

Performance of a Municipal Wastewater Treatment Plant During the COVID-19 Pandemic: A Case Study from a Coastal Tourist Region in Rio de Janeiro, Brazil

Desempenho Operacional de uma Estação Municipal de Tratamento de Esgoto Durante a Pandemia de COVID-19: Estudo de Caso em uma Região Turística Costeira do Estado do Rio de Janeiro, Brasil

Ricardo Soares,^{a,b,c,*} Rafaela Naegele Alvernaz,^{a,b,c} Pablo Vimercati Simas,^a Augusto Ahn Ka,^a Márcia Cristina Santiago de Mello,^a Paulo Henrique Zuzarte Ferreira,^a Carlos Eduardo Soares Canejo Pinheiro da Cunha^{a,b}

^aUniversidade Veiga de Almeida (UVA), Campus Tijuca, Observatório da Gestão Integrada de Resíduos Sólidos do Estado do Rio de Janeiro (OGIRERJ), Zip Code 20271-020, Rio de Janeiro-RJ, Brazil

^bUniversidade Veiga de Almeida (UVA), Campus Tijuca, Programa de Pós-Graduação em Ciências do Meio Ambiente, Zip Code 20271-020, Rio de Janeiro-RJ, Brazil

^cInstituto Estadual do Ambiente (INEA), Zip Code 20081-312, Rio de Janeiro-RJ, Brazil

*E-mail: Ricardo.soares@uva.br

Submissão: 27th February 2026 – Aceite: 16th April 2026 – Publicado online: 28th April 2026

This study assesses the performance of a municipal wastewater treatment plant (WWTP) in Saquarema, Rio de Janeiro, Brazil, between 2019 and 2024, with emphasis on the COVID-19 pandemic period. Using official monitoring data from the Rio de Janeiro State Environmental Institute (INEA), effluent parameters, including flow rate, pH, suspended solids (SS, TSS), methylene blue active substances (MBAS), biochemical oxygen demand (BOD₅), and ammoniacal nitrogen (N-NH₃), were evaluated against regulatory standards. Statistical analyses indicated operational stability during peak pandemic years, with 94.44% of BOD₅ values were below the 40 mg L⁻¹ limit, likely reflecting reduced hydraulic and organic loads due to lockdowns and decreased tourism. However, non-compliance events occurred before and after the pandemic, especially in 2019, 2023, and 2024, including simultaneous exceedances of BOD₅ (up to 141 mg L⁻¹), TSS, and MBAS. Ammoniacal nitrogen showed the most critical results: from 2022 to 2024, 22.58% of samples exceeded the 20 mg L⁻¹ legal limit, reaching 35.23 mg L⁻¹. The late inclusion of N-NH₃ in monitoring and its persistent removal inefficiency suggest structural deficiencies in biological treatment. The findings underscore the urgent need for technological upgrades, particularly nitrification and denitrification systems, to ensure regulatory compliance and protect public health and coastal ecosystems.

Keywords: Wastewater Treatment Plant (WWTP); effluent quality; COVID-19 pandemic; coastal ecosystems.

1. Introduction

Population growth continues to contribute to increasing volumes of municipal wastewater, underscoring the need for efficient treatment strategies to safeguard environmental integrity and public health. Effective management of sanitary effluents is crucial for mitigating the spread of waterborne diseases and improving public well-being.

Despite its critical importance, Brazil's sanitation infrastructure remains insufficient, with more than 45% of the population lacking access to adequate sewerage collection.^{1,2} While incremental improvements have occurred, such as a 0.2% increase in coverage between 2023 and 2024, the gap remains stark when compared with developed nations, where service coverage often exceeds 90%.² This disparity highlights the urgent need

for structural and operational improvements to national systems, particularly wastewater treatment plants (WWTPs).

Municipal WWTPs in Brazil involve the chemical, physical, or biological removal of pollutants in accordance with standards set by CONAMA Resolution No. 430/2011,³ aiming to mitigate impacts on water bodies such as rivers, lakes, reservoirs, and coastal zones. The discharge of sediments and pathogens into these environments compromises aquatic ecosystems, reduces the quality of potable water, and increases the risk of diseases such as schistosomiasis, leptospirosis, cholera, and pyodermitis.⁴ Additionally, infectious agents transmitted via the faecal-oral route, such as the SARS-CoV-2 virus, may persist in wastewater and act as a secondary source of infection, even after clinical symptoms have subsided.^{4,5}

The public health emergency caused by the COVID-19 pandemic, officially declared a global pandemic by the World Health Organization (WHO) on 11 March 2020, introduced additional challenges to sanitation systems, particularly WWTPs.⁵ Identified in early January 2020, the novel coronavirus SARS-CoV-2 led to profound disruptions that extended beyond epidemiological concerns. These disruptions altered the characteristics of domestic sewage, increasing organic loads, nutrient concentrations, and the prevalence of surfactants and recalcitrant compounds, trends observed across diverse international contexts including Kuwait and Iran.^{6–8} Such changes placed additional strain on the biological and physicochemical treatment capacities of WWTPs, particularly in developing countries. Although the WHO declared the end of the Public Health Emergency of International Concern on 5 May 2023, the pandemic's operational implications for wastewater infrastructure remain relevant.

Studies conducted between 2020 and 2022 in Istanbul, Zonguldak, Belgrade, and Prague revealed increases in influent flow and significant variations in several parameters, indicating a reduction in sewage biodegradability.^{9–11} In some cases, even tertiary treatment plants reported reduced efficiency, particularly in nutrient removal and faecal coliform reduction stages. These findings reinforce the importance of evaluating how the pandemic impacted WWTP performance in Brazil, where systematic monitoring of such effects remains incipient.

Although the potential faecal–oral transmission of SARS-CoV-2 attracted scientific and institutional attention, the most critical pandemic-related impacts on WWTPs were not limited to the viral presence in sewage. Rather, they involved broad chemical and operational changes, necessitating revisions in control standards and treatment process efficiency.^{6–12}

In this regard, the efficient operation of WWTPs assumes a strategic role as a technical barrier to the environmental dissemination of SARS-CoV-2, especially in regions where effluents from households with infected individuals are discharged without effective treatment, as is the case in Brazil. Several studies have demonstrated the persistence of viral genetic material in domestic sewage, increasing epidemiological risks linked to the potential contamination of receiving water bodies.^{2,12} Furthermore, sewage systems have increasingly been employed as tools for epidemiological surveillance, known as wastewater-based epidemiology, highlighting their strategic value in pathogen monitoring during public health crises.¹²

As such, WWTPs are now recognised not only as effluent treatment units but also as critical components of emergency response infrastructure, with implications for epidemiological monitoring, environmental control, and public policy formulation.

This study aims to evaluate the operational performance of the Bacaxá Wastewater Treatment Plant, located in the municipality of Saquarema (Rio de Janeiro, Brazil), during the COVID-19 pandemic (2020–2022). By analysing variations in key effluent parameters, such as flow rate, pH, settleable solids, total suspended solids, anionic surfactants, biochemical oxygen demand, and ammoniacal nitrogen, this case study seeks to determine the extent to which the pandemic affected the plant's ability to comply with national discharge standards. The results contribute empirical evidence to inform emergency preparedness strategies, regulatory frameworks, and the design of more resilient WWTPs in the context of future health and climate crises. We hypothesised that reduced seasonal tourism during lockdown periods would lead to measurable reductions in organic and surfactant loads, improving effluent quality parameters.

