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IMPACT OF FOAM FORMATION ON YEAR-TO-YEAR PERFORMANCE VARIATION IN WWTP OF ANNABA (EASTERN ALGERIA): A COMPARATIVE ANALYSIS

Yazid BEDOUH[1*], Fatma Zohra GUELLATI[2], Sofiane ALI RACHEDI[1], Samiha CHAIB RASSOU[2]

[1]Environmental Research Center (CRE), Avenue Boughazi Said, Annaba 23000, Algeria
[2]Ecobiology Laboratory for Marine Environments and Coastal Areas, Badji Mokhtar University of Annaba, 12.P.O. BOX, 23000 Annaba, Algeria

Abstract: Biological foam generation amplifies inter-annual variability in WWTP performance by causing recurring, season-sensitive disturbances in biomass retention, solids control, effluent stability, and operating cost. This study examines the effects of biological foam generation on inter-annual variations at the WWTP of Annaba (Algeria) located in the Mediterranean region via a comparison of 2024 (pre-foam) and 2025 (post-foam) periods. Whereas organic matter degradation (BOD_5, TSS) was less affected, nutrient removal experienced a significant reduction due to foam generation, whereby nitrogen removal decreased to below 20%, while phosphorus removal was almost non-existent. PCA analysis indicated that seasonal changes and temperatures were some of the key reasons for the biological imbalance. It can be concluded that biological foaming is a major contributor to non-compliance with nutrient discharges, calling for immediate attention towards sustainable measures within Mediterranean WWTPs.

Keywords: biological foaming, WWTP, nutrient removal, inter-annual performance, principal component analysis.

INTRODUCTION

Wastewater treatment plants (WWTPs) stand as the silent guardians of our aquatic ecosystems, tirelessly processing the complex chemical and biological cocktails of modern society (Ibrahim et al., 2025). However, the operational stability of these facilities is frequently challenged by a phenomenon that is as visually striking as it is technically disruptive: biological foaming (Guellati et al., 2025). Far from being a mere aesthetic nuisance, the sudden eruption of thick, stable foam on the surface of aeration tanks represents a profound shift in the delicate microbial balance of the activated sludge process. (Zhou et al., 2024).

Biological foam generation amplifies inter-annual variability in WWTP performance by causing recurring, season-sensitive disturbances in biomass retention, solids control, effluent stability, and operating cost (Xia et al., 2018). It is especially important when interpreting multi-year trends, because a "bad year" may reflect stronger foaming conditions rather than a fundamental deterioration of the plant (Geo et al., 2015).

According to recent studies, foam formation is a universal operating problem, since about 50% of facilities experience these phenomena at any time (Petrovski et al., 2022). In most cases, these phenomena occur due to the excessive growth of filamentous and hydrophobic microorganisms, such as *Microthrix parvicella* (Rossetti et al., 2009). They react with bubbles of air, forming stable foams on the surface of a reactor (Krohn et al., 2025). At the same time, foam formation does not only affect how a facility looks, but also has negative consequences for its operation. Indeed, large amounts of foam inhibit oxygen transfer efficiency and thus impede the degradation of organic substances and nutrients (Ibrahim et al., 2025). As a result, there appear additional problems, including increased expenses on aeration and usage of chemicals to eliminate the foam layer, and possible pollution in case of overflowing (Carballo et al., 2024).

Foaming is an occurrence that cannot only affect operations briefly but has the potential to create serious ramifications with regard to the long-term efficiency of WWTPs. According to recent research, it becomes imperative to be familiar with the seasonality and regionality aspects related to this problem. In this context, it is important to mention Mediterranean climate areas, wherein seasonal changes along with special composition of wastewater may become a cause for recurrent foaming. Knowledge of such factors is vital when trying to manage plants efficiently (Contreras-Llin et al., 2026; Mahboubi et al., 2026). Moreover, *M. parvicella* plays an important role when it comes to foaming issues in such seasons (Biological Waste Expert, 2025).

Despite the numerous technical effects of foaming that have been identified, the impact of such phenomena on inter-annual variations in performance has yet to be clarified. Traditionally, monitoring is based on visual observation, but recently developed methods of image processing and microbiome analysis in real-time conditions have started providing new insights into the causes and dynamics of foaming events (Carballo Mato et al., 2024; Zhang et al., 2025). The implementation of innovative technologies provides promising prospects for early diagnosis and better management of foaming.

This study aims to bridge the gap between short-term operational disturbances and long-term performance stability. By conducting a comparative analysis of a Mediterranean WWTP over several years, we examine how recurrent foam formation shapes the

***Correspondence**: Bedouh Yazid, Environmental Research Center (CRE), Avenue Boughazi Said, Annaba 23000, Algeria., Tel. +213655244419, email: y.bedouh@cre.dz*

inter-annual variation in treatment efficiency. Through this lens, we seek to provide plant operators and engineers with a more nuanced understanding of how to maintain high performance in the face of persistent biological challenges.

MATERIALS AND METHODS

Study Area and Sampling

The study was conducted at the WWTP of Annaba located at the northeastern part of Algeria (36°51'15.95"N and 7°46'4.92"E), over a two-year period (2024-2025). The plant in (Fig. 1) operates an activated sludge process and is representative of facilities in the region, characterized by seasonal variations in influent composition and flow. Grab samples of influent and effluent wastewater were collected monthly at designated sampling points within the WWTP.

Fig 1. Configuration of the WWTP of Annaba.

This study employed a comparative analysis approach to investigate the impact of biological foaming on the inter-annual performance variation of the WWTP. Performance data from 2024 (pre-foam period) were compared against data from 2025 (post-foam period) to assess changes in treatment efficiency across key physicochemical parameters. The experimental design focused on identifying significant shifts in removal efficiencies attributed to recurrent foam formation, as described in the introduction.

Physicochemical Analysis

Samples were immediately transported to the laboratory in pre-cleaned, sterile containers and stored at 4°C until analysis, typically within 24 hours of collection. As showed in table 1, All physicochemical analyses were performed in accordance with the "Standard Methods for the Examination of Water and Wastewater» according to the recommendations of (Rodier et al., 2009).

Table 1.

Methods of Physicochemical Parameters Analysis

Setting	Analysis Method	Unit
pH	Using a multi-parameter (Consort™ C3010).	–
Total Suspended Solids (TSS)	Filtration on porous membrane, drying at 106°C and determination by differential weighing.	(mg/l)
Chemical Oxygen Demand (COD)	Chemical oxidation of materials by excess potassium dichromate in a sulfuric medium.	(mg/l)
Biological Oxygen Demand (BOD_5)	Measured after 5 days at 20°C using a spectrophotometric method.	(mg/l)
Total Nitrogen (TKN)	Dosage by molecular absorption spectrophotometry after mineralization.	(mg/l)
Total phosphorus	Dosage by molecular absorption spectrophotometry after mineralization.	(mg/l)
Salinity	Measured by electrical conductivity (EC) and converted using the Practical Salinity Scale (PSS-78).	(g/l)

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Calculation and statistical Analysis

The degree of removal efficiency was calculated using the following equation for each pollutant:

Removal efficiency (%) = $[(C_0 - C_f)/C_0] \times 100$

C_0: represents the initial concentration (mg/l) at t = 0;

C_f: analyte concentration (mg/l), at the end of the experiment.

Statistical analyses were performed using (R) software. Before conducting any statistical analysis, the normality of the data was checked with the Kolmogorov-Smirnov (K–S) test. Descriptive statistics were used to summarize the collected data. Comparative analysis between the pre-foam (2024) and post-foam (2025) periods was performed using appropriate statistical tests to determine significant differences in treatment efficiencies. To identify differences in mean concentrations of contaminants among treatments and the control, ANOVA one-way was employed and followed by comparison analysis test ('t-Test' for normally distributed data and 'Mann-Whitney Test' for non-normally). For all the tests, differences were taken as statistically significant when $p < 0.05$. Pearson matrix correlation test was established to check the dependencies of studied parameters. Principal Component Analysis (PCA) was also employed to identify underlying patterns and correlations among operational parameters and their influence on foam formation and plant performance, as detailed in the Results and Discussion section.

RESULTS AND DISCUSSION

Fig. 2 shows the mean Influent and Effluent pollutant concentrations of TSS, COD, BOD5, total nitrogen, and total phosphorus in the WWTP during the period of study.

Evaluation of the WWTP performances

Before treatment, wastewater displayed high levels of TSS, COD, and BOD5 which are typical constituents of industrial and domestic sewage wastewaters (Bedouh et al., 2023). Compared to the Algerian standards (JORA, 2006) all of the indicators were above the permitted threshold for at least some time during the sampling period.

After treatment, the average concentrations of the analyzed pollutants in effluent do not exceeded Algeria's discharge and agricultural reuse limits (JORA, 2006) This demonstrates that the WWTP treatment is efficacious. However, phosphorus removal remains insufficient, with effluent concentrations often exceeding the recommended *2 mg/L*, presenting a risk of eutrophication in receiving waters. Total nitrogen compliance appears variable and may necessitate further monitoring to ensure sustained conformity (Plaxton., 2011).

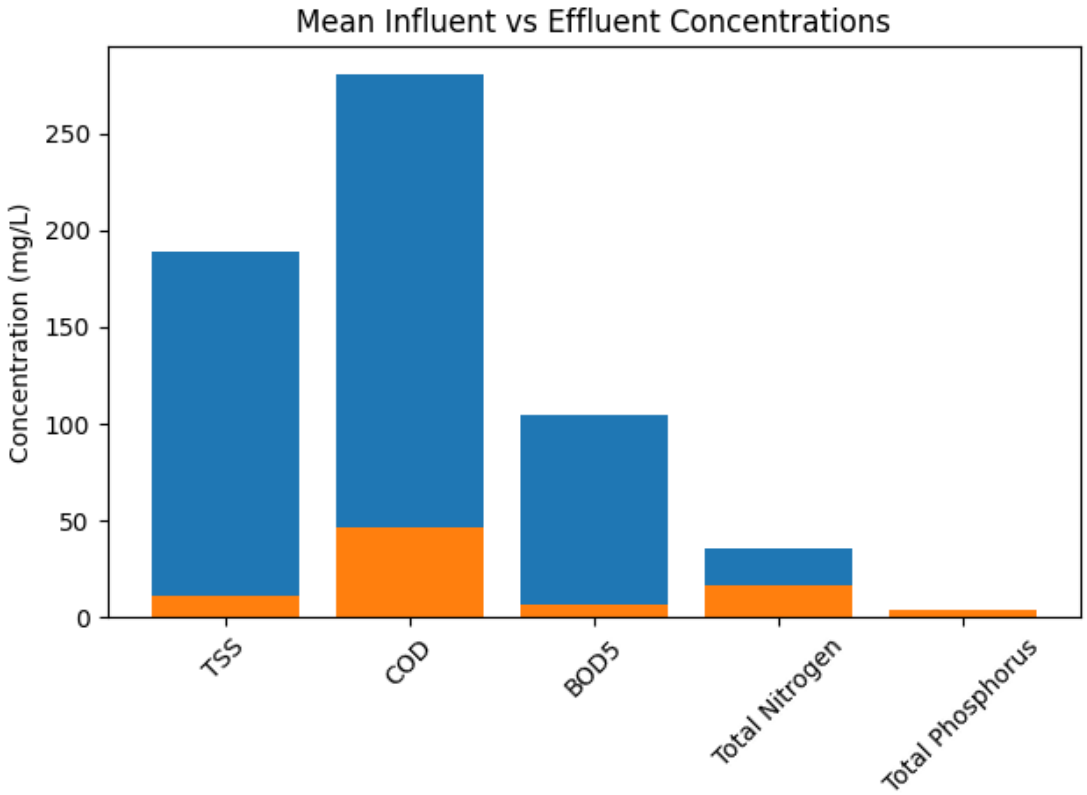

Fig 2. Comparison of Mean Influent and Effluent Pollutant Concentrations in the WWTP.

Monthly COD, BOD5, ssalinity, Nitrogen, and phosphorus removal

Monthly evolution of treatment efficiency the comparative analysis of WWTP removal efficiencies between 2024 (pre-foam) and 2025 (post-foam) vividly (Fig 3 and Fig 4) illustrates the profound and multifaceted impact of biological foaming, transforming it from a mere operational nuisance into a critical threat to treatment efficacy. This figure tells a compelling story of a plant's resilience, but more strikingly, its vulnerabilities when confronted with this pervasive challenge. Initially, in 2024, the plant

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demonstrated robust and consistent performance across key parameters. MES and BOD5 removal efficiencies (top row) remained commendably high, often exceeding 90%, suggesting a stable and effective primary organic matter removal process (Hamoud et al., 2023).

Even after foam formation in 2025, these parameters, while showing slight dips, largely maintained their high efficiency, indicating a degree of inherent resilience in the plant's ability to capture suspended solids and biodegradable organic load (Kumar et al., 2024). This suggests that the fundamental physical and biological mechanisms for these removals were not entirely crippled. However, the narrative shifts dramatically when examining COD, Nitrogen, and Phosphorus removal efficiencies (Pal et al., 2023). The DCO removal (middle-left) in 2025 exhibits a noticeable and sustained decline compared to 2024, particularly during certain months, signaling a broader compromise in overall organic matter degradation (Bedouh et al., 2024). The most striking and concerning impacts are observed in Nitrogen and Phosphorus removal (middle-right and bottom-left, respectively) (Guellati et al., 2025).

In 2024, Nitrogen removal, though fluctuating, generally met or approached compliance targets (Guellati et al., 2024). In stark contrast, 2025 reveals a severe and consistent collapse in Nitrogen removal, frequently plummeting well below 20% and consistently failing to meet the 67% compliance target. Similarly, Phosphorus removal, already variable in 2024, becomes almost non-existent or even negative in 2025, indicating a complete breakdown of this critical nutrient removal pathway, far from the 90% compliance target (Wang et al., 2024).

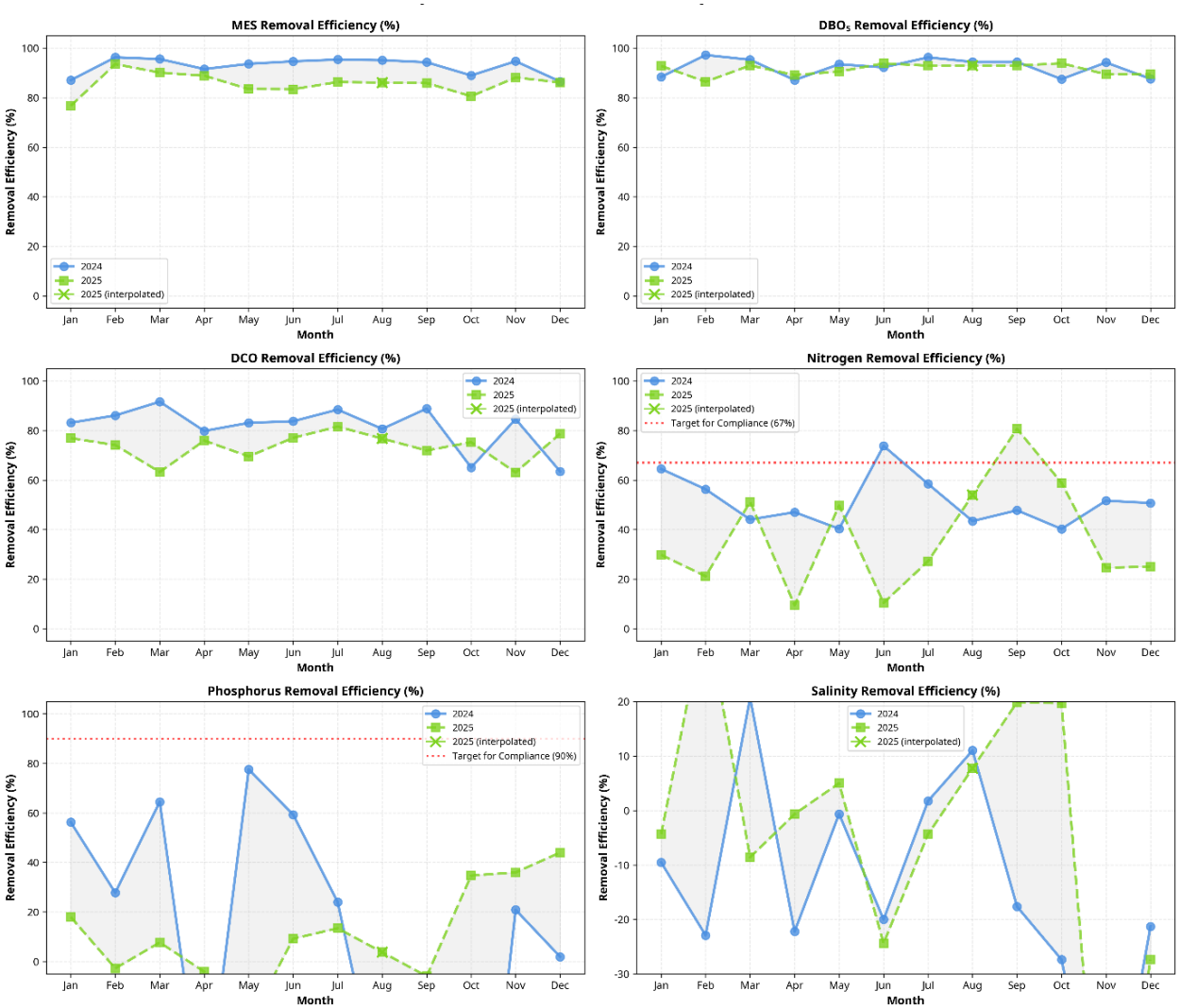

Fig 3. Monthly evolution of treatment efficiency of WWTP removal efficiencies between 2024 (pre-foam) and 2025 (post-foam).

This profound deterioration in nutrient removal highlights how foam formation directly interferes with the delicate microbial communities responsible for nitrification, denitrification, and biological phosphorus uptake (Zubrowska-Sudol et al., 2014).

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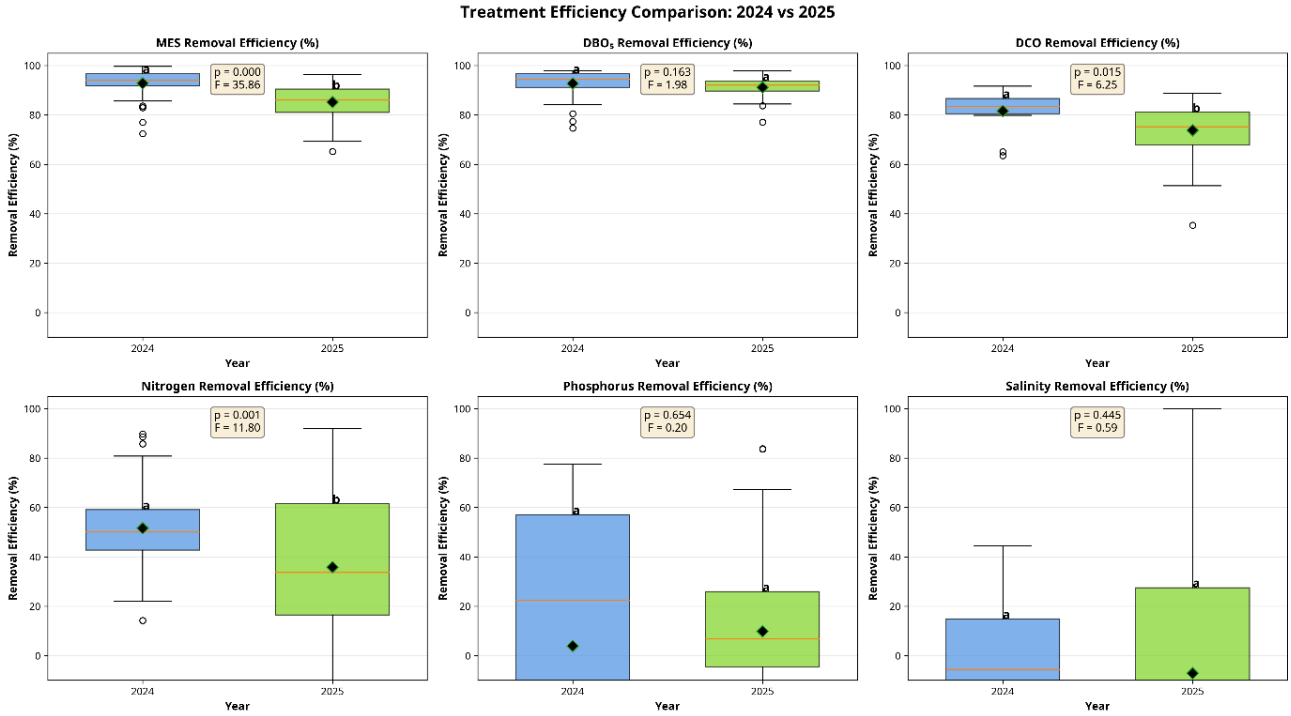

Fig 4. Comparative analysis of WWTP removal efficiencies between 2024 (pre-foam) and 2025 (post-foam).

The boxplot in Fig. 4 presents a statistical comparison of treatment efficiency across six critical water quality parameters at the Annaba Wastewater Treatment Plant (STEP) for the years 2024 and 2025. Each boxplot displays the distribution of removal efficiency data, with statistical significance testing (ANOVA) to determine whether observed differences between years are meaningful or due to random variation.

Results demonstrate that the WWTP of Annaba currently operates at a POOR performance level with critical non-compliance in nitrogen and phosphorus removal. While the facility demonstrates adequate capability for organic matter and suspended solids removal, the lack of nutrient removal capacity poses significant regulatory and environmental risks (Hamoud et al., 2025).

Correlation matrix

The correlation matrix, often perceived as a dense grid of numbers, actually tells a compelling story about the hidden relationships and dependencies within our wastewater treatment plant (WWTP). Obtained result in Fig 5, show a strong positive correlation among influent parameters such as (COD_in), (BOD5_in), and (MES_in) underscore the integrated nature of urban wastewater characteristics. This consistent co-occurrence of organic and suspended loads is a well-documented phenomenon, reflecting typical municipal discharge patterns (Miao et al., 2026).

Effective management of these combined loads is paramount for maintaining the stability of the activated sludge process, as sudden fluctuations can destabilize microbial communities and compromise treatment efficiency (Chang et al., 2026).

Crucially, the decoupling of these influent parameters from their effluent counterparts demonstrates the activated sludge process's remarkable efficiency in breaking down pollutants. This analysis provides a foundational understanding of the plant's inherent strengths and vulnerabilities, offering vital insights for anticipating operational shifts and proactively managing challenges like biological foaming. It underscores the dynamic interplay between environmental inputs and the plant's metabolic responses, essential for optimizing performance and ensuring ecological integrity (Holloway et al., 2021).

The PCA analysis of the water characteristics (Fig. 6) showed the presence of two groups along the PC1 axis, which regroups most of the parameters studied, with a large percentage of the variance (17.88%) in the data.

The Seasonal Pulse (PC1: The Environmental Driver)

PC1 serves as the "heart-beat" of the seasonality in the plant. The fact that temperature and salinity are very well correlated on this PC1 axis implies that the facility's efficiency does not remain constant throughout the year but varies depending on the Mediterranean weather. With an increase in temperature, there is a significant change observed in effluent quality, especially in phosphorus (TP) and conductivity. This means that the biological "metabolism" in the plant responds very sharply to variations in temperature, which will help predict potential biological issues such as foaming (Song et al., 2025).

The Daily Grind (PC2: The Metabolic Load)

Whereas PC1 runs with the rhythm of the seasons, the second principal component (PC2) reflects the "daily work load." These two parameters are mainly influenced by the influent flow (Qj) and organic loading (COD, BOD5, and MES). The high similarity of these factors demonstrates the existence of similar

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"shocks" in terms of both volume and quality. Importantly, the independence of effluent parameters from this axis demonstrates the stability of the plant operation, as even a significant influx does not affect the output of the facility (Xiong, Zhaoyang, et al 2025).

