Acta Scientiarum
http://periodicos.uem.br/ojs
ISSN on-line: 1807-8664
Doi: 10.4025/actascitechnol.v46i1.66304

GEOSCIENCES

Evaluation of a constructed wetlands hybrid system with and without recirculation

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ABSTRACT. The objective of this study was to evaluate the organic matter behavior under the effect of the recirculation of treated domestic sewage in a hybrid system of constructed wetlands. This study was carried out at the sewage treatment plant in the Instituto Federal Goiano campus, in Rio Verde city, Goias, Brazil. The treatment system consists of a septic tank followed by a hybrid system of constructed wetlands (CW). Sewage monitoring was performed at 3 points: PTS (previously treated sewage), TS1 (VS-CW output) and TS2 (HS-CW output). Water quality analysis were carried out weekly, between May and December 2021, in two types of operation: no recirculation (10 weeks) and 100% recirculation (17 weeks). In this research, three kinetics models were evaluated (1st Order, Monod and Monod Multi) combined with two types of idealized dynamic flow: PFR and CSTR. Results show that the water behavior of the recirculation system increasing by 335% and 59.25% in inlet and outlet flows, respectively, from the VS-CW. The overall efficiency in BOD removing was 89.26% in linear system and 83.95% in the recirculating system. In the case of COD, an overall removal system was 69.7% in the linear and 25.7% in the recirculating system. The Monod kinetic model was the most representative to describe the BOD removal in the linear system (R^2 = 0.80) and in the recirculation (R^2 = 0.61). None of the models were included in the description of the linear COD removal processes in the system. In the recirculating system, the Monod kinetic model (R^2 = 0.81) was the most representative in terms of concentration. Sewage recirculation brought new treatment dynamics and was efficient in BOD reducing (concentration). It is noteworthy that the BOD and COD removal efficiency was lower than in the recirculation by sewage dilution in the suction well.

Keywords: degradation kinetics; evapotranspiration; recirculation rate.

Received on December 15, 2022.
Accepted on May 18, 2023.

Introduction

The efficiency of constructed wetlands (CWs) in wastewater treatment has been known worldwide for at least 30 years. However, new studies, aiming to optimize the pollutant removal processes, are in progress. One of the aspects is the recirculation of wastewater that can be proposed with the aim of intensifying the occurrence of organic matter removal processes. However, recirculation is an operational procedure that has many gaps in knowledge because it depends on a set of factors that go beyond recirculation rates, such as the hydraulic regime, organic loading, type of vegetation and local climatic conditions (Stefanakis, Akratos, & Tsihrintzis, 2014; Dotro, Mander, & Rousseau, 2017; Decezaro et al., 2019).

Studies carried out in recent years show that recirculation is capable of improving the level of dissolved oxygen (DO) in wastewater, providing conditions for microorganisms to increase biodegradation and the efficiency of removal of organic matter in the system (Foladori, Ruaben, & Ortigara, 2013; Wu et al., 2015; Ilyas & Mahsi, 2017; Sharma, Minakshi, Rani, & Malaviya, 2018; Saeed, Miah, Majed, Alam, & Khan, 2021). Another advantage is that recirculation provides a longer contact time between the treated sewage and the microorganisms, which makes it possible to reduce the concentrations of organic matter in the final effluent (Decezaro, Wolff, Araújo, Carvalho, & Sezerino, 2021).

The water balance of the system is another important factor to be considered in the recirculation of wastewater in CWs, mainly because there is an increase in the flow present in the system and losses occur through evapotranspiration (ET). There are still few studies that address the behavior of the water balance in recirculating CW systems, especially in subhumid tropical climate locations, as is the case of the southwest region of the state of Goiás.

Different operational and dimensioning criteria can be used in CW systems, with emphasis on the organic loading and the adopted hydraulic regime (Fechine et al., 2020; Sezerino, Bento, Decezaro, Magri, & Philippi, 2015; Decezaro et al., 2021; Al-Wahaibi et al., 2021). Some researches have been proposed with the aim of evaluating the applicability of kinetic-hydrodynamic equations to explain the behavior of organic matter degradation in CWs systems in linear flow and/or recirculation (Saeed & Sun, 2011; Gholizadeh, Gholami, Davoudi, Rastegar, & Miri, 2015; Zhao, Hu, Zhao, & Kumar, 2018; Nguyen et al., 2018), as well as for CW design purposes.

Thus, the objective of this study was to evaluate the behavior of organic matter under the effect of the recirculation of domestic sewage treated in a hybrid system of constructed wetlands.

Material and methods

The present study was carried out at the sewage treatment plant that has been in operation since July 2016 in the Instituto Federal Goiano campus, in the municipality of Rio Verde, state of Goias, Brazil. This system is responsible for treating the domestic sewage from five residences of the institution's employees.

Figure 1 shows the schematic configuration of the treatment plant.

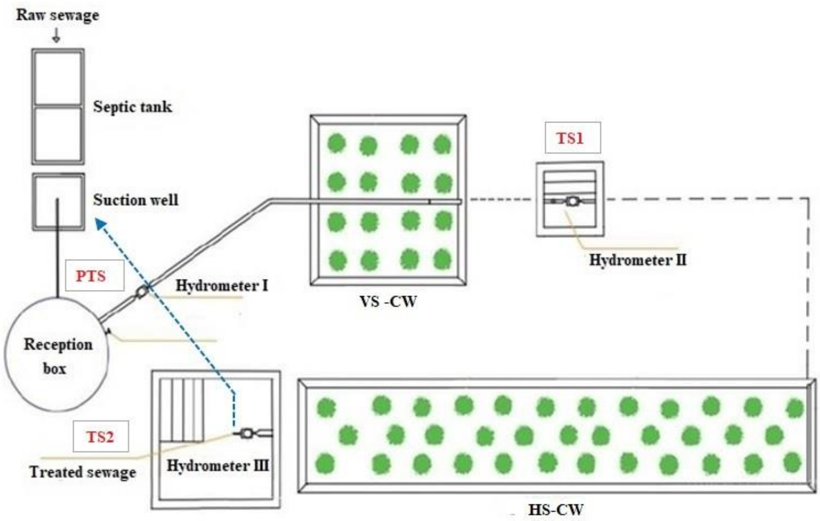

Figure 1. Treatment system of domestic sewage.

