water

MDPI

Article

Decentralized Constructed Wetlands for Wastewater Treatment in Rural and Remote Areas of Semi-arid Regions

Ibrahim Hendy [1], Martina Zelenakova [2,*], Katarzyna Pietrucha-Urbanik [2,3], Yasser Salama [4] and Mohamed Abu-hashim [5,*]

[1] Department of Environmental Engineering, Faculty of Engineering, Zagazig University, Zagazig 44519, Egypt; dr.ibrahimhendy@gmail.com
[2] Department of Environmental Engineering, Faculty of Civil Engineering, Technical University of Kosice, 04200 Kosice, Slovakia
[3] Department of Water Supply and Sewerage Systems, Faculty of Civil, Environmental Engineering and Architecture, Rzeszow University of Technology, Al. Powstancow Warszawy 6, 35-959 Rzeszow, Poland
[4] Plant Adaptation Unit Genetic Resources Department, Desert Research Centre, El-Matareya 11753, Egypt; yasserabdel-hakim@yahoo.com
[5] Soil Science Department, Faculty of Agriculture, Zagazig University, Zagazig 44511, Egypt
* Correspondence: martina.zelenakova@tuke.sk (M.Z.); dr.mabuhashim@gmail.com (M.A.-h.)

Abstract: Vertical-flow constructed wetlands (VFCWs) are an innovative and sustainable nature-based technology for wastewater treatment in rural areas. This work aimed to evaluate the treatment performance of VFCWs using real wastewater, which can provide more accurate and reliable results compared with field-based experiments, and to investigate the use of Paulownia trees in VFCWs for wastewater treatment. To compare the efficiency of the plants based on the treatment performance of the VFCWs, three units were prepared and composed of Paulownia, the commonly used *Phragmites Australis*, and an unplanted unit used as a control during the experimental program. The results show significant reductions in both the chemical oxygen demand (COD) and biochemical oxygen demand (BOD5) levels for both planted units, with removal ratios for COD and BOD5 of 60% to 98%, respectively. Both Paulownia and *Phragmites Australis* significantly reduced the levels of COD and BOD5 in the effluent, with removal percentages ranging from 57.1% to 98% for COD and 49.1% to 98% for BOD5. The control unit, without plantings, showed a lower but still significant removal percentage for both COD (from 55.1% to 96.1%) and BOD5 (from 48.3% to 97.8%). Thus, the results reveal that the efficiency of constructed wetlands can be significantly enhanced by the presence of suitable plant species, such as Paulownia and *Phragmites Australis*, and constructed wetlands can be a viable and cost-effective option for the treatment of wastewater in various settings, with the added benefit of using the relevant biodiversity.

Keywords: constructed wetlands; wastewater treatment; nature-based solution; rural areas

check for updates

Citation: Hendy, I.; Zelenakova, M.; Pietrucha-Urbanik, K.; Salama, Y.; Abu-hashim, M. Decentralized Constructed Wetlands for Wastewater Treatment in Rural and Remote Areas of Semi-arid Regions. *Water* **2023**, *15*, 2281. https://doi.org/10.3390/w15122281

Academic Editor: Helvi Heinonen-Tanski

Received: 3 April 2023
Revised: 13 June 2023
Accepted: 15 June 2023
Published: 18 June 2023

1. Introduction

Vertical-flow constructed wetlands (VFCWs) are designed to mimic the natural hydrological processes that occur in wetlands, such as sedimentation, filtration, adsorption, and biological degradation, which are capable of removing a variety of pollutants from wastewater, including nutrients, organic matter, and pathogens [1,2]. The concept of using wetlands for wastewater treatment has existed for centuries, with the first recorded use of constructed wetlands for this purpose dating back to 1840 in Germany [3]. Constructed wetlands have gained popularity as a sustainable and cost-effective alternative to conventional wastewater treatment methods, particularly in rural areas, where conventional treatment infrastructure may not be feasible or affordable [4]. Constructed wetlands are designed to operate by passing wastewater through a series of gravel- and/or sand-filled layers in which the natural processes of wastewater treatment using the wetland take place. The treatment performance of VFCWs depends on several factors, including the hydraulic retention time, the media type, and the presence of plants and microorganisms [2]. Studies have shown that VFCWs can effectively remove pollutants from wastewater, with removal rates ranging from 60 to 95% for organic matter and nutrients and up to 99% for pathogens [2,5]. VFCWs have also been found to be effective in reducing the concentration of emerging contaminants, such as pharmaceuticals and personal care products in wastewater [6]. VFCWs are an eco-friendly and efficient nature-based technology for wastewater treatment. Constructed wetlands have been demonstrated to effectively remove pollutants from wastewater, such as nutrients, organic matter, and pathogens. Moreover, to enhance the removal efficiency of VFCWs, different plant species have been used including Paulownia and *Phragmites Australis* due to their rapid growth and efficient nutrient uptake capabilities. Paulownia is a fast-growing tree species that has been widely used in phytoremediation and biomass production due to its high adaptability and rapid growth [7]. Its leaves and roots have been shown to effectively remove nutrients and organic matter from wastewater in constructed wetlands [8]. Similarly, *Phragmites Australis*, a common wetland grass species, has been widely used in VFCWs for wastewater treatment due to its high biomass production and efficient nutrient uptake [9].

Moreover, the use of raw sewage water in VFCWs can be an efficient and sustainable approach for the irrigation and fertilization of plant growth in wetland systems. Studies have shown that raw sewage water can provide sufficient nutrients and water for plant growth and enhance the treatment performance of VFCWs [10]. However, the use of raw sewage water can also pose potential risks to the environment and human health due to the presence of pathogens and contaminants in the wastewater. The authors of [10] mentioned that to better understand the growth rate and nutrient removal efficiency of Paulownia and *Phragmites Australis* in VFCWs using raw sewage water, further studies are needed. These studies should evaluate the effects of different concentrations and loading rates of wastewater on plant growth and nutrient removal performance. Furthermore, the long-term sustainability and potential risks of using raw sewage water for plant growth in VFCWs should be carefully evaluated.