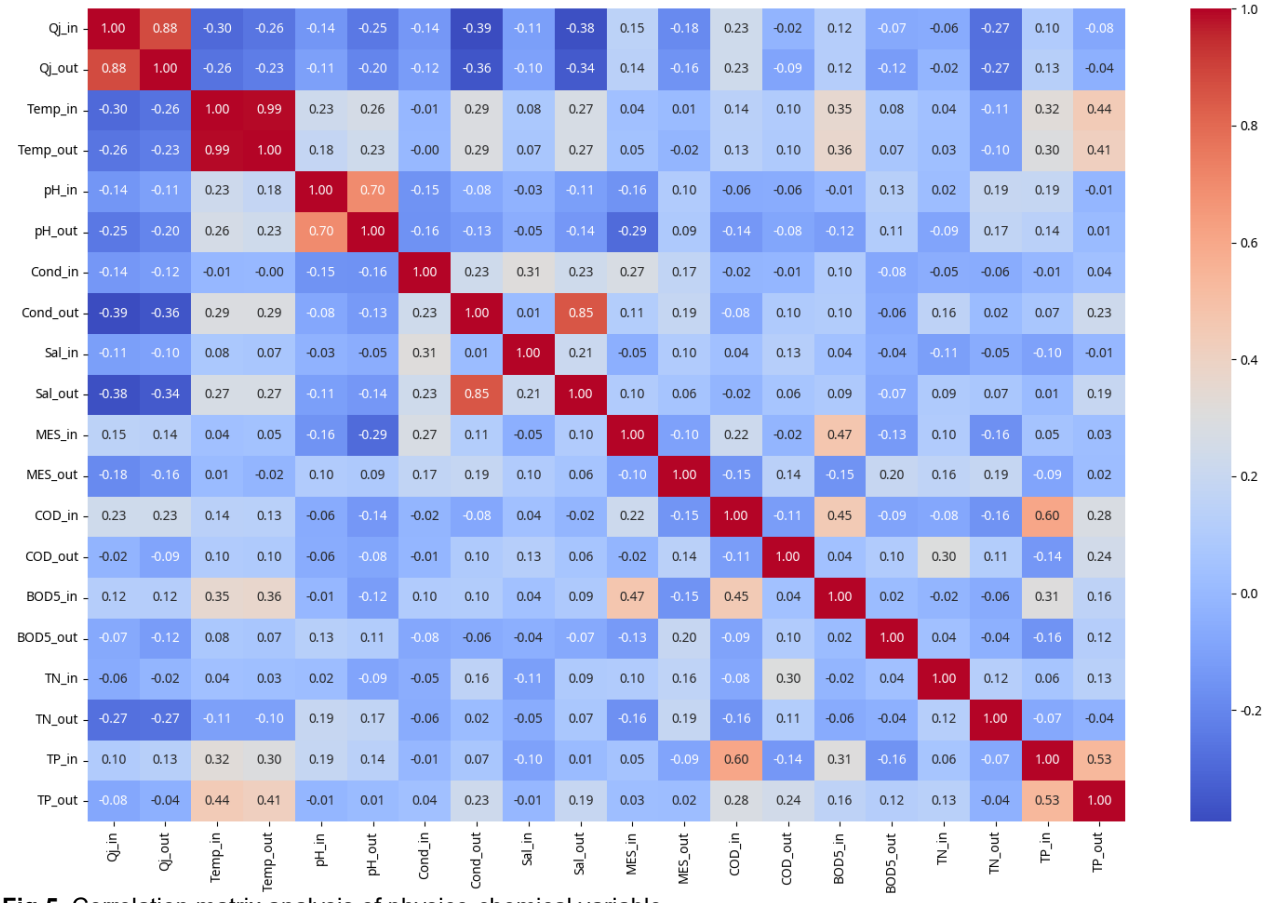

Fig 5. Correlation matrix analysis of physico-chemical variable.