The treatment system covers an area of 500 m² in which is composed by the following treatment units: septic tank, suction well, reception box, vertical subsurface flow constructed wetland (VS-CW) and horizontal subsurface flow constructed wetland (HS-CW). After treatment, the treated effluent is released on the ground.

Treatment system

This treatment system has two levels of treatment: primary and secondary. The primary treatment is carried out by septic tank (2.2 x 1.2 x 1.2 m) that has a hydraulic retention time (HRT) of 1 day.

After, from the septic tank, the sewage is sent to the suction well, which has a volume of 500 L and has a HRT close to 1 day. After the suction well, the sewage is pumped into a polyethylene reception box (1,000 L), and from there, the sewage flows by gravity to continue the treatment in the VS-CW. Figure 2a shows the layout of that system.

Then, secondary treatment is carried out by two CWs installed in series: a VS-CW followed by HS-CW. The previously treated sewage (PTS) coming from the reception box is directed to the VS-CW through a suspended pipe (Figure 2b).

Both CWs have the shape of an inverted pyramid trunk that were excavated in the ground and waterproofed with a 1.5 mm thick geotextile blanket. They are filled with gravel number 2 as a medium support layer. The vegetation used in both cells is Vetiver grass (*Chrysopogon zizanioides)*.

The VS-CW has dimensions of 2.8 x 2.8 x 0.8m, with 0.2m freeboard and 2-day HRT. The distribution of sewage in the VS-CW is done through a longitudinally perforated PVC pipe (Figure 3a and 3b). The HS-CW has a dimensions of 10 x 2 x 0.4m (Figure 3c), with 0.2m of freeboard and HRT of 3 days. The HS-CW treated sewage outlet pipe is located at the other end of the cell. After leaving the HS-CW, the treated effluent was released in the soil for infiltration (Figure 3d).

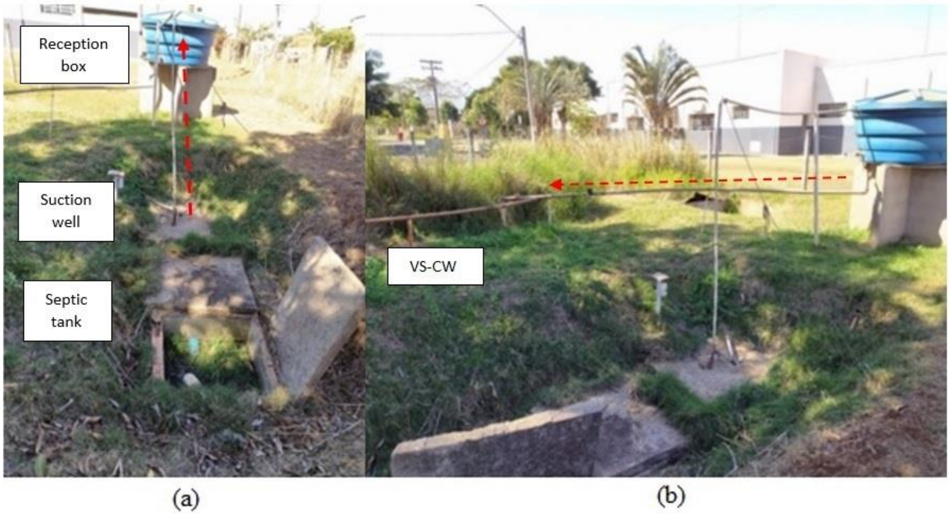

Figure 2. (a) Septic tank, suction well and reception box and (b) directing the sewage to the VS-CW.

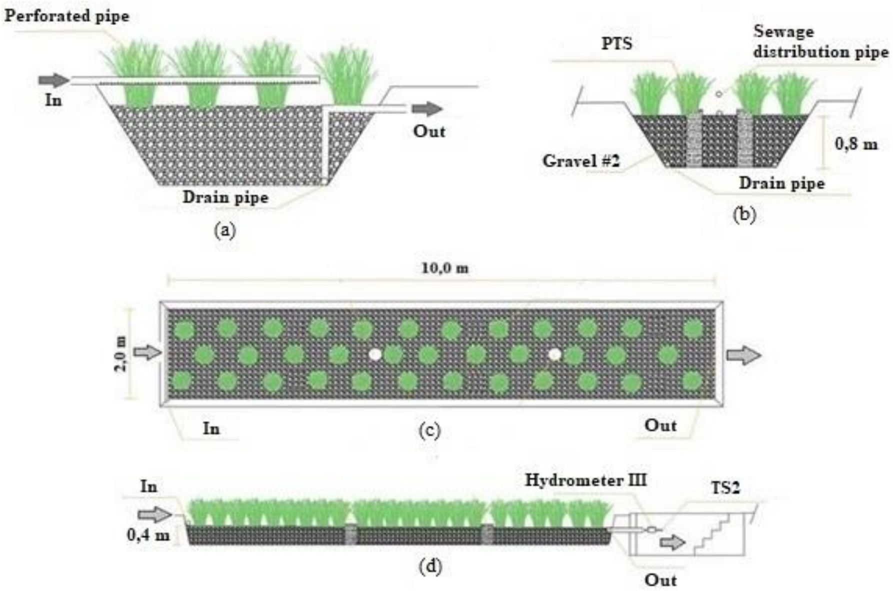

Figure 3. (a) Longitudinal profile and (b) cross section of the VS-CW and (c) floor plan and (d) longitudinal profile of the HS-CW.

