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Scientific Paper

Performance evaluation of wastewater treatment plants in Southern Brazil

Análise de desempenho dos sistemas de esgotamento sanitário do Sul do Brasil

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ABSTRACT

This study assesses the influent and effluent characteristics and the removal efficiency of 56 wastewater treatment plants (WWTPs) operating in Brazil's southern region, in the Rio Grande do Sul state. The analysis encompasses the main secondary wastewater treatment processes used in the country, such as septic tank and anaerobic filter, activated sludge with sequencing batch reactor and with extended aeration, upflow anaerobic sludge blanket reactor followed by trickling filter, anaerobic and facultative ponds, and the combination of anaerobic, facultative, and maturation ponds. The parameters evaluated were biochemical oxygen demand (BOD), chemical oxygen demand (COD), ammoniacal nitrogen (NNH_3), total phosphorus (TP), total suspended solids (TSS), and *Escherichia coli*. The influent concentrations of BOD, COD, and TSS were considerably lower than other values reported in studies in Brazil, indicating that the analyzed WWTPs operate with a diluted influent, with respective average ranges of 38–189, 203–416, and 75–242 $mg{\cdot}L^{-1}$. The effluent concentrations were also lower than the reference values, although the differences were not as pronounced as in the influent. No significant distinctions were observed between the removal efficiencies obtained and other results in the literature, except for TSS, which had a weaker performance. Concerning the technologies, lower performance was observed for BOD, COD, and TSS removal in the septic tank and higher removal rates of TP for the activated sludge systems. This study represents the first comprehensive dataset on the performance of WWTPs in Brazil's southern region, contributing to the understanding of wastewater management practices in the country by indicating potential points for improvement.

Keywords: performance evaluation; removal efficiency; wastewater treatment plants; statistic; wastewater treatment technologies.

RESUMO

O presente estudo caracteriza o afluente, o efluente e a eficiência de remoção de 56 estações de tratamento de esgoto (ETEs) em operação no Rio Grande do Sul, Brasil. A análise abrange os principais processos de tratamento de esgoto utilizados no país: fossa séptica e filtro anaeróbio, lodo ativado com reator sequencial em batelada e com aeração estendida, reator UASB e filtro biológico, lagoas anaeróbias e facultativas, e a combinação de lagoas anaeróbias, facultativas e de maturação. Os parâmetros avaliados foram demanda bioquímica de oxigênio (DBO), demanda química de oxigênio (DQO), nitrogênio amoniacal (NNH_3), fósforo, sólidos suspensos totais (SST) e *Escherichia coli*. As concentrações afluentes de DBO, DQO e SST (intervalos médios respectivos de 38–189, 203–416 e 75–242 $mg{\cdot}L^{-1}$) foram inferiores às reportadas em outros estudos no Brasil, indicando que as ETEs analisadas operam com um afluente mais diluído. O efluente também apresentou concentrações abaixo dos valores de referência, embora essas diferenças não tenham sido tão acentuadas quanto no afluente. Em geral, não foram observadas discrepâncias significativas entre as eficiências de remoção obtidas e outras estimativas da literatura, exceto para SST, com valores inferiores de remoção. Fossas sépticas obtiveram menor eficiência na remoção de DBO, DQO e SST, enquanto sistemas de lodo ativado foram melhores na remoção de fósforo. Este estudo representa o primeiro conjunto de dados abrangente sobre o desempenho de ETEs na região Sul do Brasil, identificando áreas potenciais para aprimoramento e contribuindo para uma melhor gestão desses sistemas.

Palavras-chave: avaliação de desempenho; eficiência de remoção; estações de tratamento de esgoto; estatística; tecnologias de tratamento de esgoto.

