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Assessment of the status and performance of horizontal subsurface flow constructed wetlands for industrial wastewater treatment in Tanzania

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Key words: Constructed wetland, Design flow rate, Industrial wastewater, Technological performance, Darcy's law

Abstract

Three horizontal subsurface flow constructed wetlands (HSSF-CWs) evaluated in northern Tanzania were from the meat, winery, and paper industries. The winery and paper industry CWs exhibited surface flow, while the meat industry CW did not. This difference was attributed to inadequate pretreatment, hydraulic, and organic overloads. Poor design also contributed to the issue, as the design flow rates exceeded those suggested by Darcy's law, resulting in system clogging. The clogged HSSF-CWs produced poor effluent due to insufficient contact time and area between the wastewater, microorganisms, and rhizosphere. The winery industry effluent met Tanzania and WHO standards for BOD (29±1.41 mgO_2/L), P (3.68±0.81 mgP/L), and FC (3.2±0.1 log unit) but did not comply with COD (137.5±116.67 mgO_2/L), NO_3-N (44.75±32.17 mgN/L), and NH_3-N (41.05±2.9 mgN/L). The paper industry effluent met standards for NH_3-N (0.12±0.17 mgN/L), P (0.22±0.26 mgP/L), and FC (3.4±0.1 log unit) but did not meet the standards for BOD (59.69±0.44 mgO_2/L), COD (72.5±31.82 mgO_2/L), and NO_3-N (96.5±12.02 mgN/L). The meat industry effluent met standards for NO_3-N (18.6±10.75 mgN/L) and FC (3.6±0.3 log unit) but failed to meet standards for BOD (59.5±14.85 mgO_2/L), COD (160.5±89.8 mgO_2/L), P (29.49±3.79 mgP/L), and NH_3-N (57.6±23.19 mgN/L). Therefore, proper design of HSSF-CWs requires adherence to Darcy's law and ensuring adequate information on production. Moreover, for a properly designed HSSF-CW to remain functional and have a long lifespan, regular monitoring, including water quality analysis, is essential.

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Introduction

Constructed wetlands (CWs) are engineered systems designed to replicate natural wetlands in pollutant removal (Mthembu *et al.*, 2013). These systems have gained popularity worldwide due to their environmentally friendly nature, ease of use and maintenance, efficiency in pollutant removal, low energy requirements, and cost-effectiveness (Garcia *et al.*, 2010).

They can treat a variety of wastewaters, such as domestic, industrial, hospital, agricultural run-off, municipal wastewaters, stormwater, landfill leachate, and acid mine drainage (Karungamye *et al.*, 2022; Kipasika *et al.*, 2014; Ávila *et al.*, 2013; Alobaidy *et al.*, 2010; Kantawanichkul *et al.*, 2003). They effectively reduce pollutants, such as total suspended solids, total dissolved solids, biochemical oxygen demand (BOD), chemical oxygen demand (COD), pathogens, pesticides, total phosphorus, total nitrogen, heavy metals, personal care products, and antibiotics (Zhang *et al.*, 2008; Kataki *et al.*, 2021; Gikas *et al.*, 2013; Ahmed *et al.*, 2008). These systems have been designed to simulate pollutant removal processes in natural wetlands (Garcia *et al.*, 2010). They remove pollutants through physical, chemical, and biological processes taking place in them (Vymazal, 2005). They are normally used for the secondary and tertiary treatment of wastewater (Cooper, 2009).

In the past decade, several CWs were established in different parts of Tanzania. The horizontal subsurface flow constructed wetland (HSSF-CW) is the most favorable type in the country due to the wastewater flow below the surface, which prevents mosquito breeding (Kimwaga *et al.*, 2013). Other advantages associated with the use of HSSF-CW are lack of odors and insect vectors, and minimal risk of public exposure to the wastewater. A study by Njau *et al.* (2011) and Rugaika *et al.* (2018) reported that the HSSF-CWs with baffles perform better in pollutant reduction than the ones without baffles. The presence of baffles increases the interstitial velocity of wastewater hence mass transfer by reducing the cross-sectional area and increasing the aspect ratio of the CW configuration. This is an important aspect of CW design, especially in countries where the temperature difference between hot and cold seasons is insignificant (Rugaika *et al.*, 2018).