Recirculation of treated sewage

For the recirculation of the effluent being treated, a pipe was connected to redirect the sewage from the TS2 sampling point (which was disposed in the ground) to the suction well. So that, the sewage returns to the treatment again mixing with the sewage that is entering the system.

It was defined at the beginning of the research that the sewage would be recirculated at a rate of 100%. Figure 1 refers to the schematic configuration of the treatment system with the insertion of the pipe that promotes the recirculation of the sewage (dotted blue line).

Sampling and monitoring points

The analyzes were performed weekly between May and December 2021, totaling 10 weeks of system analysis in linear flow and 17 weeks in recirculated flow (under a recirculation rate of 100%). There was a 4-week break in the analyzes (07/24 to 08/20/2021) to adapt to the system's new treatment dynamics.

In this experimental station there are 3 sampling points of sewage that were defined by: PTS, TS1 and TS2. The first sampling point (PTS) is in the sewage reception box, to characterize the sewage treated in septic tank. The second sampling point (TS1) is intended to characterize the VS-CW effluent. And finally, the third sampling point (TS2) is intended to characterize the final effluent.

The sewage quality parameters chosen to measure the degradation of organic matter (American Public Health Association [APHA], 2018) were evaluated according to the frequency of Table 1.

Table 1. Sampling plan.

Parameter	Sampling points	Frequency	Standard Methods Code
DO	PTS, TS1 e TS2	Weekly	4.500-G
BOD	PTS, TS1 e TS2	Weekly	5.210-B
COD	PTS, TS1 e TS2	Weekly	5.220-D

Along with the linear system data obtained in this research, another 22 BOD data and 30 COD data were added referring to the analyzes of research developed in this same treatment system between the years 2016 and 2018 (Silva Jr and Souza, 2023), with very similar results of efficiencies concerning to the BOD and COD removal.

Water balance

The water balance was performed by measuring the volume of sewage that flowed weekly through each CW, being quantified by reading the water meters installed in the system. The water balance analysis was performed in two study scenarios.

Basically, the water balance in each CW is based on the principle of conservation of mass in a dynamic state, according to Equation 1.

$$IS + PPT = ES + ET \qquad (1)$$

where, IS: influent sewage (mm d^{-1}); PPT: precipitation (mm d^{-1}); ES: effluent sewage (mm d^{-1}); ET: evapotranspiration (mm d^{-1}).

Kinetic-hydrodynamic models evaluated

In this research, 3 kinetic models were evaluated (1st Order, Monod and Monod Multi) combined with 2 types of idealized hydrodynamic flow: PFR (Plug Flow Reactor) and CSTR (Continuous Stirred Tank Reactor). The combination of kinetic models and flows totals 6 kinetic-hydrodynamic models, however the Monod Multi kinetics was only studied in combination with the CSTR flow, as this kinetics associated with the PFR flow generated equations of difficult analytical solution. Therefore, only 5 kinetic-hydrodynamic models were evaluated.

Kinetic-hydrodynamic models were evaluated in each CW, considering the type of operation, in terms of concentration and organic load, as shown in Table 2.

Table 2. Kinetic-hydrodynamic models evaluated.

Hydrodynamics	Kinetics	Kinetic-hydrodynamic model (concentration)	Kinetic-hydrodynamic model (load)
PFR	1st Order	$C_e = C_a . e^{-k_a . \theta}$	$L_e = L_a . e^{-k_a . \theta}$
PFR	Monod	$C_a - C_e + k_s . \ln\left(\frac{C_a}{C_e}\right) = -k_{max} . \theta$	$L_a - L_e + L_s . \ln\left(\frac{L_a}{L_e}\right) = -k_{max} . \theta$
CSTR	1st Order	$\frac{k_v . C_e}{1} = \frac{(C_a - C_e)}{\theta}$	$\frac{k_v . L_e}{1} = \frac{(L_a - L_e)}{\theta}$
CSTR	Monod	$\frac{k_{max} . C_e}{(k_s + C_e)} = \frac{(C_a - C_e)}{\theta}$	$\frac{k_{max} . L_e}{(L_s + L_e)} = \frac{(L_a - L_e)}{\theta}$
CSTR	Monod Multi	$k_{max} . \frac{C_{e1}}{(k_{s1} + C_{e1})} . \frac{C_{e2}}{(k_{s2} + C_{e2})} = \frac{(C_a - C_e)}{\theta}$	$k_{max} . \frac{L_{e1}}{(L_{s1} + L_{e1})} . \frac{L_{e2}}{(L_{s2} + L_{e2})} = \frac{(L_a - L_e)}{\theta}$

C_e: effluent concentration (mg L^{-1}); C_a: influent concentration (mg L^{-1}); C_{e1}: effluent concentration of limiting substrate 1 (mg L^{-1}); C_{e2}: effluent concentration of limiting substrate 2 (mg L^{-1}); θ: hydraulic retention time (d^{-1}); k_a: surface degradation constant (d^{-1}); k_v: volumetric degradation constant (m d^{-1}); $k_{máx}$: maximum reaction rate (mg L^{-1} d^{-1}); k_s: saturation constant (mg L^{-1}); k_{s1}: limiting substrate saturation constant 1 (mg L^{-1}); k_{s2}: limiting substrate saturation constant 2 (mg L^{-1}); L_e: effluent load (g d^{-1}); L_a: tributary load (g d^{-1}); L_{e1}: limiting substrate effluent load 1 (g d^{-1}); L_{e2}: limiting substrate effluent load 2 (g d^{-1}); $k_{máx}$: maximum reaction rate (g d^{-1}); L_s: load saturation constant (g d^{-1}); L_{s1}: limiting substrate saturation constant 1 (g d^{-1}); L_{s2}: limiting substrate saturation constant 2 (g d^{-1}).