2. Material and Methods

2.1. Study area

The state of Rio de Janeiro is marked by diverse topographic, climatic, and sociocultural characteristics shaped by complex historical and geographical processes. Within this context, the *Baixadas Litorâneas* (Coastal Lowlands) region has experienced significant transformations. Traditionally dedicated to livestock, artisanal fishing, and saltworks until the 1960s,¹³ the region has undergone intense urbanisation since the early 2000s, primarily driven by tourism and seasonal housing, now key pillars of local socioeconomic development.¹⁴

This region comprises two administrative micro-regions: the Região dos Lagos including Araruama, Armação dos Búzios, Arraial do Cabo, Cabo Frio, Iguaba Grande, São Pedro da Aldeia, and Saquarema, and the São João River Basin Region, which includes Casimiro de Abreu, Rio das Ostras, and Silva Jardim.¹³

Saquarema, where the Bacaxá WWTP is located, spans 352.13 km², with a population of approximately 89,559 inhabitants and a density of 254.34 inhabitants/km², it is the third most populous municipality in the Região dos Lagos.¹⁴ Seasonal tourism significantly increases local population pressure, challenging the capacity of sanitation systems during peak periods.¹⁴

2.2. Bacaxá WWTP

The Bacaxá Wastewater Treatment Plant (WWTP), located in the district of Bacaxá in Saquarema (Rio de Janeiro), is designed to serve up to 36,000 inhabitants, with a nominal treatment capacity of 4,320 m³ day⁻¹. Its influent originates primarily from urbanised areas and is conveyed

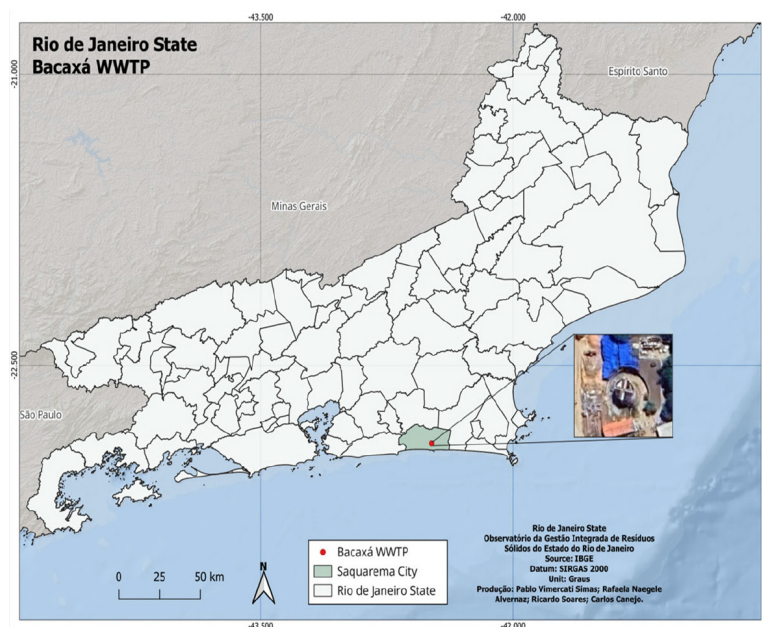


Figure 1. Location of the Bacaxá Wastewater Treatment Plant, Saquarema, Rio de Janeiro

through a Dry Weather Collection System (DWCS), supported by an interceptor in the Bacaxá River basin that directs sewage to the treatment unit.¹⁵

The plant employs secondary treatment via Submerged Aerated Biological Filter (SABF) technology, a widely adopted aerobic biological process in Brazil for organic matter removal.¹ According to the IBGE Sanitation Atlas, biological systems constitute the predominant secondary treatment strategy in the country, implemented in various configurations including septic tanks, stabilisation ponds, and activated sludge processes.¹

On average, the DWCS collects 3,456 m³ day⁻¹ via the Bacaxá River interceptor, supplemented by 864 m³ day⁻¹ from four auxiliary pumping stations. These flows are routed to the main pumping station at the WWTP entrance, where raw influent undergoes bar screening, grit and grease removal, and receives additional loads from vacuum trucks servicing non-connected areas.¹⁵

Flow measurement is performed using a Parshall flume equipped with an ultrasonic flow meter. Prior to biological treatment, polyaluminium chloride is added to enhance solids removal and sedimentation. Continuous aeration is maintained using blowers to support microbial activity in the SABF reactors.¹⁵

Effluent then flows to a secondary clarifier for solids separation and final clarification. The resulting sludge is stored in geobags, with an average production of 40 m³ day⁻¹. After drying, part of the sludge is sent to a Sanitary Landfill, while the remainder is repurposed at the Ponte dos Leites WWTP for ecological brick production.¹⁵

The Bacaxá WWTP represents 50.5% of Saquarema's total wastewater treatment capacity, within a DWCS

that collectively processes 8,552 m³ day⁻¹. Final effluent is discharged into the Bacaxá River, a tributary of the Saquarema Lagoon.¹⁵

2.3. Operational efficiency assessment of the Bacaxá WWTP

2.3.1. Monitored parameters

The performance evaluation of the Bacaxá WWTP was based on seven key effluent quality indicators: flow rate (Q), pH, settleable solids (SS), total suspended solids (TSS), methylene blue active substances (MBAS), biochemical oxygen demand (BOD₅), and ammoniacal nitrogen (N-NH₃). These parameters align with the operational conditions set forth in the facility's current environmental permit issued by the Rio de Janeiro State Environmental Institute (INEA), although Brazilian legislation includes a broader regulatory framework.^{3,16,17}

Raw data were sourced from the Effluent Monitoring Reports (*Relatórios de Acompanhamento de Efluentes – RAE*), which are submitted monthly through INEA's self-monitoring platform, known as *PROCON-ÁGUA*.¹⁷ The dataset spans from January 2019 to December 2024, enabling a longitudinal analysis of the plant's operational behavior, with special attention to changes induced by the COVID-19 pandemic. Monthly values represent arithmetic means, calculated per parameter according to national and state-level technical guidelines.^{3,16,17} It is worth noting that ammoniacal nitrogen (N-NH₃) monitoring became mandatory in April 2022 and was only reported from that point onwards.

2.3.2. Analytical procedures

Sampling was performed at the plant's final discharge point, following protocols defined by CETESB.¹⁸ Flow rate and pH were monitored daily using grab and composite samples, respectively, while the other variables (SS, TSS, MBAS, BOD₅, and N-NH₃) were analysed monthly from composite samples. All tests were conducted by laboratories accredited by INEA and certified by INMETRO, ensuring metrological traceability and methodological consistency.

Flow rate was measured using a Parshall flume with an ultrasonic sensor, enabling the quantification of daily treated volumes and the estimation of influent organic load. pH measurements were essential for evaluating the effluent's chemical balance and its suitability for discharge into receiving waters. SS and TSS were determined using gravitational settling in Imhoff cones and filtration/drying techniques, respectively, in line with standard protocols.

MBAS concentrations, indicative of anionic surfactants, were quantified using spectrophotometry using methylene blue dye, a widely used method for detecting residual detergent compounds. BOD₅ was determined after five days of incubation under controlled conditions, reflecting the level of biodegradable organic matter. Finally, ammoniacal nitrogen (N-NH₃) was measured via distillation and/or spectrophotometry and served as a proxy for nutrient removal efficiency in biological treatment processes.

All procedures adhered to the 24th edition of the Standard Methods for the Examination of Water and Wastewater, ensuring reliability, reproducibility, and international comparability.¹⁹

2.3.3. Statistical treatment and temporal approach

Operational data from the Bacaxá WWTP (January 2019 – December 2024) were organised and analysed in RStudio (version 4.5.2) using R (version 4.2.1).²⁰ Each monitored parameter underwent descriptive analysis (mean, standard deviation, minimum, and maximum) to characterise variability and identify seasonal or anomalous trends. Normality was evaluated using the Shapiro–Wilk test ($\alpha = 0.05$). If normality was rejected, the data were transformed (log, cube root, or Box–Cox), and non-normal distributions post-transformation were analysed using non-parametric tests.