Many studies have been conducted to assess the performance of HSSF-CW systems in the country (Karungamye *et al.*, 2023; Zacharia *et al.*, 2022; Mahenge and Malabeja, 2018; Njau *et al.*, 2011). However, most of the assessed CWs were reported to perform poorly due to the discharge of effluents that do not meet the WHO discharge limits into the receiving water body (Kimwaga *et al.*, 2013; Njau *et al.*, 2011). The release of poor effluent quality into the environment can jeopardize public health and destroy the environment since the effluents are normally reused for irrigation and discharged into nearby water sources. This poor performance has been reported to be caused by clogging of void spaces, overland flow, lack of a drainage system, hydraulic overloading, biological growth, poor pretreatment, blockage of outlet structures, and lack of regular monitoring and maintenance (Njau *et al.*, 2011). Knowles *et al.* (2011) reported the cause of clogging to be improper design and operations of the HSSF-CW system. Therefore, this study aimed to assess the status and performance of HSSF-CWs used for industrial wastewater treatment in northern Tanzania.

Materials and methods

Study site

Three (3) full-scale HSSF-CWs located in Arusha and Kilimanjaro regions, Tanzania (Fig. 1) were visited three times for sample collection and observation. The HSSF-CW systems include Meat industry CW, Winery industry CW, and Paper industry CW.

Sample collection and analysis

A total of six (6) samples from each visited HSSF-CW were collected, three (3) influent samples were taken at the inlet of CW (pre-treated wastewater) and three

(3) effluent samples were taken from CW outlet. Hence, a total of 18 samples were collected. The collected samples were stored in a cool box before taken to the Nelson Mandela African Institution of Science and Technology (NM-AIST) laboratory located in Arusha, Tanzania for analysis.

The physical parameters such as temperature, pH, dissolved oxygen (DO) and electrical conductivity (EC) were determined *in situ* using a multiparameter meter type Hanna HI 9829. The bio-chemical analyses were done according to the Standard Method for the Examination of Water and Wastewater (APHA, 1998).

Fig. 1. Regional map showing the location of HSSFCWs in Arusha and Kilimanjaro

Darcy's law

The maximum flow rates of the HSSF-CWs in this study were calculated using equation 1. The computed flow rates were compared with the design flow rates used to design the systems under study.

$$Q = Ks \times Ac \times s \quad \text{.......Equation 1}$$

Where Q is the flow rate (m^3/d), Ks is the hydraulic conductivity (m/d), Ac is the cross-sectional area (m^2) and s is the hydraulic gradient (m/m).

Statistical data analysis

Statistical data analysis was done using Origin Pro 9.0 software (Origin Lab Corporation, Northampton, MA, USA). Before the analysis, data were subjected to a normality test. Normally distributed data were analysed using a parametric ANOVA test and non-normally distributed data using a non-parametric Kruskal-Wallis ANOVA. Significant differences were represented by $P < 0.05$.

Results and discussion

The surveyed HSSF-CW design information, the type of pretreatment system, and vegetation used are given in Table 1, whereas their performances and loading rates are provided in Table 2 &3, respectively.

From Table 1, the winery industry HSSF-CW is a baffled system that treats wastewater from banana winery production (Fig. 2). Its basin is lined with compacted clay, and the wastewater from the production section is pretreated using an Upflow Anaerobic Sludge Blanket (UASB). The substrates utilized in the system are basalt aggregates. The CW was displayed as having surface flow throughout the system. From Table 1, the design flow rate (62.4 m^3/d) exceeds the calculated maximum flow rate (41.25 m^3/d) suggested by Darcy's law (equation 1). This inadequacy in hydraulic design and insufficient consideration of Darcy's law requirements have been reported to cause surface flow in many systems (USEPA, 1993). This assertion is supported by the study of Knowles *et al.* (2011), which indicated that hydraulic and organic loading rates exceeding the recommended values for the design and operation of HSSF-CWs are the main factors contributing to rapid clogging and long-term system failure.