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INTRODUCTION

Wastewater treatment plants (WWTPs) are facilities that use a combination of different equipment and processes to treat sewage produced by human activities, aiming to reduce health risks and environmental damage (Gómez *et al.*, 2017). Playing this crucial role in society, these systems incur substantial construction and operational costs to achieve higher pollutant removal efficiency and ensure reliable processes. The day-to-day analysis of operational data within these procedures can identify systemic limitations, which can ultimately optimize the entire WWTP. This improvement relies on continuous monitoring and effective use of its results (von Sperling; Verbyla; Oliveira, 2020). The complexity and size of these datasets combined with the operators' need for data science skills, however, make it challenging to collect, manage, and analyze these products efficiently (Newhart *et al.*, 2019). On the contrary, this analysis is necessary as the efficiency of these systems may deviate from expected values, posing a potential risk of environmental contamination.

Several academic studies have been conducted related to the physical, chemical, and biological unit processes involved in the design and operation of WWTPs. Nevertheless, research involving these systems' performance based on monitoring data is relatively scarce in Brazil, with restricted temporal and spatial coverage. To the best of the authors' knowledge, there has been no comprehensive data collection and evaluation of WWTPs operating in Brazil's southern region. In fact, there are only a few studies addressing this topic in the country, in the states of Minas Gerais and Sao Paulo (Oliveira; von Sperling, 2011; Leonel, 2016; Dantas; Barroso; Oliveira, 2021), Ceara (Monteiro, 2009), and Rio Grande do Norte (Silva Filho, 2007).

The values reported in these locations can be quite distinct from those found in the southern region, specifically in the Rio Grande do Sul state. Rio Grande do Sul has a more temperate climate compared to the tropical climate found in many other Brazilian states, predominantly humid subtropical with a hot summer (Cfa, according to the Köppen climate classification) and subtropical highland (Cfb) (Alvares *et al.*, 2013). The state's total and urban sewage system coverage was only 34.1% and 39.3% in 2021, as reported by the Brazilian National System for Water and Sanitation Data (Brasil, 2021). In contrast, these numbers were considerably higher at the national level, at 55.8 and 64.1%, respectively. The southern region's performance in this aspect falls behind that of the central-west and southeast regions, which have total coverage rates of 48.4 and 55.3%, respectively.

In this context, this study aims to describe and analyze the influent and effluent characteristics as well as the performance of the leading secondary treatment technologies used in the WTTPs in the Rio Grande do Sul state, Brazil. For this purpose, the influent and effluent concentrations of these systems were collected and compared before and after treatment. The results provide a novel perspective on the performance of WWTPs in Brazil, representing the first reported values for the southern region and covering many scrutinized structures operating over several years. In the long run, the study is an essential subsidy for public environmental protection policies and compliance with state and national regulations.

METHOD

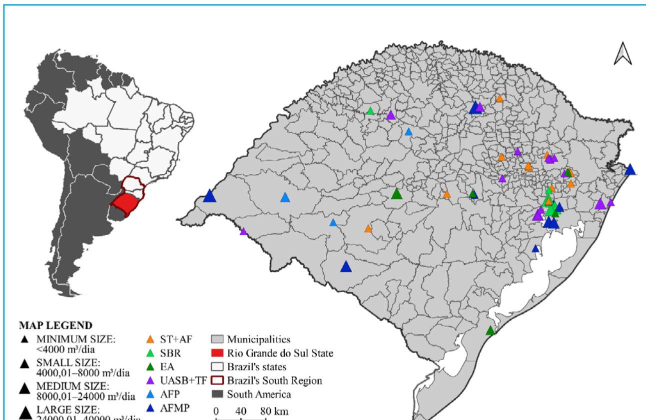
The research assessed the performance of 56 WWTPs in the Rio Grande do Sul state in south Brazil, according to six main secondary treatment technologies (Figure 1). The wastewater treatment technologies were selected based on the main typologies within the inventoried database and Brazil's most adopted secondary treatment, as published by ANA (2020). The analyzed technologies, along with their simplified designations used throughout the study, were as follows: septic tank followed by an anaerobic filter (ST+AF), activated sludge with sequencing batch reactor (SBR) and with extended aeration (EA), upflow anaerobic sludge blanket reactor along with a trickling filter (UASB+TF), anaerobic ponds plus facultative ponds (AFP), and a system of anaerobic ponds followed by facultative and maturation ponds (AFMP).

The analysis excluded WWTPs that reported having any of the following conditions:

(1) disposal of untreated sanitary wastewater in infiltration basins;
(2) non-use of a separate sewerage system; and
(3) receiving a portion of industrial wastewater.

Assessing treatment efficiency in infiltration basins is notably challenging compared to other wastewater treatment methods. Disposing of effluent into the soil can be viewed as a final destination and not properly as a treatment technology. In this regard, monitoring groundwater through wells would be analogous to monitoring the surface water body. Besides, WWTPs with combined sewers (with stormwater contribution) or industrial inputs can significantly alter constituent concentrations based on the amount of precipitation, stormwater infrastructure, and industrial typology.

The study used data from self-monitoring reports submitted by WWTPs' operators holding valid operation licenses issued by the state's environmental agency (State Foundation for Environmental Protection—FEPAM). Data collection spanned from January 2015 to December 2021. The parameters selected were determined based on the most monitored requirements in state and federal regulations: biochemical oxygen demand (BOD), chemical oxygen demand (COD), ammoniacal nitrogen (NNH3), total phosphorus (TP), and total suspended solids (TSS) recorded in $mg \cdot L^{-1}$, and *Escherichia coli* (*E. coli*) in $MPN \cdot 100\ mL^{-1}$. Influent concentrations were measured immediately at the



Source: author's production. Municipalities and Rio Grande do Sul state files (Fepam, 2005), regions and states of Brazil and South America files (IBGE, 2017).

Figure 1 – The locations of the WWTPs analyzed, differentiated by size and treatment technology, in the context of South America, Brazil, and municipalities in the Rio Grande do Sul state. Technologies designations: septic tank + anaerobic filter (ST+AF), activated sludge with sequencing batch reactor (SBR) and with extended aeration (EA), UASB + trickling filter (UASB+TF), anaerobic + facultative ponds (AFP), and anaerobic + facultative + maturation ponds (AFMP).

WWTP's entrance before the grit removal process, and effluent was collected right before final disposal in a water body.

Due to varying data availability across WWTPs, median values for influent and effluent parameters were calculated for each facility to balance the information within the sample group. This approach provides a more representative summary of the concentrations. The median was adopted as a measure of central tendency, as it is better suited to represent the lognormal distribution exhibited by these values (Oliveira; Souki; Sperling, 2012).

The concentrations' medians and the removal efficiency of the constituents were analyzed using the bootstrap method (Efron; Tibshirani, 1994) to calculate the 95% confidence interval (CIs) (Gómez *et al.*, 2017; Newhart *et al.*, 2019; Jones *et al.*, 2021). The method application involved randomly testing the original number of WWTPs with a substitution of 10,000 resamplings. The resulting CI has a 95% probability of containing the population parameter under investigation. The analysis compared the CI of the medians for each technology type across the parameters with the main reference value ranges, which, in this case, were those presented by von Sperling (2014). Besides being highly cited in studies in the country, these concentrations are usually adopted by governmental environmental agencies when planning sanitation public policies, as seen in Fepam (2017) and Fepam (2019).

RESULTS AND DISCUSSION

Influent concentrations

The results indicate that the influent concentrations of the WWTPs that use the ST+AF technology were higher, except for *E. coli* with higher values in the case of SBR and EA technologies (Table 1). The ST+AF system also stood out as the technology with the most concentrated influent in other studies in Brazil (Monteiro, 2009; Oliveira; von Sperling, 2011). The ST+AF system is usually employed as a simplified treatment structure in rural and suburban areas associated with low water consumption and smaller sewer network systems (Hussien; Memon; Savic, 2016). Due to these characteristics, influent concentrations in this system may be higher compared to other methods, as they are less affected by rainwater and other clandestine contributions (Sharma; Khursheed; Kazmi, 2014).

Regarding other treatment modalities, following the ST+AF, elevated influent concentrations were noticeable in the activated sludge variations (SBR and EA). Conversely, the lowest concentrations were observed for AFP, although the limited number of analyzed WWTPs for this system compromised the results. Interestingly, there were no significant differences in the nutrient concentrations among the various technologies (Table 1).