For normally distributed variables, repeated-measures ANOVA ($\alpha = 0.05$) was applied. *Post hoc* Bonferroni corrections were used to compare annual means when statistical significance was detected. For pairwise comparisons, paired t-tests or Wilcoxon signed-rank tests ($\alpha = 0.05$) were employed, depending on the data distribution and ensuring Type I error control.

In addition, correlations among the monitored variables were assessed to investigate potential process-level

associations in effluent quality and operational performance. Pearson's correlation coefficient was applied when the variables met parametric assumptions, whereas Spearman's rank correlation coefficient was used for non-normally distributed data or when monotonic relationships were more appropriate. Correlation analyses were performed using a significance level of $\alpha = 0.05$. The resulting correlation structure was summarised through correlation matrices to support the interpretation of associations among hydraulic, physicochemical, and organic matter-related parameters. To the best of our knowledge, studies in the international scientific literature addressing the impacts of the COVID-19 pandemic on WWTP performance have not reported multivariate correlation analyses based on Pearson's or Spearman's coefficients, as performed in the present study.^{6–12} This additional analytical step therefore provides a broader process-level interpretation of the monitored variables and represents a relevant contribution to the assessment of WWTP behaviour under pandemic-related stress.

In contrast to earlier studies, such as Yazdian and Jamshidi⁸ and Ahmed *et al.*,⁶ which lacked formal multiple comparison corrections, this analysis followed a rigorous and structured approach in line with best practices.²¹ Graphical outputs, including time-series plots and box plots, supported the interpretation of seasonal patterns, interannual trends, and outliers.

Particular attention was given to BOD₅, MBAS, and N-NH₃, due to their sensitivity to variations in organic load and effluent composition. This methodological framework ensures statistical robustness and analytical traceability, thereby providing reliable insights into the operational efficiency and resilience of the Bacaxá WWTP under pandemic-related stress.

3. Results and Discussion

3.1. Influent flow (Q)

The analysis of influent flow (Q) to the Bacaxá WWTP, from January 2019 to December 2024, revealed monthly fluctuations ranging from 2,586.8 m³ day⁻¹ (February 2021) to 4,079.5 m³ day⁻¹ (June 2019). However, Q never exceeded the design limit of 4,320.0 m³ day⁻¹ established in the WWTP's Operating Licence. The overall mean flow for the study period was 3,273.7 ± 404.5 m³ day⁻¹, corresponding to an average treatment surplus capacity of 24.3%, indicating that the installed capacity was adequate to absorb seasonal hydraulic variation.

Flow rate data followed a normal distribution according to the Shapiro–Wilk test ($W = 0.96696$, p -value = 0.05521). Repeated measures ANOVA indicated no statistically significant differences between annual mean values

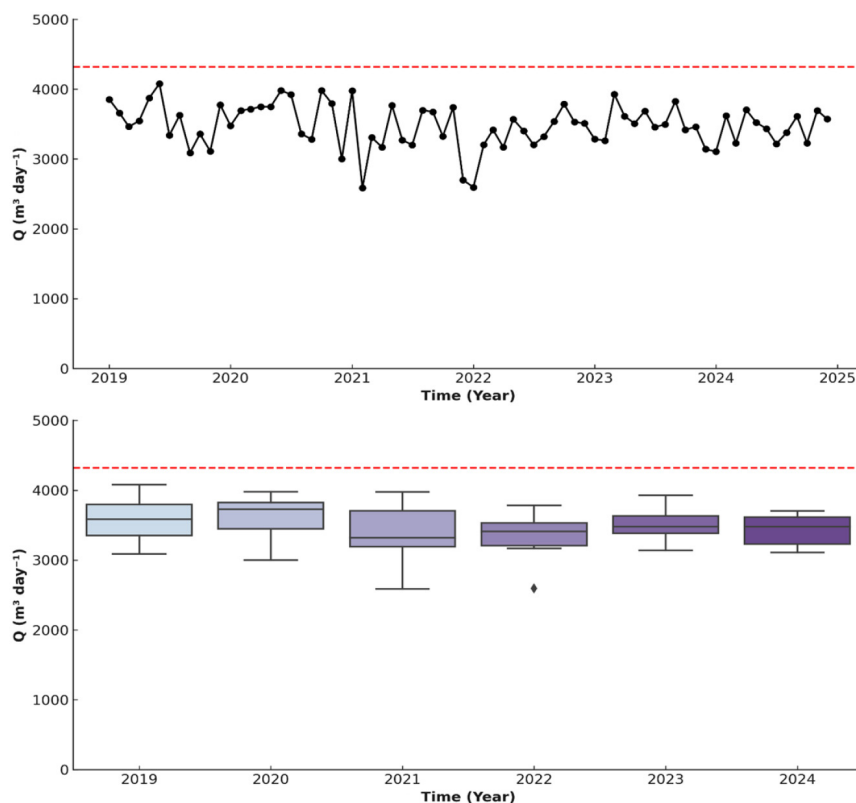


Figure 2. Time series (above) and annual distribution (below) of Q ($\text{m}^3 \text{ day}^{-1}$) treated by the Bacaxá WWTP between 2019 and 2024. The red dashed line represents the design flow rate ($4,320 \text{ m}^3 \text{ day}^{-1}$) as defined in the Operating Licence

($F(5, 71) = 2.099$, $p\text{-value} = 0.074$). Mauchly's sphericity test was satisfied ($p\text{-value} = 0.293$), thus no corrections were required. These results do not support significant interannual variation in flow during the study period.

When compared with international studies, a divergent trend is observed in several regions during the pandemic period. In countries such as Iran, and Kuwait for instance, a significant increase in sewage flow was documented in 2020, attributed to population lockdowns and intensified domestic water use, with mean increases ranging from 7% to 33% compared with previous years.^{6-8,12} In contrast, the Bacaxá WWTP appears to have been less affected, likely due to local factors such as a substantial decline in tourism and urban mobility during successive lockdowns,^{5,22} which reduced per capita sewage generation during periods typically marked by higher demand.

Moreover, the maintenance of flow rates below nominal design capacity even in critical years such as 2020 and 2021 underscores the importance of system flexibility and the availability of real-time control and monitoring tools, which are essential for anticipating and responding to abrupt fluctuations in hydraulic load, as also highlighted by Hamoda and Rashidi⁷ in their analysis of WWTP performance in the Middle East during lockdown periods. Overall, the results for the flow rate parameter indicate that the Bacaxá WWTP

maintained stable performance over the six-year assessment period, even amid global sanitary challenges such as the COVID-19 pandemic. This operational stability, supported by statistical evidence and technically sound infrastructure, represents an indicator of system robustness and provides useful insights for the development of adaptive sanitation policies in crisis scenarios.

3.2. pH, Settleable Solids (SS), and Total Suspended Solids (TSS)

3.2.1. pH

Between 2019 and 2024, pH values in the treated effluent ranged from 6.7 to 7.7 (Figure 3), remaining fully within the regulatory limits established nationally and by INEA.^{3,16} All 72 samples complied with the applicable standards, indicating consistent control of this parameter.

