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Assessment of energy efficiency indicators for a full-scale bacterial bed in a semi-arid region: Divergence between volumetric intensity and pollutant load

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ABSTRACT

In semi-arid regions such as Morocco, sustainable water management requires greater energy efficiency in treatment infrastructure. Bacterial beds, which utilise natural ventilation, are a low-energy technology well-suited to these contexts. Volumetric energy intensity (kWh/m^3) is the standard benchmark, but its interpretation can be skewed in plants operating below capacity. This study assesses this limitation at the Khénifra wastewater treatment plant (WWTP), where the biological stage relies on natural ventilation and electricity demand is concentrated in pumping and auxiliary systems. The results reveal a marked decoupling between the hydraulic load and electricity demand. While the flow rate varied by 16.7% (CV) in 2023, daily electricity consumption remained virtually constant at around 910 kWh/day (CV 2.5%), showing no positive correlation with the volume treated. The wastewater treatment plant is fully compliant with standards, achieving removal rates of 89.8% for BOD_5 and an energy intensity of just 0.123 kWh/m^3. However, between 2015 and 2023, a paradoxical discrepancy was observed: the volumetric ratio improved by 14%, whilst consumption per unit of pollutant removed (kWh/kg BOD_5) increased by 45%. This divergence is consistent with operation at 26% of nominal organic capacity on a population-equivalent basis and with progressive dilution of the influent. The results indicate that the kWh/m^3 ratio alone may give an incomplete and potentially misleading picture of performance in underloaded bacterial beds, since it responds to dilution and throughput as well as to treatment effort. For reliable benchmarking, it is essential to combine volumetric indicators with indicators normalised by the pollution removed (kWh/kg) and to systematically specify the capacity utilisation rate.

Keywords: energy benchmarking, specific energy consumption, capacity utilisation, trickling filter, fixed-film processes, wastewater reuse, semi-arid regions, Morocco.

INTRODUCTION

Wastewater treatment plants are among the more energy-intensive elements of municipal infrastructure, and at facilities where electricity represents a large share of the operating budget, controlling energy demand has become both an operational priority and a central component of sustainable wastewater management (Cardoso et al., 2021). The recast EU Urban Wastewater Treatment Directive, Directive (EU) 2024/3019, has crystallised this shift at the policy level: it sets, for the first time, a national energy-neutrality target for urban wastewater treatment of 10,000 population equivalents (p.e.) and above, to be reached by 2045 through progressive interim targets and supported by four-yearly energy audits, with renewable energy generated on- or off-site by the operators counted towards it and only a limited share permitted from external non-fossil sources (European Union, 2024). Because the target is set at national level rather than plant by plant, operators are expected to optimise investment across a portfolio, and to do so they first need reliable measures of where each plant stands (Mainardis and Kegl, 2026). Energy performance is therefore no longer only a matter of cost control but an explicit regulatory endpoint.

Energy benchmarking has developed as the principal tool for this purpose (Vaccari et al., 2018; Gallo et al., 2024). Volumetric specific energy consumption (SEC, expressed in kWh per cubic metre of treated wastewater) is the most widely reported indicator, while pollutant-normalised indicators, kWh per kilogram of BOD_5, COD or TSS removed, normalise electricity consumption to the mass of pollutant removed, thereby relating energy demand directly to treatment performance rather than to throughput (Cardoso et al., 2021; Gallo et al., 2024). Both are used to compare plants of different size, technology and loading, on the assumption that they capture genuine differences in efficiency. That assumption weakens when a plant operates well below its design capacity, which is common for facilities sized against multi-decade horizons.

Because volumetric SEC is a ratio of energy to flow, any component of electricity demand that does not scale with flow, pumping, recirculation, instrumentation and other fixed loads, can bias the interpretation of this indicator: a plant running at partial hydraulic or organic load may appear more or less efficient on throughput alone, independent of any real change in treatment (Vaccari et al., 2018; Torregrossa et al., 2019). Analysing 241 Italian plants, Vaccari et al. (2018) found the kWh m^{-3} indicator to be systematically distorted by stormwater and infiltration, so that plants on combined sewers appeared artificially efficient, and concluded that a population-normalised indicator (kWh $p.e.^{-1}\cdot y^{-1}$) gave a more meaningful benchmark, with capacity utilisation above 80% among their criteria for good performance. Bodík and Kubaská (2013) and Foladori et al. (2015) reported the same pattern in plants near 40–50% of design load, attributing high specific demand to equipment oversizing; Torregrossa et al. (2019) confirmed the effect across a larger dataset; and recent reviews continue to identify plant size, load factor and dilution as dominant determinants of energy performance (Cardoso et al., 2021; Gallo et al., 2024). This distinction between the indicator and its interpretation under partial loading is the central concern of the present study. The same concern extends to rapidly urbanising and water-scarce settings: in Cape Town, an integrated analysis of municipal billing, capacity utilisation and unaccounted-for water found that volumetric indicators can be distorted by socio-economic and operational heterogeneity rather than by treatment efficiency alone (Donn-Arnold et al., 2026).

Trickling filters are a useful and under-examined case for this question because their energy profile differs structurally from the aerated, suspended-growth systems that dominate the benchmarking literature (Lasaki et al., 2025). In an activated-sludge plant, mechanical aeration is typically the single largest electricity demand, in the range of 45–75% of plant consumption (Longo et al., 2016; Muloiwa et al., 2023). A trickling filter supplies oxygen by passive ventilation through the medium, so its electricity use is instead concentrated in influent and recirculation pumping and in sludge handling (Abyar and Nowrouzi, 2023). This makes fixed-film plants a natural test case for separating fixed from load-dependent demand, independent of any aeration-control strategy. Lower electricity demand does not, however, translate automatically into greater overall sustainability: treatment objectives, achievable effluent quality and operational constraints differ across technologies, and a full comparison must weigh nitrogen removal, sludge management and land use alongside energy (Abyar and Nowrouzi, 2023; ur Rehman et al., 2026). The interaction between loading and SEC interpretation has, in any case, rarely been examined for fixed-film plants using full-scale operational data.

In semi-arid regions, improving the energy efficiency of wastewater treatment is closely linked to maximising the value of treated effluent through safe reuse (Kamal et al., 2026). Globally, of the roughly 400 km^3 of wastewater generated each year, less than a fifth is treated, and only 2–15% of the treated fraction is reused for irrigation, despite reuse being one of the most direct levers available to water-scarce regions (Christou et al., 2024). Morocco illustrates the pressure driving this agenda: per-capita renewable water availability fell from about 2560 m^3 per year in 1960 to roughly 620 m^3

in 2020, a level the World Bank classifies as structural water stress, and is projected to approach the 500 m³ absolute-scarcity threshold by around 2030 (World Bank, 2023). National policy has responded accordingly: the National Programme for Drinking Water Supply and Irrigation (PNAEPI 2020–2027), together with the mutualised sanitation and reuse programme (PNAM), prioritises the reuse of treated wastewater, with a national target of about 100 Mm³ per year of reused treated water by 2027 (Ministry of Equipment and Water, 2024). In the Béni Mellal–Khénifra region specifically, treated effluent has been found to meet Moroccan standards and to be suitable for agricultural reuse (Faouzi et al., 2020). In this setting, accurate energy benchmarking is directly relevant to operational decisions rather than an academic exercise.

What remains comparatively underexplored, in analyses based on long-term operational data from full-scale facilities, is how loading conditions and SEC interpretation interact in practice for a fixed-film plant operating below design capacity: whether a favourable or unfavourable SEC value reflects genuine treatment efficiency or simply the ratio of a largely fixed electricity demand to a variable flow (Vaccari et al., 2018; Gallo et al., 2024). Addressing this requires operational data spanning a meaningful range of flows at a single plant, together with both volumetric and pollutant-normalised indicators. Accordingly, this study integrates treatment-performance assessment, energy benchmarking, statistical evaluation of operational data and operational interpretation, using one year of records (2023) with a commissioning-period baseline from 2015 from STEP Khénifra, a full-scale trickling-filter plant in semi-arid Morocco, to (i) characterise treatment performance and effluent quality against the applicable regulatory limits; (ii) quantify energy performance using both volumetric and pollutant-normalised indicators; (iii) examine the relationship between treated flow, capacity utilisation and electricity demand; and (iv) draw out the practical implications for interpreting energy benchmarks at underloaded fixed-film plants in water-constrained settings.

