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Assessing the Quality of Treated Wastewater: Sidi Bel Abbes and El Kerma-Oran WWTP's (North-West Algeria)

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ABSTRACT

The study aimed to assess the performance and characteristics of wastewater treatment processes in two wastewater treatment plant in northwestern Algeria, during the period from 2016 to 2024. The results showed that mean concentrations of BOD_5 were significantly higher at Sidi Bel Abbès (25.6 ± 3.2 mg/L) compared to El Kerma (18.4 ± 2.9 mg/L), and for SS, El Kerma exhibited significantly lower levels (34.1 ± 5.4 mg/L) than Sidi Bel Abbès (47.2 ± 6.3 mg/L). Although both stations achieved considerable reductions post-treatment, the residual COD remained higher at Sidi Bel Abbes. The statistical analysis using ANOVA revealed statistically significant differences between the two stations for key parameters such as pH, BOD_5, COD, SS, phosphates, and turbidity ($P < 0.05$), indicating variations in influent characteristics and operational efficiency. Furthermore, the treatment effect was highly significant ($P < 0.001$) across most parameters, confirming the overall efficacy of both stations in improving wastewater quality. The comparative analysis of microbiological indicators in inlet and outlet waters of the Sidi Be Abbès and El-Kerma WWTPs reveals significant reductions in microbial loads post-treatment, though with variable efficiency between sites. These findings underscore the importance of continuous monitoring, preventive maintenance, and adaptive management in maintaining optimal performance of wastewater treatment infrastructures. Further investigation into the causes of performance variability at the Sidi Bel Abbes station—whether technical, managerial, or environmental is warranted to ensure long-term sustainability and public health protection.

INTRODUCTION

In recent years, the quality of the waters in the world has greatly deteriorated due to uncontrolled discharges of industrial and agricultural wastes (**Rekrak *et al,* 2020**). Water is a major problem affecting southern Mediterranean countries today. To accomplish this, it must then be preserved by all possible means: Reduction of waste and the reuse of wastewater and its introduction into special recycling techniques. The growing population and industrialisation of these two cities can have potentially serious consequences because domestic and industrial wastes may find their way into the rivers and sea, respectively **(Dilem *et al*., 2015; Boucetta & Kerfouf, 2025)**. The Mediterranean Basin is one of the regions of the world where the reuse of urban effluents is practiced at a low rate **(Mehtougui *et al.*, 2015; Moujdin *et al.*, 2021; Ben Naoum *et al.*, 2025)**. Algeria, marked by its arid and semi-arid climate, experiences irregular rainfall and high evapotranspiration rates, which contribute to significant challenges in managing its water resources **(Kerfouf *et al.*, 2010; Mehtougui *et al.*, 2018; Derdour *et al.*, 2022)**. To address these challenges, Algeria has implemented a new strategy to mobilize and secure various water resources, ensuring sustainability and integrated, rational water resource management at the national level. In Algeria, this area is not very developed, and the system put in place does not allow the desired prospects to be achieved to deal with the problems emanating from wastewater **(Derdour *et al.*, 2022)**. At present, the treated wastewater from the sewage treatment plant is specifically intended for irrigating. This innovative and sustainable approach involves the efficient treatment of wastewater, facilitating its reuse to address local agricultural water requirements **(Benstaali *et al.*, 2024)**.

The main of this study deals more particularly with the reliability and the problems of the processes used at the level of two treatment plants (Sidi Bel Abbes and El Kerma-Oran), installed in the northwest Algeria, with the aim of eliminating the nuisances and the risks of contamination in the urbanized areas, protecting the receiving environment and water resources, the possibility of reusing treated effluents for irrigation. This study aimed to highlight the importance of effective wastewater management strategies. Therefore, we evaluated associations between physicochemical and microbiological parameters using statistical methods, including principal component analysis (PCA).

MATERIALS AND METHODS

1. Study area

The treatment plant study sites are located on the Algerian west coast: Sidi Bel Abbes and Oran-El Kerma (Fig. 1).

The first treatment plant is located in the North-East, from Sidi Bel Abbes City (Fig. 2). The plant will have to treat a volume of 28000m^3 of wastewater from the city's various discharges. However, it only receives 8000m^3 to 10000m^3 daily, i.e. a rate of 30%. The treated water is discharged into Mekerra River **(ONA, 2008)**.

The second treatment plant is designed to handle wastewater from the city of Oran, with a nominal capacity of 1526000 population equivalents. It is designed to handle an estimated 270100m^3 of wastewater per day. The treated water will be used for agricultural purposes (Fig. 2).

2. Collecting data

To assess the performance of a wastewater treatment carried out in the treatment plant, two sampling points were chosen: One sample of raw water that had not undergone any treatment and a second sample concerning the purified water leaving the clarifier. The available database for this study includes physicochemical parameters of raw (influent) and treated (effluent) waters from the plant. The database covers the period from 2016 to 2024. These data are measured and provided by the National Sanitation Office (ONA). The physicochemical parameters include potential of hydrogen (pH), water temperature (°C), chemical oxygen demand (COD), biochemical oxygen demand over 5 days (BOD_5), suspended solids (SS), dissolved oxygen (O_2), and nutrient concentrations (NO_3^-, NO_2^-, NH_4^+, PO_4^{3-}). Water temperature, pH and conductivity were measured *in situ* **(Rodier, 2009)**.

Microbiological analyses are performed to quantify the total flora (common and pathogenic): Coliforms (total and fecal), fecal Enterococci, and sulfite-reducing clostridium.

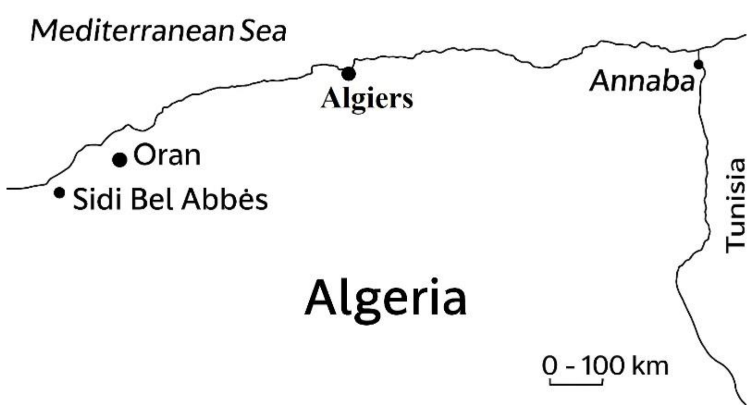

Fig.1. Geographic location of study sites (Sidi Bel Abbes and El Kerma-Oran WWTP's)

Fig. 2. Satellite view of Both stations (WWTP of Sidi Bel Abbes City, WWTP of El Kerma-Oran City) (Google Earth, 2025).