The pH data did not follow a normal distribution (Shapiro-Wilk: $W = 0.93474$, $p\text{-value} = 0.001041$). The Friedman test indicated statistically significant differences across years ($\chi^2(5) = 30.47$, $p < 0.001$) and *post hoc* Wilcoxon tests with Bonferroni adjustment revealed specific differences between 2019 and 2023 (adjusted $p\text{-value} = 0.047$) and between 2021 and 2023 (adjusted $p\text{-value} = 0.036$). Despite these differences, all values

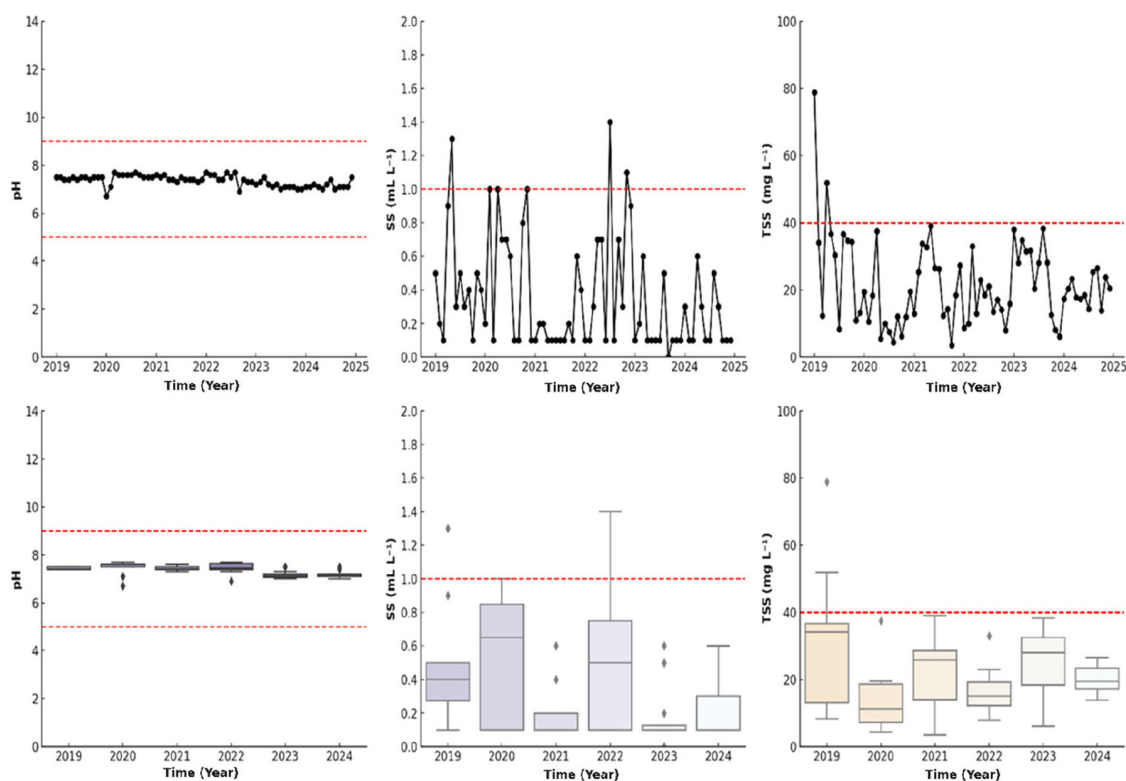


Figure 3. Time series (top row) and annual distributions (bottom row) of pH, SS (mL L^{-1}), and TSS (mg L^{-1}) at the Bacaxá WWTP between 2019 and 2024. Red dashed lines represent the Maximum Permissible Values (MPVs) for each variable: $\text{MPV}_{\text{pH}} = 5 - 9$; $\text{MPV}_{\text{SS}} = 1 \text{ mL L}^{-1}$, and $\text{MPV}_{\text{TSS}} = 40 \text{ mg L}^{-1}$

remained within the acceptable range, indicating limited practical relevance.

pH control is a critical aspect of wastewater treatment, as significant deviations can impair both biological and physicochemical processes.²¹ Fluctuations outside the optimal range inhibit aerobic microbial activity essential for organic matter degradation, compromising overall treatment efficiency and potentially posing ecological risks to receiving water bodies. In typical municipal wastewater, pH values generally range from 6.5 to 7.5.²¹ At the Bacaxá WWTP, recorded values occasionally exceeded this interval slightly, but remained within legal limits. This operational consistency reflects effective process control and suggests low residual acidity or alkalinity in the final effluent, facilitating its integration into the Bacaxá River.

These findings are consistent with international literature evaluating the impact of the COVID-19 pandemic on urban wastewater characteristics. Studies in Kuwait,^{6,7,12} Iran,⁸ Serbia,¹⁰ and Romania¹¹ also reported pH stability in treated effluents, despite socio-economic disparities and varying levels of public health restrictions. This stability has been attributed to the adaptive capacity of WWTP processes in accommodating moderate fluctuations in influent composition during crisis conditions. Thus, the Bacaxá WWTP results align with global trends, reinforcing its operational robustness and effective pH control, even under

the exceptional circumstances imposed by the COVID-19 pandemic.

3.2.2. Settleable Solids (SS)

Between 2019 and 2024, the concentration of Settleable Solids (SS) in the treated effluent at the Bacaxá WWTP ranged from 0 mL L^{-1} , recorded in September 2023, to 1.4 mL L^{-1} , recorded in July 2022 (Figure 3). Most samples (95.83%) showed concentrations below the MPV_{SS} .^{3,16} However, three samples exceeded this limit: one in May 2019 (pre-pandemic) and two during the second half of 2022 (July and November), representing 5.26% of the samples during the pandemic period.

The distribution of SS values significantly deviated from normality (Shapiro-Wilk: $W = 0.79795$, $p\text{-value} = 1.512 \times 10^{-8}$). The Friedman test indicated statistically significant differences across years ($\chi^2(5) = 12.30$, $p\text{-value} = 0.031$). However, *post hoc* analyses using Wilcoxon tests with Bonferroni correction did not confirm statistically significant differences between year pairs (adjusted $p\text{-values} > 0.05$), suggesting that the observed effects are likely attributable to non-systematic seasonal fluctuations.

Although isolated, the exceedances observed during the COVID-19 pandemic merit particular attention. These occurrences raise relevant hypotheses regarding the system's responsiveness under sanitary stress, including possible

changes in sewage composition, operational constraints, or disruptions to maintenance routines in sedimentation systems. The significance of the SS parameter lies in its direct relation to the final stages of treatment.²¹ At facilities such as the Bacaxá WWTP, which lacks tertiary polishing systems, the secondary clarifier serves as the final barrier for solid particle retention. Any underperformance in this stage directly affects the quality of the effluent discharged into the Bacaxá River.

Elevated SS concentrations may indicate operational issues such as sludge bulking, dispersion, or washout from the secondary clarifier.²¹ These issues often arise from hydraulic overloads, inefficiencies in sludge withdrawal or recirculation, or microbiological phenomena such as intensified nitrification. The latter is particularly common in humid tropical regions like Saquarema and can lead to nitrogen gas (N₂) formation, causing resuspension of settled sludge,²¹ potentially explaining the episodic increases observed in 2022, particularly under pandemic-related operational restrictions.

This parameter directly influences effluent turbidity, sediment load discharged into receiving bodies, and the health of aquatic biota. Elevated SS values may compromise drainage infrastructure, accelerate sedimentation, reduce light penetration, and adversely affect benthic ecosystems.²¹

The findings from the Bacaxá WWTP contrast with those from two small Serbian towns (populations ~5,000 and ~15,000), where a decline in SS concentrations was recorded during the COVID-19 pandemic compared with pre-pandemic levels (2015–2019).¹⁰ This decline was attributed to changes in consumption habits and domestic water use during lockdown. In contrast, no systematic reduction in SS concentrations was observed at Bacaxá WWTP, instead, isolated increases occurred. This discrepancy highlights the importance of contextual factors such as urbanisation patterns, infrastructure availability, and the resilience of operational systems.

Therefore, although the Bacaxá WWTP maintained satisfactory performance throughout most of the assessment period, the exceedances recorded during the pandemic underscore the need to reinforce operational control and systematic monitoring of this parameter, particularly under exceptional conditions. Preventive strategies are recommended, including intensified sludge recirculation and removal, the implementation of continuous monitoring, and enhanced alert systems to ensure greater operational resilience and the preservation of environmental quality in the Bacaxá River.

3.2.3. Total Suspended Solids (TSS)

During the monitoring period from 2019 to 2024, TSS concentrations in the treated effluent of the Bacaxá WWTP

remained predominantly within satisfactory standards, with the exception of two isolated episodes recorded in January and April 2019, which reached 78.9 mg L⁻¹ and 51.9 mg L⁻¹, respectively. These results exceeded the MPV_{TSS} by nearly 100% and approximately 30%, respectively.