MATERIALS AND METHODS

Plant description

The study was conducted at the Khenifra wastewater treatment plant, a full-scale municipal facility in the Beni Mellal-Khenifra region of central Morocco, located about 500 m south-west of the urban perimeter and discharging to a seasonal watercourse that drains to the Oued Oum Er-Rbia. Commissioning and water-testing trials were carried out in 2014 and routine operation began in February 2015; the plant has treated domestic wastewater by trickling-filter technology since. The site has a semi-arid Mediterranean climate, with annual rainfall of 400 to 500 mm and a mean annual air temperature of 17 to 18 °C. A general view of the facility is given in Figure 1.

The plant was designed for a nominal capacity of 153 220 population equivalents, with a planning horizon to 2025, and comprises two identical parallel treatment trains. The hydraulic design

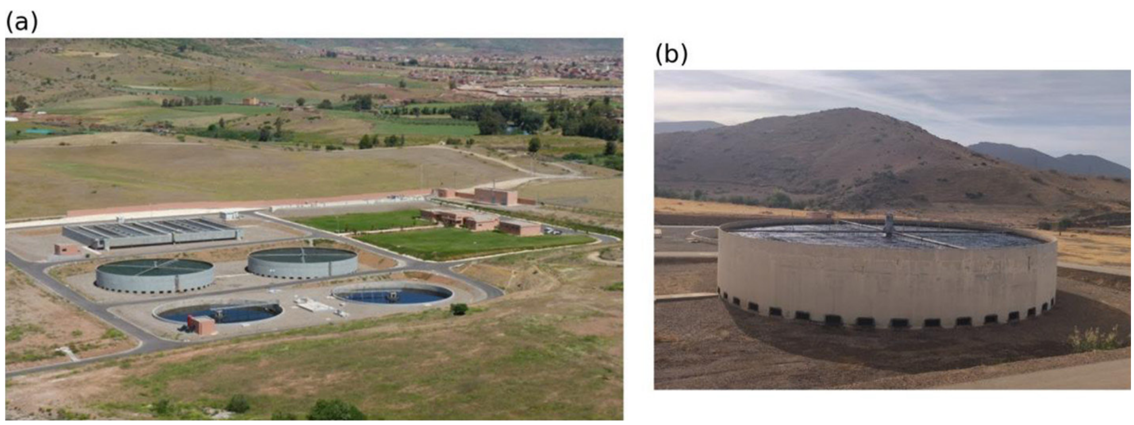

Figure 1. General views of the Khenifra wastewater treatment plant: (a) aerial view showing the Imhoff tanks, the two trickling filters and the two secondary clarifiers; (b) one trickling filter in operation, showing the rotary distributor arms and the ventilation openings around the base of the wall through which air circulates by natural draught

basis specifies an average daily flow of about 12 000 m^3 d^{-1} and a peak daily flow of 14 707 m^3 d^{-1}, with dry-weather flows of 500 m^3 h^{-1} rising to 971 m^3 h^{-1} at peak and a peak wet-weather flow of 1827 m^3 h^{-1}. Design pollutant loads are 5363 kg BOD_5 d^{-1}, 10 726 kg chemical oxygen demand d^{-1} and 5863 kg total suspended solids d^{-1}. The design basis and the operating rules summarised below are those set out in the plant's operating and maintenance procedures.

The treatment scheme comprises a water train, a sludge train and a dedicated odour-control train, shown schematically in Figure 2. Preliminary treatment consists of an automatic screen with a 6 mm bar spacing followed by two unaerated, unscraped grit channels of 20.0 by 1.65 by 1.5 m, after which flow is measured in a Venturi channel of 13.20 by 0.80 m. A distribution structure then feeds eight primary settling compartments arranged as four combined settling and sludge-stabilisation units of the Imhoff type, each 30.0 by 4.0 by 2.4 m. A second distribution canal divides the settled water between two trickling filters operated in parallel, each 30.0 m in diameter and 3.9 m deep, giving a volume of about 2757 m^3 and a combined media surface area of 1414 m^2 and a unit surface area of 707 m^2. The filters are medium-rate units packed with corrugated polyethylene ribbon media, the corrugations preventing the sheets from adhering to one another and preserving the void space through which air circulates, and are dimensioned for a maximum volumetric organic loading of 700 g BOD_5 m^{-3} d^{-1}. The primary stage is designed to remove 33% of BOD_5 and chemical oxygen demand and 60% of total suspended solids. A third distribution canal divides the filter effluent between two secondary clarifiers, each 30.0 m in diameter and 2.5 m deep with a volume of about 1 767 m^3.

A recirculation pumping station equipped with four pumps, each of 230 $m^3 \cdot h^{-1}$, returns clarified water to a point upstream of the trickling filters. This serves two purposes. First, the filters are specified to receive an applied concentration between 150 and 250 mg L^{-1}, and where the water leaving the primary stage exceeds that range it must be diluted with recirculated effluent; the required recirculation flow is obtained from the design relation given in Equation 1. Second, recirculation maintains a continuous hydraulic load on the filters during the intervals between raw-water pumping cycles, when influent would otherwise cease and the biofilm would dry. Sludge extracted from the Imhoff compartments, where it is stabilised anaerobically without energy input, is pumped to 36 reinforced-concrete drying beds with a combined volume of 3 780 m^3; the drainage water from these beds is returned to the head of the works by a dedicated pumping station. Foul air drawn from the preliminary treatment stage and from the digestion compartments of the Imhoff tanks is treated in a biofilter. A washwater pumping station on the treated-effluent main abstracts a small flow for use within the site, for cleaning structures and equipment and for irrigating the plant's green areas; the remaining effluent is discharged to the watercourse crossing the site. No regulated reuse scheme supplying external users is currently in place.

$$Q_R = \frac{Q_J(X_e - X_l)}{X_l - X_R} \quad (1)$$

where: Q_R is the required recirculation flow, Q_J the daily influent flow, X_e the concentration leaving the primary settlers, X_l the concentration required at the filter inlet and X_R the concentration in the recirculated effluent, all in mg L^{-1}.

Oxygen transfer within the filters occurs entirely by natural ventilation through the media and the openings at the base of the filter walls, so the plant has no mechanical biological aeration demand. This is a structural difference from activated-sludge plants, in which aeration blowers are usually the largest single electricity load. Electromechanical demand is therefore expected to be concentrated in influent and recirculation pumping, sludge handling and auxiliary systems.

Data sources and monitoring period

Water–quality monitoring

Influent and effluent were characterised monthly through the 2023 calendar year, giving twelve paired observations, for five–day biochemical oxygen demand, chemical oxygen demand, total suspended solids, pH, temperature and electrical conductivity. Influent is sampled by an automatic sampler installed upstream of the Venturi measuring channel, and treated effluent at a dedicated sampling and analysis station downstream of the secondary clarifiers, which carries online probes for temperature, pH, conductivity, turbidity, nitrate and phosphate. Flow is measured in the Venturi channel by ultrasonic probe, with an electromagnetic flowmeter on the treated–water main. Determinations of five–day biochemical oxygen demand, chemical oxygen demand and total suspended solids were carried out at the operator's regional laboratory in Khouribga, 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). Samples were collected weekly throughout 2023, so that each monthly mean reported here is based on four to five determinations. Because these are arithmetic means of discrete weekly samples rather than flow–weighted averages, they are best read as indicative monthly values, and this is considered in the interpretation below.

Electricity consumption

Electricity was recorded as monthly totals from the utility billing of the national electricity operator, established through a jointly validated billing statement agreed between the plant manager and the utility. Metering is at plant level only; there is no process–level sub–metering, so consumption cannot be attributed to individual items of equipment. The meter boundary covers the whole installation, including the laboratory and auxiliary services; the operator reports that non–process loads are small relative to the treatment equipment. Monthly electricity consumption was converted to a daily–equivalent basis by dividing by the number of days in each month, so that energy and treated flow are expressed on the same time basis. The supply is metered by the national utility on the plant's medium–voltage feed, and consumption was read from the monthly utility invoices, which cover the entire installation; the operator confirmed that these invoices represent the total electricity consumption of the plant.

Data completeness and historical baseline

All twelve months of 2023 had complete water–quality and electricity records; no interpolation or correction was required. Commissioning–period records from 2015 were retrieved to contextualise 2023 performance, using the same laboratory and analytical procedures. Between 2015 and 2023 mean treated flow rose by 25.3%, from 6093 to 7635 $m^3\ d^{-1}$, while influent strength declined, BOD_5 falling from 509 to 315 mg L^{-1} and chemical oxygen demand from 1105 to 629 mg L^{-1}, coinciding with the disconnection of the municipal slaughterhouse from the sewer network in late 2015. In 2015 the effluent was monitored three times per week in order to establish

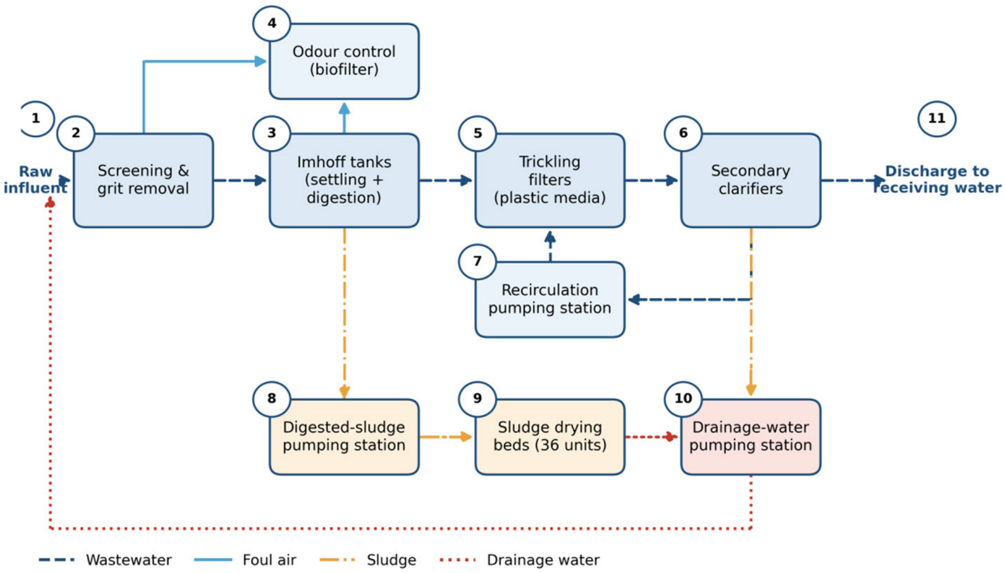

Figure 2. Process flow diagram of the Khenifra wastewater treatment plant: 1 – raw influent; 2 – screening and grit removal; 3 – Imhoff tanks combining primary settling and anaerobic sludge digestion; 4 – odour control by biofilter; 5 – trickling filters with corrugated polyethylene media; 6 – secondary clarifiers; 7 – recirculation pumping station; 8 – digested–sludge pumping station; 9 – sludge drying beds; 10 – drainage–water pumping station; 11 – discharge to the receiving watercourse. Line styles distinguish the wastewater, foul–air, sludge and drainage–water circuits.

a representative baseline, so the annual means for that year rest on approximately 150 determinations per parameter, and flow and electricity were measured with the same instruments and at the same plant–level boundary as in 2023. The monitoring frequency therefore differs between the two years, weekly in 2023 against three times weekly in 2015; only annual means were archived for 2015, so month–to–month variability for that year cannot be reconstructed.

Performance indicators

Unless stated otherwise, indicators were computed from monthly means for 2023 and reported annual values are the mean of the twelve monthly values. Removal efficiency was calculated for each parameter using Equation 2, where $C_{in,i}$ and $C_{out,i}$ are the monthly mean influent and effluent concentrations of pollutant *i* in mg L^{-1}.

$$\eta_i = \frac{(C_{in,i} - C_{out,i})}{C_{in,i}} \times 100 \quad (2)$$

Volumetric specific energy consumption was computed with Equation 3 and load–normalised specific energy consumption with Equation 4, where E_d is daily electricity consumption in kWh d^{-1}, obtained from metered monthly totals divided by the number of days in the month, and Q_d is daily treated volume in m^3 d^{-1}.

$$SEC_{vol} = \frac{E_d}{Q_d} \quad (3)$$

$$SEC_{vol} = \frac{E_d}{Q_d} \quad (4)$$

The factor 10–3 in Equation 4 converts the removed pollutant load from the product of concentration in mg L–1 and volume in m^3 d^{-1}, which yields grams per day, into kilograms per day.

Hydraulic utilisation was expressed as the ratio of mean treated flow to a design flow of 11 949 $m^3 \cdot d^{-1}$. Organic utilisation is reported on two bases, because they answer different questions and diverge markedly at this plant. On a population–equivalent basis, consistent with international benchmarking convention, the population equivalent served was obtained by dividing the applied BOD_5 load by a per–capita loading of 60 g BOD_5 per population equivalent per day, and compared with the design value of 153 220. On a direct mass–load basis, the applied BOD_5 load was compared with the design load of 5 363 kg d^{-1}. The two diverge because the influent is now more dilute than the per–capita loading assumption embedded in the conversion; the two indicators describe different aspects of loading and should therefore be interpreted separately.

Electricity–related carbon dioxide emissions were estimated as the product of annual electricity consumption and a national grid emission factor. This is a first–order approach covering electricity–related emissions only; it excludes direct process emissions of methane and nitrous oxide from the Imhoff compartments, filters and drying beds, and embodied emissions, and is therefore not a full life–cycle assessment. Published grid emission factors for Morocco differ appreciably according to source and accounting basis, direct–combustion factors being higher than life–cycle factors. Rather than adopt a single value, emissions are reported across a range of 0.565 to 0.729 kg CO_2e kWh^{-1} spanning published estimates, the sensitivity of the resulting figures to this choice being reported in Table 6. Electricity–related operating cost was estimated as the product of annual consumption and the tariff actually invoiced to the plant, 1.37 MAD kWh^{-1}, taken from the utility invoices and inclusive of value–added tax at 20% and associated charges; the corresponding pre–tax tariff is approximately 1.00 MAD kWh^{-1} (Royaume du Maroc, 2014).

Statistical analysis

The relationship between treated flow and electricity demand was examined to test whether consumption scaled with throughput or was largely independent of it. As the primary test of variability, the coefficient of variation of daily electricity demand was compared with that of treated flow across the twelve months. Daily electricity demand was then regressed on treated flow by ordinary least squares; the slope was assessed with its 95% confidence interval, and both Pearson and Spearman coefficients were computed, with residuals checked for normality using the Shapiro–Wilk test and for serial correlation using the Durbin–Watson statistic. Adjusted coefficients of determination are reported alongside unadjusted values. A secondary, illustrative regression of volumetric specific energy consumption on flow is reported separately: because the two share flow in the denominator, this association is expected to be strong by construction and is not used as independent evidence of a fixed load. Significance was evaluated at a probability of 0.05. Owing to the limited sample size of twelve monthly observations, the regression analyses are interpreted as exploratory rather than predictive, and the robustness of the fitted slope was examined through rank–based testing and leave–one–out resampling. Analyses were performed in Python using the pandas, SciPy and statsmodels libraries, and figures were produced with Matplotlib.

