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Scientific Paper

Constructed wetland for septic tank sludge management: drained water quality under different operating strategies on a bench-scale experiment

Wetlands *construídos para gestão de lodo de tanque séptico: qualidade da água drenada sob diferentes estratégias operacionais em um experimento em escala de bancada*

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ABSTRACT

The septic tank is commonly used for treating domestic effluents, especially decentralized treatment. However, it requires periodic maintenance, including the removal, treatment, and disposal of sludge, which can be difficult and costly. An alternative approach, aligned with the principles of the circular economy, is the use of wetlands sludge management units (WSMU). In this study, a bench-scale experiment was conducted using six WSMU (0.0177 m^2 each) planted with *Canna x generalis*. Different total solids (TS) loads (15, 28, and 42 kg TS m^{-2} year^{-1}) and saturation levels (0.10 m and 0.20 m) were tested, and a super-loading strategy was adopted at the beginning of the operation. Monitoring and analyses were carried out over the first 150 days of operation. The results demonstrated that already at the beginning of the operation, high removal efficiencies were obtained, especially in units with a 0.20 m saturation level, reaching 80% for TS, 93% for chemical oxygen demand, 98% for total Kjeldahl nitrogen, and 97% for orthophosphate. This work showed that WSMU are capable of a high level of treatment even with high solids loads at the beginning of operation. Furthermore, these results indicate that even larger loads can be tested to optimize treatment performance and reduce area demand. Thus, the WSMU configuration, as well as the operational strategies adopted in this paper, can be used in future, long-term, and full-scale research to better understand the active treatment mechanisms.

Keywords: sewage treatment; decentralized treatment; sludge treatment; circular economy; nature-based solution.

RESUMO

O tanque séptico é comumente utilizado para o tratamento de efluentes domésticos, especialmente em tratamentos descentralizados, no entanto ele requer manutenção periódica, incluindo a remoção, o tratamento e a disposição do lodo, o que pode ser difícil e custoso. Uma abordagem alternativa, alinhada aos princípios da economia circular, é o uso de unidades de gestão de lodo *wetlands* (UGLW). Neste estudo, foi realizado um experimento em escala de bancada utilizando seis UGLW (0,0177 m^2 cada uma), plantadas com *Canna* x *generalis*. Foram testadas diferentes cargas de sólidos totais (ST) (15, 28 e 42 kg ST m^{-2} ano^{-1}) e níveis de saturação (0,10 e 0,20 m), e uma estratégia de supercarga foi adotada no início da operação. O monitoramento e as análises foram realizados nos primeiros 150 dias de operação. Os resultados demonstraram que, já no início da operação, foram obtidas altas eficiências de remoção, especialmente nas unidades com nível de saturação de 0,20 m, atingindo 80% para ST, 93% para demanda química de oxigênio, 98% para nitrogênio total Kjeldahl e 97% para ortofosfato. Este trabalho mostrou que as UGLW são capazes de realizar um tratamento de alto nível, mesmo com cargas elevadas de sólidos no início da operação. Além disso, esses resultados indicam que cargas ainda maiores podem ser testadas para otimizar o desempenho do tratamento e reduzir a demanda de área. Assim, a configuração das UGLW, bem como as estratégias operacionais adotadas neste artigo, pode ser utilizada em pesquisas futuras, de longo prazo e em grande escala, para melhor compreender os mecanismos ativos de tratamento.

Palavras-chave: tratamento de esgoto; tratamento descentralizado; tratamento de lodo; economia circular; solução baseada na natureza.

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INTRODUCTION

Wastewater treatment is one of the most important pillars for the advancement of basic sanitation in Brazil. Law No. 14,026, of July 15, 2020, known as the "New Sanitation Legal Framework," provides that, by 2033, 90% of the Brazilian population must be provided with wastewater collection and treatment (Brazil, 2020). There are many challenges in achieving this objective since only 52.2% of the wastewater generated in Brazil is treated (SNIS, 2022). Furthermore, given the immense territorial extension of the country and considering that 45% of municipalities have fewer than 10,000 inhabitants (IBGE, 2022), centralized treatment using large sewer systems becomes even more difficult. Thus, decentralized effluent treatment alternatives have gained much attention in the search for universal sanitation in Brazil, especially for serving isolated, urban, and/or rural communities (Tonetti *et al.*, 2018; Ferreira *et al.*, 2021). These initiatives not only directly contribute to achieving Sustainable Development Goal (SDG) number 6 (Clean Water and Sanitation) of the 2030 Agenda (UN, 2015) but also imply direct and indirect improvements across all other SDGs.

Due to its simplicity as well as its environmental and economic sustainability, one of the most commonly used technologies for decentralized treatment is the septic tank (ST) (Somlai; Knappe; Gill, 2019). Its design, construction, and operation are simple; however, for the correct functioning of the ST, there must be periodic cleaning of accumulated sludge, with intervals varying from 1 to 5 years, depending on sizing (Mac Mahon; Knappe; Gill, 2022). Proper sludge management encompasses various activities, from collection and transportation to final disposal. This process is often costly due to the long distances involved and the high moisture content of the sludge (Andrade; Sperling; Manjate, 2017). To address these challenges, dewatering the sludge is essential. This step removes excess moisture, making transportation easier and facilitating subsequent disposal methods such as landfill disposal or agricultural reuse.

Constructed wetlands, which are a nature-based solution, already established for the treatment of effluents, have proven to be very interesting for the treatment of ST sludge (Magri *et al.*, 2016; Jain *et al.*, 2022; Osei; Abagale; Konate, 2022). Called wetlands sludge management units (WSMU), this technology presents great advantages over those traditionally used for sludge dewatering. Drying beds, widely used, require an extensive operational routine, with periodic removal of sludge (every 20–30 days). WSMU can operate in cycles of up to more than 10 years without the need to remove material accumulated during this period (Stefanakis; Akratos; Tsihrintzis, 2014). After removal, the dried sludge is ready for agricultural or forestry reuse, as it is a material rich in nitrogen and phosphorus and very competitive due to its low cost (Tonetti *et al.*, 2018).

The WSMU not solely focuses on dewatering and treating the sludge but also on improving the quality of the drained water. The liquid component of sewage sludge contains elevated levels of pollutants, which may leach into the drained water. Nonetheless, drained water also contains a rich array of macro and microelements, including nutrients, highlighting their potential as valuable fertilizers (Gholipour *et al.*, 2024). Therefore, the quality of the drained water determines the need for additional treatment steps or its potential for reuse. The higher the quality of the drained water, the lower the costs associated with treatment and final disposal. Depending on its quality, the drained water can be reused or recirculated in the existing effluent treatment system, undergoing secondary treatment (Andrade; Sperling; Manjate, 2017).

Research conducted at WSMU has demonstrated removal efficiencies exceeding 85% for total suspended solids and chemical oxygen demand from drained water in temperate and subtropical climates (Magri *et al.*, 2016; Gholipour *et al.*, 2024). Besides climate, it is known that the performance of WSMUs is extremely linked to constructive and operational conditions (Nuamah *et al.*, 2020). The literature shows great variability in the applied loads, and specific constructive conditions, such as bottom saturation, lack detailed studies in WSMUs. Additionally, it is known that in treatment systems based on biological processes, the initial months of operation involve adaptation phases, where achieving satisfactory treatment levels is often challenging and warrants attention.

Considering the scarcity of studies on these systems adapted to Brazilian reality, this study aimed to evaluate, under the climatic conditions of southern Brazil, a bench-scale system for the treatment of ST sludge composed of WSMU under different solid loads and saturation levels, with a focus on the quality of the drained water at the beginning of operation.

METHOD

Description of the treatment system

The experiment was installed in the city of Frederico Westphalen, Rio Grande do Sul, Brazil (27°21′33″S; 53°23′40″W). The climate in the region is classified as humid subtropical (Cfa) according to the Köppen classification system (Köppen, 1901; Alvares *et al.*, 2013). It should be noted that the bench-scale system was installed outdoors to better represent the behavior of a full-scale system.

Six experimental WSMU units were set up, consisting of PVC (150 mm) columns with a surface area of 0.0177 m² each and a useful height of 0.50 m, planted with *Canna x generalis*. This plant was chosen for its aesthetic appeal and good adaptation in vertical wetlands, as reported by Decezaro *et al.* (2021). The units were filled with gravel of 19, 25, and 50 mm in diameter and fine sand (d_{10} = 0.28 mm; d_{60} = 0.6 mm; coefficient of uniformity = 2.13), as shown in Figure 1. Three hydraulic application rates and two saturation levels were tested. The units were named $W1_{10}$, $W1_{20}$, $W2_{10}$, $W2_{20}$, $W3_{10}$, and $W3_{20}$. The subscript numbers in Figure 1 denote the saturation levels (which were adjusted using level control devices). The saturation strategy (0.10 or 0.20 m) was applied to enhance the effectiveness of the units, specifically aiming to improve nitrogen removal through denitrification in the saturated zone at the bottom (Baggiotto *et al.*, 2023).

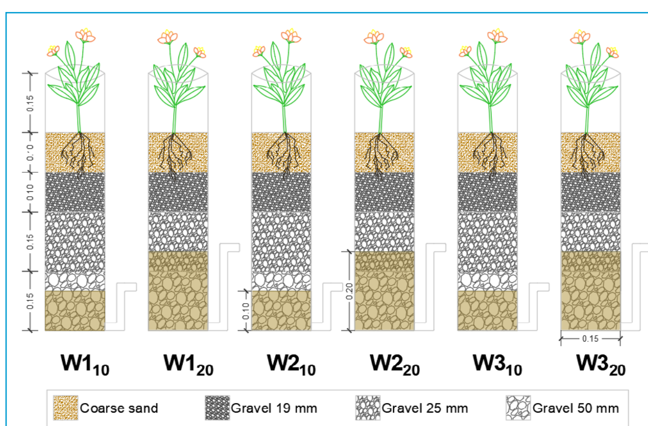


Figure 1 – Diagram detailing the constructive and operational (saturation levels) conditions of the system (units in meters).

Operating conditions

The WSMU units were fed with fresh sludge (collected at every feeding) from an ST located near the experiment site, which received only domestic effluent. The sludge was applied manually, with the help of a beaker, to the surface of the units. The pairs W1, W2, and W3 were operated with hydraulic load rates of 40, 80, and 120 L m^{-2} $week^{-1}$, respectively, representing loads of 15, 28, and 42 kg TS m^{-2} $year^{-1}$, within the range recommended by Stefanakis, Akratos and Tsihrintzis (2014), from 13 to 60 kg TS m^{-2} $year^{-1}$. The system was monitored for 150 days, consisting of 100 days of loading (the loading phase) and 50 days of rest (the resting phase).

The loading phase consisted of feeding and rest cycles. The feeding/rest cycle adopted in the WSMU units was one day of feeding followed by 6 days of rest, with the aim of preventing a significant decrease in hydraulic conductivity and, consequently, filtration media clogging.

Furthermore, a strategy of super-loading was adopted at the beginning of the operation. The first feeding had a TS concentration approximately 15 times greater than that projected for the remainder of the operation (around 10,000 mg L^{-1}). The high loading applied aimed to promote a rapid accumulation of solids at the beginning of the operation. This is because the layer of solids deposited on the surface of the wetlands tends to enhance the system's treatment performance, as observed in French system wetlands, which receive raw wastewater (Molle, 2014; Morvannou *et al.*, 2014; Kim *et al.*, 2013; Kania *et al.*, 2019). This phenomenon, also called surface clogging, can be potentialized by the low effective diameter (d_{10}) as well as the high uniformity coefficient of the filter media (Lunardi *et al.*, 2022), as it was applied in this study.

Meteorological data

Meteorological data on air temperature and precipitation were obtained at 1-h intervals for the entire operation period from an automatic station (INMET, 2024) located near the study site, within a radius of approximately 400 m.

Sampling and analytical procedures and data evaluation

The characterization of both the influent, consisting of ST sludge, and the drained water from the WSMU was conducted through seven sampling campaigns during the first 100 days of operation. The parameters analyzed included temperature, potential hydrogen (pH), total solids (TS), chemical oxygen demand (COD), total Kjeldahl nitrogen (TKN), and orthophosphate (PO_4^{3-}-P). The analyses were conducted according to the Standard Methods for the Examination of Water and Wastewater (APHA; AWWA; WEF, 2012).

