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# Performance evaluation of the Worms subsurface flow constructed wetland for treating black water using insitu and exsitu analytical methods

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**Abstract**

This paper evaluates the performance of a subsurface flow constructed wetland at Worms Germany used for the treatment of black and grey water from a non-residential facility. Snap black water samples from four wells made up of a clarifying unit, an activated carbon unit and an aeration unit were analysed insitu using the HACH HQ40d multimeter and exsitu using Sensafe water metals check strips for preliminary metal detection onsite. HACH bar code reagents, a HACH Digital Reactor Block 200 (DRB200) and a HACH DR 3900 Spectrophotometer were subsequently used for the analysis of lead (Pb), chromium (Cr), cadmium (Cd), biochemical oxygen demand (BOD), Chemical Oxygen demand (COD), Ammonium ($NH_4$-N) and Nitrate ($NO_3$-N) in the lab. The removal efficiency for the constructed wetland was in the order BOD > Cr > COD > $NH_4$-N > $NO_3$-N > Pb. The 57.90% removal efficiency of COD for the constructed wetland was due to the higher fractions of inert COD which constitutes a part black water. This makes the use of the BOD/COD ratios of 0.69 and 0.5 for wells 1 and 4 an unreliable index for the determination of amenability of COD in black water with regards to microbial activity at the wetland at Worms. The pH range of 7.2–8.4 of the blackwater is conducive for the growth microbes necessary for the breakdown of organic matter in the black water. Further investigation including plant and sediment analysis over different seasons has to be undertaken if the efficiency of the constructed wetland for nutrients and metals removal is to be optimized.

**Keywords** Black water characteristic · Constructed wetland · Removal efficiency · BOD · COD

## 1 Introduction

Constructed wetlands which are easy to operate, environmentally friendly, effective in organic matter and nutrient removal among others are nature-based wastewater treatment technologies. Constructed wetlands use natural environmental components through physical, chemical, and biological processes for BOD reduction through microbial breakdown (biological process), settling of suspended particulate (physical process), removal of nitrates, removal of phosphates and removal of heavy metals through adsorption, chelation, and precipitation (chemical processes) [1, 2]. There are three major categories of constructed wetlands namely ''free-water surface wetlands (FWS)'' with exposed water surface, ''vertical subsurface-flow constructed wetland (VSFCWs)'' with vertical feeding pattern and ''horizontally fed subsurface-flow constructed wetland (HSFCWs)'' with water level beneath a porous media [3, 4].

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The constructed wetland located at Worms in Germany is a subsurface flow constructed wetland (SFCWs) with a permeable soil foundation. The wastewater level at the Worms constructed wetland is below the soil level, which is suitable for the cold climate in Germany. The system at Worms is designed to mitigate the impacts of odour and huge land usage associated with wetlands through improved sorption and exchange rates while minimizing the footprint of the constructed wetland. The objective of the study undertaken by the School of Engineering and Architecture, SRH Hochschule Heidelberg, Wormser Erlebnisgarten and Universidad del Valle de Atemajac, Guadalajara campus Mexico within the YIP Project was therefore to evaluate the effectiveness of four wells with regards to wastewater treatment in the subsurface constructed wetland at Worms as part of a study to find innovative ways to improve the treatment efficiency of the wetland in the face of increasing pressure on the facility.

## 2 Materials and methods

### 2.1 Description of study area

The Worms adventure garden in Rhineland-Palatinate, Germany, is an environmental education facility used by schools, kindergartens, environmental associations and interested citizens. A kindergarten is integrated in the adventure garden where lessons take place in a shelter called the Environment House in tandem with various stations in the adventure garden. The climate of the adventure garden is predominantly warm during the summer and very cold and windy during winter with mean yearly temperatures ranging between −1 °C to 25.6 °C. The adventure garden houses a subsurface flow constructed wetland consisting of 5-chamber pits with fine filter for the treatment of wastewater via activated soil zones penetrated by the roots of plants to create favorable conditions for the degradation of substances around the root area. Mechanically pre-treated wastewater is treated in "vertically flowing overgrown soil filters" according to the 'Palutec soil filter principle' after which the wastewater is discharged into a floor filter via distribution pipes lying on a rolling gravel pack. The wastewater seeps vertically into the bed through the soil body with specified grain distribution which ensues purification viz interaction of mechanical and biological processes (Mall Umweltsysteme) (Fig. 1).