RESULTS

Treatment performance and evolution from 2015 to 2023

In 2023 the plant reduced mean influent concentrations of 315 mg L^{-1} BOD_5, 629 mg L^{-1} chemical oxygen demand and 301 mg L^{-1} total suspended solids to 32, 81 and 35 mg L^{-1}, corresponding to removal efficiencies of 89.8, 87.1 and 88.2% respectively (Table 1). All effluent values remained well within the Moroccan domestic discharge limits, with effluent BOD_5 a factor of 3.8 below the limit of 120 mg L^{-1}.

Relative to commissioning, when removals were 95.9, 92.8 and 96.9%, efficiencies decreased modestly, by 6.1% points on BOD_5, while remaining within the discharge limits. Over the same interval, mean influent BOD_5 concentration fell from 509 to 315 mg L^{-1} and mean treated flow rose by 25.3%, corresponding to a mean surface hydraulic loading on the filters of 0.225 m h^{-1} and a peak monthly value of 0.286 m h^{-1}, these figures being computed from treated flow alone and therefore excluding the recirculated stream. Effluent total suspended solids increased slightly over the same period. Effluent temperature showed no significant association with BOD_5 removal across the twelve months of 2023, with a correlation coefficient of −0.06 at a probability of 0.84, suggesting that seasonal temperature variation was unlikely to explain the observed changes. Effluent dissolved oxygen averaged 5.6 mg L^{-1} across the year, with monthly values between 5.0 and 6.0 mg L^{-1}, against 0.1 mg L^{-1} in the raw influent; as the plant has no mechanical aeration, this oxygen transfer is attributable to natural draught through the filter media.

Capacity utilisation

Against its design basis of 153 220 population equivalents, 11 949 m^3 d^{-1} and 5363 kg BOD_5 d^{-1}, the plant operated well below nominal capacity throughout 2023. Hydraulic utilisation reached 64%. Normalising the influent organic load to population equivalent gives about 40 100 population equivalents served, or 26% of design capacity. On a direct mass–load basis, however, the applied BOD_5 load of about 2400 kg d^{-1} corresponds to 45 % of the design load; the two figures diverge because the 2023 influent, at 315 mg L^{-1}, is substantially more dilute than the strength implied by the design, about 449 mg L^{-1}. A third measure, and the one most directly relevant to the biological stage, is the volumetric organic loading applied to the trickling filters. Allowing for the 33% removal of BOD_5 across the primary stage, the load reaching the filters in 2023 averaged about 1610 kg d^{-1} over a combined media volume of 5514 m^3, equivalent to 292 g BOD_5 m^{-3} d^{-1} or 42% of the design maximum of 700 g BOD_5 m^{-3} d^{-1}. On all three measures the plant is markedly underloaded, particularly in organic terms. The implications for energy performance are explored below.

Table 1. Influent and effluent quality, removal efficiency and compliance with Moroccan domestic discharge limits, 2023

Parameter	Influent (mg L^{-1})	Effluent (mg L^{-1})	Removal (%)	Limit (mg L^{-1})	Compliance
BOD_5	315	32	89.8	120	yes
COD	629	81	87.1	250	yes
TSS	301	35	88.2	150	yes
pH (-)	8.0	8.0	-	6.5–8.5	yes
Temperature (°C)	19.4	21.2	-	-	-

Note: BOD_5 – five–day biochemical oxygen demand; COD – chemical oxygen demand; TSS – total suspended solids. Limits are those of the Moroccan joint order on specific domestic discharge values (Royaume du Maroc, 2006).

Energy profile

Electricity, metered at plant level, totalled 332 MWh in 2023, a mean of 27 686 kWh per month, equivalent to a near–constant daily demand of about 910 kWh d^{-1}. Normalised to treated volume, the plant achieved a mean volumetric energy ratio of 0.123 kWh m^{-3} with a standard deviation of 0.022, ranging from 0.093 in December to 0.150 kWh m^{-3} in January (Table 2, Figure 3). This lies at the low end of values reported for trickling filters; in this configuration electricity demand is primarily associated with lifting and recirculation pumping, there being no forced aeration.

Flow-energy relationship

The monthly records show a marked decoupling of hydraulic load from energy demand. Treated flow varied substantially across the year, with a coefficient of variation of 16.7% and a range from 6060 to 9703 m^3 d^{-1} equivalent to 48% of the mean, whereas daily electricity demand varied within a narrow band, with a coefficient of variation of 2.5% and a range from 872 to 948 kWh d^{-1} equivalent to 8% of the mean. Relative variability in flow thus exceeded that in electricity demand by a factor of about 6.6 (Figure 4). This contrast is directly observable from the monthly data.

Ordinary least–squares regression of daily electricity demand on treated flow returned a slope of −0.011 kWh m^{-3}, with a 95% confidence interval from −0.021 to −0.001, a probability of 0.030, a coefficient of determination of 0.39 and an adjusted value of 0.33, together with a fitted intercept of 996 kWh d^{-1} slightly above the observed mean demand. The direction of this association is negative, and its magnitude corresponds to a change of only about 41 kWh d^{-1}, or 4.5% of mean demand, across the full range of observed flows. The association was not significant under a rank–based test, with a Spearman coefficient of −0.51 at a probability of 0.09, and was sensitive to individual months, leave–one–out probabilities ranging from 0.005 to 0.084. Residuals were normally distributed and showed no serial correlation, with a Shapiro–Wilk statistic of 0.946 at a probability of 0.58 and a Durbin–Watson statistic of 1.76. Taken together, these analyses provide no evidence that electricity demand increases with treated volume over the observed operating range.

A sensitivity check confirmed that the low volumetric intensity is not an artefact of individual months. Excluding the lowest–ratio month (December, 0.093 kWh m^{-3}) raised the annual mean only to 0.125 kWh m^{-3}, excluding the highest–ratio month (January, 0.150 kWh m^{-3}) lowered it to 0.120 kWh m^{-3}, and excluding both extremes gave 0.123 kWh m^{-3}, identical to the full–year mean. Even at the extremes of the mean plus or minus one standard deviation band (0.101 to 0.145 kWh m^{-3}), the plant

Table 2. Monthly energy indicators for the Khenifra wastewater treatment plant, 2023

Month	Flow (m^3 d^{-1})	Electricity (kWh $month^{-1}$)	Ratio (kWh m^{-3})	Specific (kWh kg^{-1} BOD_5)
January	6 200	28 754	0.150	0.49
February	6 060	25 089	0.148	0.44
March	7 774	28 149	0.117	0.45
April	8 596	26 929	0.104	0.35
May	6 390	28 704	0.145	0.54
June	6 350	28 451	0.149	0.53
July	7 872	28 356	0.116	0.43
August	9 124	27 732	0.098	0.32
September	9 158	26 160	0.095	0.38
October	7 348	27 651	0.121	0.37
November	7 050	28 380	0.134	0.50
December	9 703	27 874	0.093	0.42
Mean	7 635	27 686	0.123	0.43
Standard deviation	1 278	1 112	0.022	0.07

Note: Ratio denotes volumetric specific energy consumption; specific denotes energy per unit mass of five–day biochemical oxygen demand removed.