Table 1 – The parameters' average and standard deviations of influent and effluent concentrations, along with removal efficiency, for the six treatment technologies. septic tank + anaerobic filter (ST+AF), activated sludge with sequencing batch reactor (SBR) and with extended aeration (EA), UASB + trickling filter (UASB+TF), anaerobic + facultative ponds (AFP), and anaerobic + facultative + maturation ponds (AFMP).

Variable	Factor	ST+AF	SBR	EA	UASB+TF	AFP	AFMP
BOD_5	No. of WWTPs	16	6	6	15	3	10
	influent (mg·L⁻¹)	188.5 ± 139.9	129.5 ± 80.9	102.3 ± 49.4	77.3 ± 67.3	38.4 ± 41.1	81.4 ± 31.6
	Effluent (mg·L⁻¹)	79.2 ± 52.2	8.5 ± 12.8	7.2 ± 6.2	11.6 ± 11.2	10.6 ± 7.3	19.6 ± 19.9
	Removal efficiency (%)	49.7 ± 35.7	93.3 ± 5	94.6 ± 3.7	80.2 ± 10.7	61.3 ± 29.8	77.9 ± 13.3
COD	No. of WWTPs	16	6	6	15	3	10
	influent (mg·L⁻¹)	415.9 ± 233.4	396.9 ± 203.4	298.8 ± 116.9	203.8 ± 141.5	208.5 ± 206.3	202.5 ± 69.1
	Effluent (mg·L⁻¹)	230.9 ± 135.9	36.2 ± 12.1	53.6 ± 18.2	57.3 ± 35.1	80.5 ± 18.3	118.7 ± 46.5
	Removal efficiency (%)	47.7 ± 29.5	87.1 ± 11	81 ± 7.2	66.2 ± 16.1	33.1 ± 40	35.5 ± 22.1
NNH3	No. of WWTPs	10	4	5	14	3	7
	influent (mg·L⁻¹)	60.6 ± 21.9	33 ± 9.4	39.3 ± 12.3	36 ± 22.2	27.7 ± 11.9	27.2 ± 7.3
	Effluent (mg·L⁻¹)	52.5 ± 25.3	9.1 ± 8.3	16.3 ± 14.3	18.1 ± 16.2	5.8 ± 6.2	6.3 ± 8.6
	Removal efficiency (%)	14 ± 23	65.2 ± 35.7	50.9 ± 39.9	50 ± 33.4	81.7 ± 13	78.5 ± 27
TP	No. of WWTPs	5	3	2	10	3	7
	influent (mg·L⁻¹)	9.6 ± 5.2	4.9 ± 1.9	5.1 ± 1.2	4.8 ± 2.9	3.3 ± 1.2	3.2 ± 0.5
	Effluent (mg·L⁻¹)	6.4 ± 5.1	1.8 ± 1.8	1.4 ± 0.2	2.7 ± 1.9	2 ± 0.9	1.8 ± 1.4
	Removal efficiency (%)	40.8 ± 30.8	66.2 ± 22.4	72.7 ± 9.8	35.8 ± 32.2	37.8± 12.5	37.2 ± 37
TSS	No. of WWTPs	16	6	6	15	3	9
	influent (mg·L⁻¹)	241.9 ± 295.4	133.8 ± 58.7	93.7 ± 41.1	75.3 ± 47.4	81.2 ± 76.9	69.7 ± 28.2
	Effluent (mg·L⁻¹)	50.9 ± 30.5	8.5 ± 5.9	19.2 ± 8.2	19.3 ± 15.1	44 ± 11.5	60.1 ± 20.9
	Removal efficiency (%)	54.3 ± 34.1	94.1 ± 6.3	74 ± 21.1	68.1 ± 22.6	18 ± 44.1	11.2 ± 30.3
E. coli	No. of WWTPs	7	6	4	11	3	9
	influent (10⁶· MPN·100 mL⁻¹)	5.1 ± 5.9	10.5 ± 8.5	7.4 ± 0.9	6.5 ± 6.0	4.3 ± 5.1	3.6 ± 1.4
	Effluent (10³· MPN·100 mL⁻¹)	2440.0 ± 3020.0	128.0 ± 153.0	270.0 ± 324.0	608.0 ± 871.0	21.2 ± 34.7	0.4 ± 0.6
	Removal efficiency (log. units)	0.4 ± 0.3	2.3 ± 0.8	1.9 ± 0.9	1.6 ± 1.3	3.1 ± 0.8	4.3 ± 0.8