TSS values did not follow a normal distribution (Shapiro–Wilk: $W = 0.89443$, $p\text{-value} = 1.843e^{-5}$). The Friedman test revealed statistically significant differences between years ($\chi^2(5) = 12.62$, $p\text{-value} = 0.027$). However, pairwise comparisons using Wilcoxon tests with Bonferroni correction did not identify statistically significant differences (adjusted $p\text{-values} > 0.05$). Nonetheless, 2.78% of samples exceeded the regulatory threshold, and these occurrences coincided with elevated BOD₅ values, potentially reflecting isolated failures in clarification and secondary sedimentation processes. This simultaneity suggests localised impairments in the efficiency of the WWTP's physicochemical and biological processes, possibly due to organic overloads, operational disruptions, or temporary limitations in secondary sedimentation.

Elevated TSS concentrations directly impair clarification performance and negatively impact the receiving water body by increasing turbidity, reducing light penetration, and harming benthic aquatic communities in the Bacaxá River.²¹ Furthermore, high TSS levels may overburden disinfection systems and promote sediment deposition in watercourses, intensifying siltation and environmental degradation in the Saquarema Lagoon. TSS represents the fraction of solids retained after filtration through appropriate membranes, comprising both organic and inorganic suspended matter, and in raw domestic wastewater, their typical concentrations range from 120 to 360 mg L⁻¹.²¹ At the Bacaxá WWTP, measured levels in the treated effluent, except for the two 2019 outliers, remained well below these values, demonstrating the system's high removal efficiency.

Notably, no violations of the MPV_{TSS} were recorded during the critical pandemic period (2020–2022). This operational stability, even under logistical and sanitary constraints, may be attributed to the seasonal population decline resulting from social isolation measures and the temporary downturn in tourism, factors that likely reduced the influent load and provided a greater operational safety margin. By contrast, the simultaneous exceedances of TSS and BOD₅ in January and April 2019 underscore the need for more integrated and responsive monitoring of fluctuations in the organic load, since strict control of suspended solids is essential not only for regulatory compliance but also for maintaining treatment efficiency and protecting the ecological integrity of the receiving water bodies.

From a comparative perspective, the TSS data from the Bacaxá WWTP align with findings from Tehran, where TSS

levels remained stable during the COVID-19 pandemic.⁸ Conversely, they differ from studies in two Serbian cities, where significant reductions in TSS concentrations were reported during lockdown, attributed to changes in household behaviour and reduced urban activity.¹⁰ The absence of a similar decreasing trend in Bacaxá may be explained by contextual factors such as greater urban complexity, the robustness of the treatment system, and the socioeconomic profile of the serviced population, all of which modulate the pandemic's effects on effluent quality in different ways.

3.3. Methylene Blue Active Substances (MBAS), Biochemical Oxygen Demand (BOD_5), and Ammoniacal Nitrogen ($N-NH_3$)

3.3.1. Methylene Blue Active Substances (MBAS)

Between 2019 and 2024, MBAS concentrations ranged from 0.03 mg L^{-1} (February 2024) to 3 mg L^{-1} (January 2019) (Figure 4). The latter exceeded the MPV_{MBAS} (2.0 mg L^{-1}) by 50% and coincided with increases in TSS and BOD_5 , suggesting an organic and physicochemical overload likely linked to peak tourist activity and the influx of a seasonal population. Although no significant increase in flow was recorded, the elevated influent load may have briefly surpassed the plant's treatment capacity, reducing the efficiency of aerobic and clarification processes.

MBAS data exhibited strong asymmetry and a non-normal distribution (Shapiro–Wilk: $W = 0.50921$, $p\text{-value} = 3.914e^{-14}$). The Friedman test did not indicate

significant differences across years ($\chi^2(5) = 3.19$, $p\text{-value} = 0.667$), suggesting consistent surfactant levels over time. The peak in January 2019, while technically relevant, does not represent a broader pattern. During the pandemic period (2020–2022), only one sample (July 2021) approached the regulatory threshold (1.9 mg L^{-1}), supporting the hypothesis of reduced influent loads due to diminished human activity.

From an environmental perspective, MBAS, which are widely associated with household and industrial detergents, are of concern due to their low biodegradability and persistence in aquatic environments. Beyond their persistence, anionic surfactants may disrupt microbial activity and impair gas-transfer processes, which is particularly relevant in aerobic biological treatment systems. When discharged in treated effluents, these compounds can promote stable foam formation, reduce oxygen exchange at the air–water interface, and negatively affect aquatic organisms, especially in low-flushing or poorly circulated receiving waters.^{21,23}

Although the Bacaxá WWTP generally performed well in controlling MBAS concentrations, the critical exceedance in 2019 underscores operational vulnerabilities to abrupt increases in the influent load. This scenario highlights the need for preventive strategies such as reactor resizing, adjustments to aeration and hydraulic retention times, intensified sludge recirculation, and contingency planning for periods of high seasonality.

Comparatively, while the Bacaxá WWTP maintained stable MBAS levels during the pandemic, international

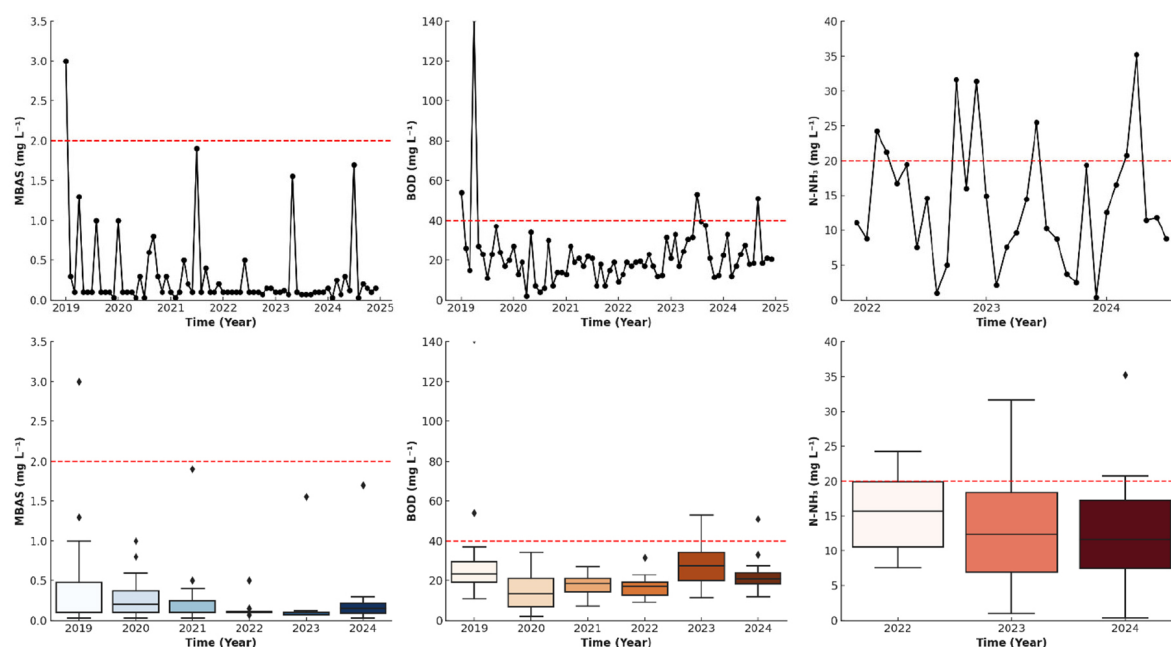


Figure 4. Time series (top row) and annual distributions (bottom row) of MBAS (mg L^{-1}), BOD_5 (mg L^{-1}), and $N-NH_3$ (mg L^{-1}) at the Bacaxá WWTP between 2019 and 2024. $N-NH_3$ analysis considers only data from May 2022 onward. Red dashed lines indicate the Maximum Permissible Values (MPVs) for each variable: $MPV_{MBAS} = 2 \text{ mg L}^{-1}$, $MPV_{BOD_5} = 40 \text{ mg L}^{-1}$, and $MPV_{N-NH_3} = 20 \text{ mg L}^{-1}$

studies have reported contrary trends. In Kuwait, for instance, substantial increases were observed in surfactants (+196%), biocides (+152%), and quaternary ammonium compounds (+331%) in wastewater, attributed to intensified use of cleaning agents during COVID-19.⁶ Similarly, WWTPs in Serbia recorded elevated surfactant concentrations, posing operational challenges due to chemical interference in biological processes.¹⁰ In contrast, the Bacaxá WWTP's satisfactory performance suggests operational resilience, likely supported by the region's demographic profile, lower industrialisation, and reduced tourist pressure during the pandemic.