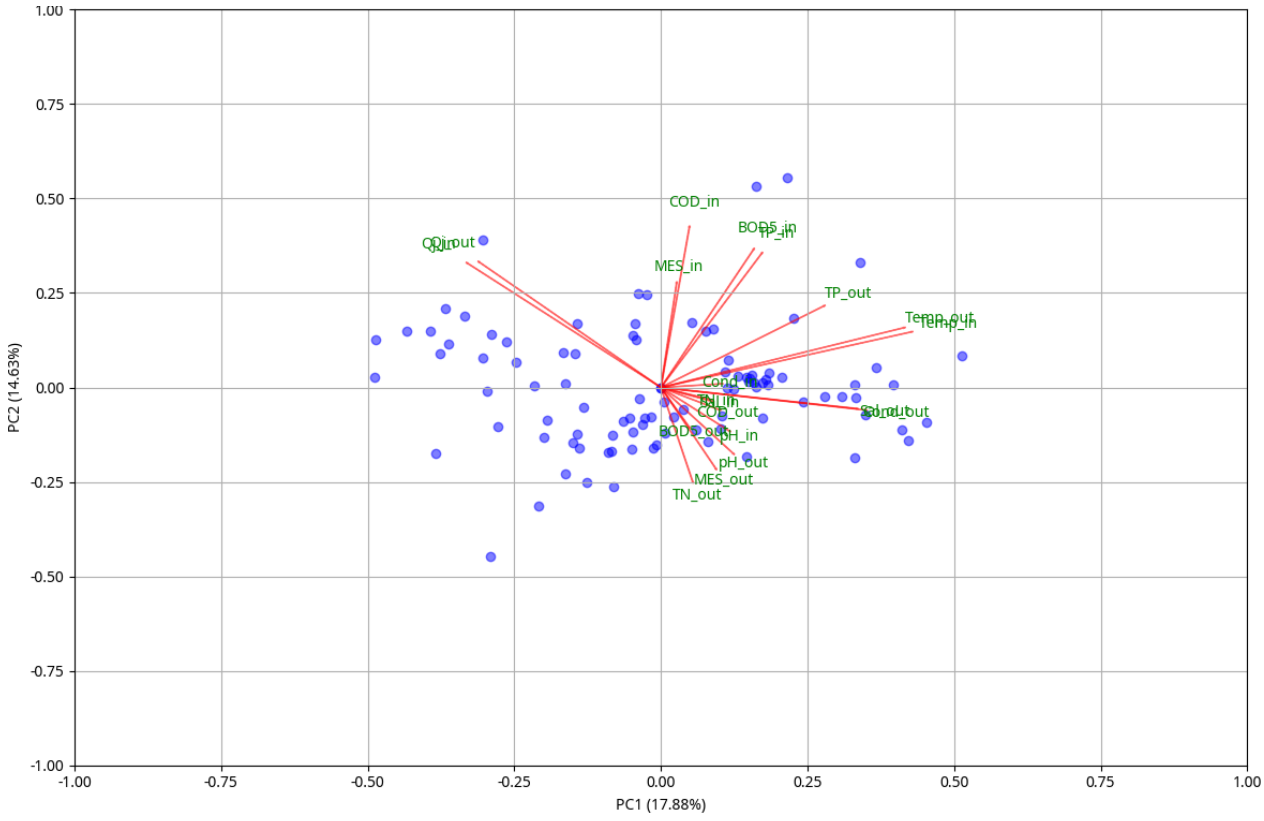

Fig 6. Factorial map applied to physico-chemical variable data conducted by Principal Components Analysis (PCA).

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The Hidden Synergies (Correlation Insights)

The correlation study has shown that there exists a "silent partnership" between organic substances and suspended solids. High coincidence of the MES, COD, and BOD_5 in the input proves the identical source of these contaminants, which can be associated with city discharges. However, the separation of these contaminants in the output water indicates the effectiveness of the biological purification process. It means that the activated sludge method does not filter out "bulk" waste but the biologically degradable part of them (Luo, Benfu, et al. 2025).

Implications for Foam Formation

With such an analysis of the "normative" operational parameters, we can pinpoint the "tipping points." According to the PCA, the riskiest moments would be when the seasonal pulse (PC1) and the metabolic pressure (PC2) meet each other—in moments such as those in which the temperature is increasing, and the bacteria are already stressed. It would be this statistical base from which we could obtain the "diagnostic map" required for predicting biological foam before it interferes with the silent safeguarding of the ecosystem by the plant (Xie, Fei, et al. 2025).

CONCLUSION

This paper offers a detailed examination into the role of biological foaming as the key element responsible for seasonal variation in performance at Mediterranean wastewater treatment facilities. Although the activated sludge technology proved resilient in its ability to remove bulk organic material such as BOD_5 and TSS, the processes of removing nitrogen and phosphorus nutrients were almost entirely disrupted. This study changes the perspective on biological foaming, moving beyond the idea of a minor operational issue and towards that of a major obstacle to complying with environmental legislation and the well-being of the receiving ecosystem.

The "seasonal heartbeat" of the facility was accurately modeled using the Principal Component Analysis (PCA) method, showing the thermal changes and metabolic shocks to be the driving force behind the microorganisms' instability. The fact that during biological foaming, the removal of nutrients became completely disconnected from organic waste removal is evidence that microorganisms responsible for nitrification and phosphorus accumulation were particularly sensitive to physical/chemical disturbances caused by *M. parvicella* and other filamentous organisms.

These conclusions are critical to the understanding of the measures required to ensure the high performance of Mediterranean facilities. Any future approach needs to incorporate climate-sensitive monitoring and early warning systems through recognition of the "tipping points" during seasons. In the end, prevention of biological foam formation should not only be seen as a means to an end, but as a condition for ensuring the sustainability of urban wastewater infrastructure.

AUTHORS CONTRIBUTIONS

*C*onceptualization & methodology: B.Y and G.F.Z; data collection C.R.S; data validation B.Y and C.R.S; data processing A.R.S and G.F.Z; writing—original draft preparation, B.Y; writing—review and editing, A.R.S.

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CONFLICT OF INTEREST

The authors have not any competing financial, professional, or personal interests from other parties"/ "The authors declare no conflict of interest.

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