For BOD, COD, and TSS, most of the influent values in Table 1 align with typical weak sanitary sewage, according to Tchobanoglous *et al.* (2014). The parameters' median values for the technologies were lower than those documented in other Brazilian regions (Silva Filho, 2007; Monteiro, 2009; Oliveira; von Sperling, 2011; Leonel, 2016; Dantas; Barroso; Oliveira, 2021). For instance, while von Sperling (2014) presented typical BOD, COD, and TSS range values of 250–400, 350–600, and 200–450 mg·L^{-1}, the CIs for the influent in ST+AF, which had the most concentrated parameters, were 98–208, 221–557, and 59–301 mg·L^{-1}, respectively. Possible hypotheses to explain these lower values could be associated with per capita water consumption, contributions from clandestine industries, limitations in sampling methodology, and lower return coefficients (Dantas; Barroso; Oliveira, 2021). Residents' dietary structure, local climate conditions, influent flow rates, and collection systems' characteristics could also account for these differences (Weirich; Silverstein; Rajagopalan, 2011; Jin; Zhang; Tian, 2014; Wang *et al.*, 2019). The present findings highlight the need to investigate the influence of each of these factors on influent concentrations in the study area.

Concerning the collection systems, Oliveira, Soares, and Holanda (2020) highlighted that connections between sewage and rainwater systems could occur through clandestine connections or accidental interceptions via surface contributions caused by rainwater entering devices, rain infiltration into the soil, and irregular contributions. It is important to highlight, though, that within the scope of this research; only those WWTPs that indicated having separate sewage collection systems were selected. Based on the concentrations observed, however, it can be shown that the system may not operate as a strictly separate one, but rather as partially separated or mixed, which allows for the dilution of sewage with rainwater (e.g., Gomes; Piveli, 2011; Rosa; Boechat; Oliveira, 2011; Dirckx *et al.*, 2019; Rashid; Liu, 2020). Additionally, it should be noted that combined sewers carry the base flow from piped streams or creeks in many cities, further contributing to sewage dilution (Benetti *et al.*, 2005).

In contrast with BOD, COD, and TSS concentrations, TP and NNH3 levels exhibited CIs that closely matched the reference values and concentrations observed in other parts of Brazil. In this case, future studies can delve into these differences, considering the procedures adopted in the WWTP operations, as distinct locations have reported varying correlations between nutrients and BOD, COD, and SST. For example, Kostadinova *et al.* (2018) reported a weak correlation between BOD and nitrogen and a significant negative correlation between BOD and TP. Iordache and Dunea (2013), though, have shown distinct patterns with mostly positive correlations between nitrogen products and BOD.