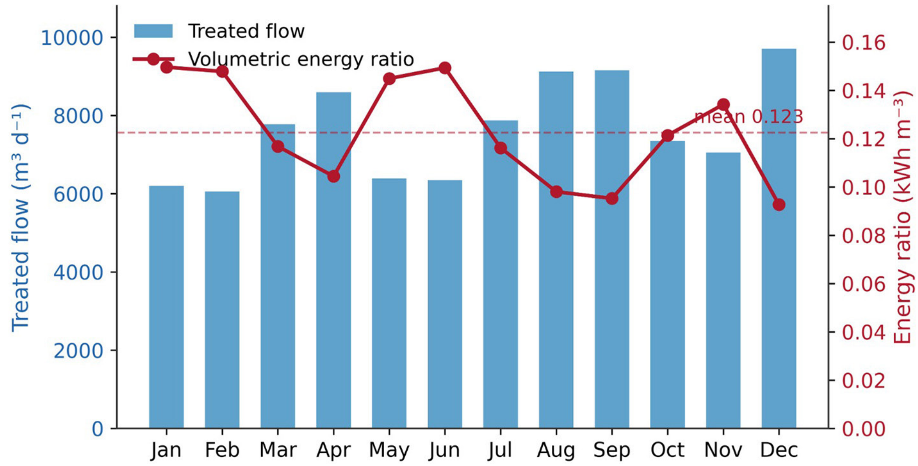

Figure 3. Monthly treated flow shown as bars against the left axis and volumetric energy ratio shown as a line against the right axis, 2023. The dashed horizontal line marks the annual mean ratio of 0.123 kWh m^{-3}. The ratio falls as flow rises while electricity demand remains nearly constant

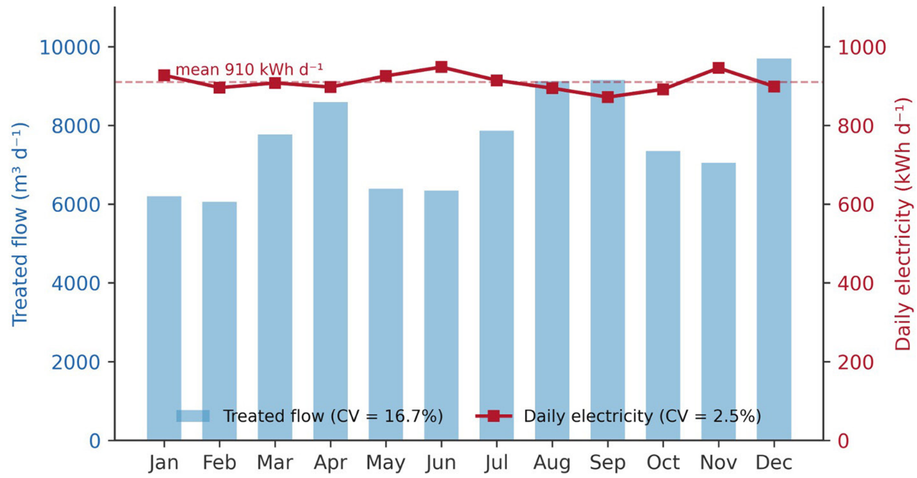

Figure 4. Treated flow shown as bars against the left axis, with a coefficient of variation of 16.7%, and daily electricity demand shown as a line against the right axis, with a coefficient of variation of 2.5%, by month for 2023. The dashed horizontal line marks the mean daily demand of 910 kWh d^{-1}. Electricity demand is essentially flat across a wide range of flows

remained between 2.3 and 3.3 times below the lower bound of the activated–sludge range of 0.33 to 0.60 kWh m^{-3}, so the conclusion that the plant is markedly less energy–intensive than activated sludge is robust to the choice of averaging period.

A secondary regression of the volumetric ratio on flow is strong by construction, because flow appears in the denominator of the ratio, giving a correlation coefficient of −0.988, a coefficient of determination of 0.977 and a probability below 10^{-8} (Figure 5). It is reported to illustrate how the definition of the indicator amplifies the appearance of flow–dependence, and is not used as independent evidence of a fixed load.

Load–normalised energy and the divergence of indicators

Expressed per unit mass of pollutant removed, the plant required 0.43 kWh kg^{-1} with a standard deviation of 0.07 for BOD_5, 0.23 kWh kg^{-1} with a standard deviation of 0.05 for chemical oxygen demand and 0.49 kWh kg^{-1} with a standard deviation of 0.19 for total suspended solids in 2023 (Figure 6b). On a population basis the plant used 8.3 kWh per population equivalent per year, against the twenty–fifth–percentile benchmark of 42 kWh per population equivalent per year proposed for plants in the 10 000 to 100 000 population equivalent class, within which the Khenifra

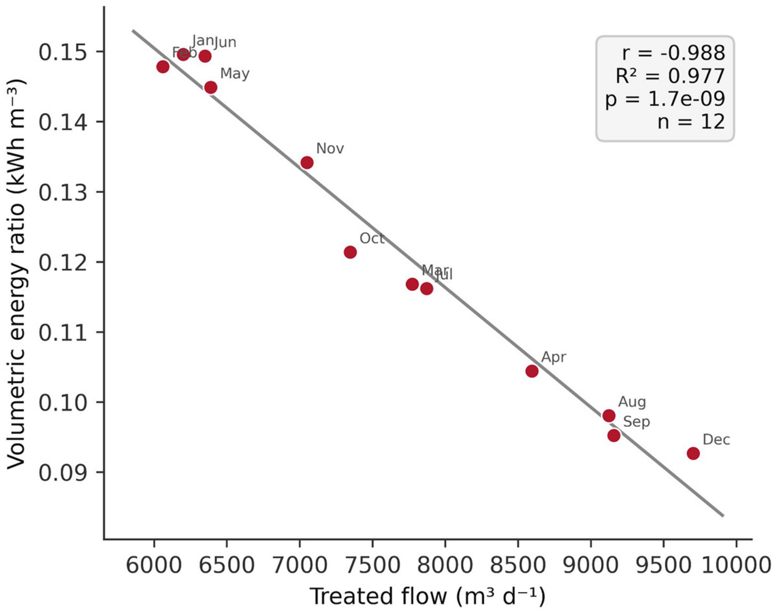

Figure 5. Volumetric energy ratio against treated flow for the twelve months of 2023, with the fitted least–squares line. Month labels identify individual observations. The strong inverse correlation is largely definitional, since flow appears in the denominator of the ratio

plant falls on the basis of population served (Vaccari et al., 2018). Expressed with their uncertainty, these load–normalised requirements are 0.43 ± 0.07, 0.23 ± 0.05 and 0.49 ± 0.19 kWh kg^{-1} (mean ± standard deviation) for BOD_5, chemical oxygen demand and total suspended solids respectively, with 95% confidence intervals of 0.39 to 0.48, 0.20 to 0.26 and 0.37 to 0.62 kWh kg^{-1}; the corresponding uncertainty for all headline indicators is summarised in Table 3.

The two energy indicators moved in opposite directions between 2015 and 2023 (Table 4, Figure 6a). The volumetric ratio improved, from 0.143 to 0.123 kWh m^{-3}, a reduction of 14%, whereas the BOD_5 specific demand increased from 0.29 to 0.43 kWh kg^{-1}, approximately 45%. Over the same interval mean treated flow rose 25.3% while mean monthly electricity consumption rose only 4.5%, and influent BOD_5 concentration fell by 38%. The volumetric ratio is therefore strongly influenced by influent dilution, whereas the substrate–specific indicator provides complementary information that is less affected by it.

Benchmarking against competing processes

Positioned against published ranges (Table 5, Figure 7), the plant sits at the low–energy end of the municipal range. Its 2023 ratio of 0.123 kWh m^{-3} lies below the trickling–filter band of 0.18 to 0.42 kWh m^{-3} and within the fixed–film range of 0.05 to 0.20 kWh m^{-3} reported elsewhere; it is 2.7 to 4.9 times lower than the activated–sludge band of 0.33 to 0.60 kWh m^{-3} (Gude, 2015; Henrich and Marggraff, 2013). The spread between these published bands is itself an indication of how sensitive volumetric benchmarks are to plant configuration and loading.

Direct comparison is nonetheless constrained by differences in scale, climate, treatment objective and loading, which are not uniformly reported in the benchmarking literature (Gallo et al., 2024). Table 5 therefore gives these attributes where they are available. The most directly comparable published figure is 0.275 kWh m^{-3}, reported for a two–stage passively aerated trickling filter treating high–strength wastewater in Tunisia, which shares the fixed–film configuration and the semi–arid setting but differs in influent strength and scale (Arous et al., 2023). Removal efficiencies at Khenifra fall within the range reported for trickling filters, and an earlier assessment of this plant validated the trickling–filter process as a best available technique (Baroud et al., 2018). Published values may also rest on different energy–metering boundaries, with influent pumping, sludge handling, tertiary treatment and auxiliary services variably included or excluded, and should therefore be read as contextual ranges rather than as directly comparable plant–level measurements.

