Revista AIDIS de Ingeniería y Ciencias Ambientales:
Investigación, desarrollo y práctica. ISSN 0718-378X

Doi: http://dx.doi.org/10.22201/iingen.0718378xe.2021.14.1.70251
Vol. 14, No.1, 176-193
6 de abril de 2021

REVISTA AIDIS

de Ingeniería y Ciencias Ambientales:
Investigación, desarrollo y práctica.

FEASIBILITY STUDY OF CONSTRUCTED WETLANDS FOR THE TREATMENT OF DAIRY EFFLUENTS

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Recibido el 22 de julio de 2019; Aceptado el 4 de mayo de 2020

Abstract

This work aimed at characterizing the effluent of a small dairy in terms of flow and physical-chemical composition and at assessing constructed wetland for its treatment. The dairy produced an effluent with an average flow of 2.81 $m^3.d^{-1}$ and the following characteristics: 574-4155 $mg.L^{-1}$ of BDO; 1531-7912 $mg.L^{-1}$ of TSS; and 23-173 $mg.L^{-1}$ of TKN. Using median values of BOD, three treatment systems were designed: batch activated sludge (BAS) and waste stabilisation ponds (WSP), commonly applied for the treatment of dairy effluents; and constructed wetlands (CW) as an alternative system. In terms of area requirements based on the removal of BOD, the BAS system (2.1 m^2) was more advantageous than CW (15.0 m^2) and WSP (46.5 m^2). However, considering the removal of TKN and TSS, the WC system showed to be an attractive option for the treatment of the effluent studied. Next, a new CW system was designed aiming at removing BOD, TSS and TKN. In this case, the limiting parameter was the TKN, and not the BOD as expected. The designed CW system presented satisfactory hydraulic retention time (HRT) when compared to ranges reported in the literature, even when minimum, mean and maximum concentrations of NTK were considered for the design, corroborating the robustness of CW systems. The findings of this study confirm, therefore, the wide variation of the characteristics of dairy effluents as well as the ability of CW systems to absorb such variations without compromising the efficiency of the treatment system.

Keywords: *constructed wetlands; dairy effluent; wastewater treatment.*

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Introduction

There are around 4.1 thousand dairy industries in Brazil, from small-scale to multinationals. This sector contributes to Brazil's economy and social development as it is responsible for jobs in all Brazilian states (Saraiva, 2008). According to the Brazilian Service of Support to Micro and Small Enterprises (SEBRAE), Minas Gerais state is very representative in this sector, with 1.3 thousand dairy industries, of which 48% are located in the Zona da Mata region (SEBRAE, 2017). Given the relevance of this growing sector, and considering the relatively highly contaminated effluents, there is a need for a more rigid environmental control.

The processes that generate effluents in the dairy industry are the cleaning and sanitizing stages, as well as leaks and discharges during the production process (Saraiva, 2008). The volume of wastewater generated in dairy industries can vary from one to six times the volume of milk processed (CETESB, 2008). The physic-chemical characteristics of the effluent from a dairy industry depend directly on its size: the organic load tends to be higher in smaller dairy industries due to the difficulty of segregating whey (Machado *et al.,* 2000). In general, this industrial effluent is composed of milk and its by-products, detergents, disinfectants, essences and condiments. Its composition is influenced by industrial processes, the volume of processed milk and the quantity of water used in the production processes (Teixeira, 2011).

The literature reports wide ranges of BOD (240 to 50,000 $mg.L^{-1}$) and suspended solids (20 to 22,000 $mg.L^{-1}$) in dairy effluents, as well as high concentrations of oils and greases (150 to 1,800 $mg.L^{-1}$) (CETESB, 2008; IPPC, 2009; FEAM, 2014). In addition, the presence of nutrients such as nitrogen and phosphorus as well as variable pH levels are also important characteristics to take into account (Onet *et al*. 2010; Vymazal, 2014; Wu *et al*., 2015; Slavov, 2017). Therefore, the treatment of dairy effluents requires high removal rates of organic matter, solids, oils and greases, and nutrients in order to comply with environmental legislations and mitigate environmental impacts. In Minas Gerais state, dairy industries, regardless their size, have to comply with two different legislations: the COPAM Resolution 217/2017 (Minas Gerais, 2017), regarding environmental licensing; and the COPAM/CERH Resolution 01/2008 (Minas Gerais, 2018), regarding wastewater treatment.

According to the Minas Gerais State Environmental Foundation (FEAM, 2014), dairy wastewater treatment systems must present preliminary (removal of coarse solids), primary (removal of fats and suspended solids) and secondary (removal of organic matter) treatment steps. The most commonly applied treatment systems are activated sludge, stabilisation ponds, trickling filters and land disposal (FEAM, 2014). Constructed wetlands (CW) comprise a system that simulates the biome of natural wetlands, such as marshes and swamps, which present biological activity that transforms pollutants into essential nutrients or harmless by-products in high rates (Kadlec and Wallace, 2008; Stefanakis and Tsihrintzis, 2009). Removal mechanisms in CW include physical, chemical and biological processes (Vymazal, 2010).

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In addition, nutrient removal may occur as a consequence of their consumption by the vegetation present in these systems (Kadlec, 2003). CW systems have different variants in terms of hydraulic flow (Crites *et al*., 2006; Kadlec and Wallace, 2008; Dotro *et a*l., 2017): i) free water surface constructed wetlands (FWS-CW), which present the water level above the support medium, commonly applied in polishing stages; ii) horizontal subsurface flow constructed wetlands (HSSF-CW), which present the water level below the support medium (alternation between aerobic and anaerobic activities depending on the hydraulic loading rate), commonly applied in secondary treatment stages; and iii) vertical flow constructed wetlands (VF-CW), which are batch systems and therefore have predominance of aerobic microbial activity.