The results of the physical-chemical monitoring were subjected to statistical analysis. The aim of this analysis was to identify significant differences between the applied loads and levels of saturation. For this purpose, an analysis of variance (ANOVA) followed by Tukey's test was employed. Prior to conducting ANOVA, Hartley's test was performed to assess the homogeneity of variances among the groups. If the results indicated homogeneity, an ANOVA was performed directly. However, if the data did not exhibit variance homogeneity, data normalization was conducted by applying a logarithmic transformation before proceeding with the ANOVA.

Macroscopic analysis

To complement the monitoring throughout the operation, macroscopic analysis was conducted to observe the development and health of the *Canna* x *generalis* specimens during the 100-day loading phase and the subsequent 50-day resting phase.

RESULTS AND DISCUSSION

Meteorological conditions

Figure 2 presents the rainfall depth and the average daily air temperature for the entire monitoring period (October 2019 to February 2020). During the study period, the average temperature was 22.7°C and the total rainfall depth was 652 mm. These values are typical of a humid subtropical climate (Köppen, 1901; Alvares *et al.*, 2013). During the loading phase, the average air temperature was 22.0°C and the total precipitation was 428 mm. In contrast, during the resting phase, the average temperature and total precipitation values were 24.2°C and 224 mm, respectively. Additionally, four episodes in the loading phase recorded daily rainfall exceeding 30 mm, with a maximum value of 56 mm. The elevated temperatures, as well as the level of precipitation obtained during the monitoring, are linked to WSMU performance. It was found that higher temperatures, in addition to promoting biological treatment, can facilitate the dewatering process, and that after heavy rainfall incidents, hydraulic conductivity is restored, preventing clogging (Stefanakis; Tsihrintzis, 2012).

Influent sludge and drained water quality

The monitoring results are presented in Table 1. The average concentration of TS in the ST sludge was 7,489 mg L^{-1}, within the range reported in Brazilian literature, which varies from 4,000 mg L^{-1} (Carrilho; Carvalho, 2016) to 11,000 mg L^{-1} (Magri *et al.*, 2016). The sludge exhibited a high concentration of carbonaceous organic matter and nitrogen. The average COD/TKN ratio was 12, lower than the value of 38 reported by Suntti *et al.* (2011) in well-stabilized sludge. The ratio typically decreases during the treatment as biodegradation releases carbon (in the form of CO_2) while nitrogen persists (Kania *et al.*, 2019). However, the COD/TKN ratio increased as it passed through the WSMU, reaching an average value of 53 in $W1_{10}$, which can be explained by the good performance of TKN removal.

The temperature recorded in the drained water of the units was very close to each other and approximately 1°C below the sludge temperature. It is noticed that this parameter does not represent a significant difference when comparing the different pairs (Table 1). Furthermore, throughout the entire duration of the study, the pH levels of both the sludge and the treatment units remained around neutral pH, conducive to biological activity (von Sperling, 2007). A slight decrease in pH was observed in the drained water of the WSMU compared to the sludge. This indicates the occurrence of biological treatment processes,

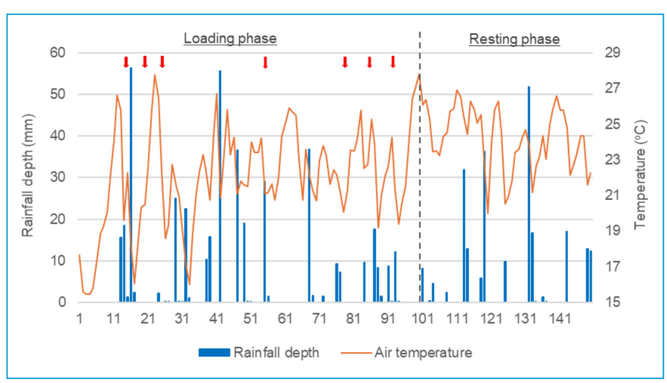


Figure 2 – Daily precipitation depth and air temperature during the loading and resting phases, with red arrows indicating sample collection (sludge influent and drained water from WSMU).

such as the aerobic removal of carbonaceous organic matter and nitrification. These processes consume alkalinity, potentially resulting in a reduction in pH. In the comparison between the WSMU, for this variable, a statistically significant difference was not found (Table 1). $W1_{10}$, with a lower applied load, presented an average pH equal to the influent value.