The substrates evaluated individually in each model were BOD and COD. In the case of the Monod Multi model, the second limiting substrate was DO.

For VS-CW, only the CSTR flow was considered in combination with the kinetic models. Thus, 3 kinetic-hydrodynamic models were evaluated in this reactor. In the case of HS-CW, kinetic models combined with CSTR and PFR flows were evaluated. Therefore, in this reactor, the five kinetic-hydrodynamic models were evaluated.

Statistical analysis

The kinetic-hydrodynamic equations were linearized to obtain the best R^2 value. The t-student test, with a significance level of $p=0.05$, was used to assess the statistical significance between the kinetic models in the scenarios studied (with and without recirculation). The GraphPad Prism 8.0.1® software was used to assess the statistical significance of the data and to graphically present the results. The kinetic constants of transformation of organic matter (k) were adjusted until obtaining the highest R^2 value from the SOLVER function of Microsoft Office Excel 2019.

Results and discussion

System water balance

Considering the daily sewage flow in the 10 weeks of linear flow treatment, it was observed that the average sewage flow at the VS-CW entrance was 1,807.0 L d^{-1}. The average sewage flow at the entrance and exit of the HS-CW was 1,337.9 and 996.5 L d^{-1}, respectively.

The outflow values of this survey were much higher than those obtained in 2018, as it was carried out during the COVID-19 pandemic period, and activities at the institution took place remotely. Thus, the resident employees spent the entire day in the residences, which possibly contributed to higher water consumption and sewage generation.

Also, considering the treatment system in recirculation, an average sewage flow applied at the entrance of the VS-CW of 2,413.28 L d^{-1} was obtained. The average sewage flow at the entrance and exit of the HS-CW was 2,130.58 and 600.64 L d^{-1}, respectively.

Figure 4 illustrates the variation in the treated sewage flow in the CWs.

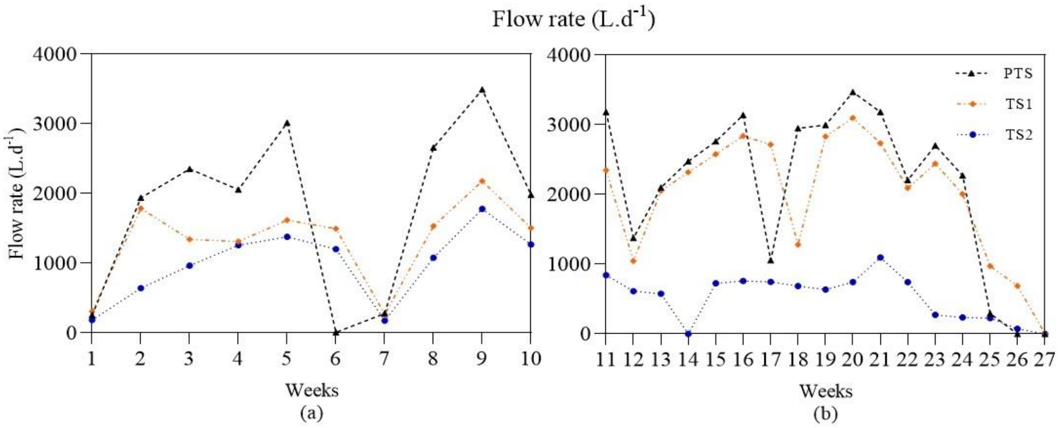

Figure 4. Variation of sewage flow in the system (a) in linear flow and (b) in recirculation.

It can be noticed that the outflow in the CWs increased when the sewage recirculation in the system was started, especially at the entrance and exit points of the VS-CW, with a reduction in the volume of sewage due to ET in the treatment cells.

Table 3 presents the PPT and ET data in the CWs according to the type of operation.

Table 3. Water balance of the system in linear flow and in recirculation.

System flow	Month	PPT (mm)	Average flow and evapotranspiration (L.d-1)					
			VS-CW			HS-CW		
			In	Out	ET	In	Out	ET
Linear	May	4	1,940.2	1,789.8	150.4	1,789.8	415.9	1,146.0
	Jun	6	2,477.1	1,427.4	1,052.8	1,445.2	1,204.7	246.5
	Jul	-	2,714.7	1,741.9	973.0	1,741.9	1,379.2	362.7
	Variation (%)		67.5	45.1	51.2	45.1	52.0	80.2
Recirculation	Aug	-	2,281.8	1,700.3	581.5	1,700.3	730.0	970.2
	Sep	9	2,621.6	2,449.4	175.6	2,449.4	517.2	1,813.6
	Oct	319	3,151.5	2,489.6	751.3	2,535.6	783.92	1,968.5
	Nov	104	2,397.0	2,181.7	267.1	1,880.3	371.9	1,893.9
	Dec	62	-	346.1	-	346.1	36.8	-
	Variation (%)		54.5	44.3	97.3	44.3	61.8	37.6

In general, the average flow at the VS-CW inlet was higher than the outlet, which consequently was higher than the HS-CW outlet, indicating water loss by ET. Considering the data in Table 3, it is evident that the flows at the entrance and exit of the CWs were greatly influenced by the type of system operation and by the PPT.