Table 1. Design information of surveyed HSSF-CW systems

CW	Design Q (m^3/d)	Size (m^2)	Water depth (m)	Substrate porosity	HRT (d)	Maximum flow rate (m^3/d) (Darcy's law)	Scale	Type of plant	Pre-treatment
Meat industry	9	Single cell of size 10.6m × 4.4 m	0.5	0.35	0.9	62.26	full	*Cyperus papyrus*	Septic tank
Winery industry	62.4	Baffled with effective L × W of 26 m × 14.3 m	0.5	0.35	1	41.25	full	*Cyperus papyrus*	Upflow Anaerobic Sludge Blanket (UASB)
Paper industry	225	Baffled with effective L × W of 20 m × 16.5 m	0.5	0.35	0.3	50	full	*Phragmites mauritianus*	Sedimentation tank

Table 2. Performance of the surveyed HSSF-CW systems

CW		Temp (°C)	pH	DO (mg/L)	EC (µS/cm)	BOD (mg/L)	COD (mg/L)	NO_3-N (mg/L)	NH_3-N (mg/L)	P (mg-P/L)	FC (log unit)
Meat industry	In	24.06± 0.99	6.79± 0.27	0.93± 1.01	2896.50± 515.48	248± 11.3	650± 226.3	25.7± 16.6	54.05± 31.8	28.75± 0.9	5.8± 0.7
	Out	21.55± 0.15	6.93± 0.25	1.37± 0.48	2987.50± 550.84	59.5± 14.9	160.5± 89.8	18.6± 10.8	57.6± 23.2	29.49± 3.8	3.6± 0.3
Winery industry	In	26.67± 1.89	7.37± 0.11	3.31± 0.42	3210.39± 242.38	92.5± 24.8	215.5± 34.7	51± 48.1	56.33± 1.5	2.58± 0.2	3.3± 0.3
	Out	24.35± 0.49	7.47± 0.13	1.56± 0.30	2718± 462.45	29± 1.4	137.5± 116.7	44.75± 32.2	41.05± 2.9	3.68± 0.8	3.2± 0.1
Paper industry	In	26.60± 0.14	6.74± 0.73	0.51± 0.23	991± 263.04	147.5± 38.9	252.5± 38.9	77± 4.2	0.54± 0.3	0.21± 0.3	3.6± 0.07
	Out	26.32± 0.02	6.93± 0.32	1.13± 0.83	1063.50± 200.11	59.69± 0.4	72.5± 31.8	96.5± 12	0.12± 0.2	0.22± 0.3	3.4± 0.1

The point of exceeding the maximum flow rate suggests that the incoming flow rate enters the inlet zone with a narrow cross-sectional area; therefore, the likelihood of surface flow formation, which should be avoided in HSSF-CWs, is high. The increased wastewater flow rate into the HSSF-CW reduces its retention time in the system, consequently leading to poor effluent quality, as there is insufficient contact time and area between the wastewater, rhizosphere, and microorganisms (Knowles *et al.*, 2011). The inadequate performance of this system is evident in Table 2, as it was able to meet the Tanzania and WHO discharge limit to the receiving water body only for BOD (29±1.41 mg O_2/L), phosphorus (3.68±0.81 mg P/L), and fecal coliform (3.2±0.1 log unit). The system could not meet the discharge limit for COD (137.5±116.67 mg O_2/L), nitrate nitrogen (44.75±32.17 mg N/L), and ammonia nitrogen (41.05±2.9 mg N/L). This could also be attributed to a lack of regular monitoring and water quality analysis, as reported by the operator of the system.