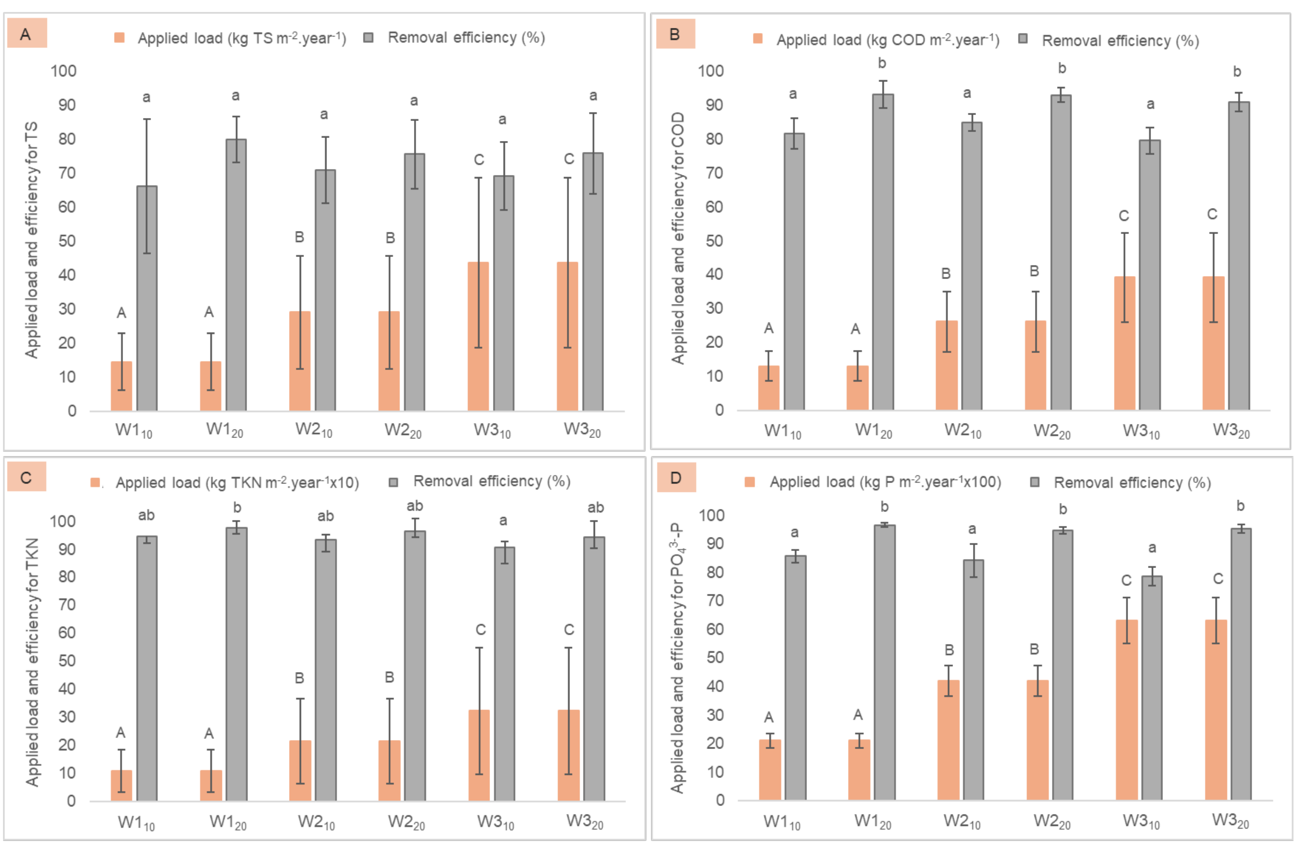
The applied loads and respective removal efficiencies of COD, TS, TKN, and PO_4^{3-}-P during the evaluated period are illustrated in Figure 3. The WSMU presented a good treatment performance at the beginning of the operation, revealing that a super-loading strategy was effective. The layer of solids accumulated at the surface of vertical wetlands can enhance solids removal, ammonia adsorption, and total nitrogen removal while also influencing surface distribution, permeability, and preventing clogging (Molle, 2014; Morvannou *et al.*, 2014; Kim *et al.*, 2013; Kania *et al.*, 2019). The hydraulic impact of this layer is particularly significant in this study, given that the top layer of the units consisted of fine sand.