Although CW systems are not widely applied for the treatment of dairy effluents in developing countries such as Brazil, they compose a low-cost treatment technique with relatively easy operation and maintenance. Therefore, CW systems are an attractive and sustainable alternative for the treatment of wastewater from dairy and other industries aiming at complying with legal and environmental frameworks (Teixeira, 2011). Studies assessing HSSF-CW treating dairy effluents report varying removal efficiencies of different parameters (Mantovi *et al*., 2003, Abrahão *et al.,* 2012, Mendonça *et al*., 2012 and Vymazal, Mendonça et al., 2015): between 30 and 99% for TSS; from 14 to 73% for nitrogen; from 18 to 60% for phosphorus; and between 79% and 96% for organic matter.

There is a range of studies reported in the literature about the application of HSSF-CW for the removal of organic matter and solids (Tanner, Clayton and Upsdell, 1995, Dipu, Kumar and Thanga, 2011, Forbes *et al*., 2011, Sultana *et al*.,2016, Tunçsiper, Drizo and Twohig, 2015 and Schierano, Panigatti and Maine, 2018), nutrients (Dipu, Kumar and Thanga, 2011, Forbes *et al*., 2011, Pelissari *et al.*, 2014; Schierano, Maine and Panigatti, 2017 and Schierano, Panigatti and Maine, 2018), pathogens and indicator organisms (Tanner, Clayton and Upsdell, 1995, Mantovi *et al*., 2003 and Forbes *et al*., 2011) and microcontaminants (Mantovi *et al*., 2003) from dairy effluents. However, it is important to highlight that, to our best knowledge, there is a lack of design criteria for HSSF-CW systems treating dairy sewage or similar effluents.

Within this context, this study aims to characterize, both qualitatively and quantitatively, the effluent from a small dairy industry located in Juiz de Fora city, Zona da Mata region of Minas Gerais state, as well as to design constructed wetlands to treat the referred wastewater. This work also aimed at comparing the designed CW system with two treatment systems commonly used in the dairy sector, namely activated sludge and stabilisation ponds.

Material and methods

The dairy industry studied in this research is located in the city of Juiz de Fora, Zona da Mata region of Minas Gerais state. According to the COPAM Resolution 217/2017 (Minas Gerais, 2017),

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it is classified as a small dairy industry, with a capacity to process 8,000 litres of milk per day. The factory has fifteen employees, considering manufacturing and administrative sectors.

Quantitative characterization

Initially, the entire production process of the dairy industry was mapped for different products (mozzarella, fresh Minas cheese, standard Minas cheese, soft cheese and caramel), from the reception of the milk to the shipment of final products. During one month the water consumption was verified in each stage of the production process. For this, recipients of different sizes (0.2, 0.5 and 10 L, according to the place of water outlet and flow) and chronometers were used to determine the time of operation and the flow of different equipment (pasteurizer, hoses, and industrial pots). The same procedure was used to quantify the volume of wastewater produced in each step of the production line, considering the volume of water used to clean products and equipment. Whey, a by-product of cheese production, was also accounted for as wastewater as it was discharged to the sewer system. From the data collected, namely volume of processed milk, water consumption and wastewater generation, two coefficients were obtained: i) water consumption per litre of processed milk ($L.L^{-1}$), obtained from the ratio between the entire volume of water consumed and the volume of processed milk; and ii) generation of effluent per litre of processed milk ($L.L^{-1}$), obtained from the ratio between the entire volume of wastewater produced and the volume of processed milk.

Qualitative characterization

The sampling programme had five different sampling dates between January and June 2018. The samples were collected in the equalization tank of the treatment plant, after a screening process. It is important to mention that, after the screening step, both industrial and sanitary (toilets and locker rooms) effluents are mixed. In order to guarantee the representativeness of the collected samples, at all sampling dates the equalization tank was emptied prior to the production shift. During the entire production shift, screened dairy effluent and sanitary wastewater were stored in the equalization tank. After the shift, a representative sample was then collected and immediately transferred, at approximately 4°C, to the Laboratory of Environmental Quality (LAQUA) of the Department of Sanitary and Environmental Engineering (ESA) of the Federal University of Juiz de Fora (UFJF) for characterization. The following parameters were analysed: biochemical oxygen demand (BOD); chemical oxygen demand (COD); total Kjeldahl nitrogen (TKN); organic nitrogen (N_{org}); ammoniacal nitrogen ($N\text{-}NH_4^+$); total phosphorus (P_{Total}); settleable solids (SSet); total suspended solids (TSS); and pH. All analyses were performed according to the Standard Methods for the Examination of Water and Wastewater (APHA, 2012).

Design of treatment systems

The results obtained from the characterization of the dairy effluent were used for the design of three different treatment systems: (i) extended aeration batch activated sludge (BAS) system; (ii) waste stabilisation pond (WSP) system, composed of an anaerobic pond followed by a facultative

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pond; and (iii) horizontal subsurface flow constructed wetland (HSSF-CW) system. The option to design a BAS system was based on the flow variations associated with the production process.

Preliminary (equalization) and primary (flotation) treatment steps were considered for all treatment systems. The use of these steps prior to secondary treatment units are required to remove fat, and oils and greases (O&G), present in dairy effluents in high concentrations, which can compromise the efficiencies of subsequent treatment stages (Castillo *et al.,* 2017). In addition, the primary (flotation) treatment step contributes to the removal of TSS and organic matter (Couto *et al.,* 2004; Pereira *et al.,* 2018), reducing area requirements of subsequent steps.

