutrient reduction, solids removal, and coliform decontamination. Overall, substantial reductions in all monitored pollutants were achieved. This study therefore successfully demonstrated the potential of the two indigenous grasses *Eragrostis curvula* (Schrader) Nees and *Paspalum dilatatum* Poir as effective macrophytes for wastewater treatment in VFCWs.

**Authors' Contribution:** Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization – U.A.W

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