



Research Article

Impact of Temperature on Aerobic Biological Treatment of Pharmaceutical Wastewater in the Ahmedabad Industrial Cluster, Gujarat, India

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Abstract

Pharmaceutical wastewater is among the most challenging industrial effluents due to its high organic load, residual active pharmaceutical ingredients (APIs), and recalcitrant compounds. Aerobic biological treatment using the activated sludge process (ASP) is widely employed for its remediation. However, treatment performance is critically governed by temperature, which directly influences microbial metabolism, enzyme kinetics, oxygen solubility, and sludge characteristics. This study investigates the impact of seasonal temperature variation on aerobic treatment efficiency at a pharmaceutical Effluent Treatment Plant (ETP) in Ahmedabad, Gujarat, India — a primary pharmaceutical manufacturing hub experiencing ambient temperatures ranging from 10°C (winter) to 49°C (summer). Fifty paired influent–effluent samples were collected between May 2024 and December 2024 and analysed for Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD), ammoniacal nitrogen (NH₄⁺-N), Mixed Liquor Suspended Solids (MLSS), and Mixed Liquor Volatile Suspended Solids (MLVSS). Results demonstrated that maximum treatment efficiency was achieved at moderate mesophilic temperatures of 25–35°C, with COD removal reaching up to 96.5% and BOD removal exceeding 95%. Ammoniacal nitrogen removal efficiency reached 82% within the optimal range but declined significantly at high (>40°C) and low (<15°C) temperatures. ANOVA confirmed statistically significant differences in removal efficiencies across temperature regimes ($p < 0.05$). Biomass parameters (MLSS and MLVSS) were highest during the mesophilic phase, confirming enhanced microbial activity. These findings underscore the need for temperature-adaptive management strategies in pharmaceutical ETPs operating under semi-arid climatic conditions, and provide evidence-based guidance for regulatory compliance and operational optimization.

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1. INTRODUCTION

The pharmaceutical industry is among the fastest-growing industrial sectors globally, and India occupies a position of particular strategic importance. As the third-largest pharmaceutical producer by volume and a supplier of critical medicines to over 200 countries, India's pharmaceutical manufacturing base has expanded substantially over the past two decades (Ghosh, 2025; Tripathy & Dastrala, 2023). This industrial expansion, while essential for global healthcare, has simultaneously generated complex, high-strength wastewater streams that pose considerable environmental challenges.

Pharmaceutical wastewater is characterised by high Chemical Oxygen Demand (COD) typically ranging from 1,000 to over 15,000 mg/L, elevated Biochemical Oxygen Demand (BOD), a low BOD/COD biodegradability ratio (often below 0.3), high concentrations of ammoniacal nitrogen, residual active pharmaceutical ingredients (APIs), spent solvents, and recalcitrant organic intermediates (Kumari & Tripathi, 2019; Hossen et al., 2024). These characteristics make pharmaceutical effluