

In-situ conversion of a natural lagoon wastewater treatment plant to aerated lagoons in semi-arid Morocco: Before/after performance and energy assessment at Mrirt

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ABSTRACT

Many medium-sized towns in Morocco and other semi-arid countries are served by natural lagoon wastewater treatment plants (WWTPs) that now operate well beyond their design capacity, and utilities must decide how to upgrade them. This study documents the in-situ conversion of the 30-year-old Mrirt WWTP (Morocco) from natural lagooning to a two-stage aerated lagoon system, using twelve months of operator monitoring data before (2015) and after (2024) conversion. Mean BOD5 removal increased from 73.9% to 89.2% and COD removal from 67.7% to 78.9% (Welch's t-test, $p \leq 0.001$), and effluent BOD5 and COD complied with the national discharge limits in 12 of 12 months, compared with 2 and 1 months before conversion. Effluent TSS did not change (144 vs 147 mg/L, $p = 0.86$) and exceeded the 150 mg/L limit in 5 months; the lower TSS removal efficiency (51.0% vs 68.1%) reflects a lower influent TSS concentration. The improvement came at a large energy cost: specific consumption rose from 0.071 to 0.85 kWh/m³ (2.15 kWh/kg BOD5 removed), i.e. about 8 kWh per additional kilogram of BOD5 removed. Electricity use was nearly constant regardless of flow or load, and effluent dissolved oxygen remained at 7.0–9.4 mg/L, indicating scope for savings through dissolved-oxygen-based aeration control. These single-site results support considering in-situ conversion among upgrading options, provided that energy use, TSS polishing and salinity are addressed.

Keywords: wastewater treatment, aerated lagoon, natural lagoon retrofit, BOD5, energy consumption, discharge compliance, semi-arid regions.

INTRODUCTION

Sustainable development is a strategic priority for Morocco, motivated both by the need to rationalise the use of natural resources and by the continuous improvement of citizens' quality of life. Wastewater treatment is an essential component of urban infrastructure, with major implications for health, the environment and socio-economic development. Globally, most wastewater is still discharged into aquatic environments without adequate treatment, posing significant health and environmental risks (WWAP, 2017). This problem is aggravated in developing regions by limited technical and financial capacity

(Mara, 2004), particularly in small and medium-sized towns undergoing rapid urbanisation (Verbyla et al., 2013).

Morocco illustrates this dual challenge. Structural water stress has made the future of the country's water resources a strategic issue (IRES, 2022). This scarcity is compounded by deteriorating water quality: pollution, including untreated sewage and salinity, reduces economic growth downstream and agricultural yields (Damania et al., 2019). Urban development and the manufacturing sector also increase wastewater production, which requires effective and sustainable sanitation infrastructure. In response, the national water and sanitation service has built numerous

wastewater treatment plants (WWTPs) over the last thirty years, many of which use natural lagooning for medium-sized towns owing to its low cost, ease of operation and suitability for local climatic conditions (Von Sperling, 2007). This natural-lagoon inventory now constitutes a substantial national asset, but one that is increasingly ill-suited to two concurrent pressures: sustained urban growth, which pushes many plants well beyond their original design capacity, and the emerging national priority of enabling agricultural reuse of treated effluent in a context of structural water stress. Deciding how to upgrade this existing fleet of plants — whether through complete replacement by new intensive facilities or through in-situ conversion of the existing infrastructure — is therefore a strategic question for the sector, yet one for which real-world, quantified operational evidence remains scarce.

However, several decades of operation have revealed the structural limitations of natural lagoons: significant seasonal fluctuations in treatment efficiency, excessive algal blooms that increase effluent turbidity, and persistent odour problems linked to anaerobic conditions (Von Sperling, 2007; Calabrò et al., 2024). The performance of a treatment plant of this type, located in Mrirt (Morocco), was documented for the reference year 2015 by Allaoui et al. (2019), who found that the average BOD5 concentration in the effluent exceeded the national discharge standard. This finding is corroborated by the more recent study of Hachi et al. (2023), who, by characterising the receiving watercourse upstream and downstream of the plant, measured a BOD5 removal rate limited to around 65%, confirming the need for structural intervention. Between 2015 and 2022, complaints regarding odour nuisance at the plant increased markedly (Hachi et al., 2022), confirming the deterioration in operating conditions and the need for technological modernisation.

For Mrirt, the conversion of the WWTP into a two-stage aerated lagoon system was aimed at sustainably improving effluent quality, stabilising seasonal performance, reducing odour nuisance and opening the way for the reuse of treated water for agricultural purposes, a crucial consideration in a context of water stress (Lazarova and Bahri, 2004); treated wastewater is increasingly regarded as an alternative water resource in semi-arid regions (Dias et al., 2024). More broadly, in-situ conversion is one of the options available for the many ageing natural-lagoon plants of Morocco

and comparable semi-arid settings, alongside the construction of new intensive facilities; the dependability of wastewater treatment plants in the semi-arid zone of Algeria has been documented (Rekrak et al., 2020), and aerated lagoons have been reported to operate reliably under the arid climate of North Africa (Bachi et al., 2022). Real-world evidence documenting such a conversion before and after, including its energy cost, nevertheless remains scarce.

This study compares the treatment performance of the Mrirt WWTP over one year before (2015) and one year after (2024) its conversion, using operator monitoring data. It (i) tests the between-year differences in effluent quality, removal efficiency and compliance with discharge limits; (ii) quantifies the energy consumption of the converted plant, including the incremental energy cost of the conversion; and (iii) explores, with appropriate control of multiple testing, the relationships between operating variables. The case is intended to inform, rather than prescribe, the choice between converting existing natural lagoons in situ and building new treatment facilities.

STUDY AREA AND SITE DESCRIPTION

Geographical and administrative context

The town of Mrirt is situated in the northern part of the Middle Atlas Mountains in Morocco, approximately 30 km north-east of the province of Khénifra, at an altitude of 1.120 m. According to the 2024 General Population and Housing Census, its population reached 46,285, with an average annual growth rate of 0.80% between 2014 and 2024 (HCP, 2024), placing increasing structural pressure on the existing sanitation infrastructure.

The initial wastewater treatment plant with natural lagooning

The Mrirt WWTP is situated 3.5 km from the town centre and covers an area of 9 ha. Commissioned in its first phase in 1992 and fully operational since 2003, it was designed for a nominal flow rate of 1,800 m³/day and a population equivalent of 31,000 (CID & ONEE-Branche Eau, 2017). In its natural lagoon configuration, the plant comprised a pumping station with manual debris removal, four parallel anaerobic ponds (unit capacity 3.400 m³; retention time 3.5–5.6 days), four

parallel facultative ponds (unit capacity 18,600 m³; retention time 19–30 days) and a drying bed (CID & ONEE-Branche Eau, 2017). The treated effluent was discharged into the receiving watercourse without significant reuse. Performance in this configuration, independently documented by Allaoui et al. (2019) and Hachi et al. (2023), showed insufficient BOD₅ removal, with a mean effluent concentration of 130 mg/L exceeding the national discharge limit of 120 mg/L (Arrêté conjoint n° 1607-06, 2006), linked to anaerobic conditions and marked seasonal variation.