In the linear system, the highest ET rates were recorded in VS-CW, especially in June and July. Mean ET values in VS-CW and HS-CW were 889.7 and 375.8 L d^{-1} (or 113.5 and 18.8 mm d^{-1}), respectively. It is worth mentioning that in this period, in the state of Goias, the meteorological conditions are very favorable to ET, mainly due to the high temperatures and low humidity.

De Lille, Cardona, Xicum, Vallejos and Franco (2021) obtained in their studies of the operation of a hybrid system of CWs in a linear system, ET rates of up to 16.07 and 17.76 mm.d^{-1}, in the CW- FSSV and HS-CW, respectively. It should be noted that these ET rates were obtained in May, the hottest month of the year, when temperatures reached up to 38.9ºC.

In the recirculation system, the HS-CW recorded the highest ET rates in all months/weeks of treatment, especially in October. The average values of daily ET in the VS-CW and HS-CW were 436.3 and 1,761.9 L d^{-1} (or 55.6 and 88.1 mm d^{-1}), respectively. It is noteworthy that the recirculation of sewage occurred in the months in which they are registered.

The average percentage of water loss by ET, in relation to the inflow, was 33.9 and 27.5% for VS-CW and HS-CW, respectively, in the linear treatment system. In the recirculating system, the average percentage of water loss by ET was 15.9 and 73.4% for VS-CW and HS-CW, respectively. Compared to the inflow, Bialowiec, Albuquerque and Randerson (2014) observed water losses by ET of up to 92.2% in a VS-CW, which further reinforces the importance of ET within CWs.

Sewage quality

Table 4 provides data regarding to DO, BOD and COD values of domestic sewage in CWs, considering the system in linear flow and in recirculation.

Table 4. Statistics referring to the values of DO, BOD and COD of the sewage.

Parameter statistical	Linear flow			Recirculation		
	PTS	TS1	TS2	PTS	TS1	TS2
DO	0.79	0.81	0.94	1.02	1.16	1.39
n	32	32	32	17	17	17
t test	-	-	-	*	*	*
BOD	77.39	23.10	8.31	25.0	9.06	4.01
n[a]	28	28	28	17	17	17
t test	-	-	-	*	*	*
COD	418.4	172.55	126.73	247.0	162.86	183.51
n	33	33	33	15	15	15
t test	-	-	-	*	**	*

* = p < 0,05 – significant at the 5% level; ** = p > 0,05 – not significant at the 5% level; n = number of weeks; [a] = part of the data from the BOD analyzes are from the year 2016 to 2018.

The DO of sewage in the reception box showed an average concentration of 0.79 mg L^{-1}, the lowest among the 3 monitored points. At the VS-CW and HS-CW outlets, mean DO concentrations were 0.81 and 0.94 mg L^{-1}, respectively. Considering the system in recirculation, it is noted that the DO of PTS also had the lowest average concentration, around 1.02 mg L^{-1}. At the VS-CW and HS-CW outlets, mean DO concentrations were 1.16 and 1.39 mg L^{-1}, respectively. Sewage recirculation increased DO concentrations at all monitored points (about 29.11, 43.2 and 47.8%, respectively), which can be explained by the longer contact time between the sewage and the roots of the plants and by the hydraulic agitation of the recirculation that improves the aeration.

For BOD, considering the linear treatment system, the data point to an average removal efficiency of 70.15% in VS-CW followed by an average removal of 64.03% in HS-CW. The mean overall efficiency for BOD removal was 89.26%. Such results are similar to those obtained by Silva Jr and Souza (2023) who got an average BOD removal efficiency of 69.1% in VS-CW, 59.6% in HS-CW and overall efficiency of 87.5%. In the recirculating system, the average efficiency of BOD removal was 63.76% in the VS-CW followed by an average removal of 55.71% in the HS-CW. The overall efficiency was 83.95%.

In percentage terms, the system with recirculation showed a slight reduction in efficiency in relation to the linear flow, mainly because in the system with recirculation the easily biodegradable organic matter is smaller.

This fact occurred due to the mixture between the sewage already treated and the sewage that entered the system.

De Lille et al. (2021), in their studies on domestic wastewater treatment in a hybrid CW system, found that the BOD removal efficiency in the recirculating system was lower than in the linear system. The authors also verified that the increase in HRT of the system culminated in the reduction of the removal efficiency.

Figure 5 illustrates the variation in sewage BOD in CWs during the weeks of analysis.

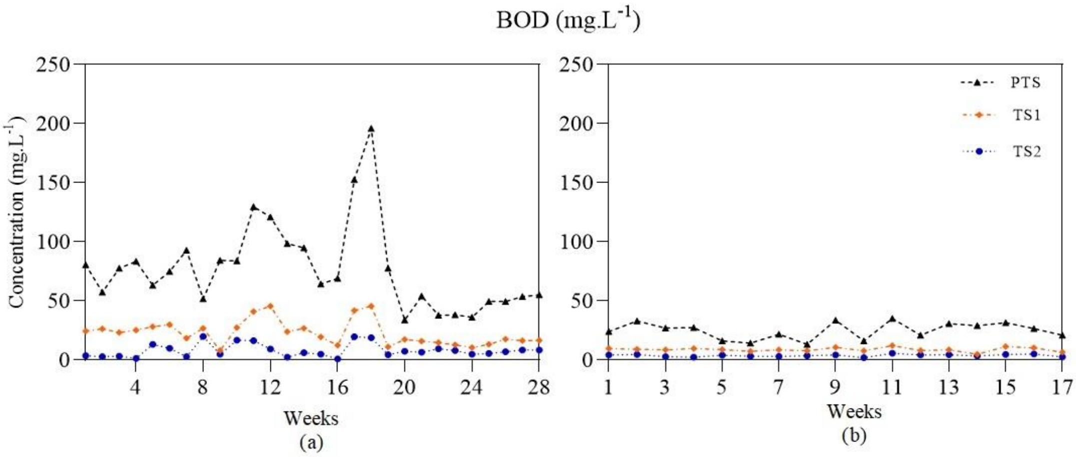

Figure 5. Variation of sewage BOD in the system (a) in linear flow and (b) in recirculation.