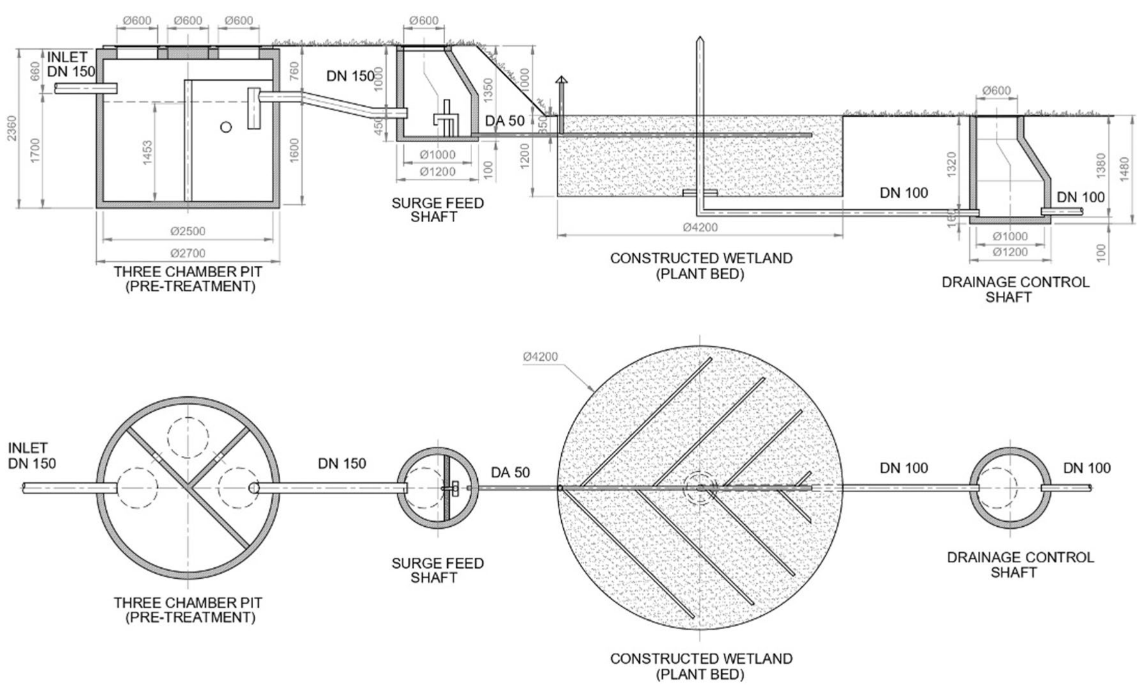


Fig. 1 Layout of Palutec sewerage treatment plant at the Worms adventure garden. Adapted from Mall Umweltsysteme's graphic for Stadtverwaltung Worms

### 2.2 Methods

Blackwater samples from conventional flushing toilets at the Worms Nature Park in Germany was were collected from four wells with varying well conditions. In-situ pH analysis was done for all four wells using test strips and validation done with the HACH HQ40d multimeter. Sensafe water metals check strips was used for a preliminary onsite heavy metal assessment. Snap and composite samples were collected in sterilized sampling bottles from a well with anaerobic conditions, a well fitted with an activation carbon unit for the removal of heavy metals, a well fitted with aeration pump for the supply of oxygen to create aerobic conditions and a well for collecting the effluent after treatment. To ensure that the original state of the black water samples were maintained, the wastewater samples were placed in a cool box packed with ice during transportation of the samples to the water lab at SRH University, Heidelberg. A HACH Digital Reactor Block 200 (DRB200), HACH LCK cuvette tests with unique barcodes labels and HACH's UV–VIS spectrophotometer DR3900 were used for the determination of BOD, COD, $NH_4$-N, $NO_3$-N, Cr Cd and Pb concentrations of the black water samples. Post the lab analysis, the data was corrected for outliers and analyzed using GraphPad Prism 7.0 and MS Excel.