The current wastewater treatment plant with aerated lagoons

The modernisation consisted of converting one facultative pond into a two-stage aerated lagoon system, each stage comprising a complete-mix basin, a partial-mix basin and a settling basin, in a configuration consistent with recognised design practice for aerated lagoons (US EPA, 2002). Oxygen is supplied not by surface aerators but by a fine-bubble diffused-air system, in which blowers feed air to diffusers installed on the basin floor. The former anaerobic ponds, identified as the main source of odour nuisance (Hachi et al., 2022), were decommissioned and replaced by an odour-treatment unit, an automatic bar screen, a grit chamber and a grease separator. This in-situ renovation approach is consistent with the performance improvements reported for a comparable aerated-lagoon plant in south-eastern Morocco (Hamid et al., 2014).

MATERIALS AND METHODS

Data sources and sampling

The monitoring data cover two complete calendar years: January–December 2015 (natural lagooning, reference year) and January–December 2024 (aerated lagooning, after conversion). The parameters measured were five-day biochemical oxygen demand (BOD₅, mg/L), chemical oxygen demand (COD, mg/L), total suspended solids (TSS, mg/L), pH, electrical conductivity (EC, μ S/cm at 25 °C) and dissolved oxygen (DO, mg/L); pH, EC and DO were not measured in 2015. Following the routine monitoring procedure of ONEE – Water Branch, influent was sampled at the plant inlet downstream of pretreatment and treated effluent at

the outlet of the final settling basin. Grab samples were collected weekly, so that each monthly value is the arithmetic mean of four to five determinations; as these are means of discrete samples rather than flow-weighted composites, they are interpreted as indicative monthly values. Samples were handled and analysed at the ONEE – Water Branch regional laboratory, which holds NM ISO/IEC 17025:2018 accreditation for physico-chemical and microbiological water analyses, following the French standards in force for water analysis and the associated reference procedures (AFNOR, 2020; Rodier et al., 2016): BOD₅ by five-day incubation at 20 °C, COD by dichromate oxidation, TSS by filtration on glass-fibre filters and drying at 105 °C, and pH, EC (referenced to 25 °C) and DO with electro-metric probes. The same laboratory procedures and analytical methods were used in both years (Table S0, Supplementary Material S1), and all reported concentrations were well above the quantification limits of these methods. The 2015 data are those analysed by Allaoui et al. (2019).

Flow and energy data

In 2015 the inlet flowmeter was out of service; daily inflow was estimated from the operating hours of the lift pumps multiplied by their rated capacity. The 13 days without pumping were included in the monthly means, since they correspond to the volume actually pumped; excluding them would raise the annual mean inflow by 3.8%. In 2024 influent and effluent flows were measured with flowmeters. Monthly electricity consumption was taken from the invoices of the national electricity operator, which cover the whole installation; metering is at plant level only, without process-level sub-metering, so consumption cannot be attributed to individual items of equipment. The 2024 records include a fixed allocation of 7.000 kWh/month for the inlet lift station; in 2015 the lift station was the only significant electrical load. Energy indicators are based on the total electricity consumption of the plant.

Calculations

The removal efficiency was calculated as follows:

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

where: C_{in} and C_{out} denote the inlet and outlet concentrations (mg/L), respectively.

Removal efficiencies were computed for each month, and annual values are means of the twelve monthly efficiencies. The daily load removed (kg/d) was calculated as $Q_{in} \times (C_{in} - C_{out})/1000$, and daily electricity consumption (kWh/d) as monthly consumption divided by the actual number of days in the month. Specific energy consumption is expressed per cubic metre treated (kWh/m³) and per kilogram of BOD₅ and COD removed (kWh/kg), both as the mean $\pm$ SD of the monthly values and as the ratio of annual totals. Compliance was assessed month by month against the limit values for the discharge of domestic wastewater: 120 mg/L for BOD₅, 250 mg/L for COD and 150 mg/L for TSS (Arrêté conjoint n° 1607-06, 2006).

Statistical analysis

Between-year differences in monthly values ($n = 12$ per year) were tested with Welch's t-test and, as a non-parametric check, the Mann–Whitney U test; p-values were adjusted with the Holm procedure (Holm, 1979), and effect sizes are given as Hedges' g. Normality was checked with the Shapiro–Wilk test. Pearson correlations were computed only between measured variables that share no term by construction: removal efficiencies and energy ratios were excluded to avoid spurious correlations of ratios (Pearson, 1897). This yielded 8 variables (28 pairs) for 2015 and 14 variables (91 pairs) for 2024. For each coefficient, the 95% confidence interval (Fisher z-transformation), the unadjusted p-value and the false-discovery-rate q-value (Benjamini and Hochberg, 1995) are reported; Spearman's ρ and Cook's distance were used to check robustness to non-normality and to influential months. With $n = 12$, $|r| \geq 0.576$ is required for $p < 0.05$, and the

correlation analysis is therefore considered exploratory. The effect of flow and load on energy use was tested by ordinary least-squares regression of absolute daily electricity consumption (kWh/d) on influent flow and influent BOD₅ load. All analyses were run in Python 3.12 (SciPy, statsmodels); the monthly dataset and the script are provided as Supplementary Data S2 and Supplementary Code S3.

RESULTS

Inlet flow rate

The average daily flow treated by the aerated lagoon system was 3.989 m³/day, with monthly variations ranging from 3.367 to 4.564 m³/day. This variability (−16% to +14% around the mean) reflects seasonal fluctuations in drinking-water consumption and the infiltration of rainwater into the collection network. This flow rate is 2.2 times the plant's initial nominal capacity (1.800 m³/day), reflecting the population growth observed since commissioning, and represents a 26.1% increase compared with the reference year for natural lagooning (3.164 m³/day; $p < 0.001$). In 2024 the measured effluent flow (3.067 m³/day) was on average 22.4% lower than the influent flow, which may reflect evaporation, infiltration through the pond bottoms or metering differences (Figure 1).

pH

The pH of the influent wastewater entering the aerated lagoon ranged from 7.35 to 8.02 (mean 7.80), typical values for domestic wastewater. The pH of the effluent ranged from 7.38

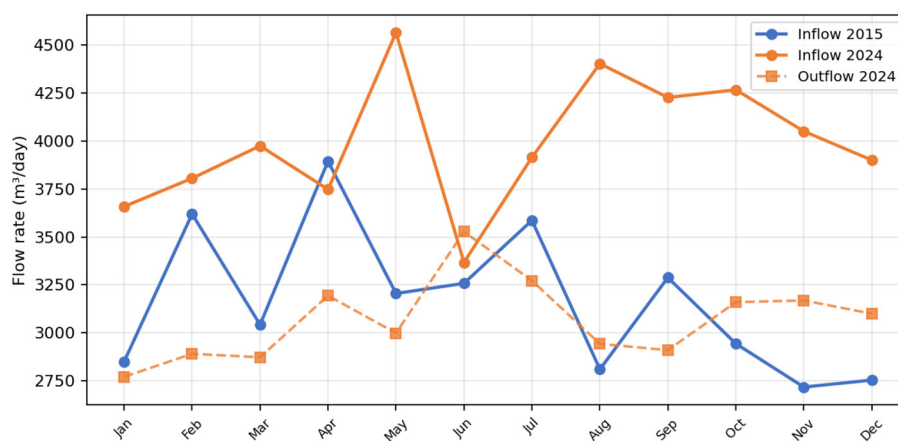


Figure 1. Monthly inflow to the wastewater treatment plant — natural lagooning vs. aerated lagooning

to 8.05 (mean 7.73), remaining within the range of 6.5–8.4 set by the Moroccan irrigation water-quality standards (Arrêté conjoint n° 1276-01, 2002). Effluent pH closely followed influent pH ($r = 0.92$), consistent with stable aerobic conditions (Rittmann and McCarty, 2001).

Biochemical oxygen demand (BOD₅)

In the aerated lagoon, influent BOD₅ varied between 340 and 575 mg/L (mean 447 mg/L). Effluent concentrations ranged from 25 to 90 mg/L (mean 49 mg/L), representing an average removal efficiency of 89.2%. Under natural lagooning (2015), effluent BOD₅ averaged 130 mg/L, exceeding the discharge limit of 120 mg/L, as documented by Allaoui et al. (2019) and Hachi et al. (2023). Mean effluent BOD₅ decreased by 81 mg/L (95% CI 67–95 mg/L; Welch's t-test, $p < 0.001$) and removal efficiency increased by 15.3 percentage points (95% CI 12.1–18.6; $p < 0.001$), whereas influent BOD₅ did not differ significantly between the two years ($p = 0.090$). Effluent BOD₅ complied with the limit in all 12 months of 2024, compared with 2 months in 2015. This improvement is consistent with the performance reported for a comparable aerated-lagoon plant in south-eastern Morocco (Hamid et al., 2014) (Figure 2).

Chemical oxygen demand (COD)

Influent COD ranged from 520 to 870 mg/L (mean 679 mg/L). Effluent COD ranged from 96 to 195 mg/L (mean 142 mg/L), representing a removal efficiency of 78.9%, compared with 67.7% under natural lagooning (mean effluent COD: 298 mg/L, exceeding the limit of 250 mg/L). The increase in efficiency (+11.3 points, 95% CI 6.0–16.6; $p = 0.001$) is significant, and effluent COD complied with the limit in all 12 months of 2024,

compared with 1 month in 2015. Influent COD was, however, significantly lower in 2024 than in 2015 (679 vs 933 mg/L, $p < 0.001$), which should be borne in mind when comparing efficiencies. This improvement results from the increased aerobic bacterial activity in the aerated tanks (Metcalf and Eddy, 2014). The effluent COD/BOD₅ ratio (approximately 2.9) indicates the presence of a residual organic fraction that is not readily biodegradable, characteristic of effluents following secondary biological treatment (Rittmann and McCarty, 2001) (Figure 3).

Total suspended solids (TSS)

Influent TSS varied between 230 and 375 mg/L (mean 300 mg/L). Effluent TSS varied between 85 and 225 mg/L (mean 147 mg/L), representing a removal efficiency of 51.0%, compared with 68.1% under natural lagooning ($p = 0.001$). Mean effluent TSS, however, did not differ between the two years (144 vs 147 mg/L; $p = 0.86$): the lower removal efficiency results mainly from the lower influent TSS concentration in 2024 (461 vs 300 mg/L; $p < 0.001$) rather than from a deterioration of effluent quality. Effluent TSS exceeded the 150 mg/L limit in 5 of 12 months in 2024 (maximum 225 mg/L in February), compared with 6 of 12 months in 2015. Residual suspended biomass in the settling basins, including algae, is a likely contributor to effluent TSS in lagoon systems (Craggs et al., 2012), but it was not measured directly (e.g. as chlorophyll-a or volatile suspended solids) (Figure 4).

Dissolved oxygen

Influent dissolved oxygen ranged from 1.0 to 3.02 mg/L (mean 2.22 mg/L), reflecting the high organic load, which rapidly consumes the available

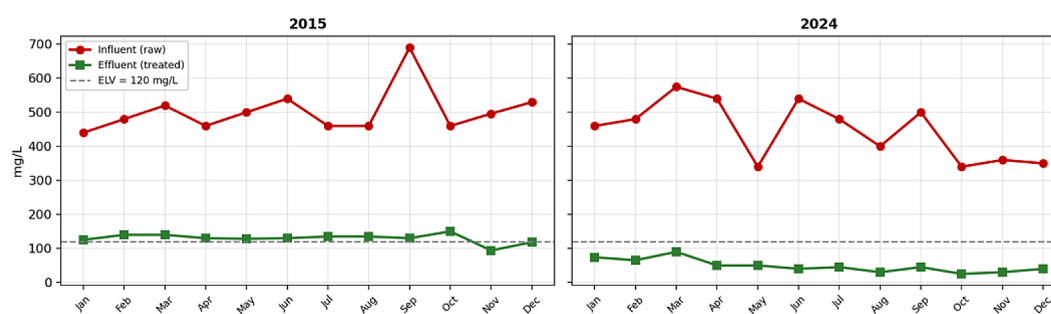


Figure 2. Monthly BOD₅ concentrations at the inlet and outlet — natural lagooning (left) vs. aerated lagooning (right)

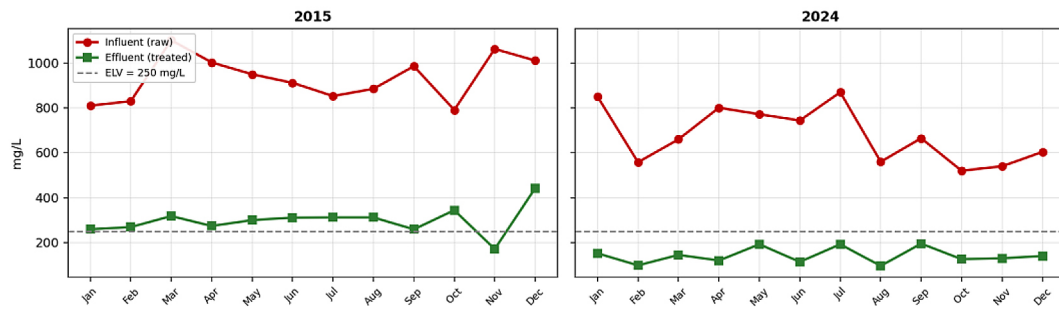


Figure 3. Monthly COD concentrations at the inlet and outlet — natural lagooning (left) vs. aerated lagooning (right)

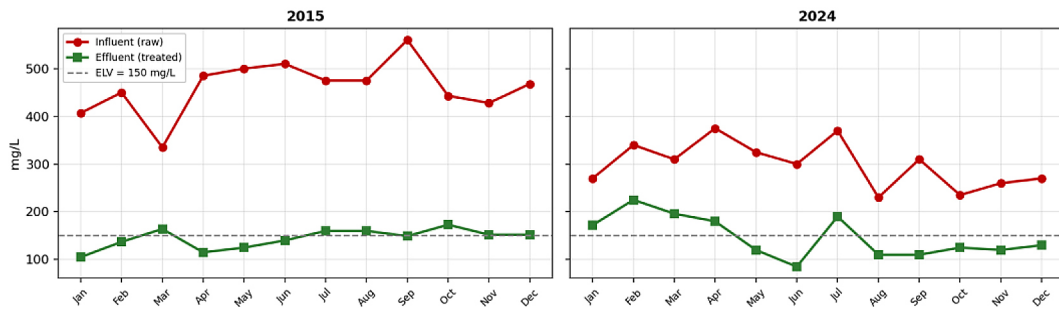


Figure 4. Monthly concentrations of suspended solids at the inlet and outlet — natural lagooning (left) vs. aerated lagooning (right)

oxygen in the raw effluent (Kayombo et al., 2002). Effluent concentrations ranged from 7.0 to 9.4 mg/L (mean 8.17 mg/L), confirming the maintenance of fully aerobic conditions throughout the year, including during the months of highest load. These concentrations, well above the 1.5–2 mg/L usually targeted in aerated basins (Metcalf and Eddy, 2014), also indicate that aeration was not adjusted to the oxygen demand (Figure 5).

Electrical conductivity

The conductivity of the influent ranged from 3.650 to 4.540 $\mu\text{S}/\text{cm}$ (mean 4.198 $\mu\text{S}/\text{cm}$); that

of the effluent ranged from 3.640 to 4.250 $\mu\text{S}/\text{cm}$ (mean 3.949 $\mu\text{S}/\text{cm}$). These high values reflect the natural mineralisation of the town's drinking water. According to FAO guidelines (Ayers and Westcot, 1985), irrigation water with an EC above 3.0 dS/m (3.000 $\mu\text{S}/\text{cm}$) falls in the 'severe restriction on use' class; the mean effluent value (3.95 dS/m) lies in this class, a major constraint for any agricultural reuse (Section 6). The Moroccan irrigation water-quality standards set a limit value of 12 mS/cm but likewise indicate that water with an EC above 3 mS/cm requires severe restrictions on use (Arrêté conjoint n° 1276-01, 2002) (Figure 6).

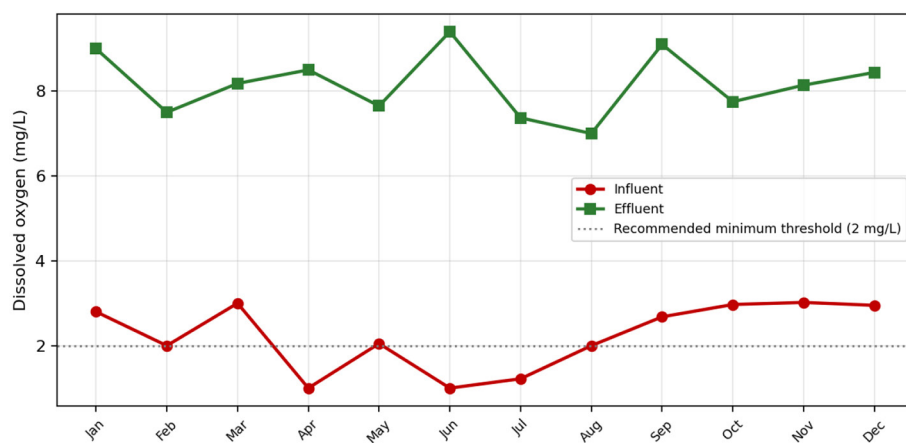


Figure 5. Monthly concentrations of dissolved oxygen at the inlet and outlet of the aerated lagoon

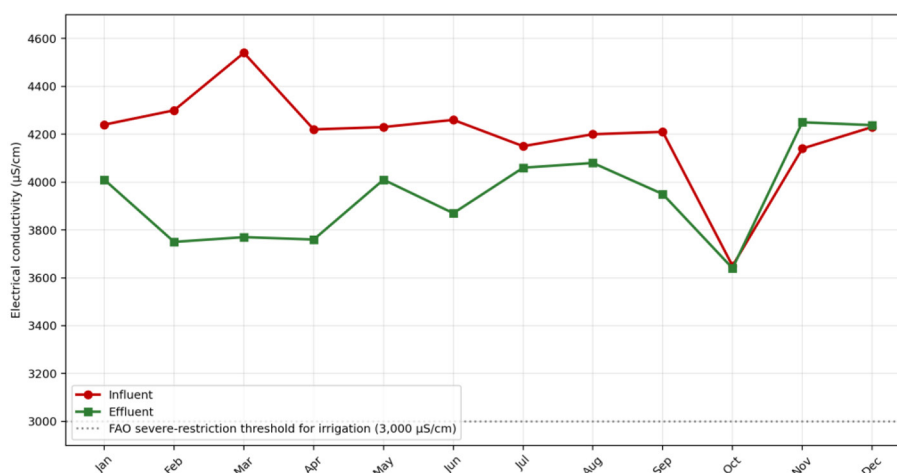


Figure 6. Monthly electrical conductivity at the inlet and outlet of the aerated lagoon; dotted line: FAO severe-restriction threshold for irrigation (Ayers and Westcot, 1985)

Comparative summary

Table 1 summarises the average inlet/outlet concentrations, removal efficiencies and compliance status observed before (natural lagoon, reference year) and after (aerated lagoon) modernisation, together with the results of the between-year tests.