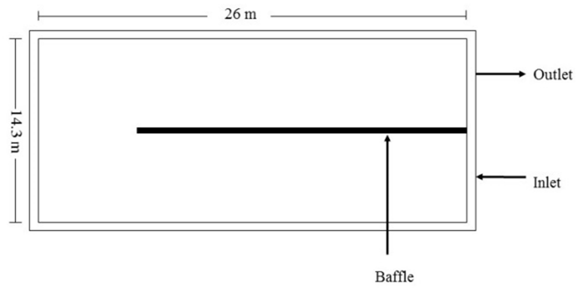

Fig. 2. Schematic layout of the winery industry HSSF-CW

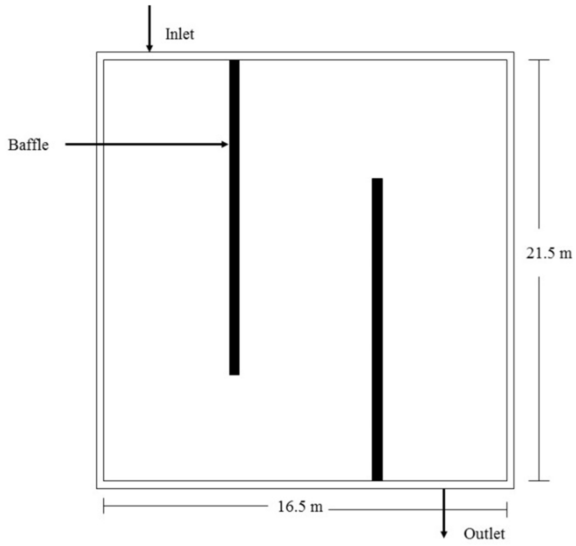

Fig. 3. Schematic layout of the paper industry HSSF-CW

The paper industry CW is a baffled system that treats wastewater from tissue paper production (Fig. 3). The basin is lined with concrete, and the substrate used is basalt aggregates. Before treatment in HSSF-CW, wastewater is pretreated in a sedimentation tank.

Table 3. Loading rates of different pollutants for the surveyed HSSF-CW systems in Northern Tanzania

CW	Q (m^3/d)	Concentration (g/m^3)	A (m^2)	Loading rate (g/m^2.d)				
				BOD	COD	NO_3-N	NH_3-N	P
Meat industry	9	248	46.64	47.86	125.43	4.96	10.43	5.55
Winery industry	62.4	92.5	371.8	15.52	36.17	8.56	9.45	0.43
Paper industry	225	147.5	330	100.57	172.16	52.5	0.37	0.14

The HSSF-CW was also observed to have surface flow. The problem of surface flow in this system could be attributed to the poor pre-treatment of wastewater influent. The paper industry uses recycled papers and raw pulps as raw materials for making tissue papers. When recycled papers are used during production, a lot of suspended solids are produced compared to when raw pulps are used. Thus, if there is no sufficient pre-treatment of wastewater influent, then suspended solids could be introduced into the CW system inlet zone and clog it.

Moreover, the inadequate design of the system could also result in surface flow. In Table 1, the design flow rate (225 m^3/d) exceeds the maximum flow rate suggested by Darcy's law (50 m^3/d) in Equation 1. Thus, the hydraulic and organic overloading (Table 3) to the HSSF-CW could also be the cause of surface flow. According to Knowles *et al.* (2011), hydraulic and solids overloading rates may be accompanied by clogging, surface ponding, and bypass of untreated wastewater in HSSF-CW systems. Ergaieg *et al.* (2021) also explained that clogging of the system by organic or inorganic particles limits the system's performance and lifespan. Besides, no maintenance is conducted in the system, which could also contribute to system clogging. In terms of this system's performance, the system poorly reduced BOD (59.69±0.44 mg O_2/L), COD (72.50±31.82 mg O_2/L), and nitrate nitrogen (96.50±12.02 mg N/L). Originally, the longevity of HSSF-CW was predicted to be 50 – 100 years (Conley *et al.*, 1991; Knowles *et al.*, 2011; Bavor and Schulz, 1993) but has now been shortened to 8-10 years (Griffin *et al.*, 2008; Wallace and Knight, 2006). This could be due to hydraulic and organic overloading into the system, giving insufficient time and area between biofilm and wastewater due to clogging. The system released a lot of nitrates in the effluent, while the amount of ammonia nitrogen entering the system was rather low. This could be attributed to the addition of a nitrate-containing product in the sedimentation tank to reduce the turbidity of wastewater before treatment in HSSF-CW, as explained by the manager.

