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Treatment of dairy cattle farming wastewater using constructed wetland system cultivated with rice

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ABSTRACT

The amount of waste produced each day by dairy cattle is one of the largest problems in intensive management systems. Therefore, disposing of residues from animal facilities has become a challenge for farmers and specialists due to its technical, sanitary, and economic aspects. Organic effluents from confined dairy production systems require proper dairy wastewater treatment before disposal. When discharged into water bodies without adequate treatment, these effluents can cause physical and chemical changes in water sources, posing risks to public health and water supply due to the presence of pathogens and/or toxic elements. This study evaluates the efficiency of a constructed wetland system (CWS) cultivated with rice (*Oryza sativa*) in removing pollutants from dairy cattle wastewater, while also assessing the crop yield as an integral indicator of the system's performance. Given the limited number of samples collected, the results presented should be considered as a preliminary analysis, providing insights into the system's performance and potential for future studies. The constructed wetland system has a surface area of 4 m² and operates with a flow of 500 L dia^{-1} and hydraulic retention time of 1.72 days; gravel was used as a support medium. The analyses conducted led to the conclusion that the constructed wetland system, cultivated with rice, demonstrated effective pollutant reduction, particularly excelling in the removal of organic matter (35%), turbidity (43%) and nitrite (36%). Rice cultivation showed adaptation to the constructed wetland system, exhibited satisfactory growth, and showed no signs of nutrient deficiency.

Keywords: biological treatment, cultivated beds, reuse, water resources.

Tratamento de águas residuais da produção de gado leiteiro utilizando sistema de wetland construído cultivado com arroz

RESUMO

Desde que a quantidade de resíduos produzidos diariamente pelo gado leiteiro foi apresentada como um dos maiores problemas em sistemas de manejo intensive, o descarte de resíduos de instalações de animais tornou-se um desafio para fazendeiros e especialistas devido aos seus aspectos técnicos, sanitários e econômicos. Efluentes orgânicos de sistemas de produção de laticínios confinados requerem tratamento adequado de águas residuais de laticínios antes do descarte. Quando despejados em corpos d'água sem tratamento adequado, esses efluentes podem causar alterações físicas e químicas em fontes de água, representando riscos à saúde pública e ao abastecimento de água devido à presença de patógenos e/ou elementos tóxicos. O presente estudo teve como objetivo avaliar a eficiência do sistema de wetland construído (CWS) cultivado com arroz (Oryza sativa) na remoção de poluentes de águas residuais de gado leiteiro, ao mesmo tempo em que avaliou o rendimento da cultura como um indicador integral do desempenho do sistema. Dado o número limitado de amostras coletadas, os resultados apresentados devem ser considerados como uma análise preliminar, fornecendo insights sobre o desempenho do sistema e potencial para estudos futuros. O sistema de wetland construído possui área superficial de 4 m² e opera com vazão de 500 L dia-1 e tempo de retenção hidráulica de 1,72 dias; cascalho foi utilizado como meio de suporte. As análises conduzidas levaram à conclusão de que o sistema de wetland construído, cultivado com arroz, demonstrou redução efetiva de poluentes, destacando-se particularmente na remoção de matéria orgânica (35%), turbidez (43%) e nitrito (36%). O cultivo de arroz mostrou adaptação ao sistema de wetland construído, exibiu crescimento satisfatório e não apresentou sinais de deficiência de nutrientes.

Palavras-chave: canteiros cultivados, reuso, recursos hídricos, tratamento biológico.

1. INTRODUCTION

Throughout their lifetime cattle produce not only the products humans require but also a range of by-products, which can be used as organic fertilizers in plant cultivation. However, if discarded improperly or used inefficiently, these by-products become waste and cause significant environment damage (Vtoryi *et al.*, 2020). Bovine manure contains significant amounts of nitrogen and phosphorus. Improper management can lead to eutrophication of water resources and soil pollution. In contrast, proper management of these stabilized residues benefits the soil and crops, reducing the need for conventional chemical fertilizers (Hamacher *et al.*, 2019; Maciel *et al.*, 2019). Treating the final disposal of this effluent is essential for maintaining environmental quality.

In this context, Constructed Wetland Systems emerge as an alternative for effluent treatment. CWS were discovered through observation of transition areas between aquatic and terrestrial environments, where beneficial nutrient input from native plants and improved water quality were observed (Hammer and Bastian, 1989). Therefore, the CWS represent artificial reproduction of this nature condition, the substrate-plant-microorganism system and solar radiation as reactors for waste purification.