Table 3. Central tendency and uncertainty of the principal performance indicators, 2023 (n = 12)

Indicator	2015	2023	Change (%)
Mean treated flow (m^3 d^{-1})	6 093	7 635	+25.3
Mean electricity (kWh $month^{-1}$)	26 497	27 686	+4.5
Influent BOD_5 (mg L^{-1})	509	315	−38
Volumetric ratio (kWh m^{-3})	0.143	0.123	−14
Specific energy (kWh kg^{-1} BOD_5)	0.29	0.43	≈ +45

Table 4. Comparison of energy indicators between the commissioning year and the study year

Technology	Scale	Setting	Ratio (kWh m^{-3})	Source
Fixed-film (trickling filter or rotating contactor)	n.r.	review	0.05–0.20	Henrich and Marggraff (2013)
Lagoons	n.r.	review	0.09–0.29	Gude (2015)
Trickling filter	n.r.	review	0.18–0.42	Gude (2015)
Activated sludge	n.r.	review	0.33–0.60	Gude (2015)
Advanced or reuse-grade	n.r.	review	0.50–2.00	Gude (2015)
Two-stage passively aerated trickling filter	n.r.	Tunisia, semi-arid	0.275	Arous et al. (2023)
Trickling filter	153 220 p.e. (design)	Morocco, semi-arid	0.143	this study, 2015
Trickling filter	40 100 p.e. (served)	Morocco, semi-arid	0.123	this study, 2023

Note: Only annual means were available for 2015, so monthly variability is not reported for that year.

Table 5. Volumetric energy ratios by process, with plant attributes where reported

Emission factor (kg CO_2e kWh^{-1})	Emissions (t CO_2e y^{-1})	Intensity (g CO_2e m^{-3})	Intensity (kg CO_2e p.e.$^{-1}$ y^{-1})
0.729 (upper bound)	242	87	6.0
0.650	216	77	5.4
0.600	199	71	5.0
0.565 (lower bound)	188	67	4.7

Note: n.r. – not reported in the source; p.e. – population equivalent.

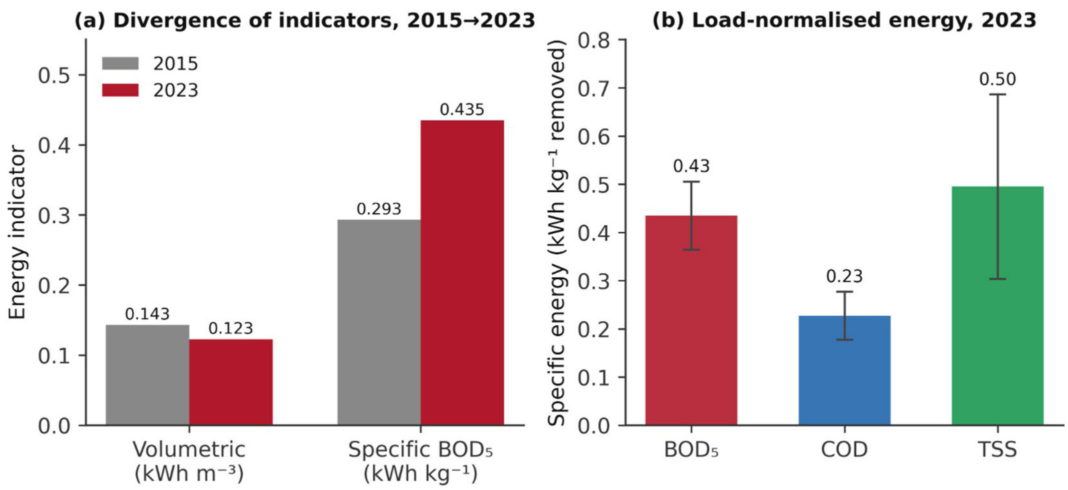

Figure 6. (a) Divergence of the volumetric and substrate–specific energy indicators between 2015 and 2023. (b) Load–normalised specific energy per pollutant in 2023; error bars show the standard deviation of the twelve monthly values.

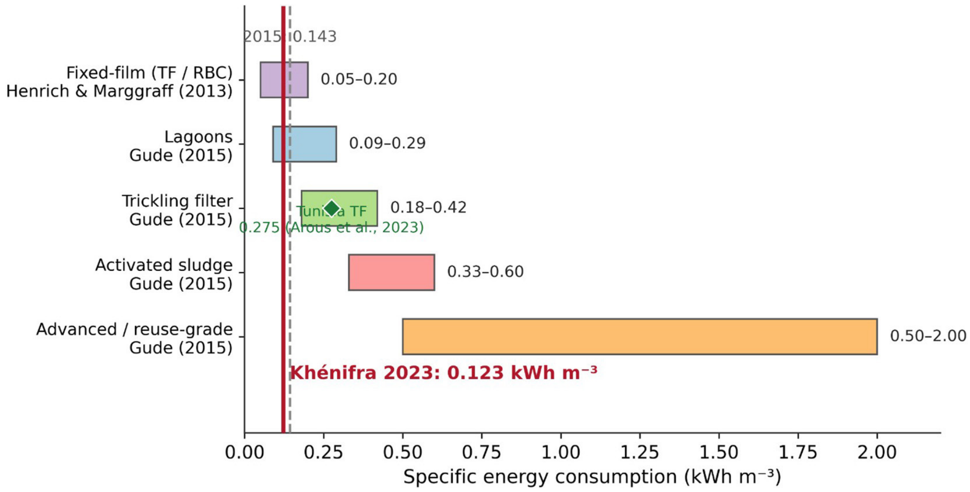

Figure 7. Energy positioning of the Khenifra plant against published reference ranges. The solid vertical line marks the 2023 value of 0.123 kWh m^{-3} and the dashed vertical line the 2015 value of 0.143 kWh m^{-3}. The diamond marks the Tunisian comparator. Bands are drawn from the sources indicated on the category labels.

Carbon emissions and operating cost

Converting the 2023 consumption of 332 MWh with a national grid emission factor gives electricity–related emissions of 188 to 242 t CO_2e per year across the range of published factors considered (Table 6). At the upper bound of 0.729 kg CO_2e kWh^{-1} this corresponds to 87 g CO_2e m^{-3} and 6.0 kg CO_2e per population equivalent per year; at the lower bound of 0.565 kg CO_2e kWh^{-1} the corresponding values are 67 g CO_2e m^{-3} and 4.7 kg CO_2e per population equivalent per year. These figures follow directly from the electricity consumption reported above and share its uncertainty. Electricity–related operating cost, at the invoiced tariff of 1.37 MAD kWh^{-1}, is about 455 000 MAD per year, equivalent to 0.163 MAD m^{-3} or 11.3 MAD per population equivalent per year.

An illustrative scenario in which on–site photovoltaic generation covers 60% of the annual electricity demand, about 199 MWh per year, is shown in Figure 8b. Such a system is estimated to avoid on the order of 145 t CO_2e per year at the upper emission factor and about 273 000 MAD per year in electricity cost at the invoiced tariff. The scenario is a first–order calculation based on annual energy balance only; it does not include system sizing, temporal matching of generation and demand, capital cost or grid–connection arrangements, and is presented for order–of–magnitude comparison rather than as a design proposal.

DISCUSSION

A predominantly fixed electrical load and what it means for benchmarking

The monthly data are consistent with a predominantly fixed electrical load at the Khenifra plant rather than with a flow-proportional demand. Daily electricity demand was nearly invariant while treated flow varied widely, and regression gave no evidence that demand rises with throughput. Where demand is dominated by a fixed component in this way, volumetric specific energy consumption becomes increasingly influenced by throughput rather than by treatment effort. The 14% improvement in the volumetric indicator between 2015 and 2023 illustrates the point: it was achieved with no process modification and coincided with a 25% rise in flow spread across a near–constant demand. The opposite trajectory of the substrate–specific indicator over the same period gives a different and complementary reading, the plant becoming apparently more efficient per cubic metre while becoming less efficient per unit of pollutant abated, because the influent grew more dilute.