Energy efficiency

With aerated lagooning, the plant processed an average inflow of 3.989 m³/day with an

average electricity consumption of 3.381 kWh/day (1,237,401 kWh in 2024), compared with 224 kWh/day in 2015, when the inlet lift station was the only significant load. Specific consumption was 0.853 ± 0.081 kWh/m³ (mean $\pm$ SD of monthly values; range 0.75–1.01 kWh/m³), or 0.847 kWh/m³ as the ratio of annual totals, compared with 0.071 kWh/m³ in 2015. Per unit of pollutant removed, consumption was 2.19 ± 0.30 kWh/kg BOD₅ (2.15 kWh/kg on annual totals) and 1.63 ± 0.27 kWh/kg COD. The conversion thus added about 3.160 kWh/day for an additional 396 kg/day of BOD₅ removed, i.e. about 8 kWh per additional

Table 1. Comparative summary of average inlet/outlet concentrations, removal efficiencies and compliance status, before (natural lagoon) and after (aerated lagoon) modernisation. ELV: emission limit value (Arrêté conjoint n° 1607-06, 2006). Values are mean $\pm$ SD of monthly values (n = 12 per year). p: Welch's t-test, Holm-adjusted. Compliance: number of months with effluent concentration $\leq$ ELV

Parameter	Influent – natural lagoon (2015)	Effluent – natural lagoon (2015)	Influent – aerated lagoon (2024)	Effluent – aerated lagoon (2024)	Change in efficiency	ELV (mg/L)
BOD ₅ (mg/L)	503 $\pm$ 67	130 $\pm$ 14	447 $\pm$ 86	49 $\pm$ 19	+15.3 pts (p < 0.001)	120
BOD ₅ removal (%)	73.9 $\pm$ 4.3	–	–	89.2 $\pm$ 3.3	–	–
COD (mg/L)	933 $\pm$ 102	298 $\pm$ 64	679 $\pm$ 125	142 $\pm$ 35	+11.3 pts (p = 0.001)	250
COD removal (%)	67.7 $\pm$ 7.5	–	–	78.9 $\pm$ 4.4	–	–
TSS (mg/L)	461 $\pm$ 56	144 $\pm$ 21	300 $\pm$ 48	147 $\pm$ 44	–17.2 pts (p = 0.001)	150
TSS removal (%)	68.1 $\pm$ 7.2	–	–	51.0 $\pm$ 11.7	–	–
BOD ₅ compliance	No (2/12 months)	–	–	Yes (12/12 months)	–	120
COD compliance	No (1/12 months)	–	–	Yes (12/12 months)	–	250
TSS compliance	Annual mean only (6/12 months)	–	–	Annual mean only (7/12 months)	–	150

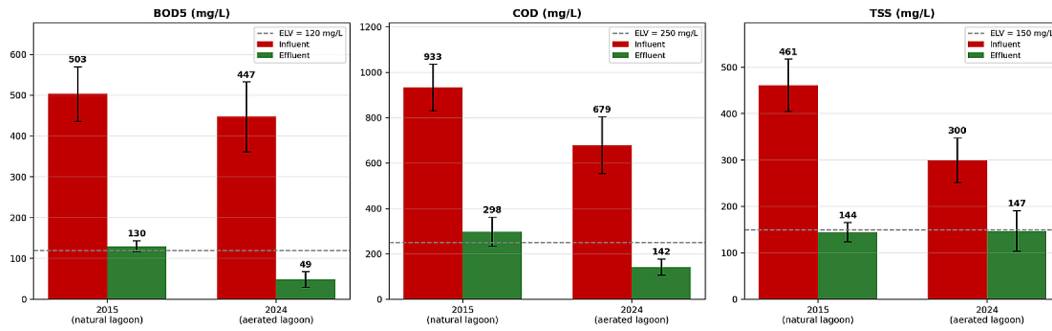


Figure 7. Mean annual influent and effluent concentrations of BOD5, COD and TSS before (2015, natural lagoon) and after (2024, aerated lagoon) modernisation. Error bars: $\pm$ SD of monthly values ($n = 12$); dashed lines: discharge limit values

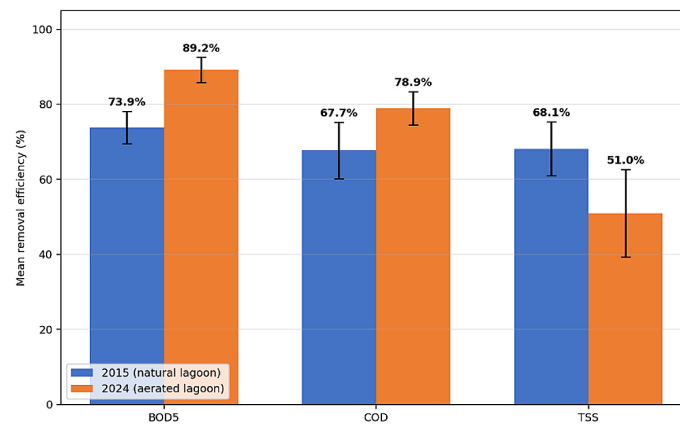


Figure 8. Mean removal efficiencies of BOD5, COD and TSS before (2015) and after (2024) modernisation. Error bars: $\pm$ SD of monthly values ($n = 12$)

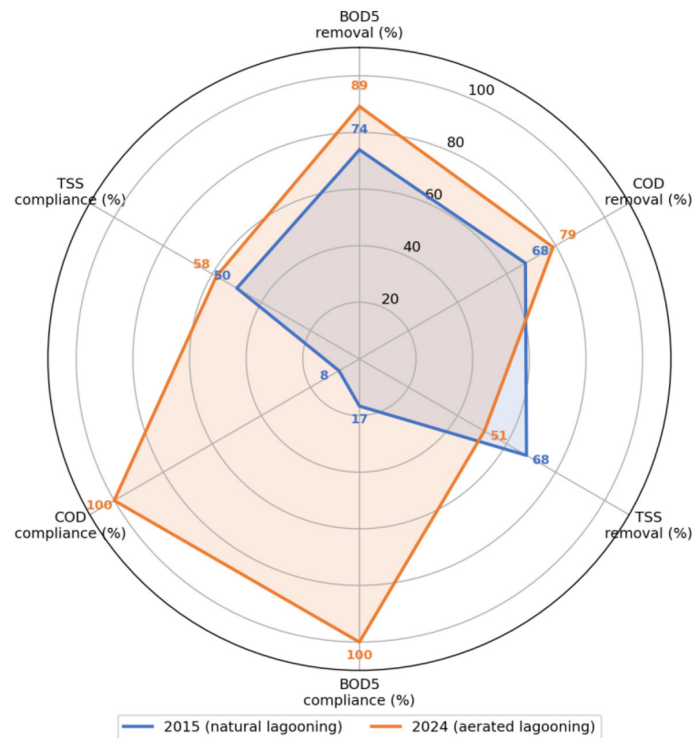


Figure 9. Radar chart of mean removal efficiency and compliance before (2015) and after (2024) modernisation. Compliance is the percentage of months in which the effluent concentration met the discharge limit value