Figure 5 shows that the influent BOD concentration is higher than the effluent in all weeks. It was noted that the recirculated system provided lower average BOD values in the 3 points analyzed. Comparing the average concentration of BOD at the analyzed points, there was a reduction of 68% in PTS, 60.8% in TS1 and 51.7% in TS2, which shows that the hybrid system in recirculation was efficient in reducing BOD.

For COD, considering the linear flow system, the data point to an average COD removal efficiency of 58.76% in the VS-CW followed by an average removal of 26.55% in the HS-CW. The overall efficiency for COD removal was 69.71%. In similar research, Silva Jr and Souza (2023) obtained an average COD removal efficiency of 52.0% in the VS-CW, 52.7% in the HS-CW and an overall average efficiency of 77.3%. In the recirculation system, the average COD removal efficiency was 34.06% in the VS-CW. In the HS-CW, it was found that there was no removal, but an increase in COD (12.68%). The mean global efficiency for COD removal was 25.7%.

Comparing the types of operation, greater efficiency in COD removal can be seen when operating the system in linear flow. However, it was perceived that the system in recirculation provided lower values of COD in 2 of the 3 points analyzed (reduction of 41 and 5.6% in points PTS and TS1, respectively).

According to the results obtained by De Lille et al. (2021) in the treatment of domestic wastewater in a hybrid CW system, the average COD removal efficiency in the recirculating system was lower than in the linear system. The authors concluded that increasing the contact time between the sewage and the system reduced the removal efficiency.

CWs are biological treatment systems responsible, mainly, for the removal of easily biodegradable organic matter, which by the way, is more easily removed/represented in BOD. When the system began to be recirculated, the easily biodegradable fraction of the sewage decreased, making the fraction of difficult degradation (indicated by the COD) more abundant in the treatment system.

During the recirculation period, it was noted that the sewage collected at point TS2 (HS-CW outlet) contained remnants of senescent vegetation and had a very yellowish color, which possibly contributed to the increase in COD at this point.

Guedes-Alonso et al. (2022) concluded that the recirculation of 50% of the effluent in a macrophyte lagoon system followed by a HS-CW caused an increase in COD.

Figure 6 illustrates the COD variation of treated sewage in CWs.

Kinetic-hydrodynamic models in linear and recirculation system

Effect on the degradation of organic matter - BOD

Concentration

Table 5 presents the results obtained for the BOD removal kinetic constants, in terms of organic matter concentration.

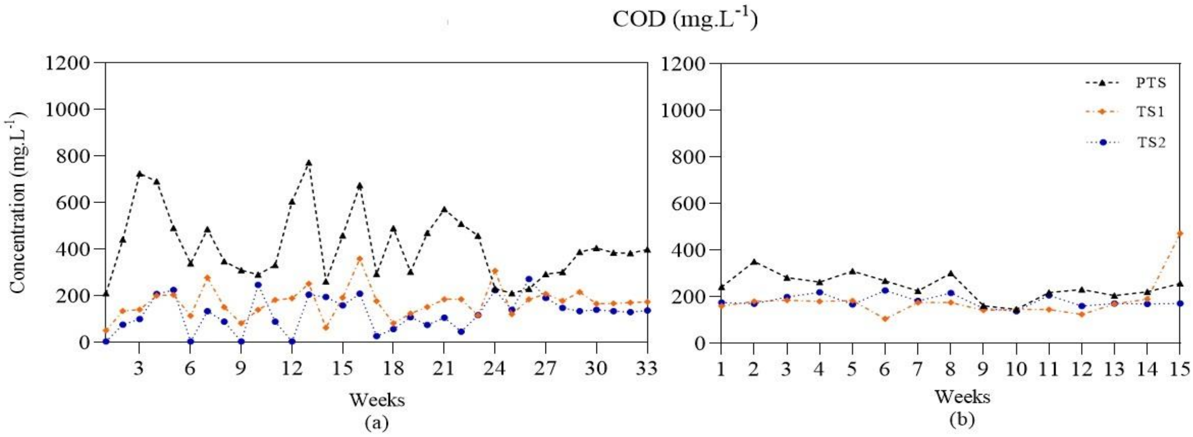

Figure 6. Sewage COD variation in the system (a) in linear flow and (b) in recirculation.

Table 5. Kinetic constants of BOD removal, in terms of concentration.

Cell	Flow	Kinetics	Linear system		Recirculation		t test
			R^2	k	R^2	k	
VS-CW	CSTR	1st Order	0.39	0.871 d^{-1}	0.03	1.264 d^{-1}	*
		Monod	0.74	16.80 mg L^{-1} d^{-1}	0.14	11.18 mg L^{-1} d^{-1}	
		Monod Multi	0.79	17.86 mg L^{-1} d^{-1}	0.14	60.73 mg L^{-1} d^{-1}	
HS-CW	PFR	1st Order	0.13	0.277 d^{-1}	0.03	0.457 d^{-1}	*
		Monod	0.30	3.97 mg L^{-1} d^{-1}	0.03	11.90 mg L^{-1} d^{-1}	
	CSTR	1st Order	0.15	0.709 d^{-1}	0.01	0.847 d^{-1}	
		Monod	0.80	3.42 mg L^{-1} d^{-1}	0.08	2.63 mg L^{-1} d^{-1}	
		Monod Multi	0.61	3.417 mg L^{-1} d^{-1}	0.24	2.645 mg L^{-1} d^{-1}	

* = $p < 0,05$ – significant at the 5% level. Statistical difference between the adjustments to the evaluated systems.

