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Wastewater treatment and industrial reuse in a semi-arid mining basin: Performance and energy efficiency of the Khouribga wastewater treatment plant (Morocco)

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ABSTRACT

Morocco's structural water scarcity has increased interest in treated-wastewater reuse for phosphate processing. This study evaluates the 2025 performance and energy intensity of the Khouribga activated-sludge wastewater treatment plant using 365 daily operator records. Concentration removal, inlet and outlet mass loads, and volumetric and COD-mass-based energy indicators were recalculated with explicit Qin/Qout definitions. Exploratory correlations were adjusted using the Benjamini–Hochberg false-discovery-rate procedure, while time-ordered regressions used Newey–West heteroskedasticity- and autocorrelation-consistent standard errors with a 7-day lag. Mean concentration removals were 91.3% for total suspended solids (TSS), 90.1% for chemical oxygen demand (COD), and 94.3% for five-day biochemical oxygen demand (BOD_5). All available TSS, COD and BOD_5 measurements met the Moroccan general domestic-discharge limits. However, only 12.1%, 34.2% and 38.4% of the corresponding observations met the more stringent historical tertiary-treatment objectives reported for this plant; these objectives are performance benchmarks rather than statutory or currently verified OCP specifications. The summer–winter COD-removal difference was 2.01 percentage points (HAC $p = 0.039$), whereas temperature was not independently significant in the multivariable model. Flow explained little variation in pollutant removal. Mean volumetric energy intensity was 0.687 kWh/m³ for all days and 0.660 kWh/m³ after excluding two very-low-flow sensitivity observations. Mean COD-mass-based intensity was 1.216 kWh/kg COD removed. Their daily correlation decreased from $r = 0.392$ in the complete series to $r = 0.035$ in the sensitivity set. The results demonstrate high average removal but also show that legal discharge compliance, attainment of stringent reuse targets, and energy benchmarking are distinct questions. The supplied code and supplementary outputs provide a reproducible workflow for future plant audits.

Keywords: wastewater treatment plant, activated sludge, industrial water reuse, unconventional water resources, treatment performance, statistical correlation, Khouribga, Morocco.

INTRODUCTION

Morocco is among the most water-stressed countries in the Mediterranean basin: per-capita water availability fell from 2560 m³/year in 1960 to under 600 m³/year in 2025, placing the country durably below the structural water-stress threshold (1000 m³/person/year) and raising concerns that the absolute scarcity threshold (500 m³/person/year) could be crossed before 2035 (World Bank, 2023). In this context, treated wastewater reuse (TWWR) is progressively emerging as a strategic alternative resource: the national fleet of wastewater treatment plants grew from

7 facilities in 2006 to 216 in 2024, the national pollution-abatement rate rose from 7% to 58% over the same period, and about 37 million m^3 of treated wastewater were reused in 2023, mainly for irrigation of green spaces and golf courses and for industrial uses (Lemfarrak et al., 2025).

Among the industrial uses of TWWR, phosphate washing and transport in the Khouribga mining basin constitute a pioneering case. Washing of raw phosphate ore, an essential upgrading operation prior to its transport and processing, is indeed one of the most water-intensive steps in the value chain of the OCP Group (Office Chérifien des Phosphates), Morocco's leading historical mining and industrial operator. Faced with this water constraint, and amid the growing scarcity of conventional resources, OCP has pursued a water-security strategy based on unconventional resources, built around two complementary levers: reuse of treated urban wastewater and, more recently, seawater desalination, the latter having led to the commissioning of a desalination plant at Jorf Lasfar and a pipeline over 200 km long connecting that plant to the Khouribga site. While desalination can mobilize considerable volumes, urban wastewater reuse remains, to date, the more advantageous option in energy and economic terms, owing to the proximity of the receiving cities and the absence of the production and long-distance transport costs inherent to desalination (OCP Group, 2025). It was with this rationale that the very first wastewater treatment plant of the OCP Group, preceding those of Youssoufia and Benguerir, was commissioned in Khouribga as early as 2010: an urban wastewater treatment plant operating on the activated-sludge process, built by OCP as part of a partnership. The primary purpose of this infrastructure is to supply the mining industry with a substitute industrial water source, thereby reducing withdrawals from conventional resources earmarked for drinking water.

Beyond its environmental function of treating urban discharges, the Khouribga WWTP is thus a link in an industrial water-valorization chain, which raises the requirements for reliability, regularity and quality of its operation. Continuous assessment of its treatment performance, rather than only occasional or average appraisal, therefore becomes as much an operational as a scientific issue, all the more so as the sustainable management of sludge generated by the rising national pollution-abatement rate is itself an emerging challenge for the sector (Moroccan National Report, 2024; Bougayr et al., 2024). Work on the performance assessment of wastewater treatment plants has multiplied in recent years, both in Morocco and internationally, drawing on increasingly refined statistical tools: probabilistic distributions and Monte Carlo methods (Młyński et al., 2020), statistical analysis of large datasets and multiple regression (Mihajlović et al., 2024), or cross-process comparisons between activated sludge and other extensive processes (Kamel et al., 2026). In the Moroccan region of Béni Mellal-Khénifra, the impact of climate variability on the treatment efficiency of several WWTPs has been characterized in detail using databases and GIS tools (Ait Ouhamchich, 2022). These approaches highlight the need to move beyond synthetic annual indicators to explore the fine-scale temporal variability of performance and its determinants (temperature, hydraulic and organic load, seasonality) – a thermal sensitivity that is also widely documented at other sites, from the Mediterranean basin (Lawrence et al., 2024) to southern Africa (Makuwa et al., 2022).

Environmental quality can respond rapidly to changes in anthropogenic pressure and activity regimes, as illustrated by the environmental recovery patterns reported during mobility restrictions by Ali et al. (2024). For treatment systems, meeting a target quality also depends on effective filtration and complementary polishing steps; modified filtration media have shown that filtration and sorption performance varies with material properties and operating conditions (Zahorodniuk et al., 2019). Microbiological surveillance is especially important where treated effluent is reused under water stress, because inadequate water and sanitation conditions sustain transmission risks for diarrhoeal and enteric diseases (El Morabet et al., 2023).

This study is part of this dynamic. It aims to (i) build and document an exploitable daily database from the 2025 self-monitoring records of the Khouribga WWTP; (ii) statistically assess its treatment performance (removal efficiencies, regulatory compliance, energy efficiency) relative to performance reported for other plants and processes; (iii) identify, through correlation and linear regression analysis, the significant determinants of performance variability; (iv) examine the consistency between volumetric and mass-based energy indicators for this activated-sludge process; and (v) discuss the practical implications of these results for the operation of the plant and its role in Morocco's wastewater reuse strategy.

The specific contribution of this work lies in the construction and fine-grained statistical analysis, over a full year, of an unprecedented daily dataset for a large-scale industrial activated-sludge facility (18,000 m^3/day), whose treated water directly feeds a mining valorization chain; this intensive, industrial operating context constitutes in itself an original case study for the Moroccan and regional literature on WWTP performance.

MATERIALS AND METHODS

Study site

The Khouribga WWTP is located in Khouribga Province (Béni Mellal-Khénifra region, central Morocco), in the OCP Group's phosphate-mining area. Commissioned in 2010, it was designed for an initial capacity of 18,000 m^3/day, corresponding to a design load of about 220,000 population equivalents, serving the populations of Khouribga, Bouljaâd/Boulanouare and Ouled Abdoun (Rajhy and Khomsi, 2020). The treated water is largely valorized by the OCP Group for washing and hydraulic transport of phosphates, amounting to roughly 5 to 6 million m^3 per year, equivalent to nearly half of the city's drinking-water needs (Rajhy and Khomsi, 2020). An expansion program launched in 2022 aims to raise the reusable-water production capacity to about 10 million m^3/year, with the addition of tertiary treatment (sand filtration and UV disinfection).

Treatment process description

The process implemented is biological treatment by activated sludge, structured into three lines (Figure 1): a water line (preliminary treatment by coarse and fine screening, then grit/grease removal, biological treatment in an aeration basin, secondary clarification, filtration, disinfection and pumping), a sludge line (thickening then dewatering of excess biological sludge), and a gas line, with biogas from digestion covering between 20% and 30% of the plant's energy needs (Rajhy and Khomsi, 2020) (Figure 2).

Data collection and database construction

The data used come from the plant's daily self-monitoring program for calendar year 2025 (365 days, from 1 January to 31 December), initially structured into 24 monthly sheets (12 raw-measurement sheets and 12 removal-rate sheets). For each day, three sampling points were recorded (raw water at plant inlet, intermediate clarified water, treated water at plant outlet): flow rate (m^3/day), pH, temperature (°C), total suspended solids (TSS, mg/L), chemical oxygen demand (COD, mg O_2/L) and 5-day biochemical oxygen demand (BOD_5, mg O_2/L); as well as outlet faecal coliforms (MPN/100 mL) and daily electricity consumption of the main distribution board (TGBT, kWh/day).

The 24 source sheets were consolidated into 365 daily observations with 19 reported fields (date plus 18 measured or operator-reported fields). Derived variables were then generated reproducibly by the accompanying Python script; they were not counted as raw measurements. BOD_5 was available on 146 days, TSS and COD on 363 days, and faecal-coliform entries on 304 days. Missing observations were retained as missing and were not imputed.

The 2025 dataset was supplied as daily operator records. A plant-specific laboratory manual,

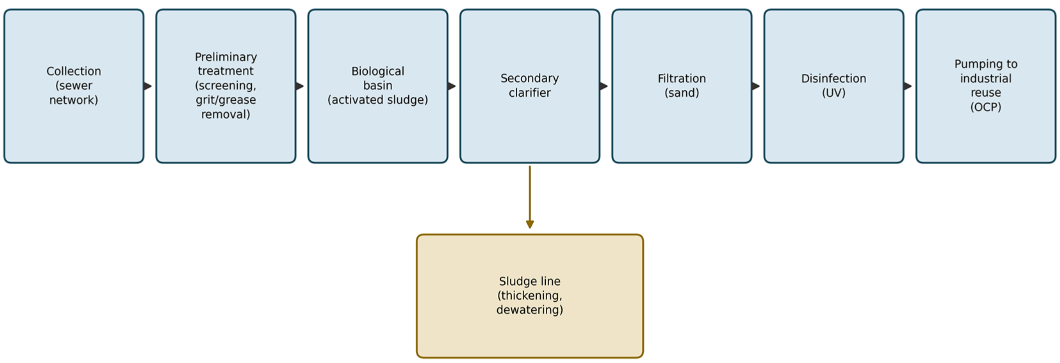

Figure 1. Simplified process flow of the Khouribga WWTP, with water, sludge and gas/energy lines shown separately

Figure 2. Views of the Khouribga WWTP: (a) overall aerial view, showing the two circular clarifiers, the aeration basins, the digester (white dome) and the storage silo, with an OCP Group phosphate-tailings pile in the background; (b) and (c) biological aeration basins in operation, showing mixing/aeration of the mixed liquor; (d) secondary clarifier with scraper bridge and digester in the background.

'Procédures des analyses labo' (OCP–delegated management, procedure 418.255 Khouribga, Revision 00, 22 January 2019), documents the historical analytical procedures at this WWTP. TSS was determined gravimetrically by filtration through 0.90-µm glass-fibre filters, drying at 105 ± 2 °C, desiccation and weighing. pH and temperature were measured with an HQ40D multiparameter instrument; the manual describes calibration with fresh buffer solutions and collection of the minimum calibration points required by the active method. BOD_5 was measured manometrically using BODTrak II, with a seeded glucose–glutamic-acid performance check. COD was measured using Hach Lange LCK314 (15–150 mg O_2/L) and LCK514 (100–2.000 mg O_2/L) cuvette tests; the procedure includes a reagent blank for each LCK314 batch and plausibility checks by dilution and/or standard addition. Faecal indicators were historically enumerated by 0.45-µm membrane filtration on TTC–Tergitol 7 medium, with 48-h incubation at 37 °C, referring to NF EN ISO 9308-1.