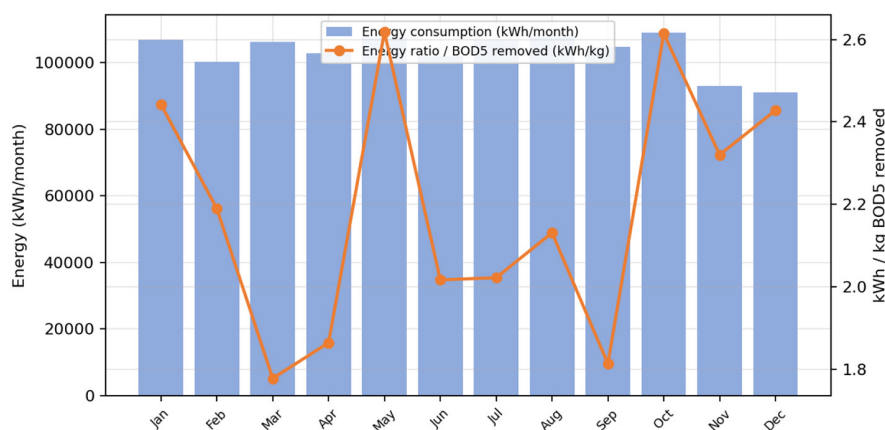


Figure 10. Monthly energy consumption and specific energy efficiency in the aerated lagoon

kilogram of BOD5 removed; part of this additional removal reflects the higher inflow in 2024. Consumption excluding the lift station, mainly aeration, accounted for about 93% of the total. At the medium-voltage tariff of about 1.00 MAD/kWh excluding taxes (Royaume du Maroc, 2014), or about 1.37 MAD/kWh including value-added tax and associated charges, the 2024 electricity cost was about 1.24–1.70 million MAD, i.e. 0.85–1.16 MAD/m³ treated. (Figures 7–10). Daily electricity use in 2024 was nearly independent of flow and organic load: the regression slopes on influent flow ($p = 0.60$, $R^2 = 0.03$) and on influent BOD5 load (p

$= 0.085$, $R^2 = 0.27$) were not significant, and the intercept (about 3.030 kWh/day) accounted for most of the consumption (Figure 13; Table S7).

STATISTICAL ANALYSIS OF CORRELATIONS

Correlations were computed only between measured variables that share no term by construction. Pairs combining a concentration with a removal efficiency derived from it, or a flow with an energy ratio divided by it, were excluded; their

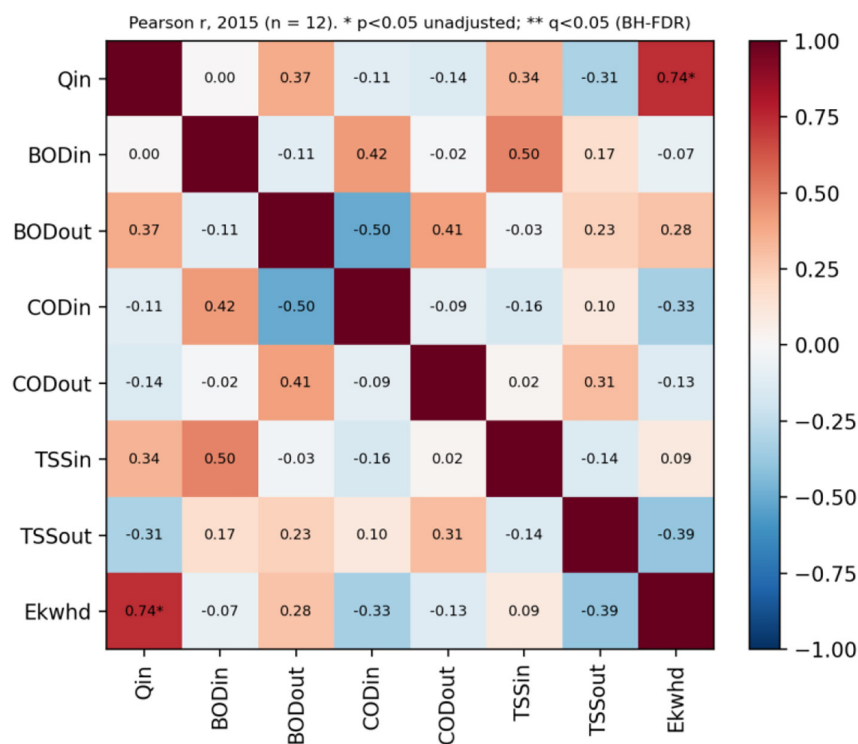


Figure 11. Pearson correlation matrix of measured variables, natural lagoon, 2015 ($n = 12$). * $p < 0.05$ unadjusted; ** $q < 0.05$ (Benjamini–Hochberg). E: electricity consumption (kWh/d)

re-evaluation is given in Table S10 of Supplementary Material S1.

Correlations under natural lagoon conditions

Among the 28 pairs tested for 2015, only influent flow and daily electricity consumption were significantly correlated before adjustment ($r = 0.74$, $p = 0.006$), consistent with a pumping energy proportional to the pumped volume; no correlation remained significant after false-discovery-rate control (Table 2, Figure 11).

Correlations in the aerated lagoon

Of the 91 pairs tested for 2024, 16 were significant at $p < 0.05$ before adjustment and two

after false-discovery-rate control: influent pH–effluent pH ($r = 0.92$), which is trivial, and influent pH–effluent BOD5 ($r = -0.85$, 95% CI -0.96 to -0.54 , $q = 0.021$) (Figure 12). The main relationships are summarised in Table 3; all coefficients, confidence intervals, q-values, Spearman coefficients and diagnostics are given in Supplementary Material S1 (Table S8).

The association between influent pH and effluent BOD5 should be interpreted with caution. Influent pH increased and effluent BOD5 decreased over the year (r with month index = 0.77 and -0.80 , respectively), so that the association is partly seasonal. Although pH influences the growth of heterotrophic bacteria in waste stabilization ponds (Mayo and Noike, 1996), the range observed here was narrow (7.35–8.02), and after controlling for the month index, the partial

Table 2. Correlations with $p < 0.05$ among measured variables, natural lagoon 2015 ($n = 12$; 28 pairs tested). q: Benjamini–Hochberg adjusted p-value. Pairs involving removal efficiencies computed from the same concentrations were excluded (Table S10)

Relationship	r [95% CI]; p; q	Operational interpretation
Influent flow <-> daily electricity consumption	+0.74 [0.29, 0.92]; $p = 0.006$; $q = 0.17$	Lift-station energy increases with the pumped volume; not significant after false-discovery-rate control.