The meat industry CW is an unbaffled HSSF system. The basin is lined with a High-Density Polyethylene (HDPE) liner and basalt aggregates are used as substrate. Wastewater from the meat processing section is pretreated in a septic tank and then enters a HSSF-CW where secondary treatment takes place. No surface flow was observed in this wetland system. This could be attributed to the adequate design of the system that considered Darcy's law in designing. This can be observed in the design flow rate being lower than the maximum flow rate suggested by Darcy (Equation 1). This means that the possibility of surface flow in this HSSF-CW system is low. Moreover, the operator of the system checks the system regularly, picks up dirty and prunes plants in the system. In terms of its performance, the system was able to meet the Tanzania and WHO discharge limits to the receiving water body for only nitrate nitrogen (18.60±10.75 mg N/L) and fecal coliform (3.6±0.3 log unit). Other parameters, BOD (59.50±14.85 mg O_2/L), COD (160.50±89.8 mg O_2/L), ammonia nitrogen (57.60±23.19 mg N/L), and phosphate (29.49±3.79 mg/L) did not meet the discharge limits to the receiving water body. The high phosphorus concentration in this system could be due to the use of a preservative known as sodium tripolyphosphate ($Na_5P_3O_{10}$) which contains 57.6% of P_2O_5. This is a very important product in meat industries; it is an alkaline salt that is applied to meat, poultry, and fish to prevent them from spoiling by raising their pH, which, as a result, increases their water-holding capacity and slows them from drying. During cleanliness in the production area, this product is washed down the drain after being used. Moreover, the use of some cleaning products/detergents that contain phosphate in the production area could also contribute to such P levels. One of the cleaning products used for removing stains on the floor and walls is called Alcolin sugar soap, which contains sodium carbonate, sodium phosphate, and sodium silicate as its main ingredients. Such information like the use of this preservative, is important information to be given to the designers of the CW system before construction so that they get more insight into the processes that will take place in production. Even though the designers include safety factors, such information will result in better designs.

Njau *et al.* (2011) mentioned that most of the established HSSF-CW systems are facing problems ranging mainly from clogging, surface flow, dying of wetland plants, and poor effluent quality. The authors went further, mentioning clogging and overland flow to be caused by the introduction of solid waste materials, lack of a drainage system, hydraulic overloading, and biological growth. Vasconcellos *et al.* (2019) also mentioned clogging as the major operational concern, which could lead to jeopardizing the treatment performance and the service span of the system. This study has demonstrated that improper designing of these systems, such as the design flow rate and hydraulic and organic overloading, contribute to clogging. According to Knowles *et al.* (2011), clogging is apparent in systems receiving more than 20 g/m^{2}d COD, which was obvious for all systems in this study. Despite the meat industry having 125.43 g/m^{2}d COD loading, the system was not clogged. This could be due to the better design of the system configuration considering Darcy's law. However, Rousseau *et al.* (2008) and Njau *et al.* (2011) documented that for a CW system to remain functional, monitoring of water quality and biological monitoring, water flow, checking of short-circuiting, maintenance of inlet and outlet structures, and removal of debris are important.

Ergaieg *et al.* (2021) reported that early monitoring and detection of the system failure relating to clogging by using the electrical resistivity method would be useful for early correction of the system failure. Although water quality monitoring might show good system performance for the first few years, proper design of the HSSF-CW system is important to prevent the problem of surface flow and sustain its lifespan. This has been emphasized by Knowles *et al.* (2011), who reported clogging to be caused by poor system design and operations.

Conclusion

The inadequate performance of HSSF-CWs assessed in this study is attributed to improper design and hydraulic and organic overloading, which lead to clogging of the system bed, as well as a lack of regular monitoring and maintenance. When designing HSSF-CWs, it is crucial to use Darcy's law to evaluate the system hydraulics to prevent surface flow problems. Additionally, hydraulic and organic loading must be taken into account when designing HSSF-CWs to ensure robust operation and performance. Therefore, designers should gather sufficient information about the industry's production processes for improved design. For a well-designed HSSF-CW to remain functional and have a long lifespan, regular monitoring, including water quality analysis, should be mandatory. Consequently, having operational and maintenance guidelines is essential.

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