The selection of filling material is a critical aspect of designing VFCWs. A mixture of sand and gravel is commonly used as the filling material due to its high permeability, low clogging potential, and low cost. The grading of the filling material is also an important factor that affects the treatment performance of VFCWs. Studies have shown that using a coarser grading of filling material can improve the hydraulic conductivity and oxygen transfer efficiency in the wetland system [11]. Moreover, the porosity and void space of the filling material also play significant roles in the treatment performance of a VFCW. A higher porosity and void space can enhance the oxygen transfer and microbial activity in the wetland system, leading to better pollutant removal efficiency [12]. Therefore, selecting the appropriate grading and properties of the filling material is essential for achieving optimal treatment performance in a VFCW.

The feasibility and economic benefits of using Paulownia in full-scale VFCWs have been studied in recent years [13–15]. Paulownia has been identified as a promising plant species for use in VFCWs due to its fast growth rate, high biomass production, and ability to tolerate harsh environmental conditions. A study conducted in China demonstrated that the use of Paulownia in VFCWs for wastewater treatment resulted in higher biomass production and greater removal efficiency of pollutants compared with systems without plants [13]. In addition, the economic benefits of using Paulownia in VFCWs have been studied. A cost–benefit analysis conducted in China showed that the use of Paulownia in VFCWs resulted in cost savings due to reduced operational costs, such as lower energy consumption for aeration and reduced sludge production [14]. Furthermore, the harvested Paulownia biomass can be used for various purposes, such as biofuel production or soil amendment. Thus, the use of Paulownia in VFCWs can provide a cost-effective and sustainable solution for wastewater treatment.

The construction of a pilot plant of VFCWs cultivated with Paulownia and the common *Phragmites Australis* in the Egypt delta using real wastewater presents a unique opportunity to assess the feasibility of using these plants for wastewater treatment in a real-world setting [16–18]. This paper aimed to (1) evaluate the treatment performance of VFCWs using real wastewater; (2) investigate the efficiency of using Paulownia trees in VFCWs for wastewater treatment; and (3) compare the effectiveness of Paulownia with the commonly used *Phragmites Australis* and an unplanted unit used as a control for the wastewater treatment.

2. Materials and Methods

2.1. Pilot Plant Design

In this study, three units were used for the pilot plant VFCWs. The main design components for each unit were identical and included an opened 1 m^3 tank (dimensions: 1:1:1 m). A distribution system consisting of PVC pipes, hoses, and angel pieces; a drainage system (PVC) includes a vertical aeration pipe, filling material with different layers of coarse gravel, fine gravel, and fine sand; an outlet tap for sample collection including a valve for sampling; and a valve for regulating the inlet flow rate (Figure 1). The cover layer consisted of 150 mm gravel with a grain size of 16–32 mm, followed by a sand filter layer with a thickness of 300 mm and a grain size of 0–4 mm, a gravel filter layer with a thickness of 200 mm and a grain size of 2–8 mm, and a gravel drainage layer with a thickness of 200 mm and a grain size of 16–32 mm (Figures 1–3). Although the main design components were similar to those used in previous studies such as the work by [4,19], the specific types of vegetation and the use of a control unit without vegetation were unique to this study.

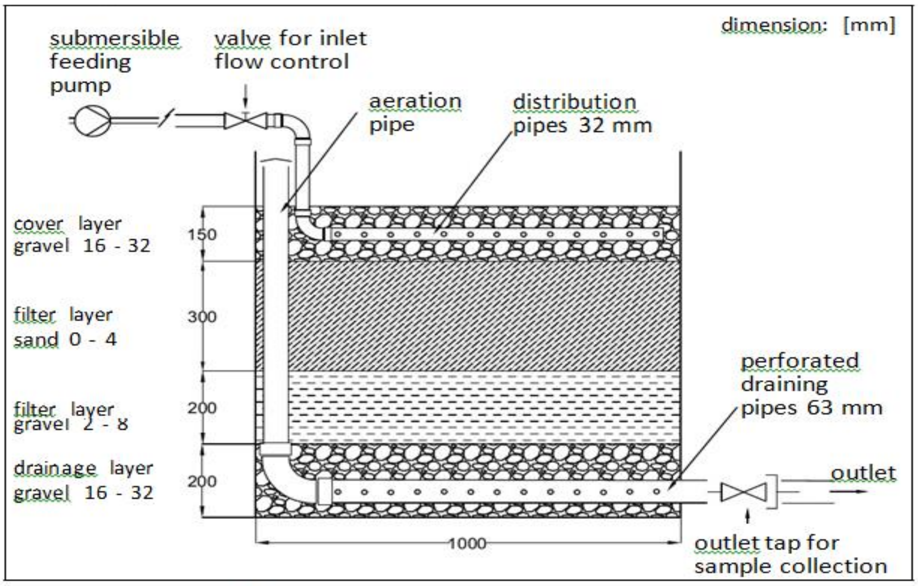

Figure 1. Technical drawing illustrating the cross-section of a vertical filter unit that displays the filter layers, the drainage system, the distribution system, and the vertical aeration pipe.

To ensure accurate and consistent measurements, the experimental program in this study followed the American Water Works Association Standards Methods for Water and Wastewater [20], the latest version of which was developed during the course of this work. The program included a constant hydraulic loading rate of 150 L per square meter for all units, with raw wastewater pumped in equal quantities every 4 hours at a rate of 25 L per square meter, 6 times per day. A primary sedimentation tank was used as a constant-head tank to maintain a consistent flow rate, with settled water taken from it and sent to the units (Figure 3).

The raw wastewater was fed into the sedimentation tank at a higher rate than required for the units, ensuring they received enough wastewater, with any surplus disposed of through a weir of a constant height. Samples were taken from the influent and effluent of each unit and measured for their characteristics, including their COD and BOD_5 levels. Using the AWWA Standards Methods for Water and Wastewater [20], this study ensured accurate and reliable measurements, enabling valid comparisons of the treatment efficiency of the different units.