The filtration theory demonstrates that the physical characteristics of the filter material, such as specific mass, specific surface area, and the arrangement of intragranular voids, are important in the filtration process (Trussell; Chang, 1999). Furthermore, solid retention in the filter material is influenced by different

Table 1 – Characterization of septic tank sludge (influent) and drained water from the WSMU.

Unit	Temp. (°C)		pH		COD (mg L^{-1})		TS (mg L^{-1})		TKN (mg L^{-1})		PO_4^{3-}-P (mg L^{-1})	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Sludge	24.8	1.2	7.1	0.5	6,122	2,066	7,489	3,482	504	355	98.8	12.5
$W1_{10}$	23.9 **a**	2.4	7.1 **a**	0.2	1,054 **b**	177	2,021 **a**	650	20 **ab**	10	14.0 **bc**	3.2
$W1_{20}$	23.9 **a**	2.3	6.8 **a**	0.3	348 **a**	90	1,314 **a**	483	8 **c**	3	3.3 **a**	0.8
$W2_{10}$	23.8 **a**	2.4	6.9 **a**	0.3	918 **bc**	364	1,892 **a**	595	24 **ab**	16	15.5 **c**	6.1
$W2_{20}$	23.7 **a**	2.3	6.8 **a**	0.5	388 **a**	42	1,556 **a**	528	12 **ac**	5	5.1 **ab**	1.2
$W3_{10}$	23.6 **a**	2.6	6.8 **a**	0.2	1,264 **b**	562	1,996 **a**	577	30 **b**	11	21.2 **c**	5.0
$W3_{20}$	23.7 **a**	2.6	6.8 **a**	0.3	506 **ac**	55	1,462 **a**	456	18 **ab**	6	4.6 **ab**	1.7

Note: Different letters on lines represent statistically significant differences between the treatment units.



Note: Different letters represent statistically significant differences between the treatment units.

Figure 3 – Applied loads and removal efficiencies for (A) TS, (B) COD, (C) TKN, and (D) PO_4^{3-}-P in the six evaluated wetland units.

mechanisms, such as transport and detachment adhesion (Amirtharajah, 1988). This results in various forms of clogging (Soares, 2015), as well as the positioning of the clogged layer in the filter medium (surface or internal) (Lunardi *et al.*, 2022). The granulometric characteristics of the filter material used in this study (fine sand), combined with the physicochemical characteristics of the sludge, likely potentiated the formation of surface clogging. Due to the high density of accumulated sludge on the surface, it is possible that the clogged layer itself has also become a filtering medium, as observed in wetlands of the French System (Kim *et al.*, 2013; Molle, 2014), contributing to the solids capture mechanisms, as well as improving the physicochemical characteristics of the drained water by increasing the detention time. Interestingly, since the system is fed intermittently, the organic material accumulated on the surface tends to dehydrate and mineralize over time, leading to the reopening of the pores, which may improve the performance of effluent infiltration hydraulics (Trein *et al.*, 2020).

Along with the solid layer, plants also play a significant role in this process. Recently, the study by Al-Rashdi, Blackburn and Ahmed (2024) demonstrated that the dewatering process was facilitated by the presence of plants, decreasing moisture content, creating aerobic conditions, and concentrating the TS.

The units operated with average organic loading rates of 13–39 kg COD m^{-2} $year^{-1}$, higher than those traditionally used in vertical wetlands in Brazil, around 7.6 kg COD m^{-2} $year^{-1}$ (Sezerino *et al.*, 2023; ABNT, 2024). The WSMU exhibited average COD removal efficiencies ranging from 80 to 93%, achieving a mean effluent concentration of 348 mg L^{-1} at $W1_{20}$. This concentration can be compared to post-primary treated wastewater effluent, thus necessitating secondary-level treatment to meet more stringent standards for effluent discharge into surface waters, according to Brazilian legislation. WSMU can provide a variable range of treatment efficacies, depending on the characteristics of sludge and design parameters (Jain *et al.*, 2022). For COD, removal efficiencies of 42% (Wang *et al.*, 2022), 62–91% (Magri *et al.*, 2016), and 94–99% (Suntti *et al.*, 2010) are reported.