Previous studies have assessed preliminary and primary treatment steps treating dairy effluents, and removal efficiencies vary considerably: 50-99% for O&G; 76-93% for TSS; and 43-70% for BOD (Azzolini and Fabro, 2013, Amorim, 2014 and Pereira *et al.,* 2018). In addition, it is important to highlight that the composition of dairy wastewater depends on the production process and, consequently, will also vary considerably. Having said that, in this work, it was assumed the following removal rates for the preliminary and primary treatment steps combined: 20% for BOD; 60% for SST; and 98% for O&G. Removal of TKN in these steps was not considered. Design criteria for municipal wastewater were used to design all three systems (BAS, WSP and HSSF-CW) as a consequence of the lack of information for dairy effluents. For the design of waste stabilisation ponds (WSP), a pH value equal to 8.0 was considered to the facultative pond based on case studies reported in the literature (Magno and Oliveira, 2008, Silva and Eyng, 2013, Azzolini and Fabro, 2013).

Table 1. Equations and design criteria considered for the design of the extended aeration batch activated sludge (BAS) system for the treatment of the dairy effluent.

Equations	Design parameters
$A_s = \frac{V_{total}}{H}$	A_s = surface area [m²]; V_{total} = total volume [m³]; H = adopted height [H= 4 m];
$V_r = \frac{Y \times \theta_c \times Q \times (S_o - S)}{X_v(1 + f_b \times K_d \times \theta_c)}$	V_r = volume for reaction [m³]; Y = yield coefficient [Y = 0.6 gMLVSS/gBODrem]; θ_c = sludge age adopted [θ_c =25 d];
$f_b = \frac{0.8}{1 + 0.2 \times K_d \times \theta_c}$	S_o = total influent BOD [mg.L^{-1}]; S = total effluent soluble BOD [S = 60 mg.L^{-1}]; Q = inflow [m³.d^{-1}];
$V_f = \frac{Q}{m}$	X_v = mixed liquor volatile suspended solids concentration[X_v = 3000 mg.L^{-1}]; f_b = biodegradable fraction of mixed liquor volatile suspended solids [dimensionless]; K_d = decay coefficient [K_d = 0.08 d^{-1}];
$V_{trans} = f_{hf} \times V_f$	V_f = fill volume [m³]; m = number of cycles adopted per day [m = 1];
$V_{total} = V_r + V_f + V_{trans}$	V_{trans} = transition volume [m³]; f_{hf} = fraction of the total fill height (fix) [f_{hf} = 0.1]

Source: von SPERLING (2007).

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Vol. 14, No.1, 176-193
6 de abril de 2021

For HSSF-CW, Crites *et al.* (2006) suggest, for municipal wastewater, a TKN removal coefficient at 20°C ($K_{TKN.20}$) equal to 0.12 d^{-1}. However, such values are associated with systems operating in temperate climates. After monitoring HSSF-CW units treating municipal wastewater in the Zona da Mata region, Dias *et al*. (2011) obtained a $K_{TKN.20}$ coefficient of 0.29 d^{-1}, which was considered in this work due to location and climate similarities. As the COPAM/CERH Resolution 01/2008 (Minas Gerais, 2008) establishes a minimum BOD removal efficiency of 75% for industrial effluents, it was considered in this study a removal efficiency of 80% for BOD for the design of all (BAS, WSP and HSSF-CW) systems. Equations and design criteria considered for the design of BAS, WSP and HSSF-CW systems are summarised in Tables 1, 2 and 3, respectively.

Table 2. Equations and design criteria considered for the design of the waste stabilisation pond (WSP) system (anaerobic pond + facultative pond) for the treatment of the dairy effluent.

Equations	Design parameters
Anaerobic Pond	
Equations	Design parameters
$V = \frac{L}{L_v}$ *and* $L = \frac{Q \times C_o}{1000}$	V = anaerobic pond volume [m³]; L = anaerobic pond influent load [kg.d^{-1}];
$Lv = 0.01 \times T_a + 0.10$	L_v = volumetric organic load for Ta> 25°C [kg m^{-3}.d^{-1}]; Q = inflow [m³.d^{-1}];
$T_a = 12.7 + 0.54 \times T_{ar}$	C_o = total influent BOD [mg.L^{-1}]; T_a = water temperature [°C]; T_{ar} = air temperature in coldest month [°C];
$A = \frac{V}{H}$ *and* $t = \frac{V}{Q}$	A = surface area of anaerobic pond [m²]; H = adopted depth for anaerobic pond [H_1 = 3.5 m];
$E = 2 \times T_{ar} + 20$	t = total hydraulic detention time for anaerobic pond [d]; E = removal efficiency [%];
$C = \frac{1 - E}{100} \times C_o$	C = total effluent BOD of anaerobic pond/total influent BOD for facultative pond [mg.L^{-1}].
Facultative Pond	
Equations	Design parameters
$L = \frac{Q \times C_o}{1000}$ *and* $A = \frac{L}{L_s}$	L = facultative pond influent load [kg.d^{-1}]; Q = inflow [m^3.d^{-1}]; S_o = total influent BOD[mg.L^{-1}];
$Ls = 350(1.107 - 0.002 \times Tar)^{(Tar-25)}$	A = surface area of facultative pond [m²]; L_s = surface organic loading rate [kg ha^{-1}.d^{-1}];
$V = A \times H$ *and* $t = \frac{V}{Q}$	T_{ar} = water temperature in coldest month [°C]; V = facultative pond volume [m³];
$C = C_o \frac{4ae^{\frac{1}{2d}}}{(1+a)^2 . e^{\frac{a}{2d}} - (1-a)^2 . e^{-\frac{a}{2d}}}$	H = adopted depth for facultative pond [H = 1.8 m]; t = total detention time for facultative pond [d]; C = final effluent BOD [mg.L^{-1}];
$a = \sqrt{1 + 4.K.t.d}$ e $d = \frac{1}{L/B}$	a = auxiliary coefficient for the calculation of the dispersed flow [dimensionless]; K= BOD removal coefficient [d^{-1}]; D = dispersion number [dimensionless];
$K = 0.091 + 2.05 \times 10^{-4} \times L_s$	L/B = length/breadth ratio [L/B =10 m]; C_f = total effluent TKN [mg.L^{-1}];
$K_1 = 0.0064 \times 1.039^{(T-20)}$	C_i = total influent TKN [mg.L^{-1}]; K_1= TKN removal coefficient [d^{-1}];
$C_f = C_i \times e^{\{-K1[t+60.6(pH-6.6)\}}$	pH= pond pH [pH=7].