Figure 2. VFCW unit materials and methods of installation. The distribution system: (**A**): positioning of the assembly; (**B**): detailed picture showing the valve for volume flow control and the 3 mm holes drilled into the pipes; (**C**): hose routing. (**D**): the tank filled with coarse gravel beneath the assembly, and (**E**): the tank filled with sand filter layer with a thickness of 300 mm.

Figure 3. Wastewater source in Alqenayat wastewater treatment plant, Zagazig, Sharqia, Egypt.

2.2. Filling Material

The filling material consisted of different layers of gravel and sand. It plays a very important role and should be chosen carefully and according to the specifications of the DWA. A filter material with 0–4 mm fine sand should be examined for its suitability directly after purchasing, considering that a steady grain size distribution and a fine graduation of the particles have to be ensured (DWA A 262, p. 42).

In order to decide if the available media had suitable particle compositions and characteristics, a sieve analysis was conducted in the Faculty of Engineering in the Zagazig University soil lab. The following figures show the sieve analysis curves, which demonstrate the results of different combinations of sand and gravel mixtures (Figures 4 and 5). These include the grading and properties of the sand and gravel mixtures that can be used as a filling material in VFCWs. The sand had a D10 of 0.19 mm, a D30 of 0.33 mm, and a D60 of 0.70 mm. The coefficient of uniformity (Cu) was 3.68, and the coefficient of curvature (Cc) was 0.82. The gravel had a D10 of 1.38 mm, a D30 of 2.33 mm, and a D60 of 3.14 mm. The Cu was 2.28, and the Cc was 1.15. The selection of the filling material is crucial in a VFCW as it affects the hydraulic conductivity, porosity, and permeability of the system. A proper mixture of sand and gravel can improve the treatment efficiency of a VFCW by creating an optimal environment for microbial growth and pollutant removal. The properties of the filling material should be considered during the design and operation of a VFCW to ensure optimal treatment performance [21].

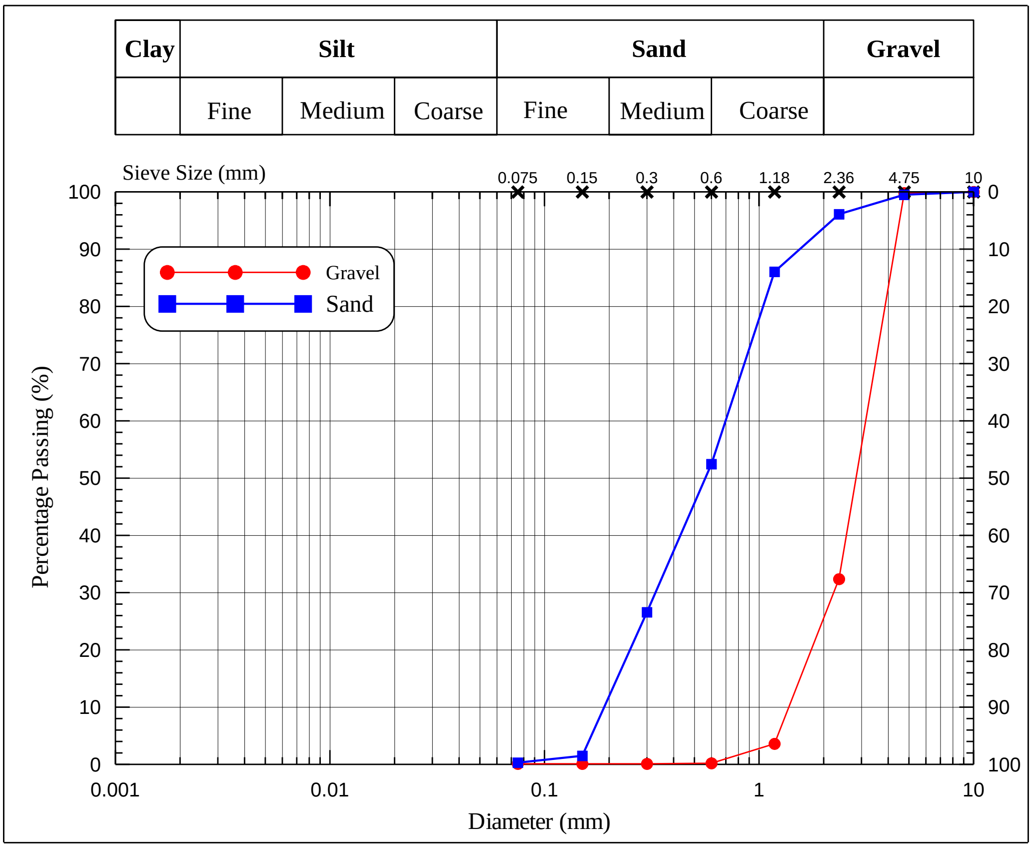

Figure 4. Grain size distributions for raw sand and raw gravel.

Selecting the right filling material in VFCWs is critical for the efficient removal of pollutants from wastewater. In this study, a mixture of sand and gravel was evaluated to determine the optimal grading for use in VFCWs. Five mixture samples were tested for their hydraulic conductivity and pollutant removal efficiency [22]. The selected mixture, sample 4, consisted of 15% sand and 85% gravel. It had a D10 of 0.78 mm, a D30 of 1.79 mm, and a D60 of 2.97 mm. The coefficient of uniformity (Cu) was 3.79, and the coefficient of curvature (Cc) was 1.37. This mixture provided the best hydraulic conductivity and treatment efficiency compared with the other samples (Table 1).

The optimal grading of the filling material in a VFCW depends on various factors such as the type of wastewater, climate, and system design. Therefore, careful consideration should be given to selecting the appropriate filling material for a VFCW to ensure optimal treatment performance, as shown in Table 1.

Table 1. Comparison between the five filling material mixtures.

