CENÁRIOS INTEGRADOS PARA TRATAMENTO DE ÁGUAS RESIDUAIS URBANAS USANDO WETLANDS CONSTRUÍDOS: UMA ANÁLISE DE AVALIAÇÃO DO CICLO DE VIDA

Gustavo Stolzenberg Colares - gustavoscolares@gmail.com
Universidade de Santa Cruz do Sul - UNISC, Programa de pós-graduação em Tecnologia Ambiental – PPGTA
Av. Independência, 2293 - Universitário, 96815-900, Santa Cruz do Sul – RS.

Carine Baggiotto – cbaggiotto@unisc.br
Universidade de Santa Cruz do Sul - UNISC, Programa de pós-graduação em Tecnologia Ambiental - PPGTA
Av. Independência, 2293 - Universitário, 96815-900, Santa Cruz do Sul – RS.

Andréia Moura Bernardes - amb@ufrgs.br
Universidade Federal do Rio Grande do Sul – UFRG, Departamento de Engenharia de Materiais (DEMAT)
Av. Bento Gonçalves, 9500, 91501-970 - Porto Alegre - RS

Adriane de Assis Lawisch Rodriguez - adriane@unisc.br
Universidade de Santa Cruz do Sul - UNISC, Programa de pós-graduação em Tecnologia Ambiental - PPGTA
Av. Independência, 2293 - Universitário, 96815-900, Santa Cruz do Sul – RS.

Ênio Leandro Machado - enio@unisc.br
Universidade de Santa Cruz do Sul - UNISC, Programa de pós-graduação em Tecnologia Ambiental - PPGTA
Av. Independência, 2293 - Universitário, 96815-900, Santa Cruz do Sul – RS.

Resumo:
Neste trabalho, foram investigados cenários de unidades de saneamento em um sistema combinado de tratamento de efluentes, composto sequencialmente por reatores anaeróbios (RAs) integrados seguidos por wetlands construídos híbridos (CWs) e unidade de ozonização (O3). O efluente considerado foi proveniente de um campus universitário no sul do Brasil. Com base nos dados de construção e monitoramento do sistema, foram realizadas avaliações do ciclo de vida. Foram realizados estudos sobre os aspectos econômicos e de sustentabilidade compreendendo os custos de construção, aquisição de equipamentos e operação. O tratamento por ozonização principalmente para a garantia de desinfecção do efluente (13,3 mg O3 L-1 - 5 minutos) possui, na escala de pontuação única, energia com percentuais de 17,5% para ozonização, enquanto para o tratamento por ozonização visando a remoção da cor do efluente (160 mg O3 L-1 - 60 minutos) a energia já ocupou 85,3% do consumo. Em relação à construção do sistema, os reatores anaeróbios e os wetlands construídos apresentaram os maiores impactos devido ao polietileno de alta densidade e à fibra de vidro, respectivamente. Sobre a operação do sistema, a eletricidade foi a causa da maioria dos impactos, com as categorias de aquecimento global, energia não renovável, efeitos respiratórios, não cancerígenos e eutrofização com maior significância. A maioria dos gastos foi relacionada ao tratamento de lodo e coleta de biomassa. Estudos futuros devem investigar a expansão do sistema de tratamento e a aplicação de materiais alternativos para reduzir os impactos e custos relacionados à construção.

INTEGRATED SCENARIOS FOR URBAN WASTEWATER TREATMENT USING CONSTRUCTED WETLANDS: A LIFE CYCLE ASSESMENT ANALYSIS

Abstract:

In this work, sanitation unit scenarios were investigated in a combined wastewater treatment system, composed sequentially of integrating anaerobic reactors (ARs) followed by the hybrid constructed wetlands (CWs) and ozonization (O_3) unit. The wastewater considered was from a university campus in southern Brazil. Based on the system construction and monitoring data, life cycle assessment and economic evaluations were undertaken. Studies on the economic aspects and sustainability were carried out comprising the costs of construction, acquisition of equipment and operation. Treatment using ozonation mainly for the wastewater disinfection guarantee (13.3 mg O_3 L^{-1} - 5 minutes) has, in the single score scale, energy with percentages of 17.5% for ozonation, while for treatment using ozonation aiming for the wastewater color removal (160 mg O_3 L^{-1} - 60 minutes) the energy has already occupied 85.3% of the consumption. Regarding system construction, anaerobic reactors and constructed wetlands showed the greatest impacts due to high density polyethylene and fiberglass, respectively. About the operation of the system, electricity was the cause of most impacts, with the categories of global warming, non-renewable energy, respiratory effects, non-carcinogenic and eutrophication with greater significance. Most of the expenses were related to sludge treatment and biomass harvesting. Future studies should investigate the expansion of the treatment system and the application of alternative materials to reduce construction-related impacts and costs.

Keywords: Clean technologies; Constructed Wetlands; Ozonation; Rural Sanitation; Sustainability.

1. INTRODUCTION

Given the current water scarcity crisis, technologies focused on local wastewater treatment and reuse are becoming increasingly attractive, especially when the primary goal is non-potable water reuse (Jabri et al., 2019). In this context, research is emphasizing the minimization of resource waste, energy consumption, and potable water demand, along with reducing waste generation and potentially recovering nutrients or generating energy from wastewater (Dell'Osbel et al., 2020).

While there are significant differences between centralized and decentralized wastewater treatment plants, the latter offers a greater potential for resource recovery, such as water reclamation (Arias et al., 2020; Albornoz et al., 2019; Albornoz et al., 2020). Constructed wetlands (CWs) have emerged as a promising alternative for decentralized wastewater treatment due to their simple construction, low maintenance requirements, and high treatment efficiency (Flores et al., 2020). Additionally, CW systems are particularly valuable in developing countries where basic sanitation is lacking. They are especially effective when used after primary treatments, such as septic tanks, which are common in isolated areas, thereby eliminating the need to transport wastewater to a central facility (De Souza Celente et al., 2020).

In rural areas, integrating CW systems with anaerobic reactors (ARs) is becoming more common, as it allows for the recovery of materials, energy, and nutrients, reduces environmental pressure, simplifies maintenance and operation, and integrates well with the natural environment (Lutterbeck et al., 2017; Pelissari et al., 2017).

When the focus is on effluent detoxification and disinfection, combining CWs with advanced oxidation processes can be effective (Horn et al., 2014). However, depending on regulatory requirements, the reuse of treated wastewater may need to comply with strict safety standards, necessitating post-treatment technologies like chlorination, ozonation, or ultraviolet (UV) radiation. Ozonation, in particular, not only ensures disinfection but also enhances water color removal, a critical

factor for water reuse (Colares et al., 2019). Researchers have explored various CW configurations, from basic systems to more complex ones, such as forced aeration CWs (Wu et al., 2014), CWs combined with algae for post-treatment (De Souza Celente et al., 2019), CWs paired with ozonation (Tripathi and Tripathi, 2011; Horn et al., 2014), and CWs with UV disinfection (Álvarez et al., 2017).

The evaluation of the possible environmental impacts concerning wastewater treatment technologies should assist decision makers on the best options for treating wastewater or adapting existing systems (Resende et al. 2019). Life Cycle Assessment (LCA) is a tool initially conceived for the quantification of the resources demand/consumption as well as environmental impacts associated with a specific product (Corominas et al., 2013; Giménez et al., 2015; Lutterbeck et al., 2017).

Although studies using LCA for wastewater treatment systems are conducted since the 1990s (Corominas et al. 2013), the access to quality information and tools are still a challenge for decision makers. In small and medium rural and urban communities from developing countries, water bodies are often becoming contaminated due to discharge of untreated or partially treated wastewaters. In this context, there is an urgent demand of studies on wastewater treatment technologies to support policymakers and elected representatives from less developed countries, to rationalize their decisions. Furthermore, investments in the wastewater treatment sector can be justifiably and support the sustainable development in these communities (Kalbar et al. 2016), what is accordance to the sixth objective of the United Nations Sustainable Development Goals for the year 2030 (United Nations Organization, 2030).

In this context, the LCA is an essential instrument for decision makers and other professionals for the integrated water resource management and sustainable development by allowing comparison between different treatment technologies and improving the sustainability of the current sanitation units. Jabri et al. (2019) investigated a treatment system composed of two moving bed biofilm reactors (MBBR) integrated with UV lamps for treating grey water from a residence and aiming for local non-potable reuse. The authors evaluated the environmental impacts from each of the treatment units through LCA. However, no analysis regarding the costs of constructing and operating the treatment system was conducted. Given that, one should be aware that the implementation of a system also depends on the costs associated with the wastewater treatment. This aspect is especially important in developing countries that may suffer from water scarcity and have limited resources for investments in basic sanitation.

Resende et al. (2019), conducted both LCA and costing of two wastewater treatment systems integrated with CWs. However, the authors did not explore the possibility of treating the wastewater aiming for its local non-potable reuse. Leong et al. (2019) also performed LCA and cost analysis of onsite water reuse, but the authors considered only greywater recycling and rainwater harvesting systems, as well as hybrid systems with both, therefore not considering black waters.

According to Yoonus and Al-Ghamdi (2020), who performed a systematic and bibliographic analysis of alternative decentralized treatment systems for local grey water reuse, even with the current water scarcity in several world regions, only a few studies were developed to evaluate the environmental performance of integrated treatment systems based on LCA and aiming water reuse.

Gallego-Schmid and Tarpani (2019), after conducting a review on LCA of wastewater treatment technologies, verified that treatments technologies, even showing potential for decentralized treatments, were still not assessed in developing countries. According to the authors, only two studies were published regarding LCA of treatments including the ozonation of wastewater. However, none of these studies investigated the costs of constructing and operating the treatment systems.

Therefore, the application of LCA and costing analysis for evaluating innovative integration of technologies, as well as improving the consolidated wastewater treatments, aiming for local water reuse, still demand investigations to overcome the main challenges and knowledge gaps, mainly in developing countries.

The objective of this study is to use the tools LCA to evaluate an integrated system for wastewater treatment and non-potable reuse, aiming to diagnose the environmental sustainability and economic viability of the treatment processes. In this study, each treatment step of an integrated

system composed of ARs, hybrid CWs and ozonation was investigated separately in terms of environmental impacts and costs associated with construction and operation.

2. MATERIAL AND METHODS

2.1 Treatment system monitoring

The combined system was built and operated at the wastewater treatment plant (WWTP) from the university campus in the south of Brazil, for a period of 12 months (2017). The climate is warm and temperate. There is significant rainfall throughout the year in Santa Cruz do Sul. Even the driest month still has a lot of rainfall. The climate classification is Cfa according to Köppen and Geiger. The average annual temperature in Santa Cruz do Sul is 18.9 °C. Average annual rainfall of 1790 mm. Santa Cruz do Sul is located in the southern hemisphere (Kottek et al., 2006). The WWTP has the capacity of treating 360 m^3d^{-1} of urban effluent or attending 18,000 people. Most of the wastewater generated in the university campus is from restrooms and urinals, with an average flow of 8 m^3h^{-1}, ranging from 70 to 120 m3h-1 during peak times. The raw wastewater, after passing through screening and grit chambers, followed by an equalization tank, being pumped to the ARs with a 1 HP (Horsepower) pump which was set on for 5 min per loading.

The combined treatment system was composed by 4 ARs (4 biodigesters), 3 staged hybrid CWs and a bench scale ozonation unit. The ARs consisted of 4 high-density polyethylene (HDPE) tanks with an operational volume of 100 L each, with 7 days hydraulic retention time (HRT), and weighting 10.8 kg. The reactors were connected through polyvinyl chloride (PVC) hoses with 20 mm diameter and 2 meters long (1.4 kg). The ARs were weekly fed with wastewater from the equalization tank, after passing only by the screening and grit removal units. Figure 1 presents a basic scheme of the studied system.

Figure 1 Wastewater treatment system integrating anaerobic reactors followed by the hybrid constructed wetlands (CWs) and ozonization.
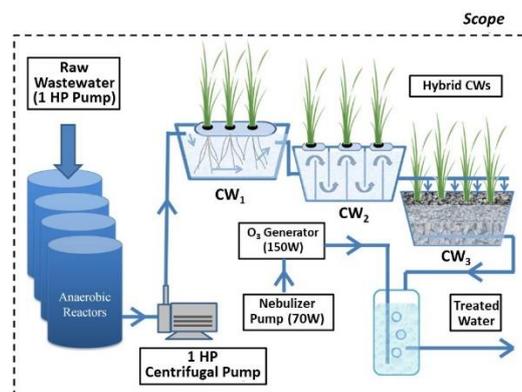
The second step of the treatment consisted of a sequential hybrid CW system composed by two HDPE boxes (CW1 and CW3) and a fiberglass box (CW2). The system receives a load of effluent every seven days, totaling 21 days. Similar to the ARs, system feeding, sampling and analytical determinations were conducted once a week for 12 months and analysis performed upon collection.

Briefly the description of the hybrid CWs system follows:

CW1: In the first unit (CW1), *Hymenachne grumosa* plants were placed in PVC pipes in the floating system - floating islands (9 plants m^{-2}), and the voids between the plants were filled with water lettuce (*Pistia stratiotes*) and duckweed (*Spirodella* sp.) in order to cover the water surface and prevent mosquitoes proliferation. PVC pipes, totaling about 2 m (or 0.10 kg), made the draining. The height of the water column was 60 cm with horizontal flow.

Realização

ABES-RS PUCRS UFRGS UNIVERSIDADE FEDERAL DO RIO GRANDE DO SUL

abes-rs@abes-rs.org.br
(51) 999330700
www.abes-rs.org.br

CW2: The second stage of the CW2 systems also consisted of a Floating Treatment Wetland (FTW) unit. However, this baffled box (CW2) presented vertical chicanes, which provided upflow and donwflow of the wastewater through the box. Similar to the first CW (CW1), the floating support (FTW - expanded polyethylene spaghetti) was also filled with *H. grumosa* plants. However, the baffled compartments were alternately filled with FTW *H. grumosa* and Salvinia sp. Plants (free floating macrophytes), and therefore alternating oxic and anoxic zones through each compartment.

CW3: The third and last CW stage (CW3) was the only one that was filled with substrate to support plant growing and to improve filtering of the wastewater. In the HDPE box's bottom layer (lower 15 cm height), pebbles were added to promote the water draining, and the upper layer was filled with gravels numbers of 0, 1 and 2 (25 cm height each). Both distribution and draining pipes were drilled and presented diameter of 20 mm. The flow from the unit was subsurface vertical.

The last treatment unit was an ozone generator (OG, RADSAT 2C) with capacity of generating 2 g O_3 h^{-1}, aiming the production of water for non-potable reuse. The application doses were 13.3 and 160 mg O_3 L^{-1}, to achieve disinfection and color removal, respectively. Dosage control was carried out using the iodometric method and by selecting the percentage of ozone generation in the generator.

2.2 Water and wastewater characterization

The system was monitored for 12 months, with weekly sample collection and analysis at the inlet and outlet of each treatment unit. More information of the system design and operation conditions can be found in Colares et al. (2019).

The following parameters were analyzed based on Standard Methods (APHA, 1998): chemical oxygen demand (COD), biochemical oxygen demand (BOD_5), total organic carbon (TOC), total carbon (TC), pH, total P, $N-NH_3$, Total Nitrogen (TN).

2. 3 Life Cycle Assessment for treatment construction and operation

LCA application was performed for a reference flow of 20 years, based on the treatment system lifespan and on research developed by Garfí et al. (2017). Functional unit was defined as 100 L of raw wastewater treated per week, which was the amount of water treated by the combined system during its monitoring. The methodological procedures followed the Brazilian Association of Technical Standards ABNT NBR 14044 (2009) - Environmental Management: Life Cycle Assessment - Principles and Framework and ABNT NBR ISO 14040 (2009) - Environmental Management: Life Cycle Assessment - Requirements and Guidance.

The software used for the LCA was the SimaPro version 8.04 and the database used in the LCA was the Ecoinvent 3 with impact method IMPACT 2002+ from the Swiss Federal Institute of Technology. Data regarding characterization, normalization and single score were considered.

The methodological approach of the assessment method "Impact 2002+" allows for a feasible implementation of a midpoint in a combined approach to damage (Lutterbeck et al. 2020). It connects all types of inventory results of the life cycle (elementary flows and other interventions), by several average levels for different damage categories (Varanda et al., 2011). The environmental impacts were evaluated according to 15 different indicators: carcinogenic (CA), non-carcinogenic (NCA), respiratory inorganic (RI), ionizing radiation (IR), ozone depletion (OD), respiratory organics (RO), aquatic ecotoxicity (AE), terrestrial ecotoxicity (TE), terrestrial acidity (TA-N), land occupation (LO), aquatic acidification (AA), aquatic eutrophication (AE), global warming (GW) non-renewable energy (NRE) and mineral extraction (ME) (Muñoz et al. 2006).

In this study, the evaluation of each treatment stage operation (ARs + hybrid CWs and O_3) and the discharge without treatment of the raw wastewater were considered under different scenarios. In addition, the treatment system's LCA was separated in construction and operation (associated transport operations were not considered), in order to identify the most impactful units in each of them. Regarding the treatment operation, two scenarios were defined, one considering the

ozone application mainly as a disinfection guarantee after the CWs units, with a dosage of 13.3 mg O_3 L^{-1}, a dosage in accordance to the literature and similar to the values applied by Lancheros et al (2020), who applied 5, 10 and 15 mg O_3 L^{-1} for the treatment of domestic wastewater also using a CWs and ozonation system. The second scenario, on the other hand, was based on the application of a much higher ozone dosage (160 mg O_3 L^{-1}), aiming for the reduction of the wastewater color, as described by Colares et al. (2019).

Additionally, a Monte Carlo simulation was conducted in SimaPro to verify the uncertainty analysis of the environmental impacts. This analysis represents a formal mechanism used to assess statistical evaluation and predict uncertain inputs (De Azevedo et al. 2017).

3. RESULTS AND DISCUSSIONS

3.2 Data characterization for life cycle inventory

For the LCA of the combined system construction and operation, a summary of the used materials and inputs are presented in Table 1. Due to the absence of OG in the Ecoinvent database it was considered that the O_3 equipment used in the present study was composed of polystyrene (plastic box), stainless steel-chromium (18/8), aluminum and copper.

Table 1. Inventory of operation inputs, and construction materials and equipment's of each treatment stage from the combined system.

	Unit	ARs	CW1	CW2	CW3	OG	Ecoinvent process
Construction							
Metal ladder support	kg	-	20	10	5.0	-	Steel, low-alloyed {RER}, steel production, converter, Alloc Rec, U
High density polyethylene	kg	120	40	-	40	17.3	Polyethylene, high density, granulate {GLO}, market for, Alloc Rec, U
Glass fibre	kg	-	-	40	-	-	Glass fibre reinforced plastic, polyamide, injection moulded {RoW}
Polyvinyl chloride (PVC) pipes	kg	1.8	1.5	0.5	1.0	-	Polyvinyl chloride resin (S-PVC), suspension polymerization, production mix, at plant RER
Polyurethane foam	kg	-	0.17	0.17	-	-	Polyurethane, flexible foam {GLO}, market for, Alloc Rec, U
Pebbles	kg	-	-	-	50	-	Gravel, crushed {GLO}, market for, Alloc Rec, U
Gravel n.2	kg	-	-	-	100	-	Gravel, crushed {GLO}, market for, Alloc Rec, U
Borosilicate glass (Beaker)	kg	-	-	-	-	0.06	Glass tube, borolosilicate {GLO}, market for, Alloc Rec, S
Polystyrene	kg	-	-	-	-	3.5	Polystyrene, general purpose {RER}, production, Alloc Rec, S
Stainless Steel - chromium	kg	-	-	-	-	0.1	Steel, chromium steel 18/8, steel production, converter, Alloc Rec, S
Copper	kg	-	-	-	-	0.03	Copper {GLO}, treatment of used cable. Alloc Def, S
Aluminum	kg	-	-	-	-	0.5	Aluminum, secondary, extruded, RNA
Operation							
Energy demand	kWh /week	0.124	0.062	-	-	0.056	Electricity, medium voltage {BRA}, Alloc Def, U