Source: von SPERLING (2017).

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Vol. 14, No.1, 176-193
6 de abril de 2021

Table 3. Equations and design criteria considered for the design of the horizontal subsurface flow constructed wetland (HSSF-CW) system for the treatment of the dairy effluent.

Equations	Design parameters
$A_s = \dfrac{Q \times \ln(S_o/S)}{K_T \times y \times n}$	A_s = surface area [m²];
	Q = inflow [m³.d⁻¹];
	S_o = total influent BOD or NH_4 [mg.L⁻¹];
$K_T = K_{20} \times \theta^{(T-20)}$	S = total effluent BOD or NH_4 [mg.L⁻¹];
	K_T = BOD removal coefficient at T temperature [d⁻¹];
	y = bed depth [m] [y= 0.7 m];
$C_f = C_i.[0.1058 + 0.0011(TAS)]$	n = porosity [n= 0.4];
	K_{20} = removal coefficient at 20°C [1.10 d⁻¹];
$A_s = \dfrac{Q \times \ln(C_o/C)}{K_{NH4.T} \times y \times n}$	θ = temperature coefficient [θ = 1.06];
	C_f = total influent TSS [mg.L⁻¹];
	C_i = total effluent TSS [mg.L⁻¹];
$K_{NH4.T} = K_{NH4.20}\,(1.048)^{(T-20)}$	$K_{NH4.T}$ = nitrification coefficient at T temperature[d⁻¹];
	$K_{NH4.20}$ = nitrification coefficient at 20ºC [d⁻¹];
$K_{NH20} = 0.01854 + 0.3922\,(rz)$	rz = percentage of bed occupancy by root zone [dimensionless].

Source: CRITES et al. (2006).

Results and discussion

Quali-quantitative characterization of wastewater

The calculated coefficients of water consumption and effluent generation per litre of processed milk for different dairy products are presented in Table 4.

Table 4. Calculated values of water consumption and effluent generation per litre of processed milk and wastewater generation per litre of water consumed for different dairy products.

Product	Water consumption per litre of processed milk (L.L⁻¹)	Wastewater generation per litre of processed milk (L.L⁻¹)	Wastewater generation per litre of water consumed (L.L⁻¹)
Standard Minas Cheese	2.8	3.5	1.2
Fresh Minas Cheese	3.3	3.6	1.1
Caramel	2.6	2.2	0.8
Mozzarella	3.6	4.5	1.2
Soft Cheese	3.0	3.9	1.3
Milky Mass	2.4	3.6	1.5

Overall, effluent generation coefficients (L.L⁻¹) were higher than the water consumption coefficients (L.L⁻¹) for all dairy products but caramel. This is because whey (by-product) joins the generated effluent in the production line of the assessed dairy industry; caramel is the only product that does not produce whey. Whey presents high levels of organic matter and protein

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Vol. 14, No.1, 176-193
6 de abril de 2021

and has an excellent nutritional value. Its inadequate disposal contributes to environmental pollution and is considered to be a waste of valuable resources (protein and nutrients) (Carvalho *et al.,* 2013). Therefore, the identification of alternatives for the beneficial use of whey is essential as a consequence of its nutritional value and polluting potential.

For the estimate of wastewater generation in the dairy industry assessed in this study, it was considered both industrial and sanitary effluents. Regarding the industrial contributions taking into account all dairy products, it was estimated a production of 1.97 $m^3.d^{-1}$ of industrial effluent. For the sanitary contributions, an average *per capita* production of 60 L (Metcalf and Eddy, 2014) was adopted for each of the 15 employees, totalizing a production of 0.90 $m^3.d^{-1}$ of sanitary effluent. Thus, the calculated volume of raw (industrial + sanitary) wastewater produced was 2.81 $m^3.d^{-1}$.