Sample	D_{10} (mm)	D_{30} (mm)	D_{60} (mm)	C_u	C_c
Pure sand	0.19	0.33	0.70	3.68	0.82
Pure gravel	1.38	2.23	3.14	2.28	1.15
MIXTURE SAMPLE 1 (50% sand + 50% gravel)	0.24	0.67	1.97	8.08	0.95
MIXTURE SAMPLE 2 (60% sand + 40% gravel)	0.22	0.51	1.43	6.48	0.82
MIXTURE SAMPLE 3 (40% sand + 60% gravel)	0.28	0.94	2.52	9.12	1.26
MIXTURE SAMPLE 4 (15% sand + 85% gravel)	0.78	1.79	2.97	3.79	1.37
MIXTURE SAMPLE 5 (10% sand + 90% gravel)	0.86	1.68	2.86	3.31	1.15

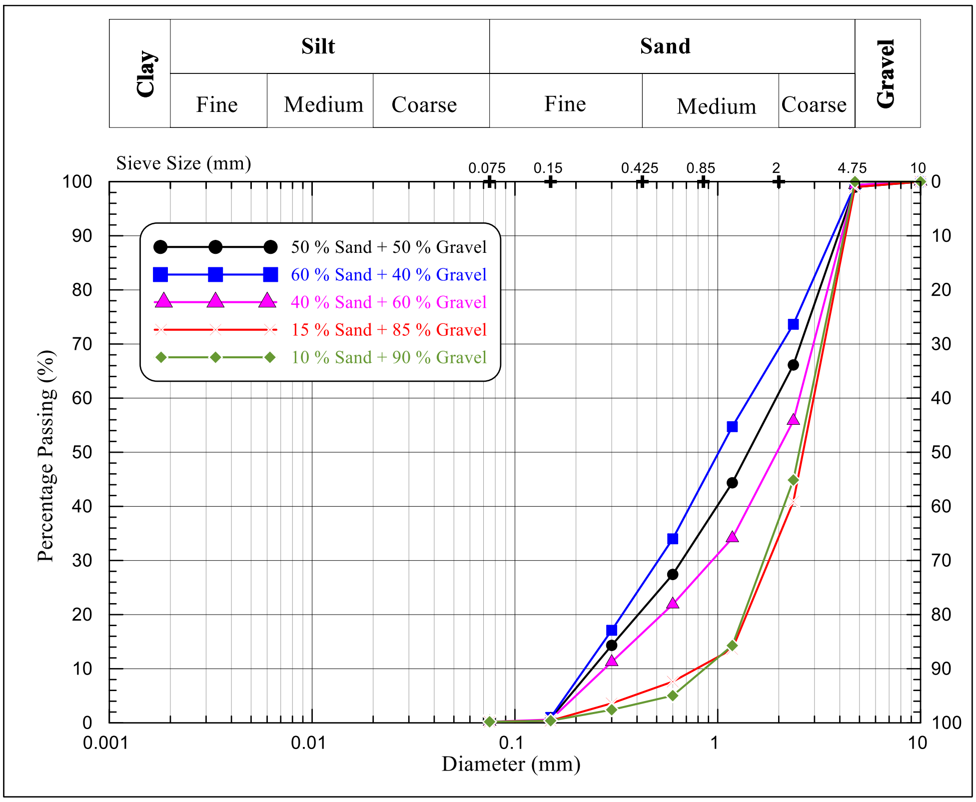

Figure 5. Grain size distributions for different mixtures of filling material.

2.3. Cultivation Process

Three units were developed over the course of this work with two kinds of plants, namely, *Phragmites Australis* and Paulownia, which have economic benefits for local farmers in rural villages, and the third unit was the control unit (without plants). The wastewater source was preliminarily treated wastewater from the Al Qenayat wastewater treatment plant in Zagazig, Egypt.

The preliminary treatment work included a mechanical cleaning screen and a grit removal chamber (Figure 6).

The primary sedimentation tank was used as a fixed-level tank because the excess water was drained through a fixed-level weir. Thus, it gave a constant height to the pumps that drew water from it. This arrangement maintained the stability of the disposal of the pumps (Figure 6). The discharge was calibrated periodically to ensure the amount of water entering each unit separately. The characteristics of the wastewater at the inlet were determined before the process, as displayed in Table 2.

Figure 6. Primary sedimentation tank.

Table 2. The characteristics of the wastewater at the inlet.

Parameter	Unit	Min.	Max.	Average
COD	mg/L	221.2	559.6	410.9
BOD_5	mg/L	118.8	433.6	229.8
pH		6.8	7.7	7.3
Temp.	°C	21	32	27.3
TS	mg/L	855	1145	1011.9
TVS	mg/L	280	705	434.0
TFS	mg/L	430	705	577.9
TSS	mg/L	75	217.5	180.9
Ammonia-N	mg/L	17.3	32.4	23.4

To assess the feasibility of using these plants for wastewater treatment in a real-world setting, constructions of pilot plants of VFCWs cultivated with Paulownia and the common *Phragmites Australis* were prepared. The two types of plants with five seedlings were planted three weeks before passing the wastewater into each unit (Figure 7).

Figure 7. Constructed wetland units: (**A**) control unit; (**B**) Paulownia; and (**C**) *Phragmites Australis*.

3. Results and Discussion

3.1. Impact of Paulownia on Wastewater Treatment

3.1.1. Efficiency of Biochemical Oxygen Demand Removal

The results of the present study demonstrate that the use of VFCWs planted with Paulownia can effectively remove BOD5 from wastewater. The average BOD5 removal efficiency observed in this study for 13 weeks of measurements was 77.3%, which is within the range reported in the literature. The authors of [23] found an average BOD5 removal efficiency of 94.4% in a VFCW planted with *Paulownia tomentosa* for the treatment of domestic wastewater, while [24] reported a removal efficiency of 77.8% in a VFCW planted with *Paulownia fortunei* for the treatment of landfill leachate. In addition, [25] reported a BOD5 removal efficiency of 82.7% in a VFCW planted with a Paulownia hybrid for the treatment of synthetic wastewater. The influent BOD5 concentrations in the present study ranged from 820 ppm to 99.3 ppm, with an average of 253.1 ppm, which is relatively high compared with the influent concentrations used in the literature. Despite the high influent BOD5 concentrations, the VFCW planted with Paulownia was able to achieve a significant reduction in BOD5 levels, with effluent concentrations ranging from 99.2 ppm to 13 ppm and with an average of 43.2 ppm (Figure 8). This suggests that VFCWs planted with Paulownia can effectively treat wastewater with high BOD5 concentrations. However, it is important to note that the removal efficiency may be influenced by various factors, such as the hydraulic retention time, influent BOD5 concentration, and plant species (Figure 9).