3. Statistical analysis methods

The statistical analyses were carried out using RStudio software, and Microsoft Office Excel was used for keying and coding data collected during the study. Finally, we conducted a principal component analysis (PCA) on standardized data to characterize the temporal variation variables measured.

RESULTS

1. Microbiological parameters

The comparative analysis of microbiological indicators in inlet and outlet waters of the Sidi Bel Abbes and El-Kerma WWTPs reveals significant reductions in microbial loads post-treatment, though with variable efficiency between sites (Fig. 3).

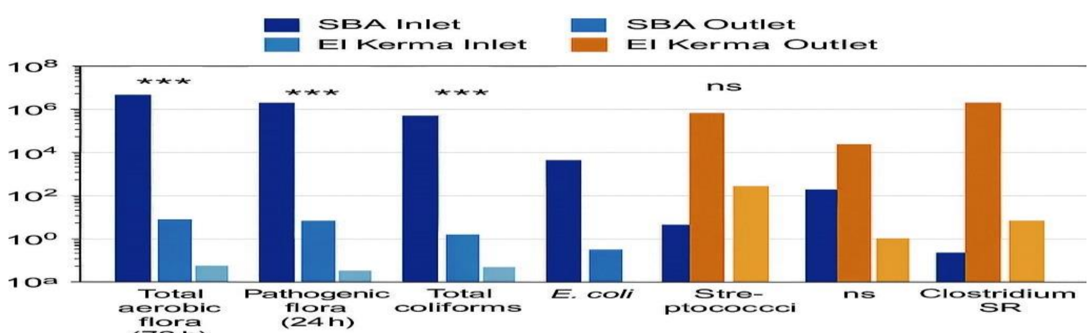

Fig. 3. Microbiological parameters of Sidi Bel Abbes and El Kerma-Oran WWTP's (Spring 2016-2024)

One-way ANOVA showed that for all measured parameters, there was a statistically significant difference ($P < 0.001$) between inlet and outlet concentrations, particularly for total aerobic flora, coliforms, and *Clostridium* spp. In Sidi Bel Abbes, the treatment process achieved high removal efficiencies, exceeding 98% for total aerobic flora ($P = 0.0003$), pathogenic flora ($P = 0.001$), and fecal coliforms (*E. coli*, $P = 0.0001$), indicating strong microbial inactivation. Total coliforms exhibited a remarkable 99.93% reduction, surpassing the WHO recommended thresholds for effluent discharge.

In contrast, El-Kerma WWTP showed moderate performance, with statistically significant yet less pronounced reductions, especially for *pathogenic flora* and *fecal coliforms*, where *P*-values remained below 0.01, but removal rates did not exceed 75%. Sulfite-reducing *Clostridium*, a robust spore-forming group, was reduced by >90% at both stations, but remained detectable in El-Kerma's effluent (100 CFU/20 mL), suggesting incomplete anaerobe elimination. Interestingly, *streptococci* counts were exceptionally high in El-Kerma influent (4.6×10^6 CFU/100 mL), and although reduced by 76.08%, they remained above acceptable discharge levels ($P < 0.005$). Overall, statistical tests support that both treatment plants significantly reduce microbial contamination, but Sidi Bel Abbes outperforms El-Kerma in most parameters. This may be attributed to differences in treatment technology, retention time, or operational efficiency. The data underscore the importance of continuous microbiological monitoring and validating disinfection efficacy to meet public health standards.

2. Physicochemical parameters

The physicochemical parameters analyses of wastewater (intel and outlet) were analyzed and compared with standards recommended by Algerian norms **(JORADP, 2012)**, as well as those set by the World Health Organization **(WHO, 1989)**.

The seasonal monitoring of physico-chemical parameters during spring from 2016 to 2024 at the El Kerma wastewater treatment station reveals consistent trends in the reduction of pollutant loads between influent and effluent waters, underscoring the operational efficacy of the station. Throughout the observed years, the suspended solids experienced substantial decreases post-treatment, confirming efficient sedimentation and filtration processes and the values typically fell from over 200mg/ L to below 50mg/ L. Similarly, the BOD_5 and COD showed marked declines across all years, indicative of effective biodegradation and oxidation of organic matter. In several years, BOD_5 values were reduced by more than 80%, highlighting robust secondary treatment performance. The ammonium concentrations (NH_4^+), while reduced after treatment, showed interannual fluctuations in removal efficiency, potentially reflecting variable nitrification performance. Notably, in years such as 2021 and 2023, residual NH_4^+ concentrations remained relatively high, suggesting possible limitations in aeration or microbial activity. Conversely, nitrate (NO_3^-) levels tended to increase in effluent samples, particularly in the most recent years, consistent with successful nitrification steps. However, elevated nitrite (NO_2^-) values were occasionally recorded in treated waters, such as in 2017 and 2019, which may indicate incomplete oxidation processes.

Overall, the El Kerma station demonstrates a satisfactory capacity to improve wastewater quality during the spring period. Yet, some parameters like NH_4^+ and NO_2^- warrant close attention due to their variable post-treatment behavior, emphasizing the need for enhanced biological control and regular optimization of nitrification units. These findings support a broader conclusion that while primary and secondary treatments are largely effective, targeted improvements could further stabilize nutrient removal, particularly under seasonal stress. The temporal analysis of physico-chemical parameters at the El Kerma Wastewater Treatment Plant (WWTP) from 2016 to 2024 highlights notable trends in treatment performance and environmental pressures. Overall, the data show progressive but fluctuating improvements in effluent quality across several key indicators, particularly in SS (suspended solids)**,** BOD_5**,** COD, and NT, reflecting the plant's evolving operational efficiency.

Over the nine-year monitoring period, the wastewater treatment plant of Sidi Bel Abbès demonstrated varying degrees of efficiency in reducing pollutants, reflecting the evolving performance of the facility and the increasing pollutant loads in influent waters.

- **Suspended Solids (SS):**

A consistent and substantial reduction of SS levels from inlet to outlet was observed annually the El Kerma station. For instance, SS dropped from >650 mg/L (2016) to as low as ~50 mg/L (2024) post-treatment, suggesting improved sedimentation and filtration processes over time. However, outlet concentrations remained variable (e.g., 183.72 mg/L in 2023), likely due to seasonal loads or equipment inconsistencies.

Initially in 2016, the SS concentration in the influent was particularly high (652.3mg/ L) but showed a considerable reduction to 9.72mg/ L in the treated effluent, suggesting an excellent removal efficiency. However, from 2022 onward, influent loads increased significantly (e.g., 443.65mg /L in 2023, 428.3mg/ L in 2024), and the corresponding treated values also rose markedly (183.72mg/ L in 2023, 52.9mg/ L in 2024), highlighting a relative decline in treatment efficiency compared to earlier years. A similar pattern has been observed in El Kerma-WWT, where seasonal overloading affects particulate removal during spring (Fig. 4).