In the units with a saturation level of 0.20 m, the highest COD removal efficiencies were achieved, reaching 93, 93, and 91% for $W1_{20}$, $W2_{20}$, and $W3_{20}$, respectively. Units with a 0.10 m saturation level achieved 82, 85, and 80% ($W1_{10}$, $W2_{10}$, and $W3_{10}$, respectively) (Figure 3). A statistically significant difference in drained water concentrations and efficiencies was found when comparing the two saturation levels (Table 1, Figure 3). This difference can be attributed to the longer hydraulic detention time in units with a 0.20 m saturation level, resulting in a longer contact time between microorganisms and substrate and higher microbiological activity, thus increasing the removal efficiency (Torrens *et al.*, 2009; Bassani *et al.*, 2021). These results are consistent with studies by Prigent *et al.* (2013) and Silveira *et al.* (2015), which found that higher COD removal efficiencies are achieved by increasing the height of the saturation layers. Additionally, no significant differences were observed between the different applied loads.

Regarding TKN, the average removal efficiencies were over 90% in all experimental units (Figure 3). The efficiencies were similar for the different applied solid loadings and saturation levels (Table 1). However, $W1_{20}$ stood out with 98% efficiency in TKN removal, showing a significant difference compared to the other units in terms of effluent concentration. Reduced hydraulic loading rates lead to decreased wastewater percolation rates, thereby prolonging the contact time between the substrate and microorganisms (Decezaro *et al.*, 2019). Zhong *et al.* (2021) also noted an increase in nitrogen removal efficiencies with decreasing hydraulic loading rate (HLR) in vertical flow-constructed wetlands. In beds receiving a lower sludge loading rate, due to a shallower sludge layer, ammonia nitrogen removal tends to be higher, indicating that aerobic processes dominate in the bed (Stefanakis; Akratos; Tsihrintzis, 2014). Given this, it is likely that the superload that occurred at the beginning of the operation, which caused a rapid accumulation of solids in the WSMU, influenced the TKN removal performance. Besides, the better performance in the unit $W1_{20}$ may be associated with the higher hydraulic detention time (HDT) due to the greater saturation level (0.20 m) and the occurrence of nitrogen transformation and removal processes in the saturated zone, that is, nitrification followed by denitrification (Silveira *et al.*, 2015; Pelissari *et al.*, 2017; Bassani *et al.*, 2021).

The average efficiency of PO_4^{3-}-P removal was over 79%, achieving average removal of 97, 95, and 95% for units $W1_{20}$, $W2_{20}$, and $W3_{20}$, respectively. Similar results in PO_4^{3-}-P removal were obtained by Magri *et al.* (2016), also in a humid subtropical climate. A statistically significant difference was found between the saturation levels, demonstrating, once again, better performance in the WSMU with a 0.20 m saturation level (Table 1, Figure 3). The PO_4^{3-}-P removal is often related to adsorption in the filter media (Bolton *et al.*, 2019; Xu *et al.*, 2022; Gao *et al.*, 2024). The longer hydraulic detention time in the 0.20 m saturation units can possibly help this process, resulting in better performance (Bassani *et al.*, 2021; Saeed; Yadav; Miah, 2022). Furthermore, the presence of the sludge layer above the porous media layers serves as an extra treatment layer, slowing down the vertical drainage of water and prolonging contact time with the porous media, thereby enhancing the removal of phosphorus through various physical, biological, and chemical processes (Stefanakis; Akratos; Tsihrintzis, 2014).

The use of WSMU in developing countries, such as Brazil, can bring benefits beyond sludge management and water quality preservation. As an ecological technology for sludge treatment, the WSMU offers the advantages of low investment and low energy consumption, thus attracting attention (HU; CHEN, 2018). The proposed system is designed for sludge treatment facilities, which are intended to process sludge from a set of STs, such as those from a small community, a municipality, or even a group of small municipalities.

Macroscopic analyses

Concerning the macroscopic analyses, Figure 4 shows two photographs of the system at the beginning of the operation, after planting the *Canna x generalis* specimens (A), and at the end of the 150-day observation period (B). When analyzing the photographs, it is notable that, despite all the plants showing good apparent general development, in units with a saturation level of 0.20 m, the plants developed more quickly, reaching greater size and height. This may be associated with the higher humidity content in the units with a higher saturation level. Regarding the applied loads, there is a slight difference in the growth of the specimens transplanted into the units with a 0.20 m saturation level. However, in the 0.10 m units, there is a noticeable difference: the greater the applied load, the better the plant development and the taller it becomes. This is related to the characteristics of the applied sludge, which contains nutrients, including nitrogen and phosphorus, in forms available for assimilation by the plants (Gholipour *et al.*, 2024). Understanding the fundamental role of plants in treatment performance (Stefanakis; Tsihrintzis, 2012), the macroscopic analysis corroborates the greater efficiencies observed in units $W1_{20}$, $W2_{20}$, and $W3_{20}$ for nitrogen and phosphorus, as plants use these elements for their growth, contributing to increased efficiency of the units (Pelissari *et al.*, 2019).

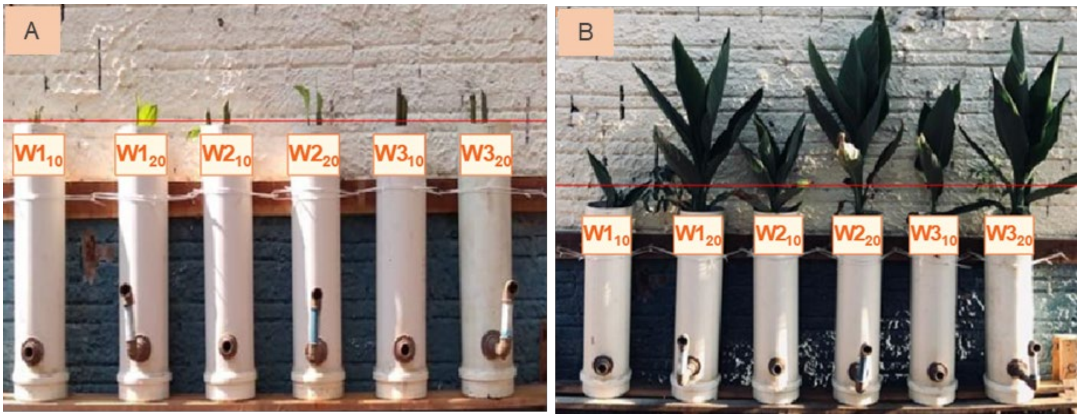


Figure 4 – (A) General view of the system after transplanting the *Canna x generalis* specimens and (B) at the end of the 150-day period (observe the red line indication and the units).

CONCLUSIONS

The system achieved good removal efficiencies, even at the beginning of operation, when compared to literature data, especially in units with a 0.20 m saturation level. This may be attributed, particularly, to the feeding mode and higher HDT due to the prolonged interaction time among microorganisms, the sludge, and the filter media.

For the climatic conditions of the study site, the operational conditions of the $W3_{20}$ unit are recommended for future studies due to the good removal efficiencies achieved (76% of TS, 91% of COD, 94% of TKN, and 95% of PO_4^{3-}-P), even with a higher TS load (120 L m^{-2} $week^{-1}$ and 42 kg TS m^{-2} $year^{-1}$). Additionally, testing even larger loads can help reduce area demand and lower implementation costs. It is also recommended to implement the super-load strategy at the beginning of operation. This can promote the rapid formation of the surface solids layer, enhancing treatment performance and avoiding sand layer clogging.

Therefore, the use of WSMU has been demonstrated to be a good alternative for the management of domestic wastewater sludge, as it requires very low maintenance, which may be advantageous in terms of medium and long-term costs. Furthermore, the system is aesthetically pleasing, adding landscaping value to the installation site, and the possibility of reusing the solids layer and drained water from WSMU units is an important factor provided by the technology, as it is aligned with the premises of circular economy and sustainable development.

AUTHORS' CONTRIBUTIONS

Santos, W.A.: Data curation, Formal analysis, Investigation. Rodrigues, G.A.: Formal analysis, Investigation, Visualization, Writing – original draft. Soares, M.: Writing – original draft, Writing – review & editing. Medeiros, R.C.: Conceptualization, Writing – review & editing. Decezaro, S.T.: Conceptualization, Formal analysis, Funding acquisition, Methodology, Project administration, Writing – original draft, Writing – review & editing.

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