3.3.2. BOD₅

During the monitoring period (2019–2024), BOD₅ concentrations ranged from 2 mg L⁻¹ (April 2020) to 141 mg L⁻¹ (April 2019), as shown in Figure 4. In 94.44% of the samples, values remained below the MPV_{BOD₅} (40 mg L⁻¹).¹⁷ Only four instances of non-compliance were recorded: two in 2019, with increases of 35% (January) and 252.5% (April), and two after the critical pandemic period, in July 2023 (32%) and September 2024 (27.5%). BOD₅ data did not follow a normal distribution (Shapiro–Wilk: $W = 0.61815$, $p\text{-value} = 2.157 \times 10^{-12}$), and the Friedman test did not reveal statistically significant differences among years ($\chi^2(5) = 10.58$, $p\text{-value} = 0.061$), supporting the interpretation that exceedances were sporadic rather than recurrent.

These episodes do not indicate systemic failure and are more likely attributable to seasonal variations in influent load, isolated operational fluctuations, or changes in the physicochemical characteristics of the sewage influenced by environmental conditions.²¹ The April 2019 peak coincided with elevated TSS and MBAS, suggesting a transient organic and physicochemical overload that may have reduced aerobic treatment efficiency.

Notably, during the peak of the COVID-19 pandemic (2020–2022), no sample exceeded the BOD₅ regulatory limit, indicating operational stability even under exceptional conditions. This performance is likely related to the reduction of the seasonal population in the municipality of Saquarema, resulting from containment measures such as beach closures, mobility restrictions, and lockdown decrees.²² The decline in tourist flow during this period may have significantly reduced the organic influent load, allowing for more stable and efficient WWTP operation, even amid uncertainty and pressure on public systems.

The stability pattern observed in the Bacaxá WWTP during the pandemic period is consistent with international studies assessing the impact of COVID-19 containment measures on urban wastewater parameters, several of which reported reductions in BOD₅ concentrations during

lockdowns, often attributed to decreased commercial activity, temporary industrial shutdowns, and increased domestic water use, factors that contributed to dilution and altered organic loading. For example, Yazdian and Jamshidi⁸ reported a reduction of up to 22% in BOD₅ concentrations in small Iranian communities, associated with increased residential water use and decreased economic activity. Similarly, Roman *et al.*¹¹ found that, although influent volumes increased in some European municipalities, BOD₅ and COD concentrations dropped significantly, suggesting dilution effects due to household confinement policies. In Kuwait, Hamoda and Rashidi⁷ observed stability in BOD₅ loads in larger WWTPs, but slight increases in others, highlighting the heterogeneous impact of behavioural shifts on wastewater systems, while Ahmed *et al.*⁶ also noted that changing surfactant and detergent use during the pandemic may have influenced BOD₅ values due to their interference with aerobic biological processes.

These international findings are consistent with the data obtained for the Bacaxá WWTP between 2020 and 2022, where no BOD₅ violations were recorded despite the uncertainties of the health crisis. In Saquarema, the seasonal population decline driven by mobility restrictions and beach closures appears to have moderated influent loads, promoting greater process stability and reinforcing the WWTP's operational resilience, in line with the international literature associating behavioural changes with shifts in the sewage organic load. Technically, BOD₅ remains one of the most relevant indicators of biodegradable organic content, as it reflects the oxygen demand for microbial decomposition under controlled time, and temperature and is influenced by factors such as per capita water use, sanitation habits, socioeconomic conditions, and local climate.²¹

3.3.3. Ammoniacal Nitrogen (N-NH₃)

The analysis of ammoniacal nitrogen (N-NH₃) concentrations in the treated effluent from the Bacaxá WWTP reveals notable operational shortcomings, particularly in the monitoring and reporting of this parameter. Although its measurement is mandatory, the concessionaire only began including N-NH₃ in reports submitted to the PROCON-ÁGUA platform in 2022. This omission of over three years represents a critical gap in environmental oversight and undermines both the historical evaluation of treatment performance and compliance with regulatory standards.

Among the 31 samples recorded since its inclusion, N-NH₃ concentrations ranged from 5.9 mg L⁻¹ (June 2022) to 34.6 mg L⁻¹ (November 2023), with 22.58% of samples exceeding the MPV_{N-NH₃} (20 mg L⁻¹).¹⁷ This recurrence suggests persistent inefficiencies in the biological treatment process, specifically with the Submerged Aerated Biological

Filter (SABF) technology, indicating likely constraints in nitrification performance.

N-NH₃ data showed significant non-normality (Shapiro-Wilk: $W = 0.72474$, $p\text{-value} = 2.59 \times 10^{-10}$). The Friedman test revealed no statistically significant differences between years ($\chi^2(5) = 5.74$, $p\text{-value} = 0.076$), indicating a relatively stable but non-compliant pattern. This supports the hypothesis of structural deficiencies in the nitrification stage and the absence of denitrification units, as observed in international literature. Alsulaili *et al.*¹² reported reduced N-NH₃ removal efficiency in mid-sized WWTPs during the pandemic, exposing the vulnerability of such systems to fluctuating influent loads.

Ecotoxicologically, ammoniacal nitrogen is among the most sensitive indicators of sewage pollution.²¹ Its persistent presence at elevated concentrations can lead to eutrophication, oxygen depletion, aquatic toxicity, and reduced water quality for recreational or potable use. Originating from protein and urea decomposition, ammoniacal nitrogen plays a crucial role in nutrient dynamics, often acting as a limiting factor that stimulates algal and cyanobacterial growth.²⁴

The Bacaxá WWTP data, despite the lack of records prior to 2022, reveal frequent exceedances, particularly in May and November 2023 and August and September 2024. These patterns indicate systemic limitations in nitrogen removal and are consistent with international reports linking pandemic-era shifts in consumption and sanitation to WWTP performance failures.

In Serbia, studies showed increased N-NH₃ concentrations in 2020 versus pre-pandemic periods (2015–2019),⁶ attributed to intensified cleaning product use, altered occupancy patterns, and elevated domestic wastewater loads. Similarly, research in Kuwait warned of interactions between quaternary ammonium compounds and chloramines, forming carcinogenic nitrosamines.¹⁰ “Slug discharges” of such substances may disrupt WWTP operations, affecting BOD₅, phosphorus, and nitrogen removal, especially in facilities lacking denitrification units, like Bacaxá.¹⁵

These findings confirm that N-NH₃ exceedances at Bacaxá are not isolated incidents but reflect broader vulnerabilities. Although data before 2022 are lacking, the post-2022 results underscore urgent structural, regulatory, environmental, legal, and operational concerns. Mandatory N-NH₃ monitoring should have been implemented over a decade ago, as outlined in federal standards,³ and the delay in incorporating this requirement into state protocols, evident from the absence of data until 2022, undermines performance assessments and weakens environmental policy enforcement. Therefore, immediate corrective measures are essential, including process reassessment and

the potential implementation of advanced nitrogen removal technologies such as integrated nitrification–denitrification systems in order to ensure legal compliance while advancing sustainability goals and preserving the integrity of aquatic ecosystems in the *Baixas Litorâneas* region.