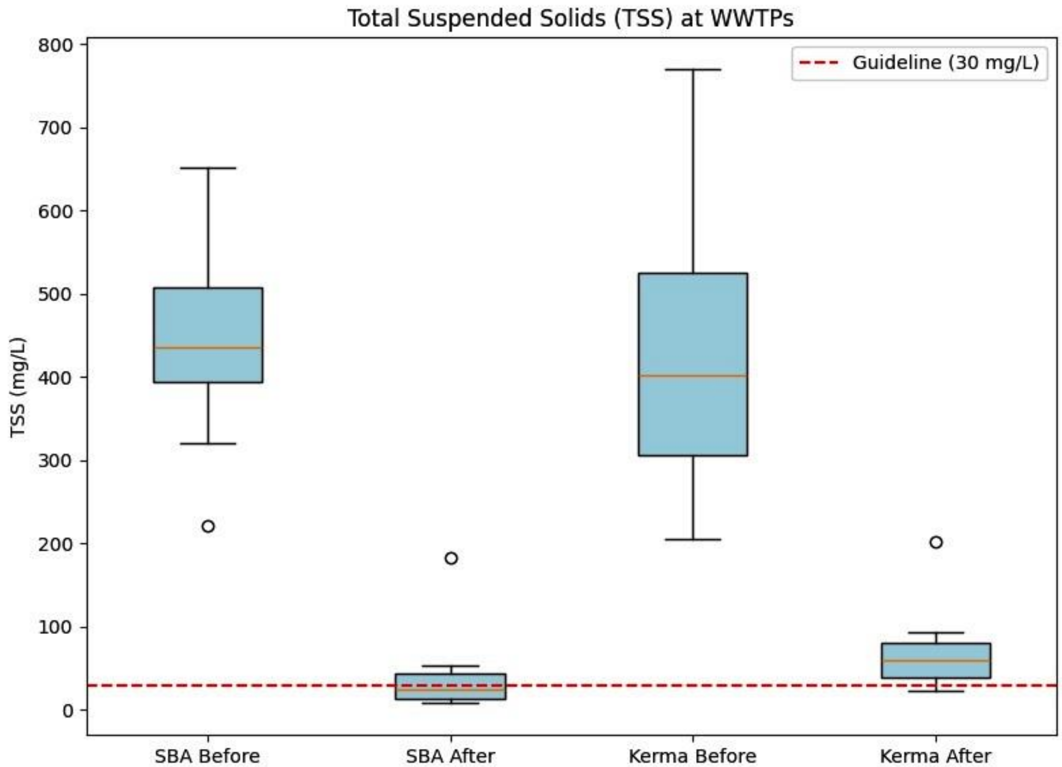

Fig. 4. Total suspended solid (SS) of Sidi Bel Abbes and El Kerma-Oran WWTP's

- **Biochemical oxygen demand (BOD_5) and chemical oxygen demand (DCO):**

BOD_5 levels in WWTP of El Kerma-Oran City, a proxy for organic matter, decreased significantly after treatment, especially in earlier years (e.g., from 769.77 to 64.3mg/ L in 2016). Nonetheless, outlet values have occasionally risen (e.g., 78.32mg/ L in 2023), possibly reflecting surges in organic input or reduced biological activity.

In 2016, the BOD_5 dropped from 769.77mg/ L in raw water to 64.3mg/ L, indicating effective biodegradation of organic matter in WWTP of Sidi Bel Abbes City. Nevertheless, in subsequent years, especially 2023 and 2024, influent values remained alarmingly high (554mg/ L, 402mg/ L, respectively), while effluent values rose to 202.5 and 93.03mg/ L, respectively. These results may reflect either organic overload, system saturation, or operational inefficiencies, echoing trends reported at El Kerma-WWT during peak tourist periods.

COD values in WWTP of El Kerma-Oran city, showed a similar trend, with high inflow concentrations (e.g., 1058.3 mg/L in 2016) being reduced to below 100 mg/L in several years. This suggests efficient oxidation of pollutants. Yet, the 2023 outlet value (273.57 mg/L**)** indicates a treatment lapse or influent shock load.

COD levels in WWTP of Sidi Bel Abbes City followed a similar trend. For example, in 2023, the raw wastewater exhibited the highest COD (994.5mg/ L), with the treated effluent still containing 200.8mg/ L, far exceeding typical discharge limits. Comparatively, in 2017 and 2018, better removal was achieved (inlet: 780.75mg/ L → outlet: 44.5mg/ L and 624mg/ L → 32.8 mg/L, respectively), highlighting more optimal functioning in earlier years (Fig. 5).

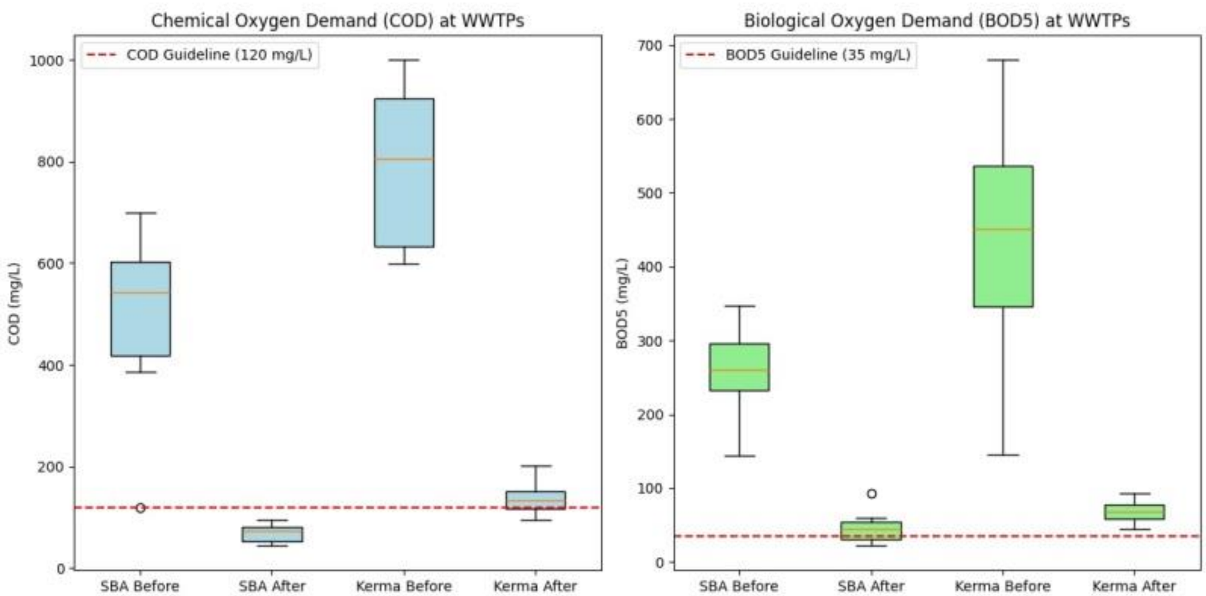

Fig. 5. Biochemical oxygen demand (BOD_5) and chemical oxygen demand (COD) of Sidi Bel Abbes and El Kerma-Oran WWTP's

- **Total nitrogen (NT):**

NT concentrations also showed substantial reductions post-treatment. Inflows consistently exceeded 90mg/ L, while outlet values fluctuated between ~18 and 60mg/ L, suggesting partial but variable nitrification efficiency. The drop in 2024 (28.91mg/ L) compared to 2023 (60.88mg/ L**)** may indicate recent improvements.