This divergence is the methodological point of the study, and it is not peculiar to Khenifra. Any facility in which a large share of electricity is consumed independently of throughput, which includes most gravity–fed fixed–film plants and more generally any plant operating well below the load for which its electromechanical equipment

Table 6. Sensitivity of electricity–related carbon emissions to the assumed grid emission factor, 2023

MISSING TABLE

Note: p.e. – population equivalent. Values are first–order estimates covering electricity–related emissions only.

was sized, may exhibit a similar divergence. In such cases a favourable volumetric figure may record dilution or spare hydraulic capacity rather than efficient operation, and an unfavourable one may record the reverse. The implication is not that the volumetric indicator should be abandoned, but that it should not be reported alone. Pairing it with a load–normalised indicator and with an explicit statement of hydraulic and organic utilisation allows a reader to distinguish these cases, and this is the practice we would advocate for underloaded fixed–film plants generally. The recommendation aligns with calls in the benchmarking literature to privilege load–normalised and population–normalised metrics, and extends them to a plant class in which the fixed component arises from pumping rather than from aeration control (Cardoso et al., 2021; Gallo et al., 2024).

Trickling filtration as an energy–sober technology

At 0.123 kWh m^{-3}, the plant sits at the low end of the trickling–filter range and well below conventional activated sludge. This is largely attributable to the inherent process configuration: the fixed–film process supplies oxygen by natural draught through the media and the openings at the base of the filter walls, avoiding the mechanical aeration that accounts for roughly half to three–quarters of electricity use in suspended–growth systems (Longo et al., 2016; Muloiwa et al.,

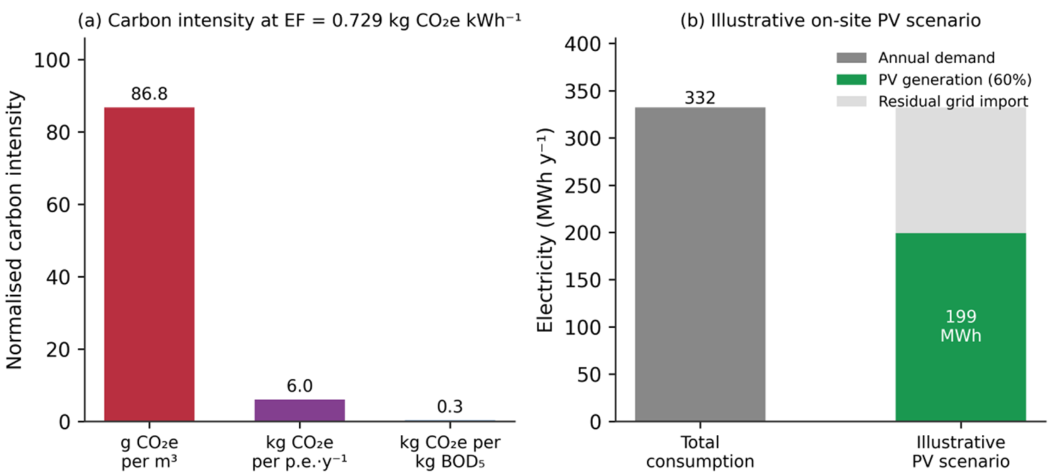

Figure 8. (a) Normalised carbon–intensity indicators for 2023 at the upper emission factor of 0.729 kg CO_2e kWh^{-1}. (b) Illustrative on–site photovoltaic scenario covering 60% of annual electricity demand, with the residual grid import shown above it

Table 7. Central tendency and uncertainty of the principal performance indicators, 2023 (n = 12)

Indicator	Mean	SD	Range	95% CI
Treated flow (m^3 d^{-1})	7 635	1 278	6 060–9 703	6 823–8 448
Daily electricity (kWh d^{-1})	910	23	872–948	896–925
Volumetric SEC (kWh m^{-3})	0.123	0.022	0.093–0.150	0.109–0.137
Specific energy, BOD5 (kWh kg^{-1})	0.43	0.07	0.32–0.54	0.39–0.48
Specific energy, COD (kWh kg^{-1})	0.23	0.05	0.16–0.32	0.20–0.26
Specific energy, TSS (kWh kg^{-1})	0.49	0.19	0.26–0.97	0.37–0.62

2023). Coupling gravity–fed filters with Imhoff tanks that combine settling and anaerobic digestion without energy input suggests that pumping constitutes an important component of electrical demand and offers the most likely explanation for the plant's position among published values, although its exact contribution cannot be quantified without sub–metering. The result is consistent with the earlier assessment of this site and with the low environmental and energy burdens reported for trickling–filter systems more broadly (Baroud et al., 2018; Abyar and Nowrouzi, 2023).

The modest decline in removal efficiency between 2015 and 2023 is best read against the two concurrent changes in operating conditions rather than as evidence of process deterioration. Mean influent BOD_5 concentration fell by 38% over the interval, and relative removal is arithmetically harder to sustain on a more dilute influent, since the residual effluent concentration is bounded below by the achievable biological floor rather than scaling with the inlet. At the same time, treated flow rose by a quarter, raising surface hydraulic loading on the filters. Elevated hydraulic loading is known to increase biofilm detachment in fixed–film reactors, and this offers a plausible explanation for the slight rise in effluent total suspended solids observed over the same period; biofilm thickness, detachment rate and detached biomass were not measured in this study, however, so the mechanism remains a hypothesis rather than a demonstrated result. The absence of any significant association between effluent temperature and organic removal makes a climatic explanation unlikely, but the present data cannot establish which of the two loading changes dominates, and disentangling them would require influent–strength–controlled monitoring across a range of hydraulic loads.

These advantages are in any case not unqualified. Trickling filters offer less granular control over nitrification and effluent polishing than activated sludge, and the trajectory from 2015 to 2023 suggests sensitivity to hydraulic stress. The technology is therefore best viewed not as a universally superior option but as an appropriate, energy–efficient secondary treatment whose performance envelope is managed largely through hydraulic regulation rather than process tuning.

Optimisation pathways for underloaded fixed–film plants

The diagnosis of an underloaded plant with a largely incompressible electrical demand points to a clear priority order for optimisation, set out here in general terms because it applies to plants in a similar condition rather than to this site alone. The first and largest lever is to raise capacity utilisation. With organic loading at roughly a quarter of design on a population–equivalent basis, connecting additional sub–catchments or accepting controlled septage would spread the fixed energy and carbon burden across a larger pollutant load, lowering intensity per population equivalent and per cubic metre without capital–intensive change; co–treatment of septage at municipal works with spare capacity is an established practice, subject to control of loading rate and ammonia inhibition (Lopez–Vazquez et al., 2014). A second, complementary option, illustrated by an underloaded trickling–filter plant in South Australia designed for an industrial stream it no longer receives, is to take one filter and clarifier train offline during sustained low–load periods, directly reducing recirculation pumping (Krampe, 2013). This requires no capital and is the closest published analogue to the situation described here; at Khenifra the two treatment trains are identical and parallel, so the operation is structurally straightforward.

Third, because pumping dominates the electrical demand of this plant class, pump control offers a further margin: retrofitting recirculation pumps with variable–frequency drives linked to real–time influent monitoring, or optimising pump scheduling, has been shown to reduce energy use and extend equipment life in water and wastewater pumping systems (Torregrossa and Capitanescu, 2019). The recirculation station at Khenifra has an installed capacity of about 920 m^3 h^{-1} against a mean treated flow of 7635 m^3 d^{-1}. The plant's own design relation makes the opportunity concrete. The filters are specified to receive between 150 and 250 mg L^{-1}, and at the design influent strength of about 449 mg L^{-1} the primary effluent would leave at roughly 301 mg L^{-1}, requiring a recirculation flow of between a quarter and two–thirds of the daily influent to bring it within range. At the 2023 influent strength of 315 mg L^{-1}, however, the primary effluent leaves at about 211 mg L^{-1}, already inside the specified band, so no recirculation is required for dilution at all. The dilution duty for which a large part of the recirculation capacity was installed has in effect disappeared with the decline in influent strength, leaving continuity of wetting as the remaining functional requirement. Modulating recirculation to that residual duty, rather than to a dilution requirement that no longer arises, is therefore a specific and documented opportunity rather than a generic recommendation. Fourth, because the residual demand is flat and largely incompressible, carbon reduction is most effectively pursued on the supply side: an on–site photovoltaic array matched to a near–constant demand profile and the region's solar resource of about 3 000 sunshine hours per year could offset a substantial share of both emissions and cost. Realising that potential would require system sizing, temporal matching of generation to demand and a capital appraisal, none of which is attempted here. Photovoltaic generation is identified as a principal route to energy neutrality for medium–scale plants that lack the sludge throughput to support significant anaerobic energy recovery (Mainardis and Kegl, 2026), a description that fits this facility.