Biomass harvesting	hr / year	-	1.0	-	2	-	-
Water (for cooling)	m³	-	-	-	-	1.0	Water, barrage
Sludge removal	m³ / 5 yr.	0.16	-	-	-	-	Sludge

Note: ARs: anaerobic reactor, CW_1: constructed wetland with floating system - floating islands; CW_2: constructed wetland with Floating Treatment Wetland (FTW) unit, CW_3: constructed wetland with subsurface vertical flow, OG: ozone generator.

Regarding the estimated pollutant removals, each stage of the integrated treatment system is presented considering as functional unit 100 L of raw wastewater (treated by week) in a reference flow of 20 years. The mass (kg) of pollutant loading was determined on the system operation period (Table 2). All parameters presented in Table 2 were considered in the LCA of the system operation. The applied methodology (20 years lifespan for the system) was similar to the ones conducted by Garfí et al. (2017) and Flores et al. (2019).

Table 2. Summary of the wastewater characterization after each treatment stage of the integrated system (n= 12).

Parameter	Inlet concentration	Outlet concentration (average±	Reference flow kg (20 years^{-1})*	Inlet concentration	Outlet concentration	Reference flow kg (20 years^{-1})*
	RAW WASTEWATER			**AR**		
BOD_5 (mg L^{-1})	-	192 ± 66	20	192 ± 66	112 ± 59	11.66
COD (mgL^{-1})	-	481 ± 266	50.1	481 ± 266	96.8 ± 14.2	10.07
TOC (mg C L^{-1})	-	140 ± 49.9	14.6	140 ± 49	30 ± 16	3.12
TC (mg C L^{-1})	-	224 ± 23.7	23.3	224 ± 23	173 ± 21	17.99
$N-NH_3$ (mg N L^{-1})	-	82 ± 9	8.5	82 ± 9	94.4 ± 12	9.82
TN (mg N L^{-1})	-	92.5 ± 25.3	9.6	92 ± 25	122 ± 27	12.69
Soluble P (mg P L^{-1})	-	3.9 ± 0.6	0.4	3.9 ± 0.6	4.96 ± 1.1	0.52
	CW1			**CW2**		
BOD_5	112.1 ± 59	64.9 ± 36.1	6.75	64.9 ± 36.1	140 ± 19.9	14.6
COD	96.8 ± 14.2	62.3 ± 14.1	6.48	62.3 ± 10.1	68.7 ± 43 .1	7.15
TOC	30 ± 16	4.3 ± 4.08	0.44	4.3 ± 4.1	11.3 ± 8.7	1.18
TC	173 ± 21	111 ± 26.4	11.53	111 ± 26.4	91.0 ± 11.9	9.464
$N-NH_3$	94.4 ± 12	65.2 ± 22.2	6.78	65.2 ± 22.2	37 ± 16.3	3.85
TN	122 ± 27	83.9 ± 37.1	8.73	83.9 ± 37.1	51.1 ± 24.2	5.32
Soluble P	4.96 ± 1.14	4.5 ± 4.1	0.47	4.5 ± 4.1	4.1 ± 0.81	0.42
	CW₃			**CW3 + OG**		
BOD_5	140.4 ± 19.9	77 ± 62.8	8.01	77 ± 62.8	30 ± 24	3.12
COD	68.7 ± 43 .1	30.6 ± 19.9	3.18	30.6 ± 19.9	86 ± 84	8.94
TOC	11.3 ± 8.7	17 ± 17.6	1.77	17 ± 17.6	29.1 ± 3.2	3.03
TC	91.0 ± 11.9	119 ± 63	12.33	119 ± 63	93.9 ± 2.57	9.77
$N-NH_3$	37.0 ± 16.3	3.25 ± 3.82	0.34	3.2 ± 3.8	4.49 ± 1.22	0.47
TN	51.1 ± 24.2	6.5 ± 8.7	0.68	6.5 ± 8.7	5.89 ± 1.30	0.61
Soluble P	4.1 ± 0.8	1.3 ± 1. 3	0.14	1.3 ± 1. 3	3.20 ± 0.65	0.33

(*Adapted from Colares et al. (2019))

Note: Note: ARs: anaerobic reactor, CW_1: constructed wetland with floating system - floating islands; CW_2: constructed wetland with Floating Treatment Wetland (FTW) unit, CW_3: constructed wetland with subsurface vertical flow, OG: ozone generator.

It is important to highlight that the treatment performance as well as the final pollutant concentrations presented in Table 2 were in accordance with the wastewater reuse standards in Brazil.

12º Simpósio Internacional de Qualidade Ambiental
2024

Data do Evento:
04, 05 e 06/11/2024

TEMA:
Desafios e soluções ambientais na adequação aos critérios ESG

such as for agriculture irrigation and toilet flushing. The treated wastewater could be classified as Class 2 by the Brazilian standards NBR 13969/97, which would allow its application on floor washing, garden irrigation, maintenance and canals for landscaping purposes. (CONSEMA no 419 de 2020).