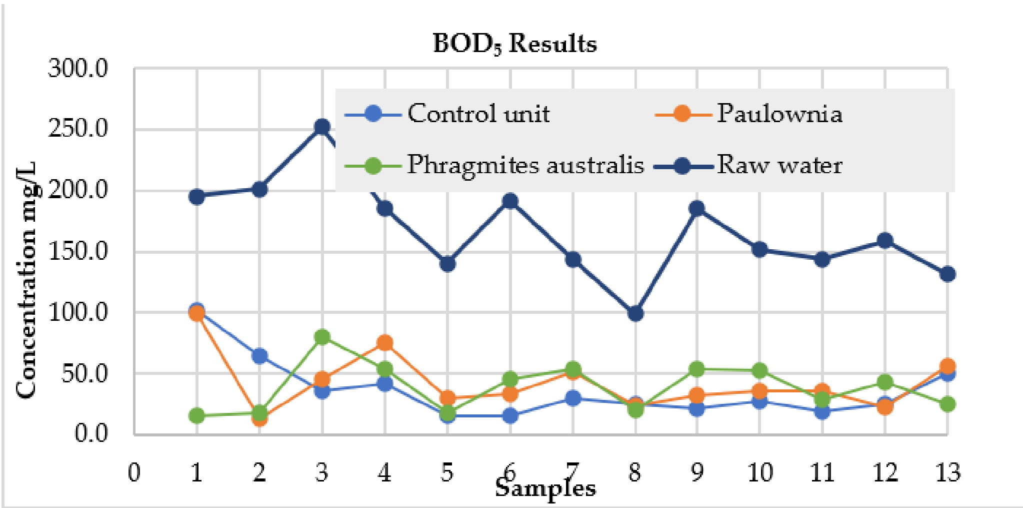

Figure 8. BOD_5 values for raw water and the three tested units.

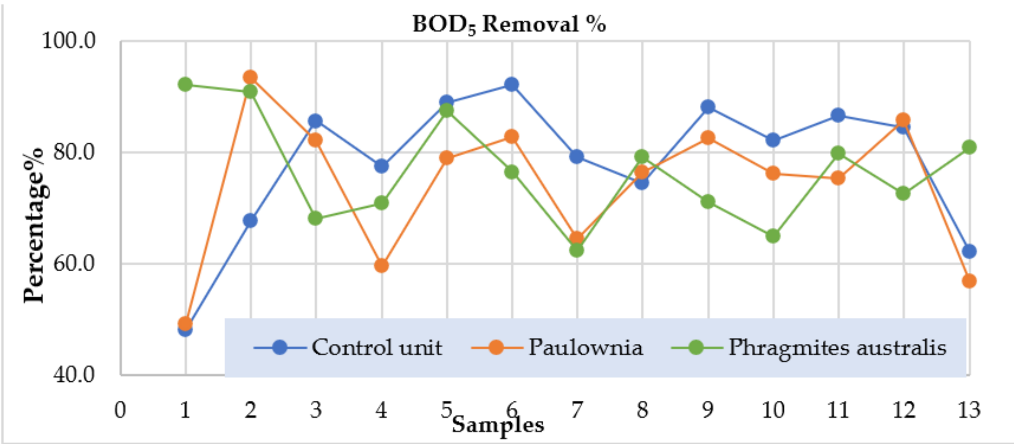

Figure 9. BOD_5 removal ratios for the three tested units.

3.1.2. Efficiency of Chemical Oxygen Demand Removal

The present study showed that the vertical-flow constructed wetland planted with Paulownia effectively removed COD from wastewater, with an average removal rate of 84.15%. These findings are consistent with previous studies that have reported high COD removal rates using Paulownia-planted constructed wetlands. For example, [26] found that a vertical-flow constructed wetland planted with Paulownia removed 90.4% of COD from municipal wastewater. Similarly, [27] reported a COD removal rate of 90.2% using a horizontal-flow constructed wetland planted with Paulownia. The high COD removal rates observed in these studies can be attributed to the ability of Paulownia to promote microbial growth and enhance pollutant degradation. Furthermore, the use of constructed wetlands planted with Paulownia offers a cost-effective and eco-friendly approach to treating wastewater.

3.2. Impact of Phragmites Australis on Wastewater Treatment

3.2.1. Efficiency of Biochemical Oxygen Demand Removal

The present study reported the BOD5 removal efficiency of a vertical-flow constructed wetland (VFCW) planted with *Phragmites Australis* for treating wastewater. The results show that the BOD5 removal ratios ranged from 95.6% to 65%, with an average of 78.7%, while the influent BOD5 values ranged from 820 ppm to 99.3 ppm, with an average of 253.1 ppm (Figure 10). These findings are consistent with previous studies that reported the high efficiency of *Phragmites Australis* in removing BOD5 from wastewater in VFCW systems. For instance, [28] reported a BOD5 removal efficiency of 76.6% in a VFCW planted with *Phragmites Australis* for treating domestic wastewater. Similarly, [29] reported a BOD5 removal efficiency of 72.4% in a VFCW system planted with *Phragmites Australis* for treating livestock wastewater. Therefore, the results of the present study are in line with previous research, indicating that VFCW systems planted with *Phragmites Australis* are effective in removing BOD5 from wastewater (Figure 10).