International context and transferability

The relevance of these findings extends beyond Morocco. International benchmarking exercises consistently record lower volumetric energy intensity in middle–income than in high–income settings, and attribute much of the difference to effluent standards and treatment intensity rather than to operational efficiency; comparing more than 300 utilities across 31 countries, Walker et al. (2021) found European utilities averaging 1.18 kWh m^{-3} against far lower values in Brazil, India and South Africa, and cautioned that cross–country comparison on a volumetric basis alone is liable to misattribute such structural differences to performance. The present study identifies a second and largely independent source of the same distortion, operating within a single plant: partial capacity utilisation. Because oversizing against multi–decade design horizons is common wherever sewer networks are still being extended, and because low–energy fixed–film and lagoon processes are widely deployed across North Africa, sub–Saharan Africa, South Asia and Latin America, plants exhibiting a favourable volumetric figure for reasons unrelated to efficiency are likely to be numerous in precisely those regions where benchmarking data are scarcest. Reporting hydraulic and organic utilisation alongside any volumetric figure is therefore a modest but consequential addition to benchmarking practice in these settings.

Implications for reuse in water–scarce settings

With renewable water availability near 600 m^3 per capita per year and projected below the severe–scarcity threshold by around 2030, and with national policy targeting 300 million cubic metres per year of reuse by 2030, a treatment train that is simultaneously low–energy, low–carbon and capable of meeting discharge standards is valuable (World Bank, 2023; Lemfarrak et al., 2025). The gap between that target and current practice is wide: agricultural reuse absorbs about 0.3% of treated volumes nationally, and limited tertiary capacity is among the principal constraints (Lemfarrak et al., 2025). At Khenifra, treated water is presently reused only within the site, for cleaning structures and equipment and for irrigating the plant's green areas, with the remainder discharged; no regulated scheme supplying external users exists, so the question is one of unrealised potential rather than of current practice. The effluent meets the physicochemical discharge limits with substantial margin, and earlier regional work has found treated effluent in the Beni Mellal–Khenifra region suitable for agricultural reuse (Faouzi et al., 2020). Two qualifications apply before reuse could be claimed formally. First, Moroccan irrigation reuse is governed not by the discharge limits but by a separate joint order whose criteria are principally microbiological, covering thermotolerant coliforms and intestinal helminth eggs in exposure–based categories, and these were not measured here (Royaume du Maroc, 2002). Second, effluent salinity is relevant to agronomic suitability: measured effluent conductivity averaged 2 857 µS cm^{-1} against 2 836 µS cm–1 in the influent, a difference of 22 µS cm^{-1}, indicating that the salinity is inherited from the source water rather than generated by treatment and cannot be reduced by modifying the secondary process; this value, equivalent to 2.9 dS m–1, falls under international irrigation–water guidance within the band of slight to moderate restriction on use and approaches the threshold of severe restriction for salt–sensitive crops (Ayers and Westcot, 1985). The residual question for reuse deployment is therefore one of microbiological polishing and salinity management rather than of energy or organic–matter removal, a distinction that matters because the first two are addressable by tertiary steps whose energy cost would need to be weighed against the low baseline established here (Christou et al., 2024). Effluent nutrient quality, including nitrogen and phosphorus release from biological treatment, is a recurring concern for discharge and reuse and warrants monitoring before any reuse scheme is implemented (Nyamweha et al., 2026); where reuse targets require polishing beyond secondary treatment, advanced tertiary options such as photocatalytic degradation have been demonstrated for the removal of persistent contaminants from wastewater (Yerima et al., 2024).

Limitations and future work

Several limitations qualify these conclusions. The analysis rests on one calendar year of monitored data, with an annual–mean baseline from 2015; a multi–year monthly series would strengthen trend and seasonal inference, and the 2015 monthly variability could not be reconstructed from the available records. With twelve observations, statistical power is limited: the regression analyses can exclude a strong positive dependence of electricity demand on flow, but they cannot resolve a weak one, and the confidence interval on the fitted slope is correspondingly wide. This is why the variability comparison, which requires no model, carries the principal weight of the argument, and why the regression results are reported as exploratory. The decomposition of energy into fixed and variable components is inferred statistically from monthly totals rather than derived from sub–metering, so the fixed component cannot be attributed to specific equipment. Water–quality data are monthly values rather than continuous or flow–weighted records, so short–term and diurnal variation is not captured. The carbon and cost figures are first–order estimates based on a national–average grid emission factor, and the sensitivity range reported above is offered in that spirit.

These limitations indicate the directions in which the work should be extended. Future research should test whether the relationships identified here hold across a wider range of fixed–film facilities operating under different climatic, hydraulic and loading conditions, and should establish at what degree of underloading the volumetric indicator ceases to be informative. Sub–metered electricity data, resolving lifting pumps, recirculation, odour control and ancillary services separately, would allow the fixed component to be attributed to individual processes and would convert the statistical inference presented here into a direct measurement. For plants intended to supply reuse schemes, coupling such energy analysis with microbiological and salinity monitoring would allow the full energy cost of reuse–grade treatment to be assessed against the low baseline established for secondary treatment.

CONCLUSIONS

This study investigated the treatment performance and energy dynamics of the Khénifra wastewater treatment plant (Morocco), a full-scale bacterial filter, in order to test the reliability of performance indicators under underloaded conditions. The main findings are essentially as follows:

1. Robust compliance: The plant removes approximately 90% of BOD_5, COD and suspended solids, complying with Moroccan discharge limits.
2. Energy efficiency: At 0.123 kWh/m^3, the process consumes 2.7 to 4.9 times less energy than conventional activated sludge systems.
3. Fixed consumption: Across the twelve monthly observations, plant-level electricity demand

varied substantially less than treated flow and showed no evidence of increasing with it. This pattern is consistent with a predominantly fixed electrical component, although its attribution to individual items of equipment cannot be established without sub–metering.
4. Divergence in indicators: The apparent 14% decrease in the volumetric ratio masks a 45% decline in efficiency per unit of pollution treated since 2015.

These results indicate that the apparent improvement in the kWh/m^3 ratio reflects the increase in flow rate and the dilution of the influent rather than a gain in treatment efficiency. In fixed-film systems of this type, the process configuration suggests that continuous pumping and the maintenance of biofilm wetting contribute more to electricity demand than the organic load treated.

This study empirically demonstrates that the exclusive use of the volumetric benchmark can lead to erroneous conclusions regarding the performance of underloaded wastewater treatment plants. It proposes a more transparent reporting methodology for infrastructure managers in semi–arid regions.

The study is limited by the absence of sub–metering of electricity consumption per piece of equipment and a monthly measurement frequency. Future research should incorporate high-resolution monitoring and assess the energy impact of tertiary treatment (microbiological and salinity) to validate the potential for safe agricultural reuse in this context of water stress. More fundamentally, these conclusions are based on one year of monthly operational data from a single full-scale facility, and their generality at other underloaded trickling-filter plants operating under different climatic and loading conditions remains to be established.

The complete monthly operational dataset for 2023, together with the derived monthly removal efficiencies and load–normalised energy indicators, is provided as Supplementary Table S1 in the accompanying supplementary file.

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