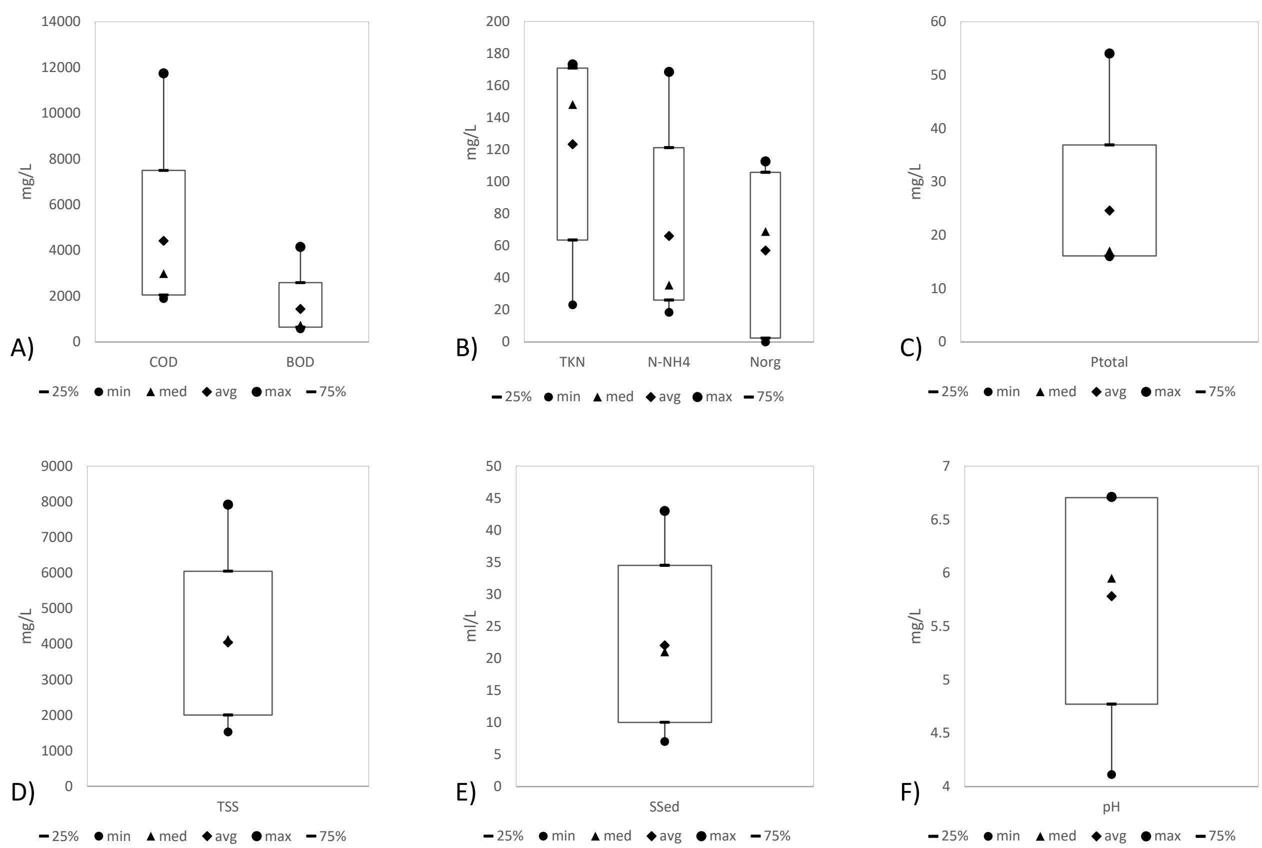

Figure 1. Boxplot graphs of the parameters evaluated for qualitative characterization of the effluent in terms of: COD and BOD (A); TKN, N-NH_4^+ and N_{org} (B); P_{total} (C); TSS (D); SSet (E); and pH (F).
25% = first quartile; min = minimum value; med = median value; avg = average; max = maximum value; 75% = third quartile; BOD = biochemical oxygen demand; COD = chemical oxygen demand; TKN = total Kjeldahl nitrogen; N-NH_{4+} = ammoniacal nitrogen; N_{org} = organic nitrogen; P_{total} = total phosphorus; TSS = total suspended solids; SSet = settleable solids.

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Figure 1 shows boxplot graphs with the concentrations of the physic-chemical parameters evaluated. these graphs allow the visualization of trends regarding the distribution, dispersion, and symmetry of the entire dataset. The symmetry of a database is interpreted according to the median and mean results: if the median is close to the centre of the box, the distribution is symmetric (Minaard *et al*., 2005).

The concentrations of the monitored parameters varied considerably (Figure 1): COD = 1,899-11,735 mg $O_2.L^{-1}$; BOD = 574-4,155 mg $O_2.L^{-1}$; TKN = 23.2-168.4 mg NH_4^+-N.L^{-1}; P_{total} = 16-54 mg PO_4^{3-}-L^{-1}; TSS = 1,531-7,912 mg.L^{-1}; and pH = 4.1-6.7. These results corroborate findings reported in the literature (IPPC, 2006, Tawfik *et al*., 2008, Onet, 2010, Vymazal, 2014, Slavov, 2017), which mention wide ranges of concentrations of different parameters in the effluent of dairy industries of different sizes. The variability associated with effluents from dairy industries at different scales, in terms of both quantity and quality, shows that it is not feasible to generalize characterization results of several cases to all dairy industries. It is important, therefore, that every dairy industry performs the characterization of its own effluents in order to select the most suitable treatment systems.

Design of treatment systems

The parameters considered for the design of the treatment systems were BOD, TSS and TKN. From Figure 1, it can be noticed that the datasets of these parameters do not follow a symmetric distribution, which leads to using median values in the designing calculations rather than averages. As it was considered a set of preliminary and primary treatment steps with BOD and TSS removal efficiencies of 20 and 60%, respectively, and no removal of TKN, the affluent to the secondary treatment systems has the following characteristics: 588 mg.L^{-1} of BOD; 660 mg.L^{-1} of TSS; and 148.2 mg.L^{-1} of TKN. Only these parameters were considered as this work focused on the removal of organic matter and solids, with additional removal of TKN. The average flow rate was considered to be 2.81 $m^3.d^{-1}$, as previously explained. From this information and considering the desired removal of BOD of 80% (see section Material and Methods), the areas and volumes of the designed systems (BAS, WSP and CW) were calculated and presented in Table 5.