The 2019 manual provides plant-specific historical evidence but is not an accreditation certificate and does not establish ISO/IEC 17025 accreditation. It also cannot confirm that every procedure remained unchanged in 2025. Confirmation of the current method identifiers, calibration frequency and complete QA/QC records was requested from OCP personnel, but no response had been received at the time of revision. The 2019 membrane-filtration procedure is inconsistent with the 'MPN/100 mL' label in the 2025 dataset; microbiological observations were therefore summarized descriptively and were not used for inferential compliance claims.

Calculated performance indicators

For each parameter p (TSS, COD, BOD_5) and each day, the overall removal efficiency (inlet → final outlet) was calculated using the classical equation (Metcalf and Eddy, 2014):

$$R^p\ (\%) = [(C_{in} - C_{out}) / C_{in}] \times 100 \quad (1)$$

For each pollutant p, concentration-based removal was calculated as 100 × (C_{in} − C_{out})/C_{in}. Influent and effluent mass loads were calculated separately as $L_{in} = Q_{in} \times C_{in}/1000$ and $L_{out} = Q_{out} \times C_{out}/1000$ (kg/day), respectively. Mass removed was $L_{in} - L_{out}$, and mass-based removal was 100 × (L_{in} − L_{out})/Lin. Volumetric energy intensity was calculated as daily TGBT electricity use/Qin. Mass-based energy intensity was calculated as daily TGBT electricity use/(Lin,COD − L_{out},COD). This definition avoids applying one flow value to both sampling locations and is implemented verbatim in the supplied script.

Statistical analysis

Descriptive statistics were computed overall and by month. Pearson correlations were treated as one exploratory family and adjusted with the Benjamini–Hochberg false-discovery-rate procedure ($\alpha = 0.05$). Linear models were fitted by ordinary least squares, but inference used Newey–West heteroskedasticity- and autocorrelation-consistent standard errors with a 7-day lag. Residual normality (Shapiro–Wilk), heteroskedasticity (Breusch–Pagan), serial correlation (Durbin–Watson and Ljung–Box at lag 7), and predictor collinearity (VIF) were reported. Because several residual series were non-normal, heteroskedastic and serially correlated, conclusions rely on HAC confidence intervals rather than conventional OLS p-values. Seasonal COD removal was estimated as a summer-versus-winter indicator contrast with the same HAC correction. All processing was performed by the accompanying Python script (Python 3; pandas, NumPy and SciPy).

The 36 pairwise correlations among the nine prespecified variables were treated as one exploratory family and corrected using the Benjamini–Hochberg false-discovery-rate procedure. Regression inference was handled separately using 7-day HAC standard errors. Effect sizes, confidence intervals and model diagnostics were considered together; statistical significance alone was not interpreted as operational importance.

Regulatory reference framework

Two benchmarks were kept strictly separate. Regulatory screening used the Moroccan general domestic-discharge limits in Joint Order No. 1607-06 ($BOD_5 \leq 120$ mg O_2/L, COD ≤ 250 mg O_2/L and TSS ≤ 150 mg/L). In addition, Rajhy and Khomsi (2020) reported plant-specific tertiary-treatment objectives of $BOD_5 \leq 10$ mg/L, COD ≤ 50 mg/L, TSS ≤ 10 mg/L and faecal coliforms ≤ 1.000/100 mL. These historical plant objectives are used only as performance benchmarks; they are not described as statutory limits or as proof of the currently applicable OCP reuse specification.

No currently applicable primary OCP reuse specification was available to the authors. Accordingly, unsupported internal limits were not used for formal compliance claims. Historical tertiary-treatment objectives reported by Rajhy and Khomsi (2020) were retained only as explicitly labelled performance benchmarks.

RESULTS

Hydraulic and physico-chemical characteristics of raw water

Over 2025, recorded influent volume totalled 5.70 million m^3 (mean 15,612 m^3/day; SD 2.380 m^3/day; range 994–24,779 m^3/day), and recorded outlet volume totalled 5.48 million m^3 (mean 15,019 m^3/day). Two dates, 8–9 December, had exceptionally low recorded Q_{in} (1.159 and 994 m^3/day). In the absence of primary operating logs, these observations are reported without assigning a cause and are retained in the main analysis; a transparent sensitivity analysis excludes Q_{in} < 5.000 m^3/day.

Against the historical tertiary objectives reported for this plant, 44/363 TSS observations (12.1%), 124/363 COD observations (34.2%) and 56/146 BOD_5 observations (38.4%) met the respective concentration targets. All 304 reported faecal-coliform values were ≤1.000/100 mL; however, 288 were recorded as zero and the 2025 enumeration method and reporting limit were unavailable, so this finding is descriptive and cannot establish microbiological compliance. The much less stringent Moroccan general discharge limits were met by all available TSS, COD and BOD_5 observations.

Inlet temperature followed a seasonal cycle (annual mean 18.3 ± 5.3 °C; range 8.0–29.9 °C), while inlet pH averaged 8.07. Several high-pH observations were present, but no operational cause was assigned because primary event and reagent-dosing logs were unavailable (Figure 3).

Overall treatment performance

Mean annual removal efficiencies are high and consistent with performance expected from a well-designed and well-operated activated-sludge