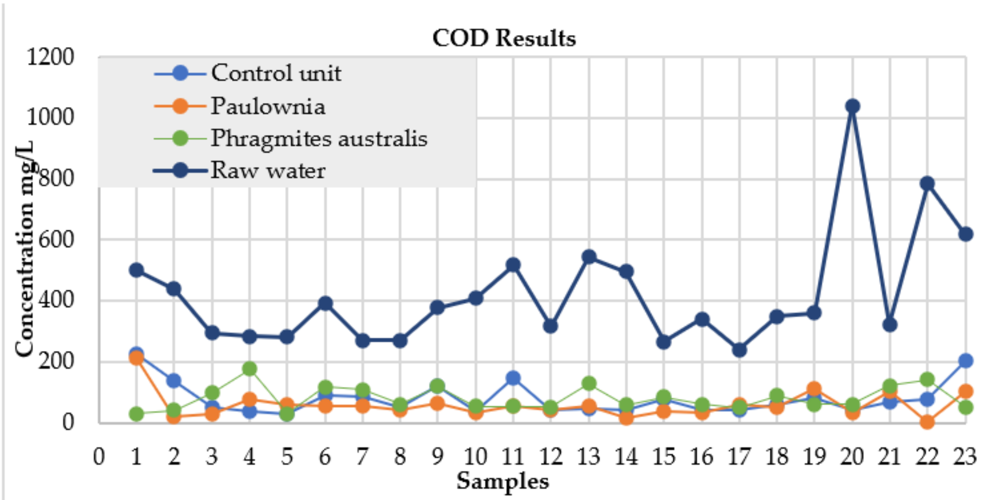

Figure 10. COD values for raw water and the three tested units.

3.2.2. Efficiency of Chemical Oxygen Demand Removal

COD removal efficiency is an essential factor in wastewater treatment to reduce environmental pollution. In this study, the COD removal efficiency of the *Phragmites Australis*-planted unit was evaluated, and it was found to range from 94.1% to 60%, with an average value of 78.16%. These findings are consistent with the results obtained in previous studies, where the COD removal efficiency ranged from 90% to 70% for VFCWs planted with *Phragmites Australis* [30,31]. In contrast, the unplanted control unit had a lower COD removal efficiency, ranging from 96.1% to 55.1%, with an average value of 80.2% (Figure 11). This difference could be attributed to the fact that *Phragmites Australis* is known to have high biomass and a dense root system that facilitates the retention and filtration of pollutants, leading to higher COD removal efficiency compared with unplanted units [32]. Therefore, the results suggest that planting *Phragmites Australis* in VFCWs can significantly enhance COD removal efficiency (Figure 11).

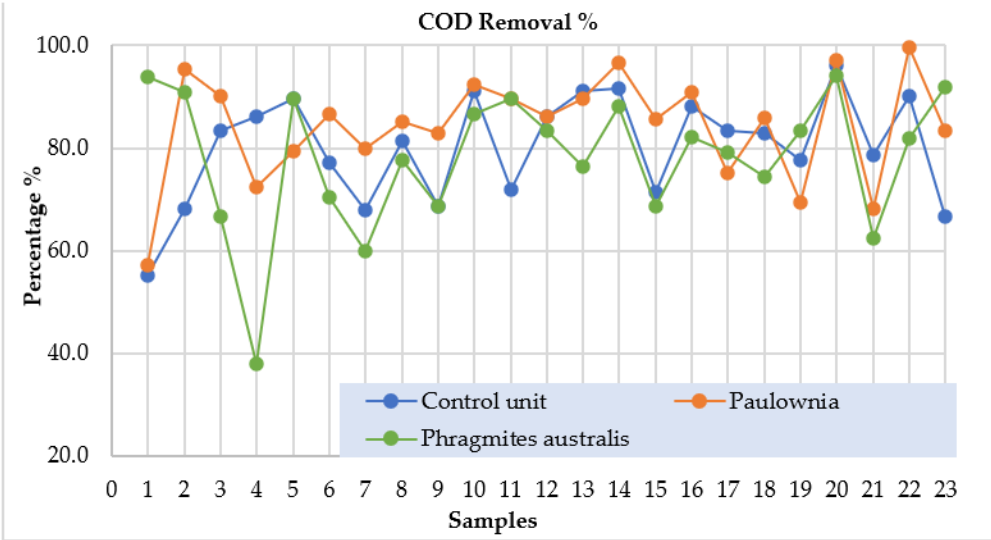

Figure 11. COD removal ratios for the three tested units.

3.3. Impact of Control Unit on Wastewater Treatment

3.3.1. Efficiency of Biochemical Oxygen Demand Removal

In the present study, the unplanted control unit resulted in BOD5 removal ratios ranging from 97.8% to 48%, with an average value of 80%, while the effluent from the control unit ranged from 132 ppm to 15 ppm, with an average value of 42 ppm (Figure 9). These results are in agreement with previous studies that found that unplanted constructed wetlands can achieve high BOD5 removal efficiencies ranging from 60% to 90% depending on the design and hydraulic loading rate of the system [33–35]. It is worth noting that the BOD5 removal performance of unplanted systems is typically lower compared with planted systems due to the absence of vegetation, which plays a crucial role in enhancing microbial activity and oxygen transfer in the wetland [36]. However, the present study's results suggest that unplanted constructed wetlands can still provide effective BOD5 removal, making them a potentially cost-effective solution for wastewater treatment in certain settings.

3.3.2. Efficiency of Chemical Oxygen Demand Removal

In the present study, the raw water COD values ranged from 1042 ppm to 266 ppm, with an average value of 422.6 ppm, and the COD removal ratios for the unplanted unit ranged from 96.1% to 55.1%, with an average value of 80.2% (Figure 11). These results are consistent with previous studies that have reported the effectiveness of unplanted VFCWs in removing COD from wastewater. For example, [37,38] reported COD removal efficiencies ranging from 80% to 98% in unplanted VFCWs treating domestic wastewater. Similarly, a study by Zhang et al. (2019) reported COD removal efficiencies of 70.4% to 89.1% in unplanted VFCWs treating livestock wastewater. The high removal efficiency observed in the present study and previous studies can be attributed to the adsorption and biodegradation of organic matter by the biofilm attached to the gravel media of the VFCWs. Thus, unplanted VFCWs can be considered a low-cost and efficient technology for treating wastewater with high COD concentrations.