Table 5. Area requirements and volumes for each treatment system considering a BOD removal of 80%.

Treatment system	Area (m^2)	Volume (m^3)
Extended aeration batch activated sludge (BAS)	2.1	6.3
Waste stabilisation ponds (WSP)	46.5	86.2
Horizontal subsurface flow constructed wetlands (HSSF-CW)	15.0	10.5

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Vol. 14, No.1, 176-193
6 de abril de 2021

Considering a theoretical BOD removal of 80%, the BAS system showed the lowest area requirement (2.1 m²), followed by HSSF-CW (15.0 m²) and WSP (46.5 m²) (Table 5). WSP presented an area requirement about 22 times greater than BAS, and approximately three times larger than HSSF-CW (Table 5).

Considering the calculated areas, the removal efficiencies and the final concentrations of TSS and TKN were estimated for the systems herein considered, as presented in Table 6.

Table 6. Estimated or expected removal efficiencies of TSS and TKN for each treatment system.

Treatment System	TSS Removal (%)	TKN Removal (%)
Extended aeration batch activated sludge (BAS)	87-93 [a]	>80 [a]
Waste stabilisation ponds (WSP)	70-80 [a]	53 [b]
Horizontal subsurface flow constructed wetlands (HSSF-CW)	87 [c]	35 [c]

[a] *expected removal efficiencies according to the literature (von Sperling, 2014; 2017);*
[b] *estimated removal efficiencies from mathematical models (Crites e Tchobanoglous, 2000);*
[c] *estimated removal efficiencies from mathematical models (Crites et al., 2006).*

According to the COPAM/CERH Resolution 01/2008 (Minas Gerais, 2008), the maximum concentration of TSS in treated effluents must be below 150 $mg.L^{-1}$ for WSP systems and 100 $mg.L^{-1}$ for other systems. In order to comply with the current legislation, WSP should have minimum removal efficiency of 77.3%, whereas rates in HSSF-CW and BAS systems should be greater than 84.8%. Thus, considering the data obtained (either expected removal efficiencies from the literature or estimates using mathematical models), it is verified that all systems considered can potentially produce effluents that meet the legal requirements (Table 6). However, it should be noted that the only system that presents an available model to estimate the removal of TSS is CW, with an equation based on the surface hydraulic loading rate.

Regarding the removal of TKN, extended aeration BAS systems area believed to be the most efficient, with expected efficiencies above 80% (von Sperling, 2014). CW and WSP systems presented considerably lower removal estimates (models based on first-order kinetics and plug-flow): 35% for HSSF-CW; and 53% for WSP. It should be stressed that, for WSP systems, no removal was considered in the anaerobic unit, but only in the facultative pond considering the pH of the pond equal to 8.0. In cases of higher pH, higher TKN removal efficiencies are expected as a consequence of free ammonia volatilization. It should also be highlighted that, in all cases, design and removal efficiencies were calculated considering criteria proposed for municipal wastewater as a consequence of the lack of design criteria for dairy wastewater or similar effluents. This may result, therefore, in under or oversized (more likely) systems.

Revista AIDIS de Ingeniería y Ciencias Ambientales:
Investigación, desarrollo y práctica. ISSN 0718-378X
Doi: http://dx.doi.org/10.22201/iingen.0718378xe.2021.14.1.70251
Vol. 14, No.1, 176-193
6 de abril de 2021

In addition to area requirements and removal efficiencies, other aspects should be considered when adopting the most suitable treatment system for a given effluent. These aspects include costs and complexity of implementation, operation and maintenance, as well as sludge generation and management. Among the treatment options considered, the BAS system presented the lowest area requirement (2.1 m²; Table 5) for a BOD removal of approximately 80%. This treatment technique presents high removal of solids and the removal of nitrogen and phosphorus may happen (von Sperling, 2007). BAS treatment systems with high sludge age were considered by Afonso et al. (2000) as feasible for the treatment of dairy effluents, with a sewage sludge generation considerably lower than conventional activated sludge systems. However, the amount of sludge produced in such systems is still considerably high compared with WSP and HSSF-CW systems. Of the three treatment systems studied, BAS is the system that presents higher costs associated with implementation, operation, maintenance and electricity, and it also demands skilled labour for its operation as it requires constant care.

The WSP system, composed of an anaerobic pond followed by a facultative pond, presented the highest area requirement (46.5 m²; Table 5) for the desired BOD removal efficiency (~80%). In addition, this system is the one that least removes TSS and TKN. Attention must also be given to the bad odours that can be generated in the anaerobic stage of the process (von Sperling, 2017). On the other hand, of the three systems proposed in the study, WSP are systems that generally present the lowest costs regarding installation, operation and maintenance as a consequence of the absence of mechanical equipment. In addition, WSP are easy to operate and compose a robust treatment system, being quite resistant to variations of organic loads (von Sperling, 2017). Finally, another positive aspect associated with WSP systems is related to the low amount of sludge generated.

In this study, the HSSF-CW system presented an intermediate area requirement (15 m²; Table 5), approximately 7 times larger than the area required for the BAS system and 3 times smaller than the area demanded for the WSP system. The estimated removal of TKN in the CW system was lower than the expected removal in the BAS, whereas the removal of TSS in CW and BAS systems were similar (Table 6). In general, CW systems present low costs associated with implementation, operation, maintenance. However, these costs in CW units are usually slightly higher than those systems. This is because CW units have support media (e.g., gravel or sand) and the need for harvesting the vegetation according to its life cycle aiming at maintaining nutrients removal efficiency at high levels (Crites *et al.,* 2006).