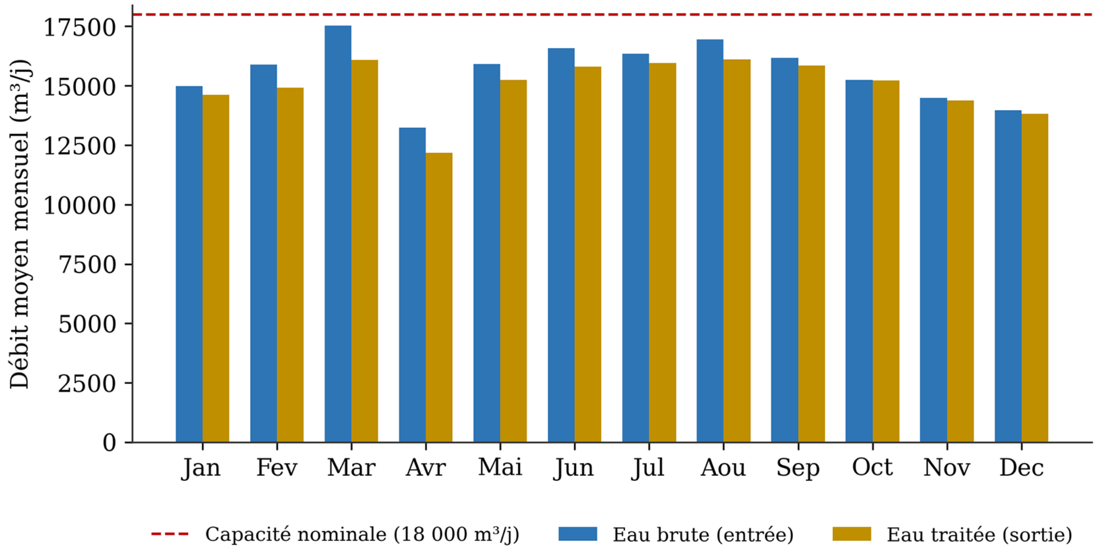

Figure 3. Monthly evolution of mean daily raw-water (inlet) and treated-water (outlet) flow rates, Khouribga WWTP, 2025. The dashed line represents the nominal design capacity (18,000 m³/day)

process: 91.3% ± 5.2% for TSS, 90.1% ± 3.6% for COD and 94.3% ± 2.1% for BOD_5. Mean outlet concentrations (16.4 mg/L TSS, 60.1 mg O_2/L COD, 15.0 mg O_2/L BOD_5) are well below regulatory limit values (150, 250 and 120 mg/L respectively), demonstrating a comfortable safety margin under normal operation.

Figure 4 shows lower monthly mean efficiencies in April and higher values during September–November. The prespecified summer–winter COD contrast was 2.01 percentage points (91.23% versus 89.22%). With Newey–West HAC standard errors at lag 7, the contrast remained significant ($p = 0.039$), but its magnitude was modest. This association should not be interpreted as a temperature mechanism because temperature was not significant in the multivariable COD-removal model (HAC $p = 0.426$).

Compared with other recently audited activated-sludge plants in the literature, these efficiencies fall in the upper range: a Romanian WWTP modernized in 2018–2023 reported COD and BOD_5 efficiencies of about 90% and 92% respectively (Fulgheci et al., 2024); an Iraqi WWTP showed BOD_5/COD/TSS efficiencies between 80% and 90% (Al-Shandah et al., 2021); and an Egyptian comparison between activated sludge and waste stabilization ponds confirmed

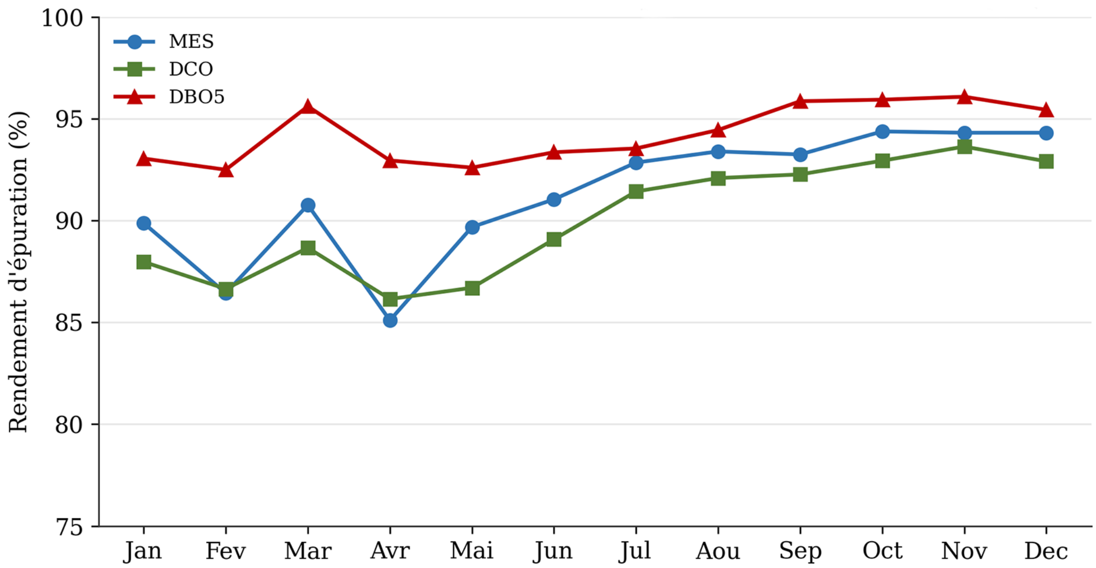

Figure 4. Monthly evolution of mean removal efficiencies (TSS, COD, BOD_5), Khouribga WWTP, 2025

the systematic superiority of the activated-sludge process for COD and BOD_5 removal on heavily loaded effluents (Kamel et al., 2026), consistent with the technology chosen for Khouribga.

Compliance with discharge limits

Relative to the Moroccan general discharge thresholds, all available outlet observations met the TSS, COD and BOD_5 limits. This screening does not establish suitability for every industrial reuse. Against the more stringent historical tertiary-treatment objectives reported by Rajhy and Khomsi (2020), the corresponding proportions were 12.1% for TSS (44/363), 34.2% for COD (124/363) and 38.4% for BOD_5 (56/146). The February high values are reported as observations only; without operating logs, their causes cannot be attributed to clarification failure, sludge carryover or another event.

The Moroccan limits and the historical tertiary objectives answer different questions and should not be conflated. The former were used for general discharge screening; the latter were used to describe how often the 2025 outlet values reached previously reported plant performance objectives. Neither analysis establishes compliance with a currently binding OCP industrial-reuse specification (Table 1).

Correlations and relationships between parameters

The exploratory matrix comprised 36 Pearson correlations among the nine prespecified variables. Benjamini–Hochberg adjusted p-values are supplied in Supplementary Material S1. Because these are time-ordered daily observations, the matrix is interpreted descriptively; regression conclusions rely on 7-day HAC standard errors. Influent concentrations were correlated, and the flow–removal relationships had very small explanatory power. Statistical significance in a large daily dataset was not treated as evidence of operational importance (Figure 5).