The kinetic model of Monod in CSTR flow, in the HS-CW, was the most representative in the description of the BOD removal processes (R^2 = 0.80 and kmax = 3.42 mg BOD L^{-1} d^{-1}), followed by the kinetic model of Monod Multi in CSTR flow in the VS-CW (R^2 = 0.79), both in the treatment system in linear flow. In the recirculating system, all models showed low linear fit (R^2 < 0.25).

Considering the BOD removal in terms of organic matter concentration, it is inferred that the adjustments to the models evaluated in the linear treatment system and in recirculation are statistically different from each other.

The models evaluated in terms of BOD concentration in CWs were more representative in describing the BOD removal mechanisms in the linear system, because the models describe the biodegradable fraction of the samples that is easier to be assimilated by microorganisms and by the plants.

The BOD suffered more variations during the operation of the system in linear flow. However, the significant increase in flow rates in the recirculation system influenced the greater variation in the weekly RHT in both CWs (variation = 107 and 66.13% in VS-CW and HS-CW, respectively) which, together with the smaller variation in data of concentration at the reactor inlets (variation = 28.24 and 19.89% in VS-CW and HS-CW, respectively), greatly reduced the fit to the models (R^2) during the recirculation period.

Figure 7 shows the relationship between PPT and BOD in the analysis weeks in 2022.

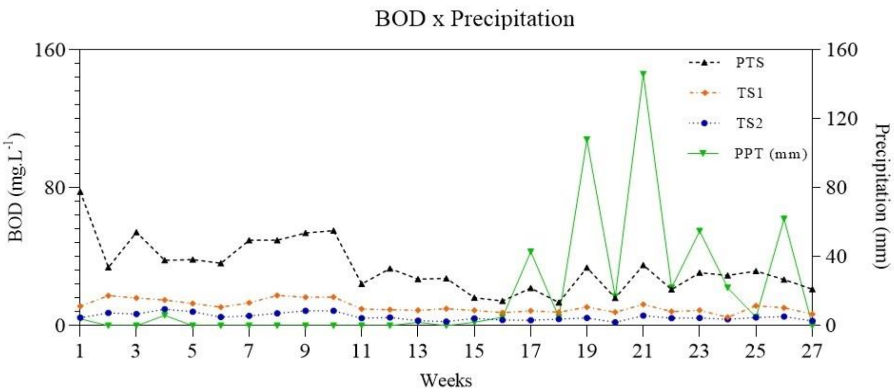

Figure 7. Comparison between weekly precipitation variation and BOD of sewage treated in the system in linear flow (weeks 1-10) and recirculated (weeks 11-27) in 2022.

As shown in Figure 7, it demonstrates that the highest precipitation rates were recorded during the recirculation period. From this, it is noted that the highest accumulated precipitation indices (weeks 17, 19, 21, 23 and 26, for example) influenced, above all, the reduction of BOD quantified in the following week in both CWs. Added to this phenomenon, it was also verified that the highest flows recorded at the entrance and exit of the CWs during this period occurred exactly in the weeks in which there were the highest precipitation rates. As a result, the accumulation of the weekly precipitated volume increased the flow rates in each reactor, causing direct dilution of the sewage and further reducing the concentration of easily biodegradable organic matter, and possibly reducing the adjustments to the models.

Organic load

From the evaluated kinetic models, Table 6 presents the results obtained for the kinetic constants of BOD removal, in terms of organic load.

Table 6. Kinetic constants of BOD removal, in terms of organic load.

Cell	Flow	Kinetics	Linear system		Recirculation		t test
			R^2	k	R^2	k	
VS-CW	CSTR	1st Order	0.31	1.801 d^{-1}	0.14	1.582 d^{-1}	**
		Monod	0.15	28.88 $g.d^{-1}$	0.02	29.35 $g.d^{-1}$	
		Monod Multi	0.01	28.88 $g.d^{-1}$	0.34	29.35 $g.d^{-1}$	
HS-CW	PFR	1st Order	0.02	0.343 d^{-1}	0.00	1.147 d^{-1}	**
		Monod	0.27	4.10 $g.d^{-1}$	0.61	10.03 $g.d^{-1}$	
	CSTR	1st Order	0.00	2.698 d^{-1}	0.02	4.857 d^{-1}	
		Monod	0.38	4.09 $g.d^{-1}$	0.16	10.01 $g.d^{-1}$	
		Monod Multi	0.70	5.32 $g.d^{-1}$	0.58	10.0 $g.d^{-1}$	

* = p < 0,05 – significant at the 5% level. ** = p > 0,05 – not significant at the 5% level. Statistical difference between the adjustments to the evaluated systems.

The kinetic model of Monod Multi in CSTR flow, in the HS-CW, was the most representative in the description of the removal of BOD (R^2 = 0.70 and kmax = 5.32 gBOD d-1), in the linear treatment system, which presupposes that there was a contribution of DO in the degradation of organic matter. The other models showed intermediate to low statistical correlation.

Considering BOD removal in terms of organic load in the CW system, it is inferred that the adjustments to the models evaluated in the linear treatment system and in recirculation did not show statistical difference between them.