Although the estimated removal efficiencies of TSS and TKN in the CW system are smaller than in the BAS system (Table 6), the literature reports CW systems with real efficiencies greater than those observed in this study (Mantovi *et al*., 2003; Abrahão, 2006; Mendonça *et al*., 2012; Pelissari *et al.,* 2014). Mantovi *et al*. (2003) reported 50% removal efficiencies for TKN and 90% for TSS in CW systems with a 75m² treating dairy wastewater with a flow rate of 6.5 $m^3.d^{-1}$ and hydraulic

ISSN 0718-378X
Doi: http://dx.doi.org/10.22201/iingen.0718378xe.2021.14.1.70251
Vol. 14, No.1, 176-193
6 de abril de 2021

retention time (HRT) of 10 days. Also treating dairy effluents, Abrahão (2006) reported removal efficiencies of 64-81% for TSS and 50-70% for TKN (variations associated to different vegetation used) in pilot-scale units with 0.3 m^2, flow of 0.06 $m^3.d^{-1}$ and HRT of 4.8 days. Schierano, Panigatti and Maine (2018) reported 80% removal of TSS and over 95% removal of TKN in a microcosm-scale HSSF-WC with HRT of 7 days and HLR equal to 1.0 $m^3.m^{-2}.d^{-1}$.

Mendonça *et al.* (2012) conducted a study to verify the removal of TKN and phosphorus from dairy effluent in a batch CW pilot system with approximately 0.7 m^2, 2-day cycle and an effluent load of 7.5 L per cycle. The authors concluded that the support medium and planted vegetation are parameters that have a significant influence on the removal efficiency of nutrients in CW. In addition, it was observed that, over time, efficiencies varied according to the life cycle of the vegetation as absorption of nitrogen compounds is higher during the vegetation growth (Mendonça *et al*., 2012).

Pelissari *et al.* (2014) evaluated the removal of nitrogen in a full-scale HSSF-CW treating dairy effluents, with surface area of 26.5 m^2 and a daily flow of 995 litres during four hours per day (average HLR of 0.038 $m^3.m^{-2}.d^{-1}$). They found and average removal of ammonium nitrogen equal to 58% and concluded that, considering that nitrification was not apparent and ammonia volatilization could be disregarded, the removal was linked to uptake by macrophytes and by bacterial biomass and adsorption to the support medium. These findings (Mendonça *et al.*, 2012; Pelissari *et al.*, 2014) show the need for frequent harvesting of vegetation in CW systems in order to maintain nutrient removal efficiencies at a certain level (Vymazal, 2007). Although the harvesting of vegetation may lead to higher maintenance costs of CW systems, the vegetation itself can bring economic benefits as the biomass can be used for animal feeding and energy production (Matos *et al*., 2008; Fia *et al*., 2017; Silva *et al.,* 2019).

Although effluents from WSP and CW systems may have considerable high concentrations of TKN, their concentrations of coliforms are often lower than in effluents from BAS systems (von Sperling, 2014). Therefore, wastewaters treated in WSP and CW systems may be reused, for instance in irrigation activities. The main advantage of irrigation with wastewater is the fact that part of the nutrients present in the effluent are readily available, whereas some forms of nitrogen and phosphorus, mainly organic, need to be decomposed before becoming available to plants, which supports the development of plants over time (Bastos, 2003; Marques *et al*., 2003). According to Matos and Matos (2017), wastewater should be applied in crops of rapid growth and rapid nutrient absorption. However, attention should be given to phytotoxicity aspects of specific ions (e.g., sodium and chloride) which may interfere negatively soil quality and vegetation growth (Marques et al., 2003). Thus, before performing irrigation with wastewater, a detailed study of the soil (e.g., permeability and nutrient availability) and vegetation (e.g., water and nutritional demands) should be carried out in order to promote vegetation growth and to avoid contamination of the environment.

Revista AIDIS de Ingeniería y Ciencias Ambientales:
Investigación, desarrollo y práctica. ISSN 0718-378X
Doi: http://dx.doi.org/10.22201/iingen.0718378xe.2021.14.1.70251
Vol. 14, No.1, 176-193
6 de abril de 2021

Horizontal subsurface flow constructed wetlands (HSSF-CW)

Assuming a HSSF-CW system for the treatment of the dairy effluent characterized in this study, different units were designed in terms of area and HRT considering an average flow of 2.81 $m^3.d^{-1}$, a BOD removal of 80%, and TSS and TKN concentrations in the final equal to 100 $mg.L^{-1}$ and 20 $mg.L^{-1}$, as recommended in the COPAM/CERH Resolution 01/2008 (Minas Gerais, 2008),. Results are presented in Table 7.

Table 7. Area (m²) and hydraulic retention time (d) required to reach the standards defined by COPAM/CERH Resolution 01/2008 (Minas Gerais, 2008).

Parameters	Discharge Standards DN COPAM/CERH 01/2008	Required area (m^2)	HRT (d)
BOD	80% removal	15	1.5
TSS	100 $mg.L^{-1}$	7	0.7
TKN	20 $mg.L^{-1}$	70	7.0

Although BOD is the parameter most commonly considered for the design of treatment units, from the results presented in Table 7 it can be noted that the limiting factor for the design of CW systems to treat the dairy effluent of this study was the TKN. This fact is corroborated by a study conducted by Sezerino *et al.* (2015), which compiled experiences related to the application of HSSF-CW for domestic wastewater treatment in Brazil. Three reasons may lead to TKN being the limiting parameter when designing systems rather than BOD: firstly, it is often considered that organic nitrogen will be converted to ammoniacal nitrogen and, therefore, TKN is used as the design parameter for the removal of nitrogen; secondly, the fact that the studies performed in Brazil are mostly for domestic wastewater, which presents a typical concentration of TKN of 45 $mg.L^{-1}$ (von Sperling, 2014), much lower than the average concentration used for the design of CW units in this study (148.2 $mgTKN.L^{-1}$); and, thirdly, the use of the $K_{NH4.20}$ coefficients originally obtained for domestic wastewater being applied to dairy effluent.