In separate HAC regressions, influent flow explained little variation in removal: $R^2 = 0.016$ for TSS, 0.002 for COD and <0.001 for BOD_5. None of the flow coefficients was significant with 7-day HAC inference ($p = 0.152$, 0.571 and 0.916, respectively). The data therefore show limited association over the observed range; they do not prove hydraulic robustness under unmeasured disturbances.

The unadjusted Pearson association between flow and TSS removal was small ($R^2 = 0.016$). Its coefficient was not significant with 7-day HAC inference ($p = 0.152$), reinforcing the distinction between an unadjusted correlation and a time-series-aware regression result.

Raw-water COD-BOD_5 relationship (biodegradability)

The linear regression between raw-water COD and BOD_5 (Figure 6) is statistically significant ($R^2 = 0.264$; $p < 0.001$; $n = 146$) and is expressed by the equation:

$$BOD_5 = 0.220 \times COD + 127.6$$
$$(R^2 = 0.264;\ n = 146;\ p < 0.001) \qquad (2)$$

The mean influent COD/BOD_5 ratio was 2.48 (median 2.33), consistent with a wastewater matrix amenable to biological treatment. This ratio is a biodegradability indicator, not proof of exclusively domestic origin. The moderate COD–BOD_5 regression fit ($R^2 = 0.264$) also indicates substantial day-to-day compositional variability.

Specific energy consumption and treated flow

Volumetric energy intensity was defined as daily TGBT electricity/Qin. The complete-series mean was 0.687 kWh/m^3. Two very-low-flow dates strongly inflated this ratio; the Qin ≥5.000 m^3/day

Table 1. Summary of 2025 annual performance of the Khouribga WWTP

Parameter	Inlet (mean)	Outlet (mean)	Mean removal (%)	Order 1607-06 limit	Compliance
TSS (mg/L)	192*	16.4	91.3	150 mg/L	100%
COD (mg O_2/L)	634*	60.1	90.1	250 mg/L	100%
BOD5 (mg O_2/L)	277*	15.0	94.3	120 mg/L	100%
Flow (m^3/day)	15,612	15,019	–	18,000 (capacity)	86.7% of capacity
Specific consumption	–	–	0.66 kWh/m³	–	–

Note: * Means calculated over available measurement days (n = 363 for TSS/COD, n = 146 for BOD5). Discharge limit per Moroccan Order No. 1607-06.

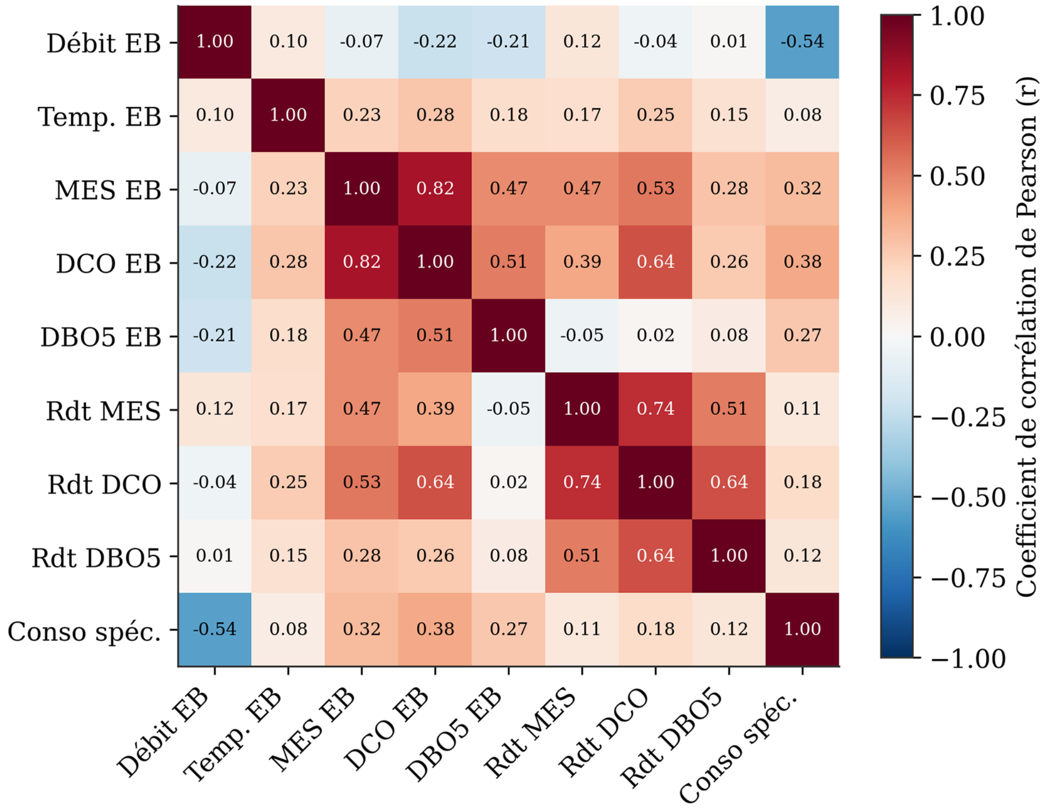

Figure 5. Exploratory Pearson correlation matrix for the nine prespecified variables. Pairwise sample size varies with data availability; FDR-adjusted p-values are supplied in Supplementary Material S1