The treatment of wastewater in CWS has proven to be efficient in removing organic matter, total suspended solids, phosphorus, and other pollutants (Vymazal, 2011; Fan *et al.*, 2013; Li *et al.*, 2014; Cui *et al.*, 2015; Hamacher *et al.*, 2019). Alongside contaminant removal, the high biological activity facilitates the transformation of these pollutants into byproducts with lower contaminant potential and into essential nutrients used in biological life (Rodrigues, 2016, Jorge *et al.*, 2022; 2023). Some authors have even addressed that there is no contamination in edible plant material that has been in contact with this material, after passing through CWS, in the case of its use as fertigation in carrots, even resulting in greater root productivity (Jorge *et al.*, 2022). In other situations, for instance, when CWS was cultivated with vetiver grass, it also showed a reduction in nitrogen forms present in the effluent due to accumulation in the plants and removal facilitated by the microbial community (Jorge *et al.*, 2023).

Wastewater treatment can be carried out through physical processes (filters), physicochemical processes (flocculation), and biological processes (digestion) (Pacheco, 1995). Although a treatment technology may involve more than one process, there is always a predominance of one process that classifies it as a physical, biological, or chemical treatment technology. Therefore, effluent predominantly containing organic compounds should be treated using a technology classified as biological. The CWS is considered a physical and biological process, as it involves the retention of physical particles and the digestion of organic matter by the biofilm formed around the support medium.

In the present study, the primary innovation lies in the use of rice (*Oryza sativa*) in CWS for the treatment of dairy cattle wastewater (DCW). Rice was chosen due to its adaptability to flooded environments, high nutrient consumption, and ability to remove pollutants through phytoremediation, enhancing water quality. Additionally, rice serves as a biomonitor, allowing continuous observation of the system's environmental quality through crop development. While rice has been previously used in CWS for other types of effluents, such as domestic sewage, the integration of this crop with the treatment of DCW, which has a higher organic load, represents a novel and unexplored solution in the literature. Additionally, the specific climatic conditions of Seropédica, a tropical region, contribute to the uniqueness of this study.

CWS have demonstrated success in treating different types of effluents. For instance, Prado *et al.* (2008), reported reductions of 99% in biochemical oxygen demand **(**BOD),79-89% in nitrogen, and 54-72% in phosphorus for dairy effluents, considering the CWS superior alternative to ultrafiltration and biological filter methods. Silva (2007) achieved 97-99% reductions in BOD, 96-100% reductions in phosphorus and 9-37% reductions in electrical conductivity when treating domestic sewage in CWS cultivated with rice. Similarly, Matos *et al.* (2010) observed 86% BOD removal 59% total nitrogen removal, and 62% of total solids removal in CWS. These findings reinforce the potential of CWS technology for diverse effluent types.

The use of aquatic macrophytes enhances pollutant removal in CWS (Queluz, 2016; Silva, 2007). Furthermore, the crop used in the CWS can provide information about wastewater quality. In this study, the choice of rice (*Oryza sativa*) is justified by its adaptability to CWS and its capacity for phytoremediation, removing pollutants present in the system. Thus, rice cultivation serves as a biomonitor, enabling continuous observation of the environmental quality within the system.

The present study aimed to evaluate the efficiency of the constructed wetland system cultivated with rice (*Oryza sativa*) in the post-treatment of dairy cattle wastewater, while also assessing the crop yield as an integral indicator of the system’s performance. Given the limited number of samples collected, the results presented should be considered as a preliminary analysis, providing insights into the system’s performance and potential for future studies.

2. MATERIAL AND METHODS

2.1. Study Area

The study was conducted in the experimental area of the Integrated Agroecological Production System (SIPA), also known as the "Agroecological Farm," located in the municipality of Seropédica, in the state of Rio de Janeiro - Brazil (latitude 22º48'00" S; longitude 43º41'00" W; altitude of 33 meters). According to the Köppen classification, the climate of the region is classified as Aw, with concentrated rainfall from November to March, an average annual precipitation of 1,213 mm, and an average annual temperature of 24.5°C (Carvalho *et al.*, 2006). The experiment was conducted between March and August 2015.

2.2. Pilot System Description

The pilot station (Figure 1) for dairy cattle wastewater treatment (DCW) was composed of a sedimentation tank (P1), anaerobic filter (P2), inert material filter (P3), and constructed wetland system (CWS) of horizontal subsurface flow" (P4).