Dry and humid biomass of macrophytes were estimated in 57.26 kg and 272.68 kg for the first and third CWs, respectively. Although the main objectives of ozone applications were color reduction (420 nm) and disinfection, those aspects are not considered in Life Cycle Inventory (LCI).
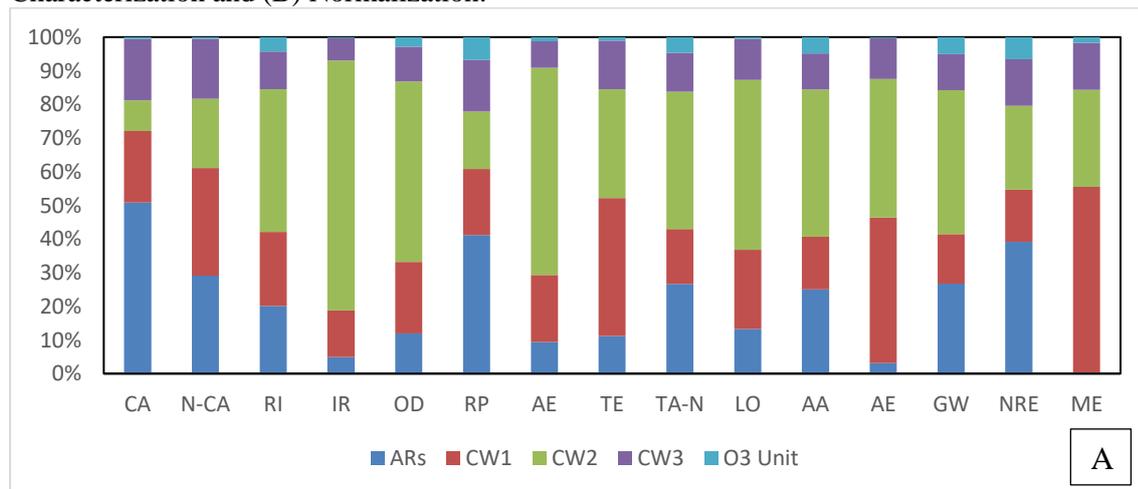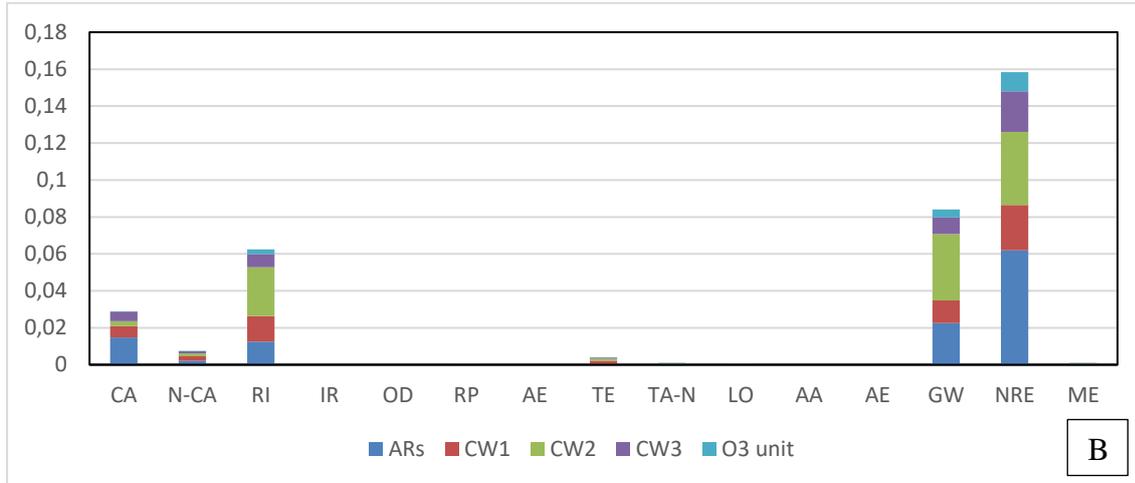
3.3 LCA from the system construction

The evaluation of the effects of the different units that make up the integrated system consisted of classifying the processes into different environmental impact categories (Impact 2002 + method) followed by characterization. Afterwards, aiming to perceive the magnitude of the impact caused by the environmental problems from a global point of view (Varanda et al. 2011), it was performed the normalization of the inventoried results.

In relation to the ARs + CWs + O_3 system construction, Figure 4 presents the most important materials according to the LCA analysis, regarding impacts characterization (Figure 4A) and normalization (4B). From Figure 4, it is possible to note that the ozonation unit (O_3) presented the lowest impacts compared to the other treatment units. On the other hand, the ARs and the second treatment wetland unit (CW2) presented the highest impacts regarding the construction phase.

Based on the normalization results depicted in Figure 2, one can note that considering the magnitude of the impacts, five categories were responsible for the highest environmental burdens: CA, N-CA, RI, GW and NRE. From the obtained data, it was verified that ARs were the most impactful unit in the categories of CA (37.4 kg from the 733.4 C_2H_3Cl from the system total) and non-renewable energy (9,424 of 24,062 MJ primary). On the other hand, the CW2 unit was responsible for the highest environmental impacts in the categories of RI (0.268 of 0.632 kg PM 2.5 eq) and Global warming (356 of 832 kg CO_2 eq). Regarding the N-CA category, the CW1 stage was responsible for the highest impacts, with 6.01 of the total system - 18.79 kg C_2H_3Cl eq., followed by the AR, with 5.47 kg C_2H_3Cl eq.

Fig. 2 Life Cycle Assessment impacts from the system construction stage using IMPACT 2002+. (A) Characterization and (B) Normalization.

Realização
ABES-RS PUCRS UFRGS UNIVERSIDADE FEDERAL DO RIO GRANDE DO SUL

abes-rs@abes-rs.org.br
(51) 999330700
www.abes-rs.org.br

Where: Ca= Carcinogenic; N-Ca = Non-carcinogenic; RI = Respiratory effects (caused by inorganics); IR = Ionizing radiation; OD = Ozone level depletion; RP = Respiratory effects (caused by organics); AE = Aquatic ecotoxicity; TE = Terrestrial ecotoxicity; TA-N = Terrestrial acidification and Nutrification; LO = Land occupation; AA = Aquatic acidification; AE = Aquatic eutrophication; GW = Global warming; NRE = non-renewable energy; ME = Mineral extraction; ARs: anaerobic reactors, CW1: constructed wetland with floating system - floating islands; CW2: constructed wetland with Floating Treatment Wetland (FTW) unit, CW3: constructed wetland with subsurface vertical flow, OG: ozone generator.

Figure 3 presents the network view of the conducted LCA. In the network view, the software presents the materials that most contributed to the overall impacts of each treatment unit. In this context, the wider the red line between the boxes, the most significant are the related impacts, while the percentages represent how much this stage contributes to the systems total impacts.