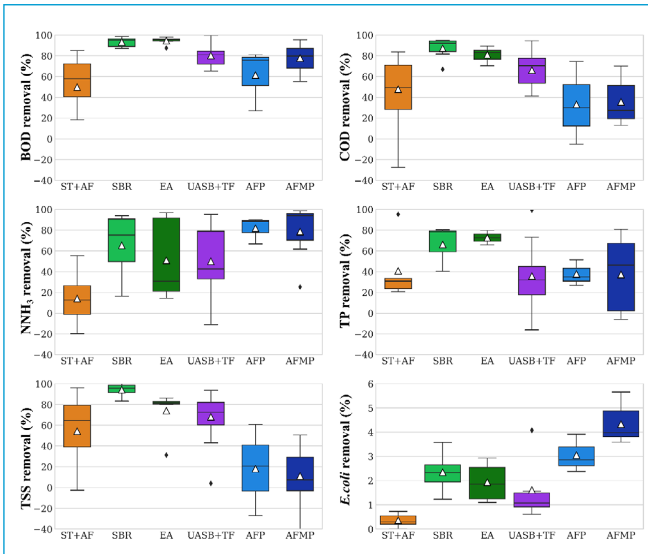
Effluent concentrations

Similar to the results reported for the influent, the effluent from the ST+AF had the highest concentrations for all analyzed parameters, except for TSS, for which pond systems had higher values (Table 1). The more elevated BOD, COD, NNH3, TP, and *E. coli* concentrations in the septic tanks can be attributed to the more concentrated influent and the relative simplicity of this method compared to others. In the ponds' configuration, the highest concentration of solids in the effluent is expected due to the presence of biomass that remains in suspension and is subsequently discarded (Mendoza-Espinosa; Stephenson, 1999). For the AFP method, the lower effluent levels are directly related to the disparities found for the influent, with the lower concentrations probably being related to the small number of WWTPs analyzed.

The lowest effluent concentrations were obtained for activated sludge variations (SBR and EA) in terms of BOD, COD, TSS, and TP, while pond systems exhibited the lowest concentrations for NH3 and *E. coli*. Oliveira and von Sperling (2011) found comparable results for these parameters among the treatment technologies analyzed, but with significantly higher values, especially for BOD, COD, and TSS. For BOD, for instance, activated sludge systems had an effluent mean concentration of 35 mg·L^{-1}, while this study found around 8 mg·L^{-1}. Nevertheless, phosphorus concentrations remained consistent, ranging between 3 and 5 mg·L^{-1} in both investigations. This contrast highlights that these systems operate similarly in the investigated locations of the two studies, with certain technologies having a higher prevalence of a more concentrated effluent. In general, though, Rio Grande do Sul's effluent concentrations were lower than those in other studies (Silva Filho, 2007; Monteiro, 2009; Oliveira; von Sperling, 2011; Leonel, 2016; Dantas; Barroso; Oliveira, 2021), although the differences between these values are not as significant as those found in the influent (Table 1).

Removal efficiency

The highest removal efficiencies between the analyzed parameters are expected for BOD, considering that biological processes in the secondary treatment target the removal of dissolved biodegradable organic matter. In this dataset, BOD removal ranged from 50% to 95%, with the top values followed by COD removal spanning from 33% to 87% (Table 1 and Figure 1). Among the technologies studied, the systems with the lowest performance for each constituent were, respectively: (i) ST+AF for BOD, NNH3, and *E. coli*; (ii) AFP and AFMP (pond systems) for COD and TSS; and (iii) UASB+TF for TP. The activated sludge systems (EA and SBR) exhibited the most effectiveness in removing BOD, COD, PT, and TSS parameters (Figure 2). Simultaneously, ponds (AFP and AFMP) yielded superior results for NNH3 and *E. coli*.



Source: author's production.

Figure 2 – Boxplots of removal efficiencies for each parameter among the six technologies evaluated. Triangles indicate the mean, and diamonds denote outliers, with each color representing a specific technology displayed on the x-axis. Technologies designations: septic tank + anaerobic filter (ST+AF), activated sludge with sequencing batch reactor (SBR) and with extended aeration (EA), UASB + trickling filter (UASB+TF), anaerobic + facultative ponds (AFP), and anaerobic + facultative + maturation ponds (AFMP).

In the case of ST+AF systems, Tchobanoglous *et al.* (2014) indicate that these systems exhibit low efficiency in removing organic matter (BOD) and microorganisms like *E. coli*. The primary function of the septic tank is the removal of sedimentable solids and partial anaerobic digestion of organic matter, achieving 30–50% removal of BOD (Adhikari; Lohani, 2019), 60–70% removal of TSS (Andreadakis; Christoulas, 1982), and less than 5% total nitrogen removal D'Amato, Liehr, and Ratanaphruks (2006). For *E. coli*, Appling *et al.* (2013) found that the reproduction of this microorganism occurs in septic tanks, which can result in zero or negative removal efficiency.