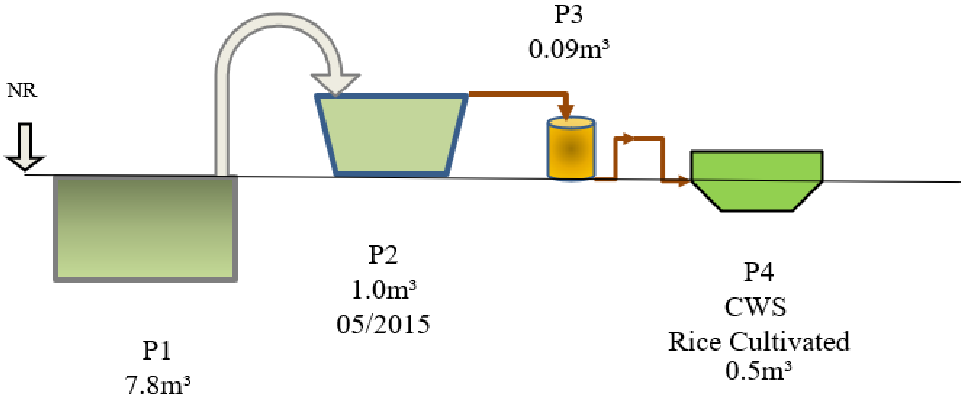

Figure 1. Scheme of the pilot experiment.

2.3. Characteristics of DCW and CWS

Considering the activity carried out at the Agroecological Farm at kilometer 47 located in the municipality of Seropédica - RJ, the concentration of dairy cattle effluent varies and is subject to characteristics peculiar to the operator, such as the volume of water used in the corral cleaning and the number of cleanings, as well as the time of year, which influences the rainfall index, leading to effluent dilution, and the number of milked cows, as the population increases during the rainy season, with an average occupation of 30 animals, of different ages. The dairy cattle wastewater comprises water from cleaning, rainfall, water troughs, urine, feces, milk, and hair. Initially, pre-treatment of the wastewater was carried out due to the high concentration of solids in the effluent. For this, a septic tank was used, where the water was kept for sedimentation for at least 14 hours. After leaving the septic tank, the effluent passed through an anaerobic filter. This filter consisted of a water tank filled with gravel (grain size ranging from 9.5 mm to 19 mm). It had a vertical and upward flow, where the wastewater passed through the gravel layer from bottom to top, maintaining anaerobic conditions. Next, the effluent passed through an inert material filter. This filter consisted of a plastic tank containing shredded plastic conduit inserted between two layers of gravel (grain size ranging from 9.5 mm to 19 mm). Finally, the effluent moved to the constructed wetland system, as described in Jorge *et al.* (2023).

The constructed wetland system (CWS) was built using masonry and lined with a 0.5 mm thick PVC liner. Its interior was filled with 40 cm of gravel 1 and 5 cm of sand to support the vegetation, covering a surface area of 4 m². The CWS was constructed in a trapezoidal shape, with a smaller base measuring 0.5 m and a larger base measuring 1.3 m.

The treatment system was fed twice a day, once in the morning and once in the afternoon, with 250 liters of effluent each time, totaling 500 liters per day. Therefore, the hydraulic detention time (HDT) in the CWS was 1.72 days (41 hours), considering the void volume of gravel 1 to be 50%.

The Table 1 below presents the variables of dairy cattle wastewater before treatment. The values were obtained by averaging 6 samples.

Table 1. Variables of dairy cattle wastewater before treatment.

Variables	Average values
Chemical Oxygen Demand (mg L^{-1})	1974
Phosphorus (mg L^{-1})	76
Ammonia (mg L^{-1})	230
Nitrate (mg L^{-1})	47
Nitrite (mg L^{-1})	2.17
Total Kjeldahl Nitrogen (mg L^{-1})	121
pH	6.79
Color (Pt Co)	6722
Turbidity (FTU)	475

2.4. Rice (Oryza sativa)

Rice (*Oryza sativa*) was selected as the study crop due to its adherence to the flooded environment, as it is a species adapted to this environment (Brasil, 2005), due to its high nutrient consumption in these flooded environments and its ability to effectively remove pollutants. from contaminated water sources and soil (Ferreira, 2012; Matos *et al.*, 2010; Silva, 2007). There are different varieties that are cultivated according to the characteristics of the environment in which they will be implanted. Therefore, for the treatment of cattle effluent, the variety SCS 116 Satoru was chosen, which has the following characteristics: long cycle, good stature, lodging resistance, high tillering, high-quality grains, average productivity of 9.4 tons per hectare, average height of 95 cm, susceptible to blast disease, and resistant to iron toxicity (EPAGRI, 2014). The seedlings were produced in seedbeds, with three seeds sown in each hole on March 10, 2015.

After 21 days, on April 1st, the seedlings were transplanted into the constructed wetland system at a spacing of 15 X 15 cm, totaling 126 plants. It is noteworthy that these seedlings were in the subperiod of vegetative development and Stage V2, where the seedling has the collar formed on the second leaf.

The harvest was conducted when the grains reached a cream color, which occurred on August 3, 2015, 143 days after germination. The CWS was subdivided to analyze the performance of the crop throughout the system, so each meter of length was considered a sector, totaling four sectors. In each sector, five representative rice plants were collected, forming five repetitions per sector, totaling twenty plants. The borders were removed to reduce the effect of external elements such as wind, increased incidence of pests, and solar radiation.