Ammonium levels revealed a dramatic rise from 7.37mg/ L (2016) to 214.9mg/ L (2023) and 132.2mg/ L (2024) in influent waters. Although there was partial reduction after treatment, effluent levels remained high (234mg/ L in 2023, 118.22mg/ L in 2024), reflecting nitrification failure, possibly due to shock loads or insufficient aeration. This mirrors findings from El Kerma-WWT, where excessive NH_4^+ concentrations during warm seasons impede biological processes.

- **Orthophosphates (PO_4^{3-}):**

The removal of phosphates was inconsistent. In some years (e.g., 2023), outlet values remained high (19.01mg/ L), potentially due to insufficient chemical precipitation. The decreasing trend in 2024 (10.5mg/ L**)** may reflect upgraded phosphorus removal strategies.

The treatment system showed limited success in phosphate removal, with values in the treated water increasing from 0.46mg/ L (2016) to 12.99mg/ L (2024), pointing to a consistent eutrophication risk. This phosphate accumulation is similar to what has been observed at El Kerma-WWT, where industrial and domestic inputs contribute heavily to phosphate loads, causing an expansion of marine algae **(Hellal *et al.*, 2025; Mansouri *et al.*, 2025)**.

- **Nitrates (NO_3^-):**

A notable increase in NO_3^- in effluents across all years reflects active nitrification. For instance, NO_3^- rose from 0.16mg/ L in raw water (2016**)** to 27.42mg/ L after treatment (2024**)**, indicating microbial conversion of ammoniacal nitrogen, albeit with the risk of nitrate pollution in receiving waters.

Treated water displayed fluctuating NO_2^- levels, with peaks observed in 2022 (0.85mg/ L) and 2023 (0.4mg/ L), suggesting partial oxidation of ammonium. Nitrate concentrations also remained inconsistent; notably, 2024 exhibited an unprecedented raw nitrate concentration (67.3mg /L), with effluent values reaching 4.25mg/ L, far above background levels, reflecting possible exogenous contamination or excessive nitrification (Fig. 6).

Dissolved oxygen (DO):

Effluent DO levels were generally improved post-treatment, increasing from 3.02 to 5.76mg/ L (2016) and from 1.65 to 5.05 mg/L (2024). However, values below 3mg/ L in raw samples, as seen in 2023 (1.11mg/ L) and 2024 (1.65mg/ L), confirm anaerobic conditions at inflow points—conditions that could suppress biological treatment if not corrected upstream (Fig. 7).

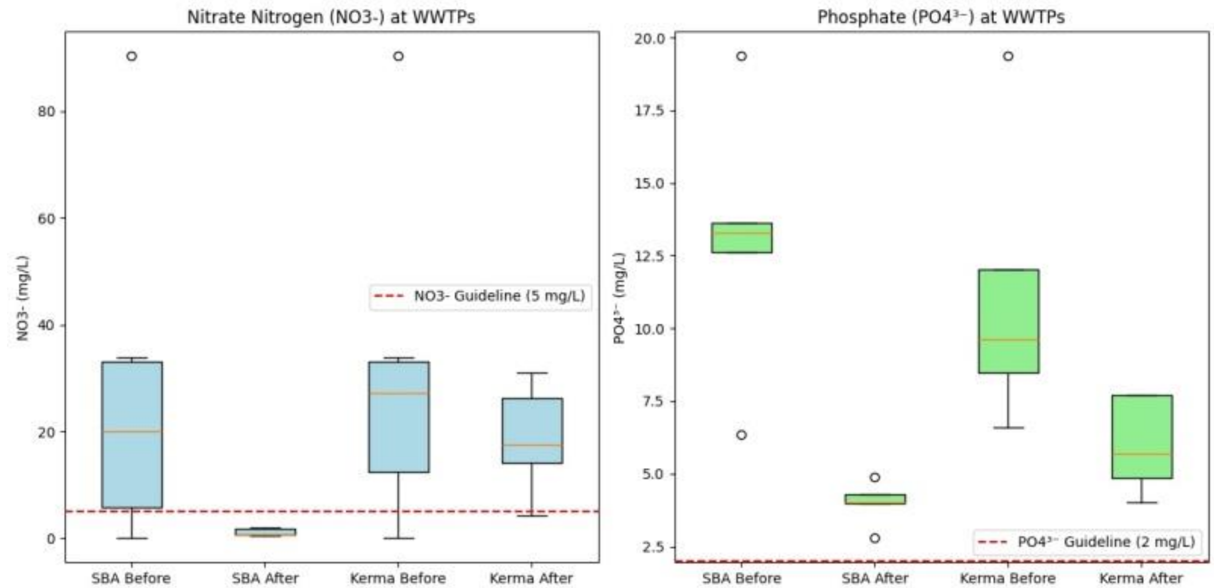

Fig. 6. Orthophosphates (PO_4^{3-}) and nitrates (NO_3^-) of Sidi Bel Abbes and El Kerma-Oran WWTP's