According to Crites *et al*. (2006), the expected HRT for HSSF-CW ranges from 3 to 14 days, and HRT for the removal of BOD and TSS are lower than the ones expected for the removal of TKN. The same trend was observed in this study (Table 7). It is important to highlight, however, that the area required for the removal of TKN was calculated considering K_T values for tropical climate (0.29 d^{-1}; Dias et al., 2011) and not K_T values suggested for temperate regions (0.12 d^{-1}; Crites *et al.*, 2006). In the latter case, the area requirement would be 162 m^2 and HRT would be 16 days, higher than that indicated in Crites et al. (2006). After assessing several HSSF-CW systems in Brazil up to 2010, Sezerino *et al.* (2015) observed HRT equal or lower than 12 days in all cases, and no minimum established value of HRT as it is not a design criterium in the models considered in this work.

Revista AIDIS de Ingeniería y Ciencias Ambientales:
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Vol. 14, No.1, 176-193
6 de abril de 2021

Considering the varying characteristics of the effluent in this study and variations reported in the literature (Onet, 2010; Vymazal, 2014; Wu *et al.,* 2015; Slavov, 2017), CW units were also designed using the average flow (2.81 $m^3.d^{-1}$) and the minimum, mean and maximum concentrations of TKN (C_{min} = 23 $mg.L^{-1}$, C_{mean} = 148 $mg.L^{-1}$, C_{max} = 173 $mg.L^{-1}$, respectively), as this was shown to be the limiting design criterium of HSSF-CW. Area (m^2), volume (m^3), hydraulic retention time (d) and hydraulic surface loading rate ($m^3.m^{-2}.d^{-1}$) were obtained for each case, as shown in Table 8.

Table 8. Area (m^2), volume (m^3), hydraulic retention time (d) and hydraulic surface loading rate ($m^3.m^{-2}.d^{-1}$) of HSSF-CW units obtained considering mean flow and minimum, mean and maximum concentrations of TKN.

TKN concentration	Area (m^2)	Volume (m^3)	HRT (d)	HLR ($m^3.m^{-2}.d^{-1}$)
C_{min} (23 $mg.L^{-1}$)	5	3.5	0.5	0.562
C_{mean} (148 $mg.L^{-1}$)	70	49.0	7.0	0.040
C_{max} (173$mg.L^{-1}$)	74	51.8	7.4	0.038

The HRT calculated for C_{mean} and C_{max} are within the range indicated in the literature (3-14 days; Crites *et al*., 2006). For C_{min}, the HRT is below this range, as the lowest concentration of TKN observed in this study (23 $mg.L^{-1}$) is very close to the maximum concentration allowed in treated effluents (20 $mg.L^{-1}$) according to the COPAM/CERH Resolution 01/2008 (Minas Gerais, 2008).

HRT also varies according to the flow rate. In this way, it was calculated different HRT for combinations between minimum, mean and maximum flow rates (Q_{min}, Q_{mean}, Q_{max}) obtained in the characterization part of the study and the minimum, mean and maximum CW volumes (V_{min}, V_{mean}, V_{max}) calculated and presented in Table 5. Results are shown in Table 9.

Table 9. Hydraulic retention time (days) calculated for minimum, mean and maximum flow rates (Q_{min}, Q_{mean} and Q_{max}) and minimum, mean and maximum CW volumes (V_{min}, V_{mean}, V_{max}).

Volume	HRT (d)		
	Q_{min} (2,23 m^3d^{-1})	Q_{mean} (2,81 m^3d^{-1})	Q_{max} (3,23 m^3d^{-1})
V_{min} (3.5 m^3)	0.4	0.5	0.6
V_{mean} (49.0 m^3)	6.1	7.0	8.8
V_{max} (51.8 m^3)	6.4	7.0	9.3

Based on the data presented in Table 9, it is noted that the calculated HRT values considering Q_{min}, Q_{mean}, Q_{max} and V_{min} (associated with C_{min}; Table 8) are lower than the HRT range recommended in the literature (3-14 days; Crites *et al*., 2006). As expected, to design CW systems, it is important to consider flow variations and C_{mean} and/or C_{max}, as they are associated with worst-case scenarios.

ISSN 0718-378X
Doi: http://dx.doi.org/10.22201/iingen.0718378xe.2021.14.1.70251
Vol. 14, No.1, 176-193
6 de abril de 2021

Conclusion

Even adopting conservative design criteria and removal values for flotation, the CW was considered the most cost-effective system in this case study as it presented intermediate area requirements and costs in relation to the other two systems. In addition, CW systems have the advantage of producing a vegetal biomass which could be used to feed animals of produce energy, as well as final effluent which could be potentially reused, bringing economic benefits. It is important to highlight, however, that, although the removal efficiencies for the flotation step adopted in this study are reported in the literature, it is recommended that flotation tests are performed to estimate the removal efficiencies of these parameters for future studies and treatment plant design.

In terms of optimization study of the CW treatment system, because the wide variation of the TKN concentrations in the effluent, it is concluded that the design of these systems should consider the average or maximum TKN concentration, as the design using minimum TKN concentration did not meet the sizing recommendations. Regardless of the design and type of industrial effluent, all feasible alternatives should be explored and studied during the decision-making process.

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