At the time of harvest, the following characteristics were determined: aboveground length (DMAP), root length (RL), aboveground dry mass (APL), and root dry mass (DMR). The length was measured with a measuring tape. The roots and aboveground parts were dried in an oven for 72 hours at 60°C, and then weighed on a scale. The harvest was carried out when the grains reached a cream color, 143 days after germination.The results were subjected to analysis of variance ($p \leq 0.05$), where the means were compared using Tukey's test.

2.5. Performance Evaluation of the System

The performance of the constructed wetland system was evaluated through the following analyses: chemical oxygen demand (COD), phosphorus, ammonia, nitrate, nitrite, total Kjeldahl nitrogen, turbidity, color, and pH.

The analyses were performed at the Environmental Monitoring Laboratory I - Water and

Effluents of the Department of Engineering at Federal Rural University of Rio de Janeiro (UFRRJ), following the recommendations outlined in the Standard Methods for the Examination of Water and Wastewater (APHA *et al.*, 1998). The primary residues from dairy cattle farming were the feces and urine of the cattle; however, the effluent also contained wash water, hair, milk (colostrum), and fat from the animal's body and milk.

3. RESULTS AND DISCUSSION

The results regarding the average values of the variables chemical oxygen demand, phosphorus, ammonia, nitrate, nitrite, total Kjeldahl nitrogen, pH, color, and turbidity at the inlet and outlet of the CWS are presented in Table 2.

Table 2. Analysis of the means and standard deviations of the inlet and outlet of the constructed wetland system.

Variables	Inlet**	Outlet**
Chemical Oxygen Demand (mg L^{-1})	987.6 ± 668.6	645.8 ± 374.3
Phosphorus * (mg L^{-1})	59.5 ± 16.6	52.1 ± 16.6
NH_3 (mg L^{-1})	212.2 ± 162.7	171.9 ± 129.2
NO_3 (mg L^{-1})	16.8 ± 3.5	14.5 ± 4.4
NO_2 (mg L^{-1})	0.9 ± 0.2	0.6 ± 0.15
Total Kjeldahl Nitrogen (mg L^{-1})	85.5 ± 23.4	70.9 ± 19.5
pH	7.2 ± 0.2	7.1 ± 0.1
Color (Pt Co)	3106.2 ± 897.1	2464.6 ± 953.0
Turbidity (FTU)	148.7 ± 38.7	86.4 ± 32.2

NH_3 : Ammonia; NO_3 : Nitrate; NO_2 : Nitrite.
*Phosphorus values were measured as orthophosphate (PO_4)
** Results based on the evaluation of 6 samples.

It was observed that the concentration of all variables analyzed in the effluent at the outlet of the CWS was lower than the concentration at the inlet, indicating a reduction of these variables in the system. The reduction of pollutants is observed in several studies with different types of wastewater using constructed wetland systems, whether cultivated or not (Tee *et al.*, 2009; Mendonça *et al.*, 2015; Silva and Roston, 2010; Cui *et al.*, 2015).

The high standard deviation values can be explained by the lack of control over the wastewater reaching the DCW receiving tank, which came directly from the cattle pen and was pumped directly into the treatment system. This resulted in variations in the concentration of elements and pollutants in the wastewater used. High standard deviation values have also been observed by Wu *et al.* (2014) in various studies that used different types of CWSs for pollutant removal in wastewater.

The observed pH remained within the neutrality range. Within this range, the nutrients necessary for crop development are available, which helps in the better performance of the CWS. Determining and controlling pH is important as it influences treatment processes, whether physical, chemical, or biological. pH affects the availability of ions (Jimenez *et al.*, 2004) and microbial activity. Therefore, pH is considered an easily monitored parameter that quickly indicates any issues in the treatment station.

The removal efficiency and standard deviation of the variables COD, phosphorus, ammonia, nitrate, nitrite, total Kjeldahl nitrogen, color, turbidity, and pH, using the subsurface horizontal flow constructed wetland (CWS) cultivated with rice, can be seen in Figure 2.