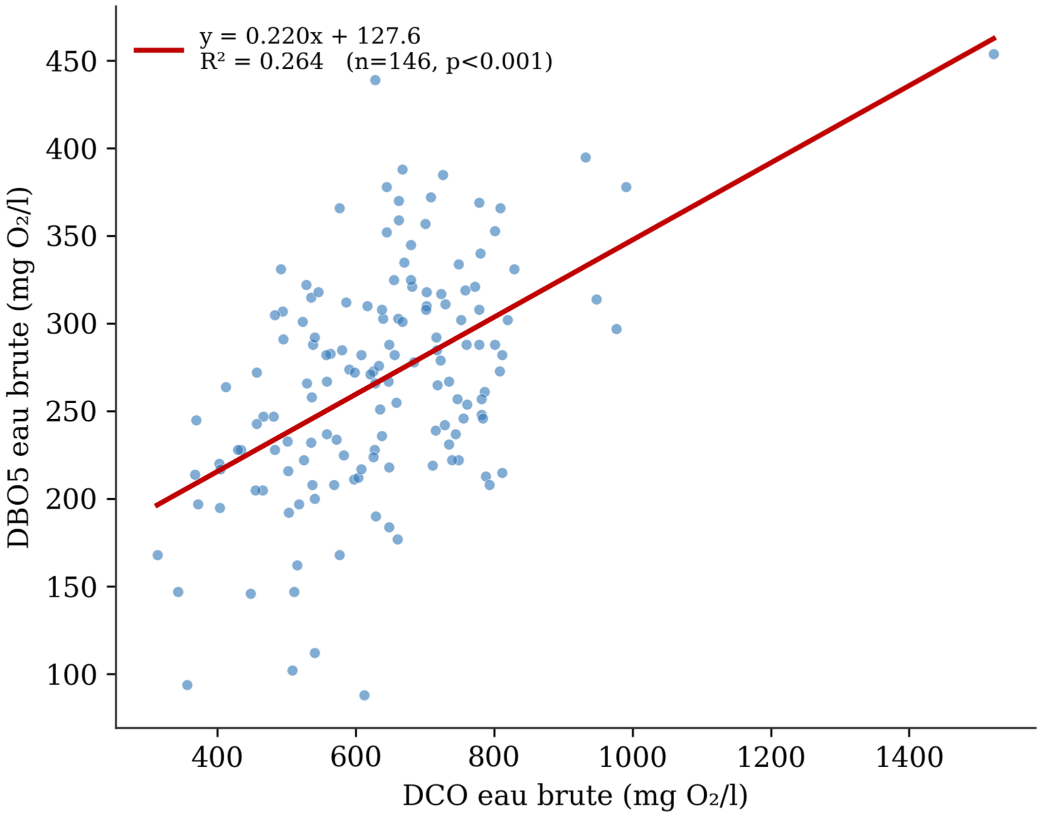

Figure 6. Relationship between raw-water COD and BOD_5, Khouribga WWTP, 2025 (n = 146 days with paired measurements)

sensitivity mean was 0.660 kWh/m^3. In a multivariable model including Qin and influent COD load, neither coefficient was significant with 7-day HAC inference. Accordingly, the earlier simple-regression equation and economy-of-scale causal claim are not retained as confirmatory results.

The complete regression coefficients, HAC confidence intervals and diagnostic tests are reported in Supplementary Material S1. The routine-flow estimate is retained as a sensitivity summary rather than a new primary analysis. Comparisons with literature ranges should account for system boundaries, treatment level and whether electricity is net of on-site recovery (Figure 7).

Comparison of mass-based and volumetric energy indicators

Recent literature on the energy efficiency of wastewater treatment plants notes that a volumetric indicator (kWh/m^3 treated) and a mass-based indicator relative to pollutant load removed (kWh/kg pollutant removed) do not necessarily rank periods or facilities in the same way, particularly when flow is strongly influenced by infiltration/inflow water or by seasonal variations unrelated to organic load (Longo et al., 2023; Molinos-Senante and Maziotis, 2022). Such a divergence between volumetric and mass-based indicators, which can lead to contradictory energy-efficiency diagnoses for the same facility, has already been reported in the literature for other treatment processes. To check whether this phenomenon also occurs for Khouribga's intensive activated-sludge process, a mass-based indicator was calculated for each day with both inlet and outlet COD measurements, relating daily electricity consumption (kWh/day) to the COD load actually removed (kg COD removed/day):

$$\begin{aligned}Cmass &= TGBT\ consumption\ (kWh/day)\ / \\ &\quad COD\ load\ removed\ (kg/day)\end{aligned} \quad (4)$$

Using separate inlet and outlet flows, mass-based energy intensity averaged 1.216 ± 0.342 kWh/kg COD removed (median 1.149; n = 363). Volumetric energy intensity averaged 0.687 kWh/m^3 across all 365 days. The two daily indicators were moderately correlated in the complete series ($r = 0.392$, $p < 0.001$), driven in part by 8–9 December, when recorded Qin was below 1.200 m^3/day and volumetric intensity exceeded 5 kWh/m^3. With Qin ≥ 5.000 m^3/day, mean volumetric intensity was 0.660 kWh/m^3 and the indicator correlation fell to $r = 0.035$. Thus, the earlier claim of unconditional divergence is replaced by an operational-state-dependent interpretation. Monthly mean rankings were not significantly associated (Spearman $\rho = -0.322$, $p = 0.308$; 12 months) (Figure 8).