Fig. 3 Network view from the LCA of the construction stages of the AR + CWs + O_3 System.
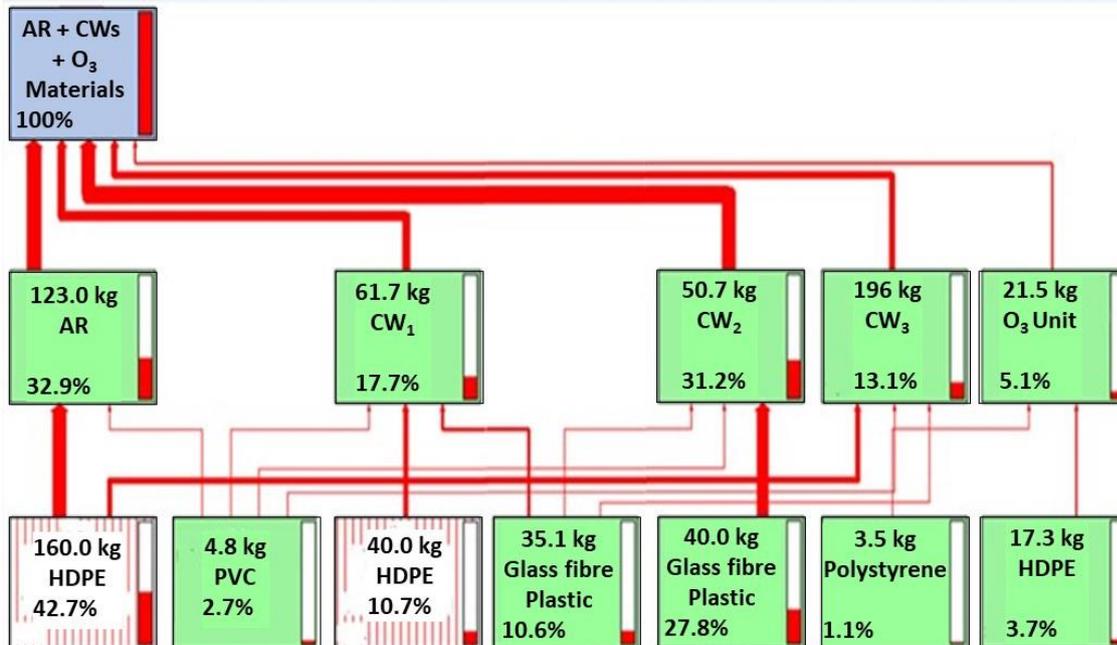
Adapted from the data obtained with the SimaPro software. Note: ARs: anaerobic reactor, CW1: constructed wetland with floating system - floating islands; CW2: constructed wetland with Floating Treatment Wetland (FTW) unit, CW3: constructed wetland with subsurface vertical flow, OG: ozone generator.

Realização

ABES-RS PUCRS UFRGS UNIVERSIDADE FEDERAL DO RIO GRANDE DO SUL

abes-rs@abes-rs.org.br
(51) 999330700
www.abes-rs.org.br

As shown in Figure 3, the materials that most impacted the system production were the HDPE, utilized most at the ARs treatment stage, and the glass fiber reinforced plastic, applied to the CW2 unit. Similar results were found by Resende et al. (2019) and Lutterbeck (2017), which reported that most of the impacts of the construction of CW systems for wastewater treatment were due to the fiberglass tanks. However, after comparing the scenario using fiberglass tanks with a scenario using masonry (bricks and steel), the authors concluded that the potential to cause impacts from the fiberglass tanks were lower than the masonry materials. However, when choosing the best materials for the treatment system construction, it important to verify the availability of different materials in the region where the system will be constructed, based also on the reverse logistics of each of the materials according to the local economy.

The ARs and CW2 units accounted for more than half of the overall construction impacts (33.0 and 31.2%, respectively). The OG, on the other hand, accounted for only 5.1% of the construction impacts. Although CW1, CW2 and CW3 boxes had the same weight (40 kg each), the application of the HDPE boxes resulted in lower impacts than the fiberglass tank. In this context, the replacement of the fiberglass tank by HDPE boxes may be an alternative to minimize construction impacts.

Moreover, Lutterbeck et al. (2017) states that another possibility to reduce the environmental pressure of the anaerobic units is to recover energy from biomethanation as well as sulfur from H_2S emissions. In that case, it is possible that a regeneration as elemental sulfur in a cyclic reduction system, when $FeCl_2$ is used as a gas burner pretreatment to recover it (Szarblewski et al. 2012). In addition, the produced electricity could be used to reduce the energy for the pumping and ozonation processes.

Corominas et al. (2013), with low-tech treatments, including CWs, showed that the construction phase can account for up to 80% of the negative environmental impacts. Nevertheless, despite some negative effects, the environmental performance of CWs is much better in comparison to other treatment technologies, mainly because they are decentralized wastewater treatment systems, that also allow on-site sludge treatment, avoiding sludge transportation.

3.4 LCA from the ARs + CWs + OG system operation

The present section brings the results of the environmental performance concerning the operation of the integrated system. The environmental benefits as well as direct impacts are presented in Figures 4 (A and B) and Figure 2, mainly concerning pollutants removal that can potentially reduce oxygen levels in water, increasing eutrophication conditions. In this context, LCA is indicated as an important tool in order to evaluate environmental gains and negative effects from each stage of the combined system ARs + CWs + OG.

As shown in the impact's characterization graph (Figure 4A), for almost all impact categories (with exception to global warming) the discharge without treatment of the raw wastewater (Raw WW) was the most significant, followed by the ozonation treatment stage. In relation to the global warming (GW), the raw ARs treatment stage would be the most important, due to the energy consumption for wastewater feeding, considering the Brazilian energy matrix, and due to the biogas production and thus methane emission from the anaerobic digestion process present in this stage. Similar results were obtained in previous studies (Lutterbeck et al. 2017, Lopes et al. 2020). The CW2 and CW3 presented lower impacts than other units concerning most impact categories due to the treatment efficiency and the lack of electricity demand on those stages.

Fig. 4 Impacts of the AR + CW + OG. (A) Impacts characterization and (B) Impact's normalization.