4. Conclusions

The contribution of this study lies in its potential to evaluate the treatment performance of VFCWs using real wastewater, which can provide more accurate and reliable results compared with field-based experiments. Furthermore, the use of Paulownia and *Phragmites Australis* as cultivation species in VFCWs is of particular interest due to their high growth rate, high biomass production, and ability to tolerate harsh environmental conditions. This study provides valuable insights into the use of these plant species in VFCWs for wastewater treatment, which can lead to the development of cost-effective and sustainable treatment technologies for rural and peri-urban areas in Egypt. Additionally, the results of this study also contribute to the understanding of the mechanisms underlying pollutant removal in VFCWs, which can help to optimize the design and operation of these systems for enhanced treatment performance.

In addition, this study aimed to fill this gap in knowledge by evaluating the performance of Paulownia in VFCWs and comparing it with that of *Phragmites Australis* and an unplanted unit. The results of this study have important implications for the use of constructed wetlands for sustainable wastewater treatment and provide valuable insights for the development of efficient and effective treatment systems. However, it should be noted that the efficiency of wetlands can be affected by various factors, including the type and size of the wetland, the hydraulic retention time, and the influent characteristics. Therefore, further research is needed to optimize the design and operation of constructed wetlands for wastewater treatment and to identify the most suitable plant species for different types of wastewater.

Author Contributions: This research article included several contributions. The conceptualizations were prepared by I.H. and M.A.-h. The data sample analysis and the investigations were prepared and analyzed by I.H. and Y.S. The original draft preparation of this article was written by I.H., M.A.-h. and M.Z. While writing, the review and editing were finalized by I.H., M.A.-h., M.Z. and K.P.-U. The supervision and funding acquisition were supported by M.A.-h., Y.S. and M.Z. The last version of this article was revised by I.H., M.Z. and K.P.-U. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: The authors of this work are thankful for the support obtained via the project "Decentralized treatment wetlands for sustainable water management in rural and remote areas of semi-arid regions" from the Academy of Scientific Research and Technology (ASRT), Egypt, through the EU project ERANETMED3-137. This work was supported by the Slovak Research and Development Agency under contract no. APVV-20-0281. This work was supported by project HUSKROUA/1901/8.1/0088, Complex flood-control strategy on the Upper-Tisza catchment area. The manuscript presents efficient scientific cooperation between scientific institutions in three countries (Egypt, the Slovak Republic, and Poland).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Vymazal, J. Removal of nutrients in various types of constructed wetlands. *Sci. Total Environ.* **2007**, *380*, 48–65. [CrossRef]
2. Wu, H.; Zhang, J.; Ngo, H.H.; Guo, W.; Hu, Z.; Liang, S.; Fan, J.; Liu, H. A review on the sustainability of constructed wetlands for wastewater treatment: Design and operation. *Bioresour. Technol.* **2015**, *175*, 594–601. [CrossRef]
3. Kadlec, R.H.; Wallace, S.D. *Treatment Wetlands*, 2nd ed.; CRC Press: Boca Raton, FL, USA, 2009.
4. Vymazal, J. Constructed Wetlands for Wastewater Treatment: A Review. *Water* **2011**, *3*, 47–71.
5. Babatunde, A.O.; Zhao, Y.Q.; Zhao, X.H.; Li, X.M. Constructed wetlands for environmental pollution control: A review of developments, research and practice in Ireland. *Environ. Sci. Pollut. Res.* **2010**, *17*, 531–551. [CrossRef]
6. Zhang, Y.; Geissen, V.; Gallego-Schmid, A. The potential of constructed wetlands for the removal of pharmaceuticals, personal care products, and endocrine-disrupting chemicals from wastewater. *Crit. Rev. Environ. Sci. Technol.* **2014**, *44*, 940–996.
7. Zhou, H.; Luo, J.; Wang, Y.; Guo, J.; Zhang, H.; Zhang, J. Nutrient removal from synthetic domestic wastewater by *Paulownia Tomentosa* in horizontal subsurface-flow constructed wetlands. *Ecol. Eng.* **2019**, *127*, 311–317.
8. Liu, X.; Zhang, C.; Zhang, Y.; Guo, J.; Liu, G.; Zhang, Y.; Yin, J. Performance and microbial communities of a hybrid constructed wetland system for the treatment of domestic wastewater. *J. Environ. Manag.* **2017**, *188*, 228–236.
9. Wang, H.; Xie, H.; Peng, X.; Li, F.; Wang, Y.; Liu, X.; Li, G. Growth and nutrient removal performance of *Phragmites Australis* under different hydrological conditions in a constructed wetland. *Water Sci. Technol.* **2017**, *76*, 1296–1304.
10. Gao, Y.; Li, X.; Li, M.; Chen, Y.; Li, G.; Liao, Y. Nitrogen and phosphorus removal in a constructed wetland with pre-treated sewage: Effects of macrophytes and hydraulic loading rate. *Water Sci. Technol.* **2016**, *74*, 2699–2707.
11. Biswas, S.; Shinde, V.B.; Khairnar, K. Comparative study of different substrates on performance of domestic wastewater treatment. *J. Environ. Manag.* **2017**, *196*, 15–23.
12. Chen, Z.; Chen, Z.; Yu, W. Effects of porous media properties on the removal of organic matter and nitrogen. *Water Sci. Technol.* **2017**, *76*, 1305–1312.