3.4. Process-level correlation patterns reveal solids retention and nitrification stability as dominant controls on effluent quality

The Spearman correlation matrix indicated that only a limited number of pairwise associations were strong enough to support a clear process-based interpretation. Overall, the correlation structure was predominantly negligible to weak, suggesting that effluent variability arose from partially independent hydraulic, physicochemical, and biological controls rather than from a single dominant driver (Figure 5).

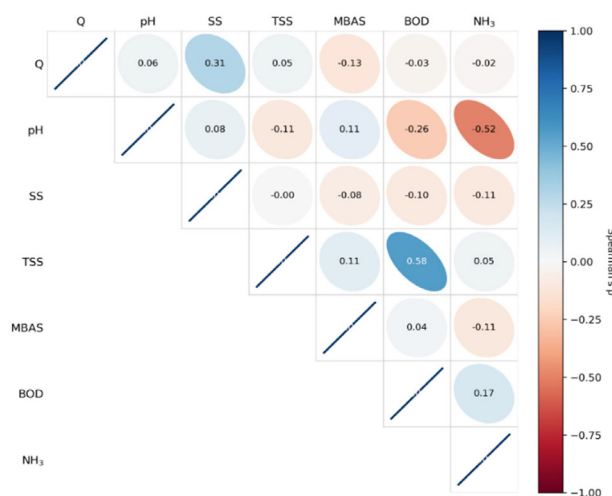


Figure 5. Upper triangular Spearman correlation matrix among Q, pH, SS, TSS, MBAS, BOD, and NH₃. Ellipse color and geometry represent the sign and magnitude of Spearman's correlation coefficient (ρ). Numbers within cells denote ρ values. Statistical significance was evaluated at $\alpha = 0.05$ (95% confidence level)

The most relevant positive association was observed between TSS and BOD ($\rho = 0.58$), corresponding to a moderate positive correlation. This result indicates that increases in total suspended solids tended to coincide with higher residual biodegradable organic matter in the treated effluent. From a process perspective, this pattern strongly suggests that deterioration in solid-liquid separation was directly associated with deterioration in organic matter removal. In practical terms, periods of solids carryover or reduced settling efficiency were likely accompanied by higher BOD in the final effluent. This was the clearest positive signal in the matrix and identifies particulate retention as a key determinant of effluent organic quality.

The strongest negative association was observed between pH and N-NH₃ ($\rho = -0.52$), corresponding to a

moderate negative correlation. Lower pH values tended to coincide with higher ammonia concentrations, indicating a relevant operational gradient linked to nitrogen removal performance. In biological wastewater treatment systems, this pattern is consistent with reduced nitrification stability or process conditions that simultaneously affect ammoniacal nitrogen conversion and system buffering capacity. This relationship is also chemically plausible, since ammonia speciation is pH dependent and nitrification is closely associated with alkalinity consumption. Although correlation does not establish causality, the moderate magnitude of this association indicates that pH was an informative indicator of process conditions with respect to ammonia removal.

The association between Q and SS ($\rho = 0.31$) was weakly positive. This result suggests that higher flow rates tended to coincide with increased settleable solids, which is consistent with a limited hydraulic influence on sedimentation performance and on solids release. Although weaker than the previous associations, this pattern is operationally plausible and may reflect shorter effective settling times or reduced clarification efficiency under higher flow conditions.

All remaining correlations were weak or negligible and have limited interpretative value (Figure 5). In particular, MBAS showed little association with the other variables, indicating that surfactant variability was largely decoupled from the main gradients controlling solids, organic matter, and ammonia. Likewise, the weak or negligible correlations involving N-NH_3 with variables other than pH suggest that ammonia dynamics were more specifically related to nitrification-related process chemistry than to generalised deterioration in effluent quality.

Taken together, the matrix identifies two dominant process signals, both in the moderate range: the positive relationship between TSS and BOD, highlighting the importance of efficient solids retention for final organic effluent quality, and the negative relationship between pH and N-NH_3 , indicating that nitrogen removal stability was closely linked to the acid-base condition of the system. Therefore, the results suggest that process optimization should focus primarily on improving solid-liquid separation and maintaining stable nitrification conditions, as these were the most relevant controls on effluent quality variability during the monitored period.

This study has some limitations that should be acknowledged. First, the absence of influent quality data prevented direct calculation of removal efficiencies for the monitored parameters. Second, ammoniacal nitrogen monitoring only began in 2022, limiting the long-term assessment of nitrogen removal performance. Third, complementary variables such as COD, nitrate, nitrite, alkalinity, dissolved oxygen, phosphorus, and pathogen-

related markers were not available, which restricts a more detailed mechanistic interpretation of the treatment performance during and after the pandemic period.

4. Conclusion

The longitudinal assessment of the Bacaxá WWTP (2019–2024) showed that the plant performance was conditionally stable under reduced loading, but remained vulnerable to operational deterioration under variable demand conditions. During the COVID-19 period (2020–2022), lower influent pressure coincided with flows closer to the design conditions and generally improved compliance with key parameters, suggesting that reduced external loading contributed to more stable treatment performance. However, the recurrence of non-compliance events in 2019, 2023, and 2024 demonstrates that this stability was not sustained under higher hydraulic and organic stress, which is consistent with the seasonal pressure typically imposed by tourist regions.

These findings partially support the initial hypothesis that reduced seasonal tourism during lockdown periods would improve effluent quality by lowering system loading. This pattern was more clearly observed for organic matter-related parameters and overall compliance stability than for surfactant-related variability, while ammoniacal nitrogen remained a persistent limitation in treatment performance. Thus, the results suggest that the pandemic period was associated with temporary operational relief, but not with a uniform improvement across all monitored variables.

The correlation structure provided an additional process-based perspective on these performance limitations. Among the pairwise relationships, the only moderate associations were the positive correlation between TSS and BOD and the negative correlation between pH and NH_3 . These results indicate that reduced solid-liquid separation efficiency was closely linked to poorer organic effluent quality, whereas nitrogen removal performance was closely related to process stability and acid-base conditions. Together, these findings suggest that the most relevant sources of effluent variability were concentrated in two core operational domains: particulate retention and nitrification-related stability.

Ammoniacal nitrogen represents a particularly important concern. Although NH_3 monitoring was only introduced in 2022, the observed exceedances indicate insufficient nutrient removal and reveal a treatment limitation with direct implications for receiving water quality. The absence of historical NH_3 data also restricts the retrospective evaluation of long-term nitrogen removal performance, underscoring the need for broader and more consistent monitoring frameworks.

Overall, the Bacaxá WWTP demonstrated a degree of operational resilience under reduced load conditions, but it lacks the structural robustness required to ensure consistent compliance under fluctuating hydraulic and organic inputs. Future interventions should therefore prioritize improvements in solid-liquid separation, strengthening of nitrification-denitrification capacity, and expansion of real-time monitoring of hydraulics, solids, and nitrogen species. Beyond the case-specific diagnosis, these results provide evidence that wastewater systems in highly seasonal coastal regions require not only greater treatment robustness, but also monitoring and regulatory strategies capable of capturing the effects of transient population-driven loading on plant performance.

Author Contributions

Ricardo Soares: Conceptualization, Software, Validation, Visualization, Writing/Review, and Editing.

Rafaela Naegele Alvernaz: Conceptualization, Investigation, Data Curation, Software, Writing – Original Draft, Writing/Review, and Editing.

Pablo Vimercati Simas: Conceptualization, Software, Writing/Original Draft, Data Curation, and Editing.

Augusto Ahn Ka: Data Curation, and Investigation.

Márcia Cristina Santiago de Mello: Visualization, Writing and Editing.