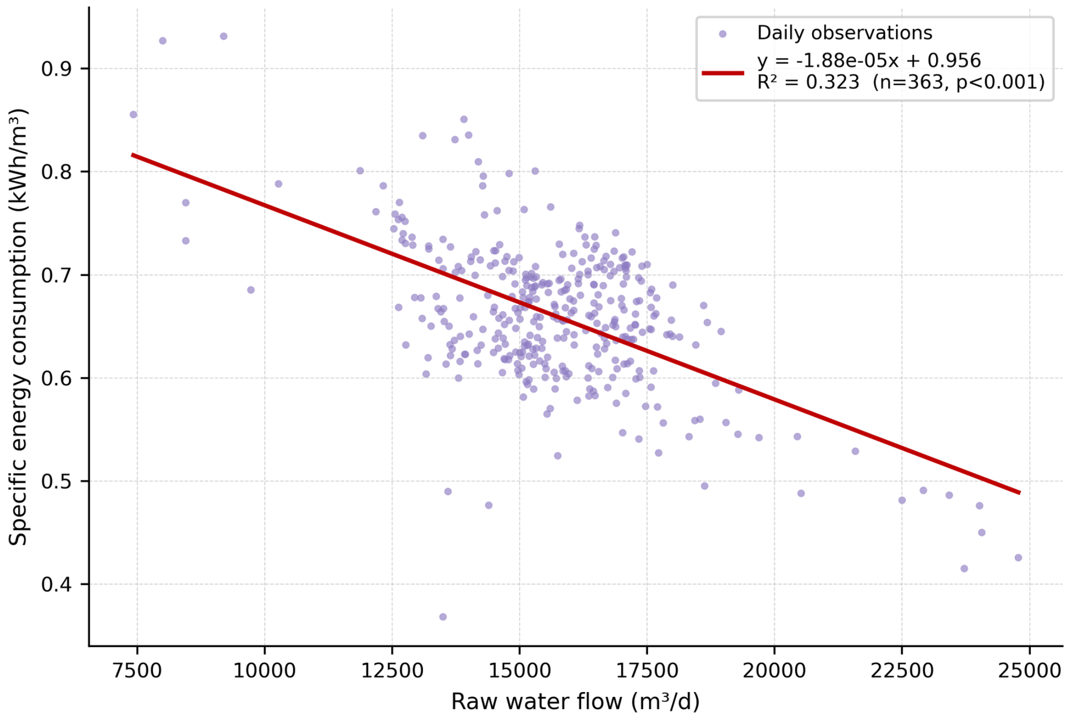

Figure 7. Volumetric energy intensity versus Qin for all 365 days and for the Qin ≥ 5.000 m^3/day sensitivity set. The two very-low-flow observations are highlighted; no operational cause is assigned

Effect of organic load and temperature

In the multivariable COD-removal model (R^2 = 0.422), influent COD was the dominant predictor (HAC $p < 0.001$). Inlet temperature (p = 0.426) and Qin (p = 0.172) were not significant after simultaneous adjustment and HAC inference. The analysis therefore supports an association with influent concentration, not an independently demonstrated temperature effect.

Distribution of inlet and outlet concentrations

The box plots confirm the marked reduction in concentration dispersion between inlet (highly variable, with many extreme values reflecting urban load variations) and outlet (distribution tightly clustered around low values), reflecting the clipping and qualitative regularization function performed by biological treatment and secondary clarification (Figure 9).

Reuse potential

The recorded outlet volume (5.48 million m^3) confirms the quantitative importance of reclaimed water for the reported industrial use. However, only 12.1–38.4% of available TSS, COD and BOD_5 observations met the historical tertiary concentration objectives reported for this plant. Although all 304 reported faecal-coliform values were below 1.000/100 mL, the predominance of zeros and missing analytical protocol/reporting limit prevent a firm microbiological compliance conclusion. Suitability for continued industrial reuse therefore requires the applicable OCP specification and operational risk controls; the present dataset alone should not be generalized to other reuse applications. The present evaluation is limited to the monitored parameters and the reported industrial use. Application-specific reuse decisions require the currently applicable operator specification and appropriate microbiological, chemical and operational risk controls.

DISCUSSION

Treatment performance broadly consistent with activated-sludge standards

The observed annual concentration-removal efficiencies were high (91.3% TSS, 90.1% COD and 94.3% BOD_5), and all available values met the Moroccan general discharge thresholds. This favorable statement must be balanced against the historical plant tertiary objectives, met on only 12.1%, 34.2% and 38.4% of measured days for TSS, COD and BOD_5, respectively. High percentage removal and legal discharge screening therefore do not by themselves demonstrate attainment of a stringent industrial-reuse target.

Seasonal contrast and limits of causal interpretation

The summer–winter COD-removal difference was modest (2.01 percentage points) and remained

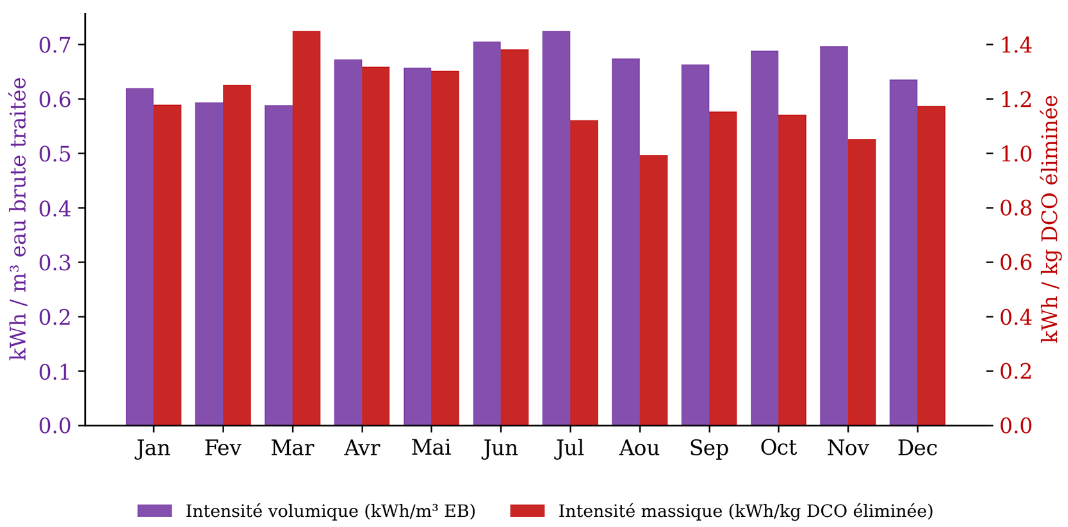

Figure 8. Monthly mean volumetric energy intensity and COD-mass-based energy intensity shown on separate aligned panels because the indicators have different units and denominators

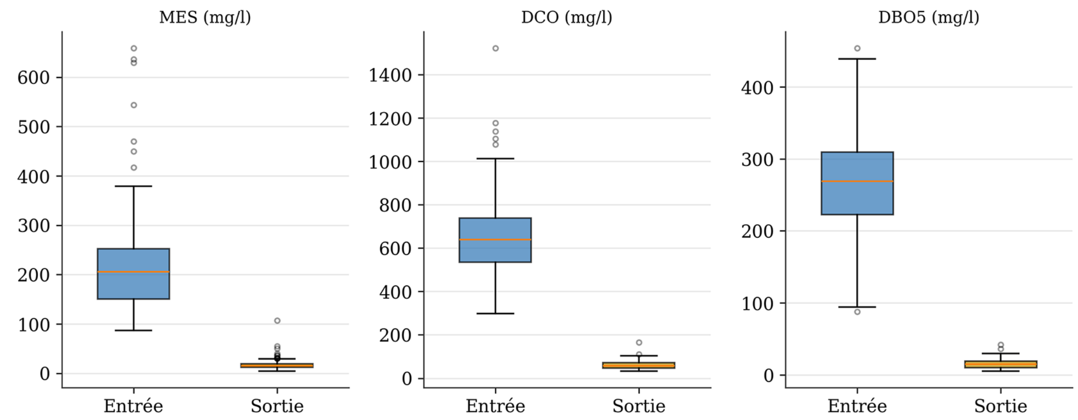

Figure 9. Compared distributions of TSS, COD and BOD_5 concentrations at inlet and outlet of the Khouribga WWTP, 2025 (box plots; n = 363–365 depending on the parameter)

significant with HAC inference ($p = 0.039$). However, temperature was not independently significant in the multivariable model. The seasonal contrast is therefore reported as an association that may reflect several covarying operational or influent conditions, rather than as confirmation of a temperature-driven biological mechanism.