In pond systems, reduced total suspended solid removal is linked to algae's presence in the effluent (von Sperling, 2007). In these ecosystems, ammonia nitrogen from effluents can be removed through a combination of algae's photosynthetic activity, nitrification, and incorporation of nitrogen and ammonium into algal biomass (Barroso Júnior *et al.*, 2022).

For the UASB+TF system, it was expected to have a lower phosphorus removal efficiency compared to aerobic systems such as SBR and EA, which demonstrated better performance. Anaerobic systems like UASB reactors generally have low nitrogen and phosphorous removal efficiency (Chernicharo, 2015). In fact, according to Sobrinho and Jordão (2001), the removal of phosphorus in treatment plants using an anaerobic reactor can only be effective if chemical products such as iron or aluminum salts are used for nutrients' precipitation.

The results of the removal efficiency for most parameters indicate that, in general, the analyzed technologies are consistent with the values reported in the reference literature in Brazil (Silva Filho, 2007; Monteiro, 2009; Oliveira; von Sperling, 2011; Leonel, 2016; Dantas; Barroso; Oliveira, 2021). This is also supported by the overlap between the calculated 95% CIs and the comparison ranges from von Sperling (2014) presented in Table 2. The first exception in this agreement was the TSS parameter, where ST+AF, EA, UASB+TF, AFP, and AFMP performed below the typical comparison range, with the 95% CI falling short of the characteristic values. The prevalence of low removal efficiency for TSS across the evaluated technologies is a result that stands out, indicating a systemic factor at play. Further investigation and understanding of this relationship can be explored in future studies based on the concentrations obtained.

Another point of difference is that the ST+AF technology performed worse for BOD, COD, and TSS parameters compared with the reference values. A large percentage of WWTPs using this system had removal efficiencies below the typical range for the constituents studied, such as 88% for BOD, 69% for COD, and 75% for TSS. Additionally, the median CIs for the removal efficiencies of ST+AF did not overlap with the typical comparison ranges, meaning they are different. The ST+AF efficiency is related to the accumulation of sludge and scum in its chambers (Jordão; Pessôa, 2014). Consequently, the poor performance of some WWTPs in this modality for BOD, COD, and TSS might be attributed to insufficient maintenance of these structures. This could involve the absence of periodic cleaning or inadequate cleaning and incorrect handling of the accumulated sludge. Sludge accumulation reduces the space available for sedimentation, impairing the system's functionality and generating a more concentrated effluent with a higher solid content.

The removal efficiency for phosphorous was notably higher in the activated sludge systems in batch (SBR) and EA modalities, achieving levels above 70%

Table 2 – Comparison between the distribution of medians by bootstrap and values reported in the literature for the removal efficiency of the parameters. Septic tank + anaerobic filter (ST+AF), activated sludge with sequencing batch reactor (SBR) and with extended aeration (EA), UASB + trickling filter (UASB+TF), anaerobic + facultative ponds (AFP), and anaerobic + facultative + maturation ponds (AFMP).

Variable	Factor	ST+AF	SBR	EA	UASB+TF	AFP	AFMP
BOD_5 (%)	Median	57.76	95.37	95.59	81.04	75.8	79.91
	95% CI[1]	39-72	87-97	91-97	72-83	27-76	65-88
	Typical values[2]	80-85	90-97	90-97	80-93	75-85	80-85
	WWTPs below the typical range	88%	33%	17%	50%	47%	33%
COD (%)	Median	49.24	92.18	83.06	70.40	29.88	27.32
	95% CI[1]	28-70	74-94	70-86	50-76	(-5)-75	16-51
	Typical values[2]	70-80	83-93	83-93	73-88	65-80	70-83
	WWTPs below the typical range	69%	33%	50%	90%	60%	67%
NNH3 (%)	Median	12.87	75.15	30.77	42.55	88.39	93.75
	95% CI[1]	(-6)-28	16-92	14-91	27-78	67-88	25-95
	Typical values[2]	<45	>80	>80	<50	<50	50-65
	WWTPs below the typical range	0%	50%	60%	14%	0%	0%
TP (%)	Median	30.91	77.80	72.65	32.02	35.03	46.40
	95% CI[1]	21-33	40-78	66-73	15-47	27-51	(-6)-65
	Typical values[2]	<35	<35	<35	<35	<35	>50
	WWTPs below the typical range	0%	0%	0%	57%	0%	0%
TSS (%)	Median	64.53	95.76	81.56	72.69	20.59	7.41
	95% CI[1]	31-78	87-99	31-83	58-82	(-27)-21	(-6)-29
	Typical values[2]	80-90	87-93	87-93	87-93	70-80	73-83
	WWTPs below the typical range	75%	17%	100%	100%	80%	100%