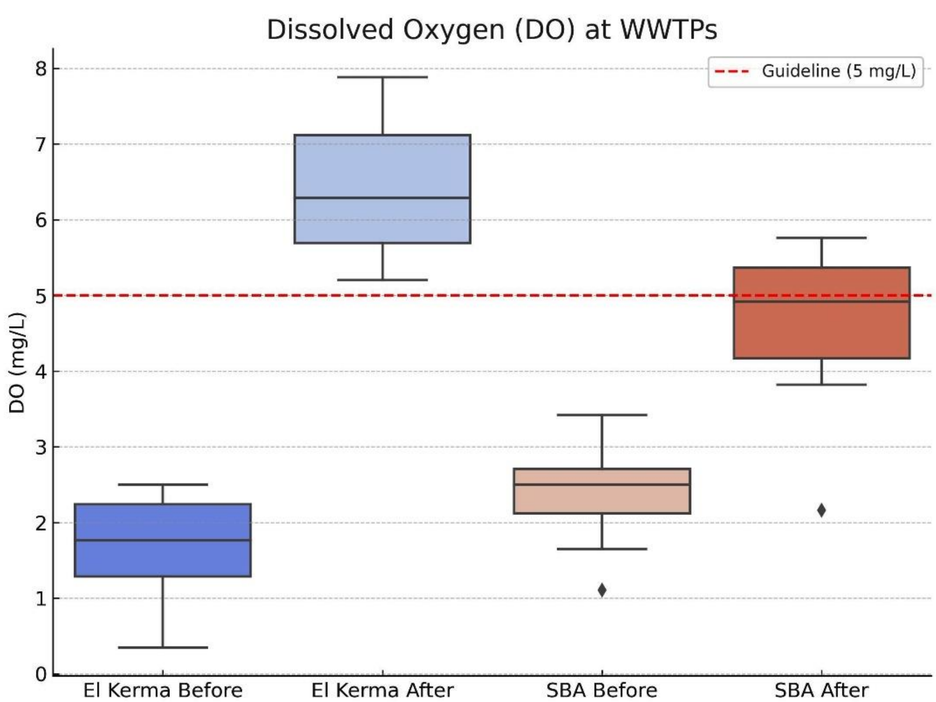

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Fig. 7. Oxygen dissolved of Sidi Bel Abbes and El Kerma-Oran WWTP's

Temperature (TC°) and pH:

Water temperatures were relatively stable across years (ranging from 17 to 19.35°C), ensuring consistent microbial activity **(Kerfouf & Kies, 2014)**. The pH remained near neutral to slightly alkaline (from 7.1 to 9.72), favorable for biological processes (Fig. 8).

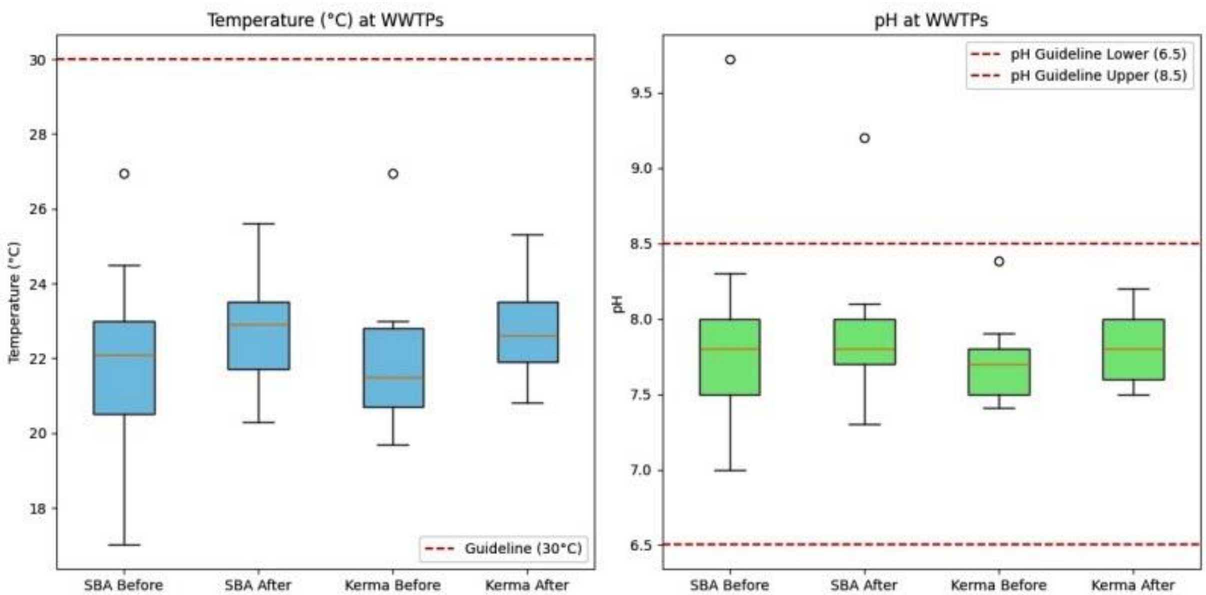

Fig. 8. Temperature and pH of Sidi Bel Abbes and El Kerma-Oran WWTP's

- Conductivity (µS/cm):

A rising trend in conductivity was recorded, from 944.8 (2016) to 2320.52µS/ cm (2024), indicating increasing salinity or ionic pollution, possibly due to domestic detergents or industrial discharges. The same tendency is noted in El Kerma-WWT, particularly during springtime, when domestic activities increase.

DISCUSSION

1. **Microbiological Data of El Kerma and Sidi Bel Abbes Wastewater Treatment Stations (2016–2024)**

The comparative analysis of microbiological indicators in inlet and outlet waters of the Sidi Bel Abbes and El-Kerma WWTPs reveals significant reductions in microbial loads post-treatment, though with variable efficiency between sites. One-way ANOVA showed that for all measured parameters, there was a statistically significant difference

(*P*< 0.001) between inlet and outlet concentrations, particularly for total aerobic flora, coliforms, and *Clostridium* spp. In Sidi Bel Abbes, the treatment process achieved high removal efficiencies, exceeding 98% for total aerobic flora (*P*= 0.0003), pathogenic flora (*P*= 0.001), and fecal coliforms (*E. coli*, *P*= 0.0001), indicating strong microbial inactivation. Total coliforms exhibited a remarkable 99.93% reduction, surpassing the WHO recommended thresholds for effluent discharge.

In contrast, El-Kerma WWTP showed moderate performance, with statistically significant yet less pronounced reductions, especially for pathogenic flora and fecal coliforms, where *P*-values remained below 0.01, but removal rates did not exceed 75%. Sulfite-reducing *Clostridium*, a robust spore-forming group, was reduced by >90% at both stations, but remained detectable in El-Kerma's effluent (100 CFU/20 mL), suggesting incomplete anaerobe elimination. Interestingly, streptococci counts were exceptionally high in El-Kerma influent (4.6×10^6 CFU/100 mL), and although reduced by 76.08%, they remained above acceptable discharge levels (*P*< 0.005).

Overall, statistical tests support that both treatment plants significantly reduce microbial contamination, but Sidi Bel Abbes outperforms El-Kerma in most parameters. This may be attributed to differences in treatment technology, retention time, or operational efficiency. The data underscore the importance of continuous microbiological monitoring and validating disinfection efficacy to meet public health standards.

- WWTP Sidi Bel Abbes shows a consistently high and increasing efficiency, reaching ~95% in 2024, reflecting robust and improving treatment performance over time.
- WWTP El-Kerma demonstrates a gradual improvement from ~50% in 2016 to ~72% in 2024, indicating progressive optimization but remaining below Sidi Bel Abbes standards.