Paulo Henrique Zuzarte Ferreira: Visualization, Writing and Editing.

Carlos Eduardo Soares Canejo Pinheiro da Cunha: Validation, Visualization, Writing/Review, and Editing.

Bibliographic References

1. Instituto Brasileiro de Geografia e Estatística – IBGE.; Atlas de saneamento: abastecimento de água e esgotamento sanitário / IBGE, Coordenação de Geografia e Coordenação de Recursos Naturais e Meio Ambiente, 3a. ed., Rio de Janeiro, 2021. Available at: <https://biblioteca.ibge.gov.br/visualizacao/livros/liv101885_completo.pdf>. Accessed on: February 1, 2026.
2. Trata Brasil.; Relatório completo: Ranking do saneamento de 2024. Available at: <<https://tratabrasil.org.br/wp-content/uploads/2024/04/Relatorio-Completo-Ranking-do-Saneamento-de-2024-TRATA-BRASIL-GO-ASSOCIADOS.pdf>>. Accessed on: February 1, 2026.
3. Brasil. Conselho Nacional do Meio Ambiente (CONAMA).; Resolução nº 430, de 13 de Maio de 2011. Diário Oficial da União. Brasília, 2011. Available at: <<https://www.ibama.gov.br/sophia/cnia/legislacao/CONAMA/RE0430-130511.PDF>>. Accessed on: February 1, 2026.
4. Bandala, E. R.; Kruger, B. R.; Cesarino, I.; Leao, A. L.; Wijesiri, B.; Goonetilleke, A.; Impacts of COVID-19 pandemic on the wastewater pathway into surface water: A review. *The Science of the Total Environment*, **2021**, 774, 145586. [Crossref]
5. Silva, C. M.; Soares, R.; Machado, W.; Arbilla, G.; A Pandemia de COVID-19: Vivendo no Antropoceno. *Revista Virtual de Química* **2020**, 12, 1001. [Crossref]
6. Ahmed, M. E.; Al-Haddad, A.; Bualbanat, A.; Possible Impacts of COVID-19 Pandemic on Domestic Wastewater Characteristics in Kuwait. *Journal of Environmental Engineering and Landscape Management* **2022**, 30, 393. [Crossref]
7. Hamoda, M. F.; Al Rashidi, N. S.; Impact of Corona virus pandemic on wastewater characteristics, treatment, and water reuse in a municipal plant. *Frontiers in Environmental Engineering* **2023**, 2, 1270854. [Crossref]
8. Yazdian, H.; Jamshidi, S.; Performance evaluation of wastewater treatment plants under the sewage variations imposed by COVID-19 spread prevention actions. *Journal of Environmental Health Science and Engineering* **2021**, 19, 1613. [Crossref]
9. Colak, S.; Oztekin, E.; Effect of COVID-19 Pandemic on Chemical Parameters of Wastewater Treatment Plant: a Case Study in Zonguldak City, Turkey. *Environmental Engineering and Management Journal* **2022**, 21, 805. [Crossref]
10. Pešić, V.; Bečelić-Tomin, M.; Leovac Mačarak, A.; Kulić Mandić, A.; Tomašević Pilipović, D.; Kerkez, D.; The Impact of Public Policy Measures during the COVID-19 Pandemic on the Characteristics of Urban Wastewater in the Republic of Serbia. *Sustainability* **2023**, 15, 3047. [Crossref]
11. Roman, M.-D.; Sava, C.; Iluțiu-Varvara, D.-A.; Mare, R.; Pruteanu, L.-L.; Pică, E. M.; Jäntschi, L.; Biological Activated Sludge from Wastewater Treatment Plant before and during the COVID-19 Pandemic. *International Journal of Environmental Research and Public Health* **2022**, 19, 11323. [Crossref]
12. Alsulaili, A.; Al-Fadhli, F. M.; Garcia, H. A.; Ali, O.; Alenezi, N.; COVID-19 and Wastewater Management in Semi-Arid Regions: Observations and Global Comparisons from a GCC Country. *Water* **2025**, 17, 1332. [Crossref]
13. Imprensa Oficial do Estado do Rio de Janeiro – IOERJ.; Cadernos regionais do Estado do Rio de Janeiro: Região das Baixadas Litorâneas. IOERJ, Niterói. Available at: <<https://www.gov.br/empresas-e-negocios/pt-br/portais-desconhecidos/observatorioapl/biblioteca-apl/publicacoes/caderno-regional-baixadas-litoraneas-rj.pdf>>. Accessed on: February 1, 2026.
14. Instituto Brasileiro de Geografia e Estatística – IBGE.; Saquarema: panorama do município. IBGE. Available at: <<https://cidades.ibge.gov.br/brasil/rj/saquarema/panorama>>. Accessed on: February 1, 2026.
15. Agência Reguladora de Energia e Saneamento Básico do Estado do Rio de Janeiro – AGENERSA.; Relatório de Fiscalização AGENERSA/CASAN Nº45/2022 - Estação de Tratamento de Esgoto Bacaxá. Rio de Janeiro, 2022. Available at: <https://www.rj.gov.br/agenersa/sites/default/files/arquivos_paginas_basicas/RF-045-2022_0.pdf>. Accessed on: February 1, 2026.

16. Instituto Estadual do Ambiente – INEA.; Estabelece critérios e padrões de lançamento de esgoto sanitário, NOP-INEA-045 R-00 de 25/02/2021. Rio de Janeiro, 2021. Available at: <<https://www.inea.rj.gov.br/wp-content/uploads/2021/03/NOP-INEA-45.pdf>>. Accessed on: February 1, 2026.
17. Instituto Estadual do Ambiente – INEA.; Programa de Autocontrole de Efluentes Líquidos (Procon Água). Rio de Janeiro, 2021. Available at: <<https://www.inea.rj.gov.br/procon-agua/>>. Accessed on: February 3, 2026.
18. Companhia Ambiental do Estado de São Paulo – CETESB; Agência Nacional de Águas – ANA.; Guia nacional de coleta e preservação de amostras: água, sedimento, comunidades aquáticas e efluentes líquidos (2a. ed.). CETESB/ANA, São Paulo/Brasília, 456 pp. Available at: <https://biblioteca.ana.gov.br/sophia_web/VisualizadorPdf?codigoArquivo=165531&tipoMidia=0>. Accessed on: February 3, 2026.
19. Lipps, W. C.; Braun-Howland, E. B.; Baxter, T. E.; American Public Health Association; American Water Works Association; Water Environment Federation, organizadores Standard Methods for the Examination of Water and Wastewater, 24th edition American Public Health Association: Washington, 2023.
20. R: The R Foundation. Available at: <<https://www.r-project.org/foundation/>>. Accessed on: February 1, 2026.
21. Von Sperling, M.; Verbyla, M. E.; Oliveira, S. M. A. C.; Assessment of Treatment Plant Performance and Water Quality Data: A Guide for Students, Researchers and Practitioners. IWA Publishing, 2020. [[Crossref](#)]
22. Soares, R.; Maestá, B.C.; Motta, F. D.; Naegle, R.; Cunha, C. E. S. C. P.; Impact Assessment of 2020 COVID-19 Lockdown on Landfill Leachate Treatment in Rio De Janeiro. *Revista Virtual De Química* **2022**, *14*, 510. [[Crossref](#)]
23. Nunes, R. F.; Teixeira, A. C. S. C.; An Overview on Surfactants as Pollutants of Concern: Occurrence, Impacts and Persulfate-based Remediation Technologies. *Chemosphere* **2022**, *300*, 134507. [[Crossref](#)]
24. Omar, A.; Almomani, F.; Qiblawey, H.; Rasool, K.; Advances in Nitrogen-rich Wastewater Treatment: A Comprehensive Review of Modern Technologies. *Sustainability* **2024**, *16*, 2112. [[Crossref](#)]