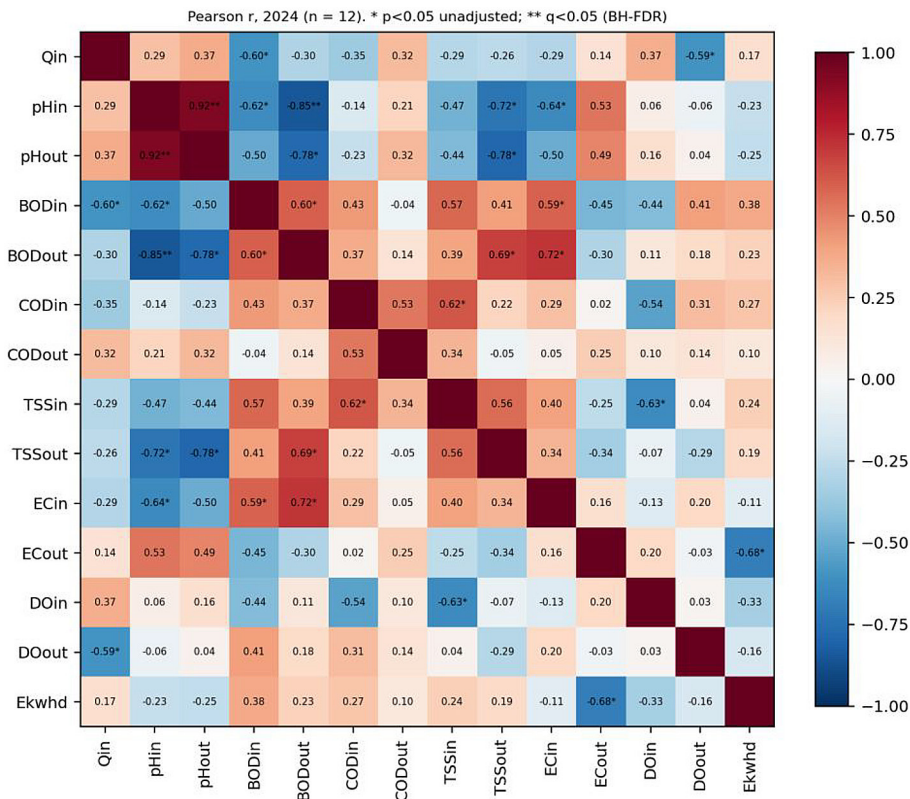
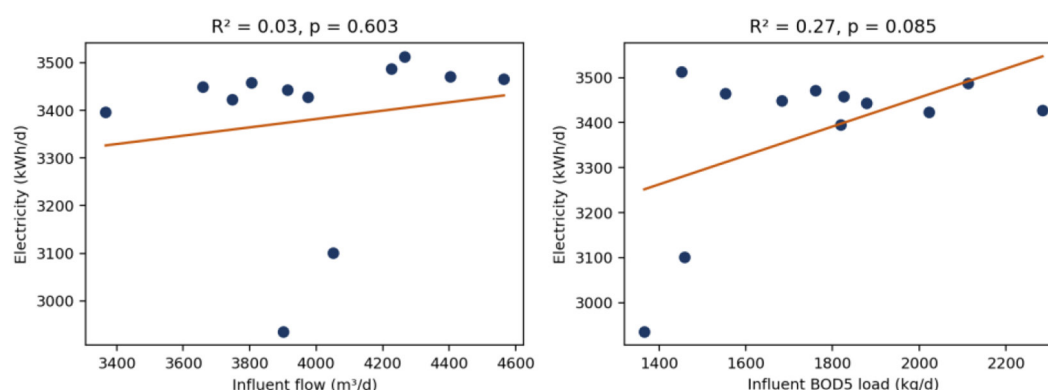


Figure 12. Pearson correlation matrix of measured variables, aerated lagoon, 2024 ($n = 12$). * $p < 0.05$ unadjusted; ** $q < 0.05$ (Benjamini–Hochberg). Ekwhd: electricity consumption (kWh/d)

Table 3. Main correlations among measured variables, aerated lagoon 2024 (n = 12; 91 pairs tested). q: Benjamini–Hochberg adjusted p-value

Relationship	r [95% CI]; p; q	Operational interpretation
Influent pH <-> effluent BOD5	−0.85 [−0.96, −0.54]; p < 0.001; q = 0.021	Lower residual BOD5 in months with higher influent pH; partly a shared seasonal trend (partial r controlling for month = −0.61, p = 0.034).
Influent pH <-> effluent TSS	−0.72 [−0.92, −0.26]; p = 0.008; q = 0.14	Same seasonal pattern as for BOD5; not significant after false-discovery-rate control.
Effluent BOD5 <-> influent conductivity	+0.72 [0.24, 0.91]; p = 0.009; q = 0.14	Higher residual BOD5 in months with more mineralised influent; requires confirmation.
Effluent BOD5 <-> effluent TSS	+0.69 [0.19, 0.90]; p = 0.014; q = 0.16	Residual suspended solids contribute to effluent BOD5.
Influent TSS <-> influent dissolved oxygen	−0.63 [−0.89, −0.09]; p = 0.027; q = 0.25	More concentrated raw wastewater contains less dissolved oxygen.
Influent flow <-> influent BOD5	−0.60 [−0.87, −0.04]; p = 0.040; q = 0.25	Dilution of the influent in high-flow months.
Influent flow <-> effluent dissolved oxygen	−0.59 [−0.87, −0.03]; p = 0.042; q = 0.25	Slightly lower residual oxygen at higher hydraulic load.
Influent flow <-> daily electricity consumption	+0.17 [−0.45, 0.68]; p = 0.60	Electricity use independent of flow: no load-responsive economy of scale.

**Figure 13.** Daily electricity consumption versus influent flow (left) and influent BOD5 load (right), aerated lagoon 2024, with ordinary least-squares fits

correlation weakened to -0.61 ($p = 0.034$). A simple linear model evaluated by leave-one-out cross-validation reduced the prediction error (RMSE) from 20.1 to 11.9 mg/L, but this internal validation on a single year provides no estimate of sensitivity or specificity for an alarm threshold. Influent pH is therefore not proposed as a predictive or alarm indicator; its value as a rapid complement to BOD5 monitoring would require validation on independent data (Figure 13).