A

B
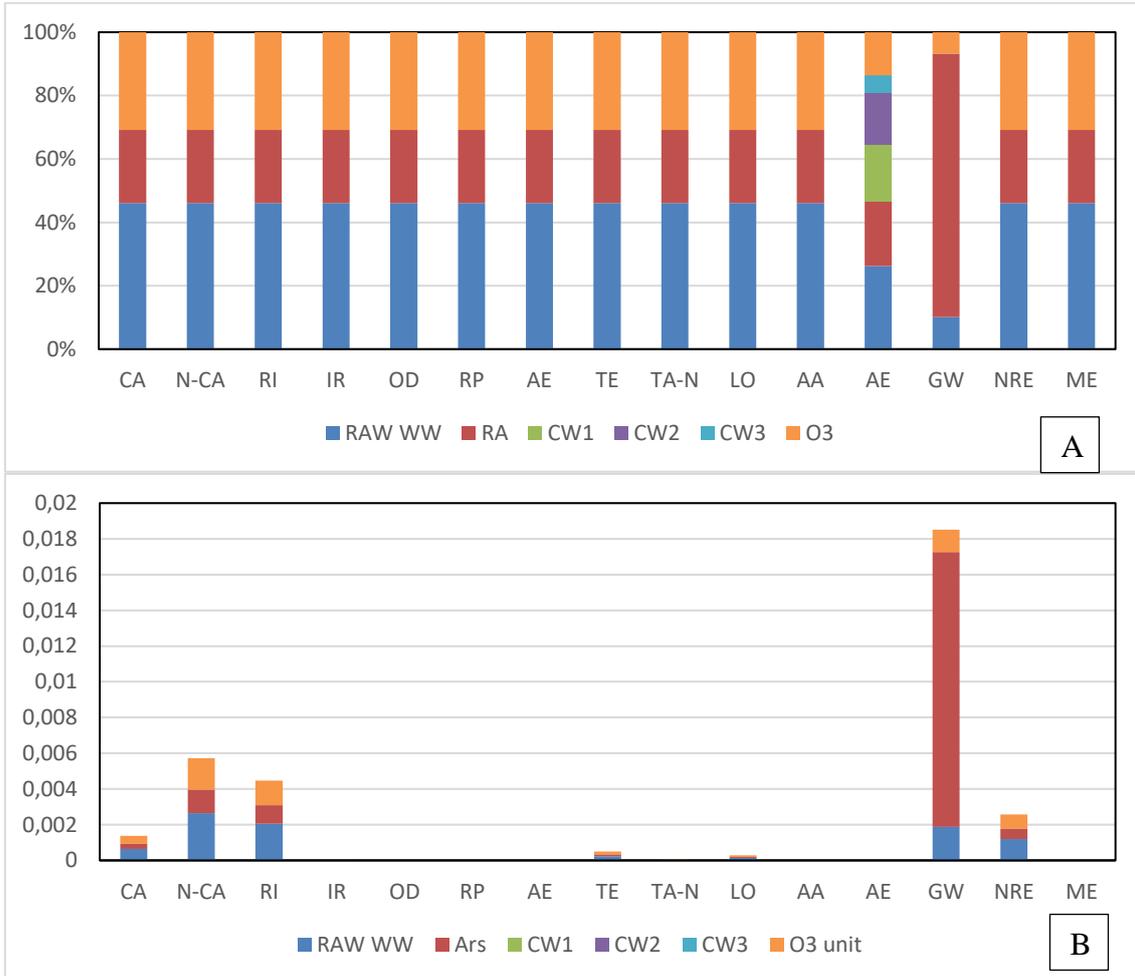
Where: Ca= Carcinogenic; N-Ca = Non-carcinogenic; IR = Respiratory effects (caused by inorganics); IR = Ionizing radiation; OD = Ozone level depletion; RP = Respiratory effects (caused by organics); AE = Aquatic ecotoxicity; TE = Terrestrial ecotoxicity; TA-N = Terrestrial acidification and Nitrification; LO = Land occupation; AA = Aquatic acidification; AE = Aquatic eutrophication; GW = Global warming; NRE = non-renewable energy; ME: Mineral extraction. Note: ARs: anaerobic reactor, CW1: constructed wetland with floating system - floating islands; CW2: constructed wetland with Floating Treatment Wetland (FTW) unit, CW3: constructed wetland with subsurface vertical flow, OG: ozone generator.

When analyzing the normalization results (Fig. 4B) one can observe that seven different categories were the most impacted categories: CA, N-Ca, RI, TE, LO, GW and NRE. As already mentioned, the OG was the most impactful unit of the integrated system because of the high energy demands. Lutterbeck et al. (2020), notes that the use of treatment methods that require high electrical power requirements can significantly increase the environmental load of the system.

In addition to the ozonation as a disinfection guarantee, a second operation scenario was defined based on the methodology described by Colares (2019), who applied a much higher O_3 dose aiming for wastewater discoloration. In this second scenario, the OG (30 W) and the peristaltic pump (70 W) would be operated for 71 h per week, with an ozone application of 160 mg O_3 L^{-1}.

Statistical evaluation of the data was performed using the SimaPro software and through Monte Carlo simulations (Table 3).

Table 3: Uncertainties resulted from the Monte Carlo simulations in the LCA of the system operation.

Impact category	Unit	Mean	SD	CV	U (2.5%)	V (97.5%)	Mean standard error

Realização

ABES-RS   PUCRS   UFRGS
UNIVERSIDADE FEDERAL
DO RIO GRANDE DO SUL

abes-rs@abes-rs.org.br
(51) 999330700
www.abes-rs.org.br

Climate change	kg CO2 eq	1140	76.8	6.72%	1120	1320	0.00129
Ecosystem quality	PDF*m2*yr	112	21.8	19.4%	69.7	157	0.00371
Human health	DALY	0.00105	4.3E-05	4.13%	0.00104	0.00115	0.00079
Resources	MJ primary	25700	1290	5.03%	22900	28600	0.0096

SD - standard deviation, CV - coefficient of variation, Range (U: 2.5th percentile, V: 97.5th percentile).

The coefficient of variation (CV), which is the indicator of dispersion in the category indicator data, can suggest that a large degree of uncertainty is present in the results obtained from some categories. Goffi et al. (2018), after performing LCA and Monte Carlo simulations in bioethanol production from cattle manure, identified that the categories with most uncertainties were ionizing radiation, freshwater eutrophication and freshwater ecotoxcity, with CVs of 93.8, 55.2 and 50.7%, respectively, therefore higher than at the present study.

Additionally, the LCA results are in accordance with the bibliometric maps (Figure 2 and 3) since energy demand played an important role regarding environmental impacts in both bibliometric and LCA analysis. Moreover, the maps and the LCA also indicate that CW can be an interesting alternative in wastewater treatment and water reuse mainly due to reduced environmental impacts and low energy demand.

4. CONCLUSIONS

This study is a novel attempt of separately quantifying the environmental sustainability and the economic costs of the construction and operation of a combined system composed of ARs + CWs + OG for the treatment and local reuse of urban wastewaters generated in a house or in a small community, in order to identify the most significant treatment stages in terms of environmental impacts and economic feasibility, and propose further investigation aspects for the combined system overall improvement.

Concerning the system construction, most impacts were related to the construction of the ARs and the CW2 stages, due to the application of high-density polyethylene and fiberglass. The first was the most responsible for CA emissions (37.6 kg from the 73.4 kg of CH_2H_3Cl eq) and NRE (9424 of 24062 MJ primary), while the CW2 presented the highest impacts regarding RI (0.268 of 0.627 kg PM2.5 eq) and GW (356 of 832 kg CO_2 eq.) In the treatment operation, the ozonation stage accounted for most of the environmental impacts, due to its energy consumption. These impacts may be drastically reduced through onsite generation of renewable energy.