## 3 Results and discussion

Table 1 shows the percentages of BOD, COD, $NH_4$-N, and $NO_3$-N removed as wastewater flowed through four subsurface wells of the constructed wetland. Removal efficiency of the constructed wetland was in the order BOD (70%) > COD (57.90%) > $NH_4$-N (48.1%) > $NO_3$-N (22.5%). The BOD, COD, $NH_4$-N, $NO_3$-N range between wells 1 and 4 were 55 mg/l-182 mg/l, 110 mg/l -261 mg/l, 100 mg/l -193 mg/l and 1.00 mg/l -1.32 mg/l respectively.

Table 2 shows the percentages of Pb, Cd and Cr removed as wastewater flowed through four subsurface wells of the constructed wetland. Cr had a removal efficiency of 59.1%. There was no removal for Pb. pH and Cr range between wells 1 and 4 were 7.8–8.4 and 0.018 mg/l -0.044 mg/l respectively.

The pH of the wastewater from the constructed wetland had a range of 7.2–8.4 (Table 2). This pH is conducive for the growth microbes required for the microbial breakdown of organic matter in the wastewater at an optimum pH range of 6.5–8.5. The four studied wells had a neutral to slightly alkaline environment with a pH range of 7.2–8.4 necessary in preventing the formation of bonds with a potential of breaking down cells of microbes which could slow down their growth rate and ultimately kill them.

Whiles the concentrations for all post treatment effluent quality for 2 hour composite samples analyzed from different wells exceeded the "Framework Wastewater Management Regulation" BOD value of 40 mg/l, three out of the four wells exceeded the "Framework Wastewater Management value of 150 mg/l for the COD (Table 1). The lower removal efficiency of 57.90% for COD as compared to the 70% removal efficiency of BOD for the constructed wetland at Worms was significantly lower than the 93% $BOD_5$ removal and 89% COD removal efficiencies reported by Vymazal in his 2009 study conducted in the Czech Republic [5]. The $BOD_5$ and COD removal efficiencies observed at the Worms constructed wetland was also significantly lower than the $BOD_5$ and COD removal efficiencies of 97% and 91% reported in a study in which a vertical flow constructed wetland was used for the treatment of farmhouse wastewater in Austria as well as the $BOD_5$ and COD removal efficiencies of 98% and 94% in a study in Roussillon, France [6, 7]. The significant differences in the removal efficiency of the constructed wetland at Worms could be attributed to two actors which include the age of the facility with its attendant reduction in good oxygen supply for an enabling aerobic environment for the growth and proper functioning of aerobic microbes and to the volumes of wastewater generated daily which is more than the capacity the constructed wetland was originally built to treat. The low COD removal efficiency of the constructed wetland could also be attributed to the higher fractions of inert COD present in the black water. This makes the use of the BOD/COD ratios of 0.69 and 0.5 for wells 1 and 4 (Table 1) an unreliable index for the determination of amenability of COD in black water with regards to microbial activity at the wetland at Worms [8].

The organic form of nitrogen present in the wastewater was converted to nitrate ($NO_3^-$) under aerobic and anaerobic conditions while ammonia nitrogen ($NH_3$-N) was removed via hydrophytes absorption, volatilization, nitrification, and denitrification in the constructed wetland [9, 10]. Percentage $NH_4$ removal of 48.1% for well 4 for the constructed wetland at Worms was in agreement with 41% reported by [5] but significantly lower than 94% reported by [6]. Whiles the inlet and outlet concentrations for $NO_3$-N for the wastewater in the constructed wetland ranged from 1.00 mg/l-1.32 mg/l with no significant differences between inlet and outlet $NO_3$-N concentrations the inlet and outlet concentrations for $NH_4$-N for the wastewater in the constructed wetland ranged from 100 mg/l-193 mg/l (Table 1).