DISCUSSION

The results show a substantial and statistically significant improvement in organic-matter removal following modernisation. The increase in BOD5 removal efficiency, from 73.9% to 89.2%, is consistent with the values reported by Hamid

et al. (2014) for a comparable aerated lagoon WWTP in Errachidia, Morocco, and lies in the upper part of the range reported by Boutayeb and Bouzidi (2013) for five natural-lagoon WWTPs of the Chaouia-Ouadgha region, Morocco (74–92% for BOD5, 63–83% for COD and 54–87% for TSS); COD removal (78.9%) also falls within that range, whereas TSS removal (51.0%) falls below it. Conversely, BOD5 removal by the Mrirt natural lagoon in 2015 (73.9%) was at the lower limit of that range, consistent with its hydraulic overload (mean inflow about 1.8 times the design capacity). The 2024 performance is also consistent with that of aerated lagoons operating under the arid climate of North Africa (Bachi et al., 2022). These findings also align with a recent systematic review and meta-analysis of lagoon-based wastewater treatment, which reported organic-matter removal efficiencies ranging widely from

25% to 98% across 63 case studies and found that aerated configurations consistently outperformed non-aerated ones, regardless of the type of wastewater treated (Calabrò et al., 2024).

This improvement can be attributed to several technical factors. Fine-bubble diffused aeration maintains the dissolved oxygen concentration in the effluent above 7 mg/L throughout the year, ensuring fully aerobic conditions that promote intense bacterial activity (Rittmann and McCarty, 2001). The decommissioning of the anaerobic tanks, the main source of odour nuisance (Hachi et al., 2022), has eliminated the reducing conditions that were detrimental to the mineralisation of organic matter. The two-stage configuration optimises the contact time between biomass and organic matter, in accordance with established design principles for aerated lagoons (US EPA, 2002). The comparison nevertheless relies on two years nine years apart, during which inflow increased by 26% and influent COD and TSS concentrations decreased; part of the differences may therefore reflect changes in influent characteristics rather than the conversion alone.

The decline in TSS removal efficiency (from 68.1% to 51.0%) mainly reflects the lower influent TSS concentration in 2024, since mean effluent TSS was unchanged (144 vs 147 mg/L). TSS removal in 2024 was also below the 70–87% typically reported for lagoon systems, whereas BOD₅ removal exceeded the typical range of 75–85% (Ruto et al., 2025). Effluent TSS nevertheless exceeded the discharge limit in 5 of 12 months, and residual suspended biomass in the settling basins, including algae, is a likely contributor, as observed in high-rate algal ponds (Craggs et al., 2012). An additional polishing stage, such as micro-screening, a rock filter or a macrophyte bed, would help to ensure compliance, particularly in the months of highest effluent TSS, in line with recent reviews of nutrient-management technologies suited to small-community lagoon systems (Ruto et al., 2025). Measurements of chlorophyll-a or volatile suspended solids would help to confirm the algal contribution.

From an energy standpoint, aeration is generally the main energy consumer in biological wastewater treatment (Metcalf and Eddy, 2014). At Mrirt, the conversion multiplied specific consumption by about twelve, from 0.071 to 0.85 kWh/m³, and each additional kilogram of BOD₅ removed required about 8 kWh. This energy cost is the main operating trade-off of the conversion

and must be weighed against the compliance gains. Because electricity use was nearly constant regardless of flow and load, while effluent dissolved oxygen remained at 7.0–9.4 mg/L, aeration appears not to be adjusted to the oxygen demand. Dissolved-oxygen-based control or scheduling of the blowers, which typically aims at 1.5–2 mg/L in aerated basins (Metcalf and Eddy, 2014), therefore offers a potential source of energy savings that should be quantified on site; the additional electricity required by the conversion alone represents about 1.2–1.6 million MAD per year at current tariffs. Consequently, the lower consumption per cubic metre in high-flow months reflects a near-constant consumption spread over a larger volume, not a load-responsive economy of scale.

The high conductivity of the effluent (3.95 dS/m) places it in the FAO ‘severe restriction on use’ class for irrigation (Ayers and Westcot, 1985). Any reuse would require salt-tolerant crops, adequate drainage and a leaching fraction of about 0.11–0.15 for target soil salinities of 8–6 dS/m, or blending with water of lower salinity (Lazarova and Bahri, 2004; Jiménez and Asano, 2008). Moreover, microbiological indicators, sodium adsorption ratio, chloride, boron, nutrients and trace elements were not measured during the study period, so compliance with the Moroccan irrigation water-quality standards (Arrêté conjoint n° 1276-01, 2002) cannot be assessed from the present data. These standards also specify how conformity must be demonstrated for treated wastewater: 24 composite samples per year at the plant outlet (one every 15 days) for bacteriological, parasitological and physico-chemical parameters, and four per year for heavy metals. A dedicated monitoring programme would therefore be required before any reuse. With regard to salinity, the same standards note that barley can still reach 50% of its potential yield with water of 8.7 mS/cm, which supports the choice of salt-tolerant crops. An ongoing project aimed at reducing the mineral content of the city’s drinking water should lead to a further reduction in this parameter over the longer term.

From a policy perspective, this single-site comparison indicates that the in-situ conversion of an overloaded natural lagoon can restore compliance for organic matter within the existing site, but at a substantially higher energy demand. A full economic comparison with alternatives such as new construction or activated sludge would require the capital and operating costs of each

option within defined system boundaries, as well as a life-cycle assessment; these data were not available for the present study.

CONCLUSIONS

The conversion of the 30-year-old Mrirt WWTP from natural lagooning to a two-stage aerated lagoon system significantly improved organic-matter removal: BOD5 removal rose from 73.9% to 89.2% and COD removal from 67.7% to 78.9%, and effluent BOD5 and COD complied with the national discharge limits in every month of 2024, against 2 and 1 months in 2015. Effluent TSS was unchanged and exceeded the limit in 5 of 12 months, indicating the need for a polishing stage. These gains came with a twelve-fold increase in specific energy consumption (from 0.071 to 0.85 kWh/m³; about 8 kWh per additional kilogram of BOD5 removed). Because consumption did not vary with flow or load while effluent dissolved oxygen remained at 7–9 mg/L, dissolved-oxygen-based aeration control is a priority for reducing operating costs. The effluent salinity (3.95 dS/m) is a major constraint on agricultural reuse, which would also require microbiological and ionic characterisation. Exploratory correlations associated influent pH with effluent BOD5, partly through seasonal variation; this relationship requires independent validation before any operational use.

These conclusions are based on a single plant and one year per configuration, nine years apart, during which inflow and influent composition changed, and the 2015 flows were estimated from pump operating hours. Odour was not monitored systematically, so the expected reduction in odour nuisance after decommissioning of the anaerobic ponds remains to be quantified. The capital and operating costs of the conversion and of alternative options were not available, and a life-cycle assessment was beyond the scope of this study. Multi-site studies of similar conversions, including economic data, microbiological and ionic parameters and longer monitoring periods, are needed before generalising these findings.

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