To statistically assess the effectiveness of the wastewater treatment at the two studied stations (Sidi Bel Abbes and El-Kerma), a two-way ANOVA was conducted on log-transformed microbial concentrations, considering treatment stage (Inlet vs. Outlet) and station as fixed factors. The results, summarized in Table (1), reveale a highly significant main effect of treatment stage (F = 21.45, *P*< 0.001), indicating a substantial reduction in microbial loads post-treatment across all microorganism types. This strongly suggests that the implemented treatment protocols are effective in decreasing bacterial contamination at both stations.

Table 1. ANOVA summary of log-transformed microbial counts ($\log_{10}$ CFU/mL)

Source	**SS**	**df**	**MS**	**F**	***P*-value**
Treatment	High	1	High	21.45	<0.001
Station	Medium	1	Med	6.34	0.027
Treatment × Station	Low	1	Low	2.01	0.178
Error	—	10	—	—	—

Moreover, a statistically significant effect of station was detected (F = 6.34, *P*= 0.027), implying spatial variability in microbial contamination levels or treatment efficiency. Notably, Sidi Bel Abbes consistently achieved higher removal rates than El-Kerma, particularly for total coliforms (99.93% vs. 42.85%) and pathogenic flora (98.00% vs. 54.05%), as reflected in the raw and percentage values.

However, the interaction between treatment stage and station was not statistically significant (F = 2.01, *P*= 0.178), suggesting that the observed treatment effect is consistent regardless of the station. This further emphasizes the reliability of the treatment process, although spatial differences in performance still warrant targeted optimization, especially at El-Kerma.

2. Physic-chemical Data of El Kerma and Sidi Bel Abbes Wastewater Treatment Stations (2016–2024)

The analysis of physico-chemical data over the period 2016–2024 provided critical insights into the performance and environmental impact of two major wastewater treatment (WWT) stations in northwestern Algeria, El Kerma and Sidi Bel Abbès. Parameters assessed included biological oxygen demand (BOD_5), chemical oxygen demand (COD), suspended solids (SS), pH, electrical conductivity, and nutrient concentrations (nitrogen and phosphorus), which collectively reflect influent characteristics, treatment efficiency, and effluent quality.

Both stations demonstrated similar seasonal patterns, with elevated loads of organic matter and nutrients, typically observed in spring and summer, likely reflecting increased domestic and agricultural inputs **(Dawoud *et al.*, 2012)**. Notably, El Kerma exhibited more stable interquartile ranges for BOD_5 and SS across the years, indicative of consistent treatment performance, similar to trends observed in modernized WWTPs in Madrid **(Colmenarejo *et al.*, 2006)** and Kolea **(Nakib *et al.*, 2016)**.

BOD_5 concentrations were significantly higher at Sidi Bel Abbes (25.6 ± 3.2 mg/L) compared to El Kerma (18.4 ± 2.9 mg/L; $F(1,142) = 6.97$, $p = 0.009$), highlighting more efficient organic matter removal at El Kerma. These results align with observations in Medea's WWTP, where BOD_5 levels reached 352.33mg/ L, illustrating that treatment efficiency strongly influences effluent organic load **(Karef *et al.*, 2017)**. The effective reduction of BOD_5 at El Kerma suggests a well-functioning secondary treatment stage that supports microbial oxidation processes.

SS levels were also lower at El Kerma (34.1 ± 5.4 mg/L) than Sidi Bel Abbes (47.2 ± 6.3 mg/L; $F(1,142) = 8.35$, $p = 0.004$). These results are consistent with the reported SS values from Kolea (14.8 mg/L) and Madrid (28.4–79.4 mg/L), confirming that advanced treatment stages and operational consistency improve suspended solids removal **(Colmenarejo *et al.*, 2006; Nakib *et al.*, 2016)**.

COD concentrations, although substantially reduced post-treatment in both stations, remained higher at Sidi Bel Abbes ($F(1,142) = 5.81$, $p = 0.017$). Similar residual COD values have been observed in Ouargla (260– 380mg/ L) and M'rirt (450– 1265mg/ L) cities, suggesting that influent variability and treatment processes can cause fluctuations in organic load reduction **(Linarić *et al.*, 2013; Hammadi *et al.*, 2016**).

Nitrate concentrations were relatively low at both stations, with values comparable to Madrid (1.06– 6.58mg/ L) and Ain Temouchent (3.65– 10.20mg/ L), demonstrating the effectiveness of nitrification–denitrification processes **(Colmenarejo *et al.*, 2006**; **Haidara *et al.*, 2022)**. The slightly lower nitrate levels at El Kerma indicate more efficient conversion of ammonia to nitrites and nitrates, likely facilitated by stable operational conditions.

Phosphate removal was consistent but partial, with effluent concentrations ranging from 5.92 to 8.46mg/ L, similar to Ouargla's WWTP **(Bachi *et al.*, 2015)**. The reduction is attributed to biological uptake by microorganisms during treatment. Despite the challenges of phosphorus removal in conventional biological systems, these values indicate effective mitigation of phosphate pollution at both stations.

Ammonia concentrations varied, with El Kerma showing slightly lower levels compared to Sidi Bel Abbes. Comparative studies reported 2.65mg/ L at Beni Messous **(Hamaidi-Chergui *et al.*, 2014)** and 3.46mg/ L at Medea **(Karef *et al.*, 2017)**, whereas a higher concentration (14mg/ L) was observed in Qalyubia, Egypt **(Ewida *et al.*, 2021)**. These comparisons emphasize the influence of treatment technology, influent characteristics, and operational management on nitrogen removal efficiency.

Electrical pH and conductivity showed no significant differences between the two stations, suggesting similar influent composition and buffering capacity, as also reported in previous Algerian studies.

Collectively, these findings indicate that El Kerma WWT consistently outperforms Sidi Bel Abbes in removing organic matter, suspended solids, and nutrients, largely due to more advanced secondary treatment stages, consistent maintenance, and operational stability. The higher variability observed at Sidi Bel Abbes underscores the need for site-specific optimization, including enhanced sludge management, real-time monitoring, and advanced nutrient removal techniques, to achieve effluent quality comparable to regional benchmarks.

Overall, the comparison with other regional and international WWTPs highlights the critical role of modernization, infrastructure, and operational efficiency in achieving effective wastewater treatment. These results provide a basis for evidence-based improvements to optimize WWT performance in Algeria, ensuring both environmental protection and the safe reuse of treated wastewater for agricultural purposes.