[1]Obtained by the resampling bootstrap method with 10,000 iterations; [2]based on von Sperling (2014).

compared to less than 46% in the other technologies. This can be attributed to the competition for carbon between phosphorus removal and denitrification processes with the microorganisms responsible for organic matter oxidation (Tchobanoglous *et al*., 2014). A higher carbon/phosphorus ratio in a batch reactor results in greater phosphorus removal efficiency (Bueno *et al*., 2019). Thus, among the modalities analyzed, SBR and EA had the highest carbon/phosphorus ratios in raw wastewater, which may explain the superior performance of this system for TP removal, despite the limitations of each process.

CONCLUSIONS

In summary, the findings for influent concentrations reveal that WWTPs with the ST+AF technology exhibited higher influent concentrations for most parameters, followed by activated sludge. Overall, influent concentrations of BOD, COD, and TSS were significantly lower than those found in other studies in Brazil, indicating a weak sanitary sewage input. In contrast, phosphorus and nitrogen levels were aligned with the reference values. The diluted raw sewage is a result that stands out, pointing toward the necessity for future studies to investigate potential variables influencing these findings, including the influent flow rates, capacity, and collection systems of the WWTPs.

As for the effluent concentrations, activated sludge variations produced the lowest levels for BOD, COD, and TP, while pond systems yielded less concentrated effluents for NNH3 and *E. coli*. Septic tanks had higher levels of BOD, COD, NH3, TP, and *E. coli* due to their concentrated influent and simple treatment. Meanwhile, ponds produced higher effluent solids as a result of suspended biomass. These results are consistent with previous research conducted in the country. The concentrations found; however, were notably lower, as they were influenced by the low influent values.

Regarding removal efficiency, the activated sludge systems (EA and SBR) showed the highest removal efficiencies for BOD, COD, PT, and TSS parameters, while ponds (AFP and AFMP) delivered superior results for NNH3 and *E. coli* removal. Across the six analyzed technologies, most removal efficiencies fell within typical ranges reported in the literature in other Brazilian regions. However, there were exceptions, particularly in TSS removal, where ST+AF, EA, UASB+TF, AFP, and AFMP showed performance below the typical comparison range. This indicates the presence of potential systemic factors that warrant further investigation in future studies to better understand the observed relationships based on the obtained concentrations. Furthermore, the ST+AF technology displayed inferior performance for BOD, COD, and TSS, with many WWTPs exhibiting removal efficiencies below the usual ranges. Possible reasons for this problem could include sludge accumulation and inadequate maintenance. Lastly, activated sludge systems demonstrated notably higher TP removal efficiency, surpassing 70%, which can be attributed to enhanced carbon/phosphorus ratios.

There is a lack of research focusing on the performance of WWTPs based on monitoring data in southern Brazil. This study aimed to fill this gap by conducting a comprehensive analysis of influent and effluent concentrations and the performance of the secondary treatment technologies employed in WWTPs in the Rio Grande do Sul state. The results highlighted differences in the influent and effluent characteristics of various WWTP technologies and discrepancies from findings in other regions of Brazil. These insights provide a basis for future research and suggest potential improvements in wastewater treatment practices in Rio Grande do Sul and, more broadly, Brazil.

AUTHORS' CONTRIBUTIONS

Camelo, L.: Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. Brito, D.O.: Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Supervision, Validation, Writing – original draft, Writing – review & editing. Silva, M.C.A.: Investigation, Project administration, Supervision, Validation.

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