Energy indicators and sensitivity to operating state

Energy results were sensitive to operating state. The two very-low-flow dates produced volumetric intensities more than eight times the routine-flow mean, but no cause is assigned without primary logs. In HAC-adjusted multivariable analysis, the available data did not support a confirmatory independent flow or COD-load effect on volumetric intensity. The actionable conclusion is therefore to report both all-day and routine-flow sensitivity estimates and to investigate low-flow electricity baseload using operator records.

The volumetric and COD-mass indicators answer different questions. Their complete-series daily correlation was $r = 0.392$, but it fell to $r = 0.035$ in the Qin ≥5.000 m^3/day sensitivity set; monthly mean ranks were not significantly associated (Spearman $\rho = -0.322$, $p = 0.308$). The evidence therefore supports joint reporting with explicit operating-state sensitivity, not a universal claim that one indicator is superior.

This finding should, however, not be hastily generalized: a recent study of a Polish activated-sludge plant recovering biogas, based on eight years of monitoring (2015–2022), concludes on the contrary that the volumetric indicator (kWh/m^3) remains the best predictor of energy demand among several indicators tested, including mass-based indicators relative to BOD_5, COD, TSS, nitrogen and phosphorus removed (Mielcarek et al., 2025). This divergence in conclusions between studies could be explained by contextual differences: the presence of biogas energy recovery, which can offset fixed-load effects, the scale and stability of treated flow, or the nature of the mass-based indicators compared (a single pollutant, COD, in the present study, versus several parameters in the Polish study). This contrast underscores that the relative robustness of volumetric and mass-based indicators is probably not universal but depends on facility-specific characteristics – which reinforces, rather than contradicts, the recommendation of combined monitoring of both indicators rather than an a-priori choice of either one.

Study limitations

Sampling frequency was heterogeneous (BOD_5 n = 146; TSS/COD n = 363; faecal-coliform entries n = 304). Residual diagnostics rejected simple independent-error assumptions for several models, so inference used HAC standard errors. Two very-low-flow dates materially affected volumetric energy intensity, but their operational cause is unknown. The 2019 plant laboratory manual documents historical procedures and selected quality checks; it does not prove unchanged use in 2025, provide the complete 2025 calibration/AQ-QC files, or demonstrate ISO/IEC 17025 accreditation. The unresolved discrepancy between the historical membrane-filtration microbiology procedure and the 2025 MPN label further limits microbiological interpretation.

The analysis covers one year at one site. Although temporal dependence and multiple comparisons were addressed, the observational design does not establish causality and the results should not be generalized to other OCP plants or climatic years without external validation.

The dataset does not include measurements of nitrogen, phosphorus, micropollutants or heavy metals, which are nonetheless relevant for a complete assessment of the industrial and agricultural reuse potential of the treated water.

Outlook

These energy-management issues are also part of an international regulatory dynamic that extends beyond the Moroccan case alone: the recast European directive on urban wastewater treatment (Directive (EU) 2024/3019) now sets binding energy-neutrality targets for European wastewater treatment plants by 2045, suggesting a progressive spread, including outside the European Union, of energy-reporting requirements finer than the sole kWh/m³ ratio – an area in which a dual volumetric/mass-based indicator such as the one proposed here could find direct application.

Future work could usefully: (i) incorporate multi-year monitoring to consolidate the seasonal trends identified and detect any medium-term performance drift; (ii) strengthen the frequency and coverage of bacteriological and nutrient measurements, particularly in view of the tertiary-treatment expansion; (iii) couple treatment-performance data with fine-scale energy-operation data (hourly load curves) to refine the energy-saving opportunities identified in §4.3, drawing on multi-indicator benchmarking frameworks (Longo et al., 2023); and (iv) replicate this statistical methodology – including the volumetric/mass-based energy-indicator comparison introduced in §3.4 – at other OCP Group WWTPs (Kasbat Tadla, etc.), in order to build a comparative cross-process performance benchmark at the group and regional scale.

CONCLUSIONS

This study aimed to build an exploitable daily database and to statistically assess, over a full year (2025), the treatment performance and reuse potential of the Khouribga wastewater treatment plant, as well as to identify its main determinants.

As the first OCP-associated wastewater treatment plant commissioned at Khouribga, the facility is an important case of industrial water substitution. The present results quantify its 2025 treatment and energy performance but do not constitute a comparative techno-economic assessment against seawater desalination.

Mean annual concentration removals were high (91.3% TSS, 90.1% COD and 94.3% BOD_5), and all available observations met the Moroccan general discharge limits. However, attainment of the historical tertiary objectives was much less frequent (12.1% for TSS, 34.2% for COD and 38.4% for BOD_5). The summer–winter COD-removal contrast was modest, and temperature was not independently significant in the multivariable model. Flow explained little variation in removal. Volumetric energy intensity averaged 0.687 kWh/m³ for all days and 0.660 kWh/m³ in the routine-flow sensitivity set; COD-mass-based intensity averaged 1.216 kWh/kg removed. The relationship between the two indicators depended strongly on inclusion of the two very-low-flow observations.

This work provides a reproducible pipeline for deriving mass balances, adjusting exploratory correlations, applying HAC regression inference and reporting sensitivity analyses. The central operational implication is to evaluate legal discharge screening, stringent reuse targets and energy performance separately, while retaining traceable Qin/Qout definitions and documenting abnormal operating states.

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