Performing a statistical analysis on the treatment cells in isolation, the models evaluated in VS-CW and HS-CW, respectively, also showed no statistical difference between them.

Effect on the degradation of organic matter - COD

Concentration

From the kinetic models evaluated, Table 7 presents the results obtained for the kinetic constants of COD removal, in terms of concentration.

Table 7. Kinetic COD removal constants in terms of concentration.

Cell	Flow	Kinetics	Linear system		Recirculation		t test
			R^2	k	R^2	K	
VS-CW	CSTR	1st Order	0.03	0.482 d^{-1}	0.68	0.333 d^{-1}	*
		Monod	0.13	75.15 mg L^{-1} d^{-1}	0.81	52.61 mg $L^{-1}.d^{-1}$	
		Monod Multi	0.12	84.65 mg L^{-1} d^{-1}	0.15	76.07 mg $L^{-1}.d^{-1}$	
HS-CW	PFR	1st Order	0.02	0.122 d^{-1}	0.52	-0.066 d^{-1}	*
		Monod	0.02	22.23 mg L^{-1} d^{-1}	0.58	-10.13 mg $L^{-1}.d^{-1}$	
	CSTR	1st Order	0.18	0.600 d^{-1}	0.52	-0.043 d^{-1}	
		Monod	0.06	81.74 mg L^{-1} d^{-1}	0.52	-53.24 mg $L^{-1}.d^{-1}$	
		Monod Multi	0.09	10.09 mg L^{-1} d^{-1}	0.47	-111.7 mg $L^{-1}.d^{-1}$	

* = p < 0,05 – significant at the 5% level. ** = p > 0,05 – not significant at the 5% level. Statistical difference between the adjustments to the evaluated systems.

The kinetic model of Monod in CSTR flow, in the VS-CW, was the most representative in the description of the COD removal processes (R^2 = 0.81 and kmax = 52.61 mgCOD L^{-1} d^{-1}), in the recirculation treatment system.

Considering COD removal in terms of organic matter concentration in the CW system, it is inferred that the adjustments to the models evaluated in the linear treatment system and in recirculation are statistically different from each other.

Contrary to the representation of BOD removal mechanisms, all models evaluated in terms of COD concentration in CWs were more representative in the recirculating system than in the linear system. A justification for this fact is that the COD also suffered more variations during the operation of the system in linear flow. However, when the system began to recirculate the effluent, there was a mixture of the pre-treated sewage that arrived in the system with the effluent that had already been treated, so the sewage was no longer easily biodegradable and became recalcitrant, which brought less impact on COD terms and improved data fit (R^2) to models evaluated in recirculation.

Organic load

From the evaluated kinetic models, Table 8 presents the results obtained for the kinetic constants of COD removal, in terms of organic load.

Table 8. Kinetic constants of COD removal, in terms of organic load.

Cell	Flow	Kinetics	Linear system		Recirculation		t test
			R^2	k	R^2	K	
VS-CW	CSTR	1st Order	0.22	2.128 d^{-1}	0.20	0.522 d^{-1}	**
		Monod	0.04	152.98 g d^{-1}	0.07	196.59 g d^{-1}	
		Monod Multi	0.02	152.99 g d^{-1}	0.13	31.09 g d^{-1}	
HS-CW	PFR	1st Order	0.01	0.170 d^{-1}	0.23	0.686 d^{-1}	**
		Monod	0.24	14.07 g d^{-1}	0.45	145.78 g d^{-1}	
	CSTR	1st Order	0.01	0.819 d^{-1}	0.01	1.550 d^{-1}	
		Monod	0.04	14.15 g d^{-1}	0.25	146.55 g d^{-1}	
		Monod Multi	0.35	14.4 g d^{-1}	0.71	147.79 g d^{-1}	

** = p > 0,05 – not significant at the 5% level. Statistical difference between the adjustments to the evaluated systems.

The Monod Multi kinetic model, in HS-CW in CSTR flow, was the most representative in the description of COD removal processes (R^2 = 0.71 and kmáx = 147.79 g COD d^{-1}) in the treatment system in recirculation. The other kinetic models showed low linear fit (R^2 < 0.45).

Saeed and Sun (2011) concluded that the 1st Order kinetic models (R^2 = 0.01 and kv = 0.5 m d^{-1}) and Monod (R^2 = 0.1 and kv = 44.5 g m^2 d^{-1}), in CSTR flow, were not adequate to represent COD load removal mechanisms.

Silva Jr and Souza (2023) also observed in his research that the 1st Order kinetic model was not representative in the description of the COD removal mechanisms in any of the CWs of this same treatment plant (R^2 ⩽ 0.15), obtaining the maximum rate of degradation kv = 7.14 d^{-1}, in terms of organic load.

Considering COD removal in terms of organic load in the CW system, it is inferred that the adjustments to the models evaluated in the linear treatment system and in recirculation did not show statistical difference between them.

The models evaluated in terms of organic COD load in the CWs were more representative in describing the COD removal mechanisms in the recirculating system than in the linear system.

The organic load is directly related to the sewage flow. As already mentioned, during recirculation the flows in the CWs increased, reducing the RHT of the system.

Conclusion

In conclusion, the inlet and outlet flows of the CWs were greatly influenced by the type of system operation and the PPT, which reinforces that recirculation caused changes in the system in terms of flow and ET. However, despite to the significant increase in flow rates, it is noteworthy that there were no overflows in both reactors.

As for the organic matter degradation, sewage recirculation brought new treatment dynamics and was efficient in reducing BOD. It is noteworthy that the BOD and COD removal efficiency was lower in the recirculation by sewage dilution in the suction well.

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