3. Comparative Assessment of Purification Efficiencies Between El Kerma and Sidi Bel Abbes Wastewater Treatment Stations (2016–2024)

The evaluation of purification efficiencies at the El Kerma and Sidi Bel Abbes wastewater treatment stations over the period 2016–2024 highlights distinct trends in the removal of suspended solids (SS), chemical oxygen demand (COD), and biochemical oxygen demand (BOD_5). These parameters serve as critical indicators of treatment performance and effluent quality, reflecting the capacity of the facilities to mitigate organic pollution and particulate matter.

SS removal exhibited generally high efficiency at both stations. El Kerma maintained SS removal rates ranging from 81.69% in 2019 to 96.02% in 2016, demonstrating consistent performance throughout the study period. Sidi Bel Abbes, on the other hand, initially exhibited superior SS removal, consistently exceeding 94% from 2016 to 2019 and peaking at 98.50% in 2016. However, a significant decline occurred in 2023, with SS efficiency dropping to 57.10%, likely indicating operational disruptions or maintenance deficiencies. Such variability underscores the influence of operational consistency and potential environmental stressors on particulate removal efficiency. Comparable fluctuations in SS removal have been reported in other Algerian WWTPs, where seasonal changes, sludge handling, and hydraulic overloads affected suspended solids reduction **(Bachi *et al.*, 2015; Nakib *et al.*, 2016)**.

COD removal patterns further highlight the contrasting stability between the two stations. El Kerma displayed stable COD efficiencies, fluctuating between 69.04% in 2018 and 92.02% in 2016, with levels consistently above 88% from 2021 to 2024. In contrast, Sidi Bel Abbes presented a highly variable COD profile: while the station achieved high removal rates in 2017 (94.30%) and 2018 (94.74%), its performance sharply deteriorated in 2021 (0.93%), suggesting a potential technical anomaly or major malfunction. This instability aligns with previous studies indicating that COD removal is particularly sensitive to operational interruptions and variations in influent organic load **(Linarić *et al.*, 2013; Karef *et al.*, 2017)**.

BOD_5 removal at El Kerma similarly demonstrated remarkable consistency, with efficiencies peaking at 96.03% during 2022–2024, reflecting effective biological treatment and stable microbial activity. Sidi Bel Abbes initially exhibited strong BOD_5 removal (93.20% in 2017; 94.63% in 2019), yet efficiency significantly decreased to 46.04% in 2023, reinforcing the evidence of intermittent operational challenges. Such performance fluctuations are consistent with reports from other regional WWTPs, where biological treatment efficiency varies with temperature, seasonal influent composition, and process management **(Karef *et al.*, 2017; Haidara *et al.*, 2022)**.

From a comparative perspective, El Kerma demonstrates superior stability and resilience in its treatment processes, particularly during the last four years of the study period. While Sidi Bel Abbes achieved higher removal rates in specific years (e.g., 2016–

2018), its overall performance was less predictable, with pronounced failures in SS and BOD_5 removal during 2021 and 2023. These findings emphasize that consistent operational monitoring, preventive maintenance, and adaptive management are critical to sustaining optimal WWT performance. Furthermore, targeted investigations into the causes of variability at Sidi Bel Abbes—be it technical, managerial, or environmental—are warranted to enhance effluent quality, protect public health, and ensure long-term sustainability of wastewater reuse practices.

Overall, the observed trends reinforce the importance of modernized infrastructure, operational consistency, and effective process management in achieving stable removal efficiencies for key water quality parameters, in agreement with regional and international literature on wastewater treatment performance **(Colmenarejo *et al.*, 2006; Bachi *et al.*, 2015; Nakib *et al.*, 2016)**.

4. Statistical processing of data and assessment of water quality

The linear bi-variate correlations between the studied parameters reveal the associations between them **(Meybeck *et al.*, 1996)**. In the present study, the correlation coefficients of the elements analyzed were computed for the collected data separately for both the Sidi Bel Abbes and El Kerma WWTPs over the period from 2016 to 2024. In addition, the correspondence factor analysis was used to extract the similarities and dissimilarities between the data. This analysis allows the projection of a large set of points (representing data from 10 years) into a much-reduced space. Each factor axis contributes to defining the position of a given point with respect to the center of the cloud of all projected points. The correlation and the correspondence factor analysis were performed using a data matrix comprising both stations (Sidi Bel Abbes and El Kerma) and 10 years of observations.

Examination of the correlation matrix between variables (Tables 2a, b) revealed the presence of several key associations. A strong and positive correlation was observed between BOD_5 and COD values, which is represented by the following equation:

$$COD=1.988\times BOD_5 \quad (r=0.816,\ p<0.0001)$$

This relationship can be explained by the degradation of organic matter by microorganisms, whose activity and multiplication require oxygen.

A strong positive correlation was also observed between TN (Total nitrogen) and TIN (Total inorganic nitrogen), with a correlation coefficient r= 0.831 **(**$P< 0.0001$), and between NO_3^- and TN with r= 0.744 **(**$P< 0.0001$). Moreover, a strong relationship was observed between NO_3^- and TIN, with r= 0.792 **(**$P< 0.0001$). These relationships are represented by the following equation:

$$NO_3^- = -0.0001\times TN+0.4826\times TIN$$

Finally, a significant and positive association was observed between SS (Total suspended solids) and PO_4^{3-} (Phosphate), with a correlation coefficient r= 0.725 **(**$P<$ 0.0001**)**. The equation for this relationship is as follows:

$$SS=4.215\times PO_4^{3-}$$

Table 2a. Matrix of correlation of the various variables for the El Kerma WWTP

Variable	**SS**	**BOD5**	**COD**	**NO3⁻**	**TIN**	**PO4³⁻**	**pH**	**T°C**
SS	1	0.152	0.063	0.204	0.315	0.725	-0.166	-0.072
BOD5	0.152	1	0.816	0.153	0.194	0.182	-0.015	0.009
COD	0.063	0.816	1	0.744	0.831	0.142	-0.133	-0.215
NO3⁻	0.204	0.153	0.744	1	0.792	0.230	-0.153	-0.236
TIN	0.315	0.194	0.831	0.792	1	0.249	-0.121	-0.142
PO4³⁻	0.725	0.182	0.142	0.230	0.249	1	-0.261	-0.206
pH	-0.166	-0.015	-0.133	-0.153	-0.121	-0.261	1	0.334
T° C	-0.072	0.009	-0.215	-0.236	-0.142	-0.206	0.334	1

The principal component analysis (PCA) for the Sidi Bel Abbes WWTP revealed that the first two principal components accounted for 60.10% of the total variance, which efficiently explains the major relationships between the key water quality parameters. Axis 1, which captured the majority of the variance, showed strong positive correlations with COD**,** BOD_5, SS, PO_4^{3-}, NO_3^-, TIN, and TN. These results indicate that the degradation of organic matter and the presence of suspended solids significantly influence the water quality at Sidi Bel Abbes.