Acknowledgments

REFERÊNCIAS

Albornoz, L.L., Centurião, T.C., Giacobbo, A. Zoppas-Ferreira J., Bernardes, A.M. (2020). Influence of rain events on the efficiency of a compact wastewater treatment plant: a case study on a university campus aiming water reuse for agriculture. Environ Sci Pollut Res 27, 41350–41360

Albornoz, L.L., Marder, L., Benvenuti, T., Bernardes, A. M. (2019). Electrodialysis applied to the treatment of an university sewage for water recovery, Journal of Environmental Chemical Engineering, Volume 7, Issue 2.

Álvarez, J. A., Ávila, C., Otter, P., Kilian, R., Istenič, D., Rolletschek, M. & Jorgensen, C. (2017). Constructed wetlands and solar-driven disinfection technologies for sustainable wastewater treatment and reclamation in rural India: SWINGS project. Water Sci. Technol., 76(6), 1474-1489.

Arias, A., Rama, M., González-García, S., Feijoo, G., & Moreira, M. T. (2020). Environmental analysis of servicing centralised and decentralised wastewater treatment for population living in neighbourhoods. Journal of Water Process Engineering, 37, 101469.

Colares, G. S., De Souza Celente, G., Da Silva, F. P., De Loreto, A. C., Lutterbeck, C. A., Kist, L. T., & Machado, Ê. L. (2019). Combined system for the treatment and reuse of urban wastewater: the efficiency of anaerobic reactors+ hybrid constructed wetlands+ ozonation. Water Sci. Technol. 80(2), 254-264.

Corominas, L., Foley, J., Guest, J. S., Hospido, A., Larsen, H. F., Morera, S., & Shaw, A. (2013). Life cycle assessment applied to wastewater treatment: state of the art. Water Res. 47(15), 5480-5492.

Dell'Osbel, N., Colares, G. S., de Oliveira, G. A., de Souza, M. P., Barbosa, C. V., & Machado, Ê. L. (2020). Bibliometric Analysis of Phosphorous Removal Through Constructed Wetlands. Water Air Soil Poll. 231(3), 1-18.

De Souza Celente, G., Colares, G. S., da Silva Araújo, P., Machado, Ê. L., & Lobo, E. A. (2020). Acute ecotoxicity and genotoxicity assessment of two wastewater treatment units. Environ. Sci. Pollut. R. 1-8.

De Souza Celente, S. G., Colares, G. S., Machado, Ê. L. & Lobo, E. A. (2019) Algae turf scrubber and vertical constructed wetlands combined system for decentralized secondary wastewater treatment. Environmental Environ. Sci. Pollut. R. 26 (10), 9931–9937

Flores, L., García, J., Pena, R., & Garfí, M. (2020). Carbon footprint of constructed wetlands for winery wastewater treatment, Ecological Engineering, Volume 156.

Gallego-Schmid, A., & Tarpani, R. R. Z. (2019). Life cycle assessment of wastewater treatment in developing countries: a review. Water Res., 153, 63-79.

Garfí, M., Flores, L., & Ferrer, I. (2017). Life cycle assessment of wastewater treatment systems for small communities: activated sludge, constructed wetlands and high rate algal ponds. J. Clean. Prod. 161, 211-219.

Giménez, J., Bayarri, B., González, Ó., Malato, S., Peral, J., and Esplugas, S. (2015). Advanced Oxidation Processes at Laboratory Scale: Environmental and Economic Impacts. ACS Sustainable Chemistry & Engineering 3 (12), 3188-3196 DOI: 10.1021/acssuschemeng.5b00778

Horn, T. B., Zerwes, F. V., Kist, L. T., Machado, Ê. L. (2014). Constructed wetland and photocatalytic ozonation for university sewage treatment, Ecological Engineering, Volume 63, , Pages 134-141.

ISO 14040, 2006. International standard. In: Environmental Management – Life Cycle Assessment – Principles and Framework. International Organization for Standardization, Geneva, Switzerland. 838

ISO 14044. Environmental management - life cycle assessment - requirements and guidelines. Geneva: International Organization for Standardization (ISO); 2006.

Jabri, K. M., Fiedler, T., Saidi, A., Nolde, E., Ogurek, M., Geissen, S. U., & Bousselmi, L. (2019). Steady-state modeling of the biodegradation performance of a multistage moving bed biofilm reactor (MBBR) used for on-site greywater treatment. Environ. Sci. Pollut. R, 26(19), 19047-19062.

Lopes, T. A., Queiroz, L. M., Torres, E. A., & Kiperstok, A. (2020). Low complexity wastewater treatment process in developing countries: A LCA approach to evaluate environmental gains. Science Sci. Total. Environ., 720, 137593.

Lutterbeck, C. A., Kist, L. T., Lopez, D. R., Zerwes, F. V., & Machado, Ê. L. (2017). Life cycle assessment of integrated wastewater treatment systems with constructed wetlands in rural areas. J. Clean. Prod. 148, 527-536.

Lutterbeck, C. A, Colares, G. S., Dell'Osbel, N., Da Silva, F. P., Kist, L. T., & Machado, Ê. L. (2020). Hospital laundry wastewaters: a review on treatment alternatives, life cycle assessment and prognosis scenarios. J. Clean. Prod. JCLP_122851

Muñoz, I.; Peral, J.; Antonio Ayllon, J.; Malato, S. et al. Life cycle assessment of a coupled solar photocatalytic–biological process for wastewater treatment. Water Res., 40, n. 19, p. 3533-3540, 11// 2006

Pelissari, C., Ávila, C., Trein, C. M., García, J., de Armas, R. D., & Sezerino, P. H. (2017). Nitrogen transforming bacteria within a full-scale partially saturated vertical subsurface flow constructed wetland treating urban wastewater. Sci. Total. Environ. 574, 390-399.

Resende, J. D., Nolasco, M. A., & Pacca, S. A. (2019). Life cycle assessment and costing of wastewater treatment systems coupled to constructed wetlands. Resour. Conserv. Recycl. 148, 170-177.

Szarblewski, M., de Souza Schneider, R. D. C., & Machado, E. L. (2012). Métodos para a remoção de sulfeto de hidrogênio de efluentes gasosos aplicáveis a reatores anaeróbios. Revista Jovens Pesquisadores.

Tripathi, S. & Tripathi, B. D. Efficiency of combined process of ozone and bio-filtration in the treatment of secondary effluent. Bioresource Technol. 102 (13), 6850–6856.

VARANDA, M. G.; PINTO, G.; MARTINS, F. Life cycle analysis of biodiesel production. Fuel Processing Technology, 92, n. 5, p. 1087-1094, 2011/05/01/ 2011.

Wu, S., Kuschk, P., Brix, H., Vymazal, J., & Dong, R. (2014). Development of constructed wetlands in performance intensifications for wastewater treatment: a nitrogen and organic matter targeted review. Water Res., 57, 40-55.