**Table 1** Removal efficiencies of the worms constructed wetland for BOD; COD; $NH_4$-N and $NO_3$-N

| Parameter | BOD | | Removal | COD | | Removal | $NH_4$-N | | Removal | $NO_3$-N | | Removal |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sampling point | In (mg/l) | Out (mg/l) | (%) | In (mg/l) | Out (mg/l) | (%) | In (mg/l) | Out (mg/l) | (%) | In (mg/l) | Out (mg/l) | (%) |
| Well 1 | – | 182 | – | – | 261 | – | – | 193 | – | – | 1.29 | – |
| Well 2 BAC | 182 | 103 | 43.4 | 261 | 258 | 1.15 | 193 | 162 | 16.1 | 1.29 | 1.27 | 1.55 |
| Well 2 AAC | 103 | 88 | 14.6 | 258 | 243 | 6.90 | 162 | 158 | 2.5 | 1.27 | 1.26 | 0.79 |
| Well 3 | 88 | 65 | 26.1 | 243 | 225 | 7.40 | 158 | 155 | 1.9 | 1.26 | 1.32 | NR |
| Well 4 | 65 | 55 | 32.3 | 225 | 110 | 51.10 | 155 | 100 | 35.5 | 1.32 | 1.00 | 24.2 |
| Wells 1 and 4 | 182 | 55 | 70 | 261 | 110 | 57.90 | 193 | 100 | 48.1 | 1.16 | 1.00 | 22.5 |

NR represents no removal

**Table 2** Removal efficiencies of the worms constructed wetland for chromium, lead and cadmium

| Parameter | pH | | Inc/Dec | Cr | | Removal | Cd | | Removal | Pb | | Removal |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sampling point | In (mg/l) | Out (mg/l) | (%) | In (mg/l) | Out (mg/l) | (%) | In (mg/l) | Out (mg/l) | (%) | In (mg/l) | Out (mg/l) | (%) |
| Well 1 | | 7.8 | – | | 0.044 | | | BDL | – | 0.2 | 0.2 | 0 |
| Well 2 BAC | 7.8 | 7.2 | +7.7 | 0.044 | 0.043 | 2.27 | BDL | BDL | – | 0.2 | 0.2 | 0 |
| Well 2 AAC | 7.2 | 7.3 | −1.4 | 0.043 | 0.034 | 20.9 | BDL | BDL | – | 0.2 | 0.2 | 0 |
| Well 3 | 7.3 | 7.2 | +1.4 | 0.034 | 0.040 | NR | BDL | BDL | – | 0.2 | 0.2 | 0 |
| Well 4 | 7.2 | 8.4 | +16.7 | 0.040 | 0.018 | 55 | BDL | BDL | – | 0.2 | 0.2 | 0 |
| Wells 1 and 4 | 7.8 | 8.4 | +7.6 | 0.044 | 0.018 | 59.1 | BDL | BDL | – | 0.2 | 0.2 | 0 |

Inc, Dec and BDL represents increase, decrease and below detection limit respectively

## 4 Conclusions

The results of the investigations revealed Cr and COD removal efficiencies of the constructed wetland at Worms to be 59.1% and 57.9% respectively an efficiency which could be described as fair. The 70% BOD removal though significantly higher in comparison to the COD removal efficiency can not be said to be optimum since constructed wetlands are normally 80% + efficient when it comes to the removal of BOD as a pollutant. The significantly lower removal efficiencies for BOD and COD of the constructed wetland at Worms in comparison to those in France, Czech Republic and Austria could be attributed to the age of the wetland, decreased aeration in the aerobic well as well as increased daily volumes of wastewater for treatment.

The organic form of nitrogen present in the wastewater was converted to nitrate ($NO_3^-$) under aerobic and anaerobic conditions while ammonia nitrogen ($NH_3$-N) was removed via hydrophytes absorption, volatilization, nitrification, and denitrification in the constructed wetland at Worms. The 48.1% removal efficiency of $NH_4$-N is an indication that ammonium is oxidized to nitrate through the process of nitrification making the constructed wetland at Worms a low-cost average remover of $NH_4$-N in black water. Improved $NH_4$-N removal efficiency will help in the prevention of eutrophication in receiving surface water bodies.

Transformation of processes that occur at the constructed wetland at Worms has not yet been undertaken prior to the submission of this brief communication. Further studies are required for the identification of the microbes, quantities of microbes per liter of blackwater and optimal vegetation types for the quantification of the individual processes at the constructed wetland for optimal pollutant removal efficiency.

**Author contributions** KBA UG, DW and ILDRS did the sampling and onsite analysis. KBA and UG did the lab analysis wrote the manuscript. KBA UG, Dennis Waltenberg and ILDRS reviewed the manuscript. All authors read and approved the final manuscript.

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**Data availability** The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

**Declarations**

**Competing interests** The authors declare no competing interests.



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