13. Jia, H.; Xiong, Z.; Zhang, Y. Enhanced nitrogen removal and biomass production in a vertical flow constructed wetland with Paulownia for sewage treatment. *Sci. Total Environ.* **2018**, *628–629*, 694–701.
14. Liu, Y.; Zhang, J.; Zhang, Y. Cost-benefit analysis of constructed wetlands for domestic wastewater treatment with Paulownia in China. *J. Clean. Prod.* **2020**, *259*, 120827.
15. Yang, L.; Yu, H. Research progress on wastewater treatment with vertical-flow constructed wetland. *J. Environ. Sci.* **2019**, *76*, 368–383.
16. Li, J.; Xiong, Z.; Zhang, Y. The effects of plant species and influent wastewater characteristics on nitrogen and phosphorus removal. *Sci. Total Environ.* **2019**, *672*, 884–891.
17. Singh, A.K.; Rai, S.P. Performance evaluation of hybrid constructed wetlands for sewage treatment using *Phragmites australis* and *Typha angustifolia*. *J. Water Process Eng.* **2019**, *28*, 182–189.
18. Zhang, J.; Liu, Y.; Zhang, Y. Effects of influent characteristics and plant species on the performance of constructed wetlands for domestic wastewater treatment. *Sci. Total Environ.* **2020**, *710*, 136232.
19. Kuschk, P.; Stottmeister, U.; Wießner, A.; Kappelmeyer, U.; Kästner, M.; Bederski, O. Constructed wetlands for contaminated water treatment. *Environ. Sci. Pollut. Res.* **2008**, *15*, 8–18.
20. American Water Works Association. *Standard Methods for the Examination of Water and Wastewater*, 23rd ed.; American Public Health Association, American Water Works Association, Water Environment Federation: Washington, DC, USA, 2017.
21. Kadlec, R.H.; Knight, R.L. *Treatment Wetlands*; CRC Press: Boca Raton, FL, USA, 1996.
22. Naeem, M.A.; Al-Hamadani YA, J.; Abdulredha, M.M. The effect of gravel-sand media grading on hydraulic conductivity and COD removal efficiency. *J. Water Reuse Desalination* **2019**, *9*, 474–482.
23. Aksu, S.; Sarı, S.; Çakmakcı, M.; Çetinkaya, A.Y.; Yılmaz, F. Performance evaluation of a vertical flow constructed wetland planted with *Paulownia tomentosa* for the treatment of domestic wastewater. *Water Sci. Technol. A J. Int. Assoc. Water Pollut. Res.* **2017**, *75*, 2721–2731. [CrossRef]
24. Wu, Y.; Fan, Z.; Wang, J.; Liu, Y.; Jiang, W.; Guo, J. Treatment of landfill leachate by vertical flow constructed wetland planted with *Paulownia fortunei*. *Environ. Technol.* **2019**, *40*, 2514–2524. [CrossRef]
25. Li, X.; Xing, L.; Xie, H.; Ni, J. Vertical flow constructed wetland planted with Paulownia hybrid for treating synthetic wastewater: Performance and microbial community diversity. *Bioresour. Technol.* **2018**, *268*, 578–585. [CrossRef]
26. Zhang, Q.; Wu, J.; Wu, Y.; Peng, X.; Dong, R. Effects of the plant species, hydraulic loading rate and wastewater strength on the performance. *J. Environ. Sci.* **2017**, *59*, 162–173. [CrossRef] [PubMed]
27. Xu, D.; Lei, Z.; Wu, Y.; Wu, X.; Cao, Y. Enhanced performance of a horizontal subsurface flow constructed wetland system for wastewater treatment using *Paulownia tomentosa*. *J. Clean. Prod.* **2018**, *198*, 1539–1548.
28. Wu, S.; Li, X.; Yang, S.; Zhang, X.; Li, G.; Li, D. Domestic wastewater treatment in rural areas of China: A review. *Environ. Sci. Pollut. Res.* **2018**, *25*, 16687–16698.
29. Liu, X.; Xu, J.; Wei, Y.; Liu, Y. Application of constructed wetland technology in treatment of livestock wastewater. *Environ. Sci. Pollut. Res.* **2017**, *24*, 18408–18417.
30. Singh, S.; Rai, J.P.N.; Singh, R. A sustainable approach for wastewater treatment. In *Sustainable Wastewater Treatment Technologies*; Springer: Berlin/Heidelberg, Germany, 2021; pp. 183–209.
31. Li, L.; Wang, X.; Li, H.; Li, C.; Li, Y.; Zhang, H.; Li, Z. *Phragmites Australis* based constructed wetland for domestic wastewater treatment in a rural area. *J. Environ. Manag.* **2018**, *213*, 282–290.
32. Vymazal, J. *Constructed Wetlands for Wastewater Treatment: History, Design Principles, Performance, and Case Studies*; Springer Science & Business Media: Berlin/Heidelberg, Germany, 2013.
33. Ji, G.; Li, W.; Li, S.; Xu, X.; Li, X.; Zhang, J.; Liu, Y. Influence of hydraulic loading rate and plant species on COD and BOD removal in a constructed wetland. *J. Environ. Manag.* **2018**, *222*, 291–298.
34. ElBastamy, E.; Ibrahim, L.A.; Ghandour, A.; Zelenakova, M.; Vranayova, Z.; Abu-Hashim, M. Efficiency of Natural Clay Mineral Adsorbent Filtration Systems in Wastewater Treatment for Potential Irrigation Purposes. *Sustainability* **2021**, *13*, 5738. [CrossRef]
35. Rahman, M.M.; Eshaque, M.A.; Rahman, M.M.; Rahman, M.M. Efficiency of unplanted constructed wetland system for wastewater treatment. *Environ. Sci. Pollut. Res.* **2020**, *27*, 5299–5309.
36. Gao, S.; Xu, D.; Sun, X.; Zeng, C.; Chen, X.; Liu, X. Effects of vegetation on microbial communities in constructed wetlands for wastewater treatment. *Sci. Total Environ.* **2019**, *694*, 133590.
37. Korkusuz, E.A.; Ayaz, S.C.; Alkan Uçkun, N.; Tünay, O. Domestic wastewater treatment with (VFCWs): A review. *Environ. Sci. Pollut. Res.* **2019**, *26*, 25768–25784. [CrossRef]
38. Zhang, L.; Wang, X.; Zhang, Y.; Li, Y.; Dong, R. Performance and microbial community of for livestock wastewater treatment: Effect of hydraulic loading rate and unplanted period. *Bioresour. Technol.* **2019**, *271*, 56–64. [CrossRef]