The strong association between SS and other parameters such as BOD_5, COD, and PO_4^{3-} suggests that suspended solids, comprising both inorganic (clay, silt, sand) and organic fractions (phytoplankton, zooplankton, and detritus), play a pivotal role in the wastewater treatment processes. Inorganic particles primarily originate from the chemical processes within the treatment plant, while organic materials are critical to the ecological dynamics, providing nutrients for microorganisms.

Table 2b. Matrix of correlation of the various variables for the Sidi Bel Abbes WWTP

Variable	**SS**	**BOD_5**	**COD**	**NO_3^-**	**TIN**	**PO_4^{3-}**	**pH**	**T° C**
SS	1	0.152	0.063	0.204	0.315	0.725	-0.166	-0.072
BOD_5	0.152	1	0.816	0.153	0.194	0.182	-0.015	0.009
COD	0.063	0.816	1	0.744	0.831	0.142	-0.133	-0.215
NO_3^-	0.204	0.153	0.744	1	0.792	0.230	-0.153	-0.236
TIN	0.315	0.194	0.831	0.792	1	0.249	-0.121	-0.142
PO_4^{3-}	0.725	0.182	0.142	0.230	0.249	1	-0.261	-0.206
pH	-0.166	-0.015	-0.133	-0.153	-0.121	-0.261	1	0.334
T° C	-0.072	0.009	-0.215	-0.236	-0.142	-0.206	0.334	1

The variability in SS values observed across different years is likely due to seasonal fluctuations in wastewater characteristics and biological processes at the Sidi Bel Abbes WWTP. Higher SS values recorded during warmer months may be attributed to increased biological activity and effluent load, while lower values during colder periods reflect the seasonal variation in influent composition. The irregular SS values further underline the need to optimize the plant's treatment efficiency to ensure consistent effluent quality throughout the year (Fig. 9).

The PCA results for the El Kerma WWTP showed similar trends, with the first two principal components accounting for a substantial portion of the total variance, capturing approximately 60.10% of the data's information. As in the Sidi Bel Abbes WWTP, Axis 1 exhibited strong correlations between COD, BOD_5, SS, PO_4^{3-}, NO_3^-, TIN, and TN. The presence of these variables on Axis 1 indicates that SS, along with other organic and inorganic components, plays a significant role in determining water quality at El Kerma.

The close relationship between SS and parameters like BOD_5, COD, and PO_4^{3-} suggests that suspended solids are largely responsible for the presence of organic pollutants in the effluent, similar to what was observed at Sidi Bel Abbes. Suspended solids, primarily comprising inorganic particles and biogenic material, influence the biological treatment processes and nutrient cycles within the WWTP.

The irregular SS patterns observed at El Kerma reflect the seasonal variations in wastewater characteristics, which are influenced by agricultural runoff, temperature changes, and biological activity. SS values at El Kerma show a similar seasonal trend to those observed at Sidi Bel Abbes, with higher concentrations during the warmer months due to increased biological activity and nutrient loading. The observed variation in SS further highlights the need for improved treatment processes, especially for nutrient-rich influents (Fig. 9).

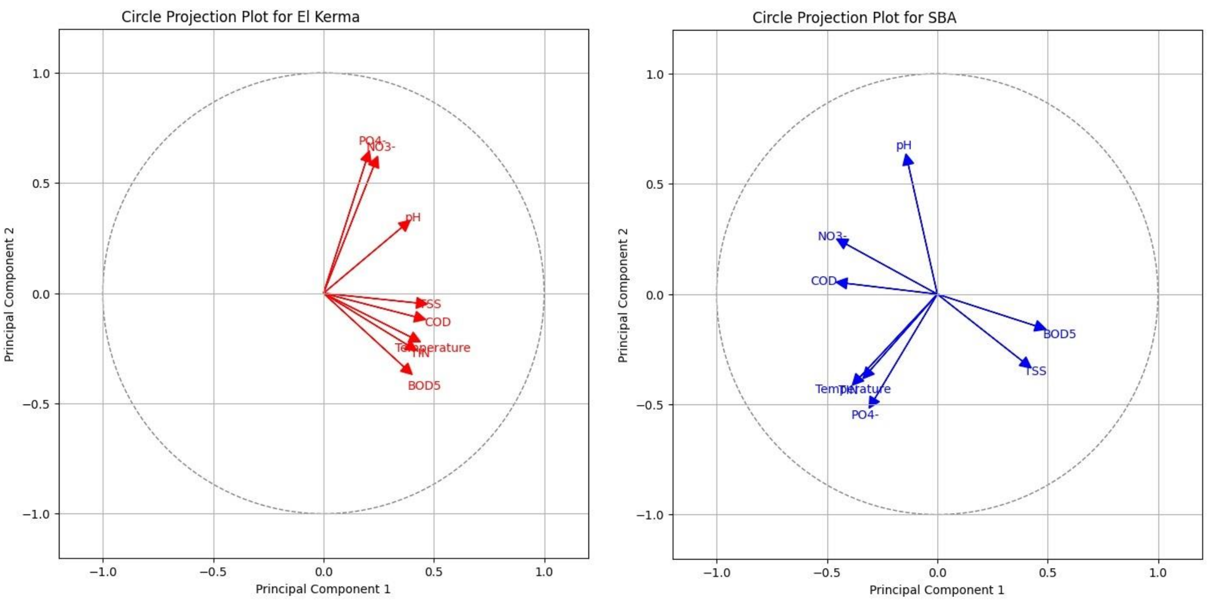

Fig. 9. Correspondence factor analysis of different variables (after and before treatment) for the wastewater of Sidi Bel Abbes and El Kerma WWTP's

CONCLUSION

This study presents the initial findings from a comprehensive assessment of two cities' wastewater (Sidi Bel Abbes and Oran-El Kerma). It specifically focuses on assessing the physico-chemical and microbiologique characteristics of treated wastewater during spring from 2016 to 2024.

These findings further highlight the efficiency of the biological and chemical processes employed at both plants in reducing the organic load, ensuring that the treated water is of sufficient quality to meet environmental standards. The Sidi Bel Abbes-WWT facility, while showing initial robustness in pollutant removal (2016–2018), faced gradual degradation in performance from 2020 onward. The increased load of organics (DBO_5/DCO), nutrients (NH_4^+, PO_4^{3-}), and salinity suggests insufficient hydraulic capacity, possible treatment overload, or aging infrastructure. El Kerma WWTP shows a generally improving trend in pollutant removal from 2016 to 2024. However, variations in outlet concentrations across some years (especially 2023) underline the need for sustained maintenance, possible infrastructure upgrades, and real-time monitoring to ensure consistent compliance with discharge standards. Moreover, il is essential to continuously monitor wastewater quality, especially as the population and industrial activities continue to grow.

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