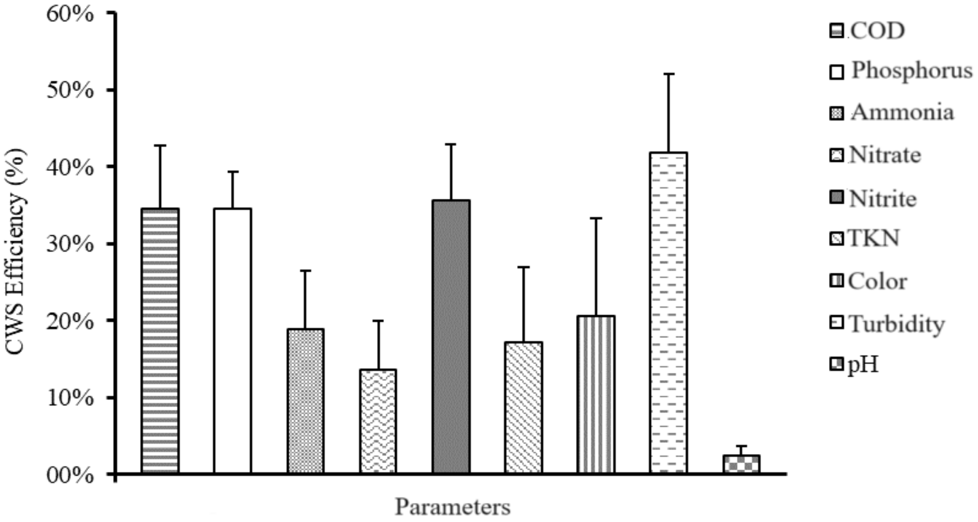

Figure 2. Removal efficiencies and standard deviations of the variables chemical oxygen demand (COD), phosphorus, ammonia, nitrate, nitrite, total Kjeldahl nitrogen (TKN), color, turbidity, and pH using the subsurface horizontal flow constructed wetland (CWS) cultivated with rice.

3.1. Chemical Variables

As stated in the methodology, the average COD at the treatment system inlet is 1974 mg L^{-1}; however, the objective of this study is the analysis of a specific component of the treatment system, the CWS. Therefore, the values presented below refer to the inlet and outlet of the CWS.

The COD at the inlet and outlet of the CWS was 987.6 and 645.8 mg L^{-1}, respectively, indicating a high organic load for the treatment system. Regarding the COD parameter, a reduction of 35% was observed, which was lower than the values found by other authors (Oliveira *et al.*, 2015; Mendonça *et al.*, 2015; Silva and Roston, 2010; Matos *et al.*, 2010), who observed removal efficiencies ranging from 70 to 99%. However, Vymazal (2014) conducted a literature review analyzing the efficiency of CWS utilization in different types of effluents, and through this review, it was found that the minimum COD removal was 30%. Wu *et al.* (2014) analyzed different studies conducted with CWSs and found a wide range in COD removal efficiency, with the lowest and highest values observed being 5% and 98.7%, respectively.

High fat concentration was observed in the effluent, potentially originating from milk, feces, and/or the animals themselves. The high lipid concentration in the effluent increases the percentage that cannot be digested by microorganisms. Lipids are only removed by biological processes (lipases, digestion) or physical processes (grease trap) (Mendes *et al.*, 2005). This lipid was accounted for in the COD, but was not removed by the system, increasing the percentage not eliminated by the treatment process. A longer contact time between the treatment system and the effluent is necessary for microorganisms to decompose this organic load.. To achieve this, increasing the size of the CWS and/or reducing the inlet flow rate is essential. Another option is to install a vertical flow CWS before the horizontal flow CWS. Vertical flow promotes the oxygenation of wastewater, favoring the reduction of COD concentration at the inlet of the CWS. Cui *et al.* (2015) achieved better COD removal results in a hybrid CWS using vertical CWS followed by horizontal CWS with a hydraulic retention time of two days. The removal of COD likely occurred through the removal of organic matter via aerobic pathways in the root zone and anaerobic pathways in the lower part of the CWS, where there is no oxygen supply by the macrophytes (Mendonça *et al.*, 2015).

Similarly, Thalla *et al.* (2019) also emphasized the benefits of hybrid systems combining vertical and horizontal flow constructed wetlands for the treatment of domestic wastewater. These configurations enhance COD removal by leveraging the oxygenation provided by vertical flow and the anaerobic pathways supported by horizontal flow. The COD removal efficiencies reported in their study (62–74%) were higher than those observed in the present study (35%). This difference could be attributed to the high organic load in dairy cattle wastewater, the short hydraulic retention time (1.72 days), and the purely horizontal configuration of the constructed wetland system used here.

It was found that the average concentrations of phosphate, ammonia, and nitrate in the effluents at the outlet of the rice-cultivated CWS were 52.1, 171.9, and 14.5 mg L^{-1}, respectively, indicating that there is still a pollutant potential in the effluent if improperly disposed of in the environment, even after treatment. Thus, regarding these nutrients, potential forms of wastewater reuse, especially agricultural reuse, should be encouraged provided that agronomic and environmental criteria are considered.

The efficiency of the CWS in removing phosphorus was 12.3%. According to Vymazal (2007), phosphorus removal in all types of CWSs is low unless special substrates with high adsorption capacity are used. The use of alternative substrates such as lightweight clay aggregates and industrial slag, among others, can increase phosphorus removal efficiency in constructed wetland systems. Thalla *et al.* (2019) further highlighted the challenges in phosphorus removal in horizontal flow systems, even with engineered substrates aligning with the 12.3% removal efficiency found in this study. This result was higher than that obtained by Pelissari (2013), who achieved 10% phosphorus removal efficiency using CWS. Most of the phosphorus is removed by the accumulation of organic phosphorus in the support medium and due to its immobilization by microorganisms (Matos *et al.*, 2010). The same authors achieved phosphorus removal efficiencies ranging from 33 to 55%; however, they emphasized that there are studies in the literature where the phosphorus concentration increased after the wastewater passed through CWS treatment, thus not achieving efficiency in water treatment. They highlighted that a possible cause for low removal or an increase in phosphorus concentration at the CWS outlet is water loss from the system through evapotranspiration, underestimating or nullifying the efficiency obtained in CWS.

The values found for phosphorus ranged from 29 to 80.50 mg L^{-1}, with an average removal percentage of 1.5%. Figure 3 shows the variation of this parameter over time, with a reduction in phosphorus concentration observed in all sample collections. The low removal of this parameter may be due to the short contact time between the effluent and the CWS and the high organic load at the inlet (Fia *et al.*, 2010).

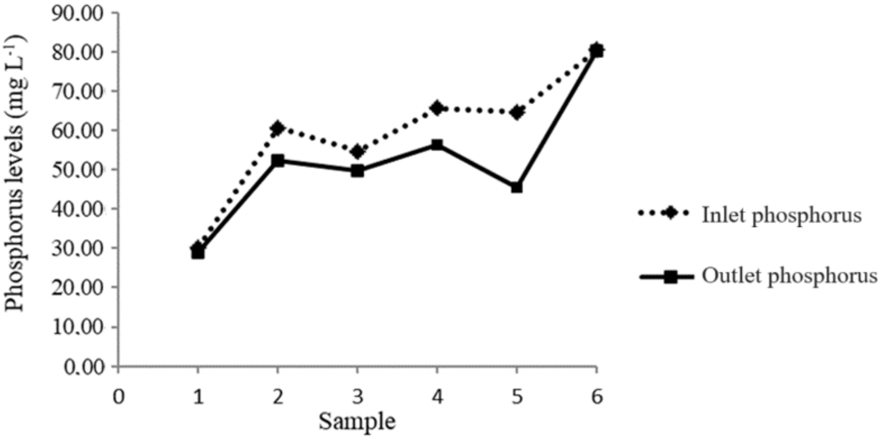

Figure 3. Variation of phosphorus values at the inlet and outlet of the CWS.

Nitrogen exists in various forms in the effluent. The removal of nitrogen in CWSs begins after the transformation of organic nitrogen into inorganic nitrogen, a process called ammonification. Organic nitrogen can be converted into ammonia (NH_3) or ammonium (NH_4^+), where environments with Ph near or below neutrality favor the predominance of NH_4^+ (Nunes, 2012). The ammonium ion can be absorbed by the crop and/or oxidized to nitrate through the nitrification process (Saeed *et al.*, 2012). The removal of ammonia (NH_3) was 19%. The high organic load applied at the CWS inlet likely favored the ammonification process, increasing ammonia values in the effluent. Consequently, the contribution of this substance by the crop and the nitrification process were masked by the favoring of ammonification, thus reducing the system's efficiency.

The nitrite concentration was low, ranging between 0.6 and 0.9 mg L^{-1}, indicating good oxygen transfer conditions through the rice root system, maintaining an aerobic environment in the root zone (Sousa *et al.*, 2000). Nitrite is an ion in intermediate reaction conditions, as it is formed from the nitration process, which is the first oxidation of ammonia in the nitrification pathway (Nunes, 2012). For this reason, it is common for nitrite to be found in low concentrations in constructed wetland systems.

It is noteworthy that the average concentrations of chemical oxygen demand, phosphorus, ammonia, nitrate, nitrite, total Kjeldahl nitrogen, Ph, color, and turbidity in the effluent at the outlet of the CWS remained dependent on the concentrations of these variables in the incoming livestock wastewater into the system. There was no observed concentration pattern of the analyzed variables at the system's outlet.

Nitrate removal was 14%. Nitrate removal occurs through the process of denitrification, where nitrate is reduced to atmospheric nitrogen. This metabolic pathway occurs in environments with oxygen restriction, namely the lower part of the CWS (Saeed *et al.*, 2012). Nitrate can also be absorbed by the crop (Wu *et al.*, 2014). To achieve higher nitrate removal efficiency, it would likely be necessary to adopt a longer hydraulic retention time (Matos *et al.*, 2010; Vymazal, 2009), given ideal Ph conditions, availability of organic carbon, and anaerobic conditions in the lower part of the CWS. According to Wu *et al.* (2014), low nitrate removal typically occurs in CWSs.

Nitrite is an ion in intermediate reaction conditions, as it is formed from the nitration process, which is the initial oxidation of ammonia in the nitrification pathway (Nunes, 2012). Therefore, it is common to find it in low concentrations in constructed wetland systems. Treatment using the CWS provided good nitrite removal, which was 36%.

The data presented showed an average removal of 17%, indicating nitrogen input by the treatment system. As highlighted earlier, achieving higher removal would require a longer hydraulic retention time (Matos *et al.*, 2010; Vymazal, 2009), as the lack of necessary contact time between the effluent and the CWS substrate can reduce system efficiency (Fia *et al.*, 2010). Sousa *et al.* (2000) achieved an 87% reduction in TKN in a SAC cultivated with emerging macrophytes (*Juncus sp*), attributed to nitrification and denitrification processes. Pelissari (2013) observed an 80% removal of TKN in a horizontally-flowing CWS treating effluent from dairy cattle farming. Tanner *et al.*, (2005) used constructed wetlands in treating wastewater from dairy cattle farming and achieved a total nitrogen removal of 79% in the first year and only 21% in the second year of the study.

According to Vymazal (2007), simple constructed wetland systems cannot achieve high total nitrogen removal due to their inability to provide aerobic and anaerobic conditions simultaneously. While vertical flow constructed wetlands successfully remove ammonia, denitrification occurs only to a limited extent in these systems. On the other hand, horizontal flow constructed wetlands offer good conditions for denitrification, but their capacity to nitrify ammonia is very limited. Therefore, the use of more than one type of constructed wetland is recommended to achieve better efficiency in removing this pollutant.

When compared to another type of wastewater treatment chamber setup, this reduction in pollutants was also observed, especially for the removal of *E. coli*. This system also consisted of three stages: a septic tank, a sand and biochar filter chamber, and a chlorination chamber, providing a comprehensive solution and proving viable for the treatment of domestic wastewater (Majumder and Das, 2022). This demonstrates that alternative methods can also be highly effective for wastewater treatment, as long as their efficacy is validated across various scales.

3.2. Physical Variables

The turbidity showed a removal rate of 43%, with values ranging from 5.52 to 195.50 FTU. The wide range in the analyzed values is due to consecutive days of heavy rainfall, resulting in the dilution of the effluent.

The removal of turbidity results from the filtration process through the substrate and root system. Similar findings were reported by Wurochekke (2014) in the use of constructed wetlands for greywater treatment. Oliveira *et al.* (2015), also working with greywater, achieved a turbidity removal of 94%; however, to obtain this result, the authors used a horizontal flow constructed wetland followed by a vertical flow wetland system. Figure 4 illustrates the behavior of this variable at the inlet and outlet of the constructed wetland.

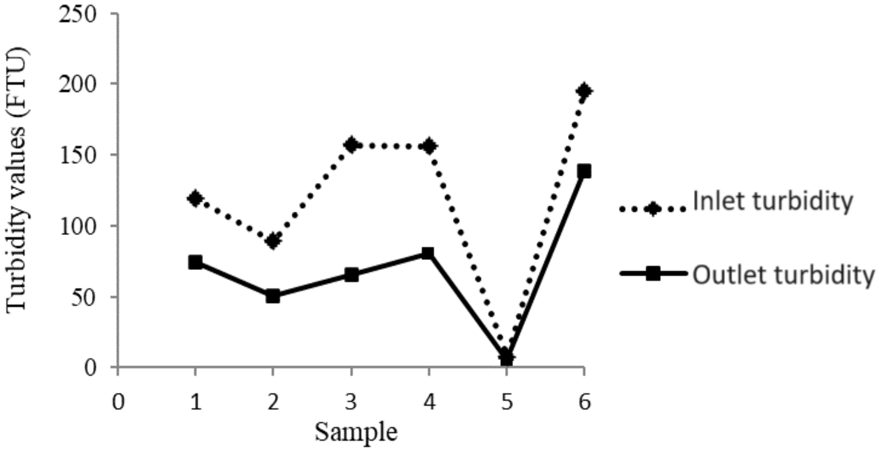

Figure 4. Variation of turbidity values at the inlet and outlet of the CWS.

The color parameter showed a removal of 21%, ranging from 1300 to 4125 PtCo. To achieve a greater removal of this parameter, it would be necessary to increase the contact time of the effluent with the support medium, as stated by Oliveira *et al.* (2015), where the time required to remove the high amount of dissolved solids exceeds two days.

3.3. Rice crop analysis

The average values of dry mass of the aboveground part , dry mass of the root , root length, and aboveground part length of the rice crop along the constructed wetland system can be observed in Table 3.

In principle, it is important to highlight that Sector 1 is the closest location to the arrival of the wastewater, while Sector 4 is the farthest. Therefore, we can infer that the first sector is more susceptible to interference from pollutants present in the wastewater since it is in contact with more concentrated wastewater than the other sectors.

The dry mass of the aerial part and the roots in the first sector was statistically higher than in the other sectors. These results highlight two important facts. The first fact is that the pollutants present in the dairy cattle wastewater (DCW) did not cause damage to the crop, thus concluding that there was no phytotoxicity. The second fact involves the beneficial value of

DCW for the crop, as the plants that had more contact with the DCW showed greater mass. These results are in line with those found by Nogueira (2003), in which rice shows good development and is advantageous for the sewage treatment system.

Table 3. Average values of dry mass of the aboveground part (DMAP), dry mass of the root (DMR), root length (RL), and aboveground part length (APL) of the rice crop along the constructed wetland system.

Sector	DMAP (g)	DMR (g)	RL (cm)	APL (cm)
S1	91.2 a	79.6 a	26.0 b	97.2 ^{ns}
S2	70.4 b	38.1 b	30.2 ab	98.2 ^{ns}
S3	75.9 ab	43.2 b	35.0 a	101.0 ^{ns}
S4	69.3 b	39.8 b	37.2 a	100.2 ^{ns}

^{ns} - not significant at 5% significance level by Tukey's test. Values in the same column, followed by identical letters, do not differ from each other by Tukey's test at 5% significance level.

The root length in the first sector was different from the third and fourth. It is observed that the farther from the origin of the bovine wastewater (DCW), the longer the root length, which can be explained by the hydraulic regime of the CWS. At the beginning of the CWS, besides a higher concentration of pollutants, there is a closer proximity of the DCW to the surface; as the length increases, the subsurface flow establishes itself, and the CWW becomes slightly farther from the surface. Therefore, the rice plants in the initial sectors received more pollutants at shallower depths, so there was no need to develop the root system for water and nutrient uptake. The values found were lower than those found by Sarmento (2010), where a root length of 35 cm was observed for the three studied crops: Cyperus sp, Heliconia rostrata, and Hedychium coronarium.

The length of the aboveground part did not show statistical difference along the CWS; this result may be attributed to the fact that the cultivar had already reached its maximum height, since the values found were higher than those established by the cultivar, which is 95 cm (EPAGRI, 2015).

The good performance of this crop not only demonstrates its good adaptation to the CWS but also indicates that the DCW provided the necessary nutrients for its development. Additionally, no symptoms of toxicity or nutrient deficiency were observed in the rice crop, based on visual analysis of the leaves, roots, and grains.

In the study conducted by Ferreira (2012) on the treatment of swine wastewater using surface flow constructed wetlands (CWS) cultivated with rice, a good development of the crop was observed. However, difficulties were reported during the transplanting of seedlings into the CWS, as the high concentration of nutrients in the wastewater favored eutrophication, leading to plant death. In the current study, there were no difficulties during transplanting, as the flow is subsurface, and therefore there was no initial contact of the root system with the wastewater.

The greater efficiency of constructed wetlands (CWS) with vegetation compared to CWS without crop cultivation is not unanimous; however, most studies have shown that systems with plants have higher treatment efficiency, especially in the removal of organic matter and nutrients (Vymazal, 2011).

According to Vymazal (2009), satisfactory results in treating dairy cattle wastewater using horizontal subsurface flow constructed wetlands (CWS) have been observed by several authors regardless of the crop used in the CWS. However, Tee *et al.* (2009) compared CWS with and without crops and found better nutrient removal performance using cultivated CWS. According to the same authors, this occurs due to the creation of microaerobic zones in the root zone of CWS plants, allowing for a faster rate of biodegradation and nutrient uptake by the plants.

4. CONCLUSIONS

The use of rice in constructed wetland systems is important due to the adaptation of this crop to flooded environments and its high nutrient consumption, as evidenced by analyses which found that the constructed wetland system cultivated with rice showed good pollutant removal, with higher efficiency in the removal of organic matter (35%), turbidity (43%), and nitrite (36%), and low removal of nitrate (14%), TKN (17%) and color (21%). In terms of biomass production, rice showed greater gain in the first cultivation sector, both in the aerial parts and in the root system, where the highest concentration of nutrients was found. This demonstrated no phytotoxicity, as the nutrients present in this livestock wastewater were essential in the initial sector for the proper growth and development of the crop. This was not observed in the last cultivation sector, where there was a reduction in biomass gain, although there were no visible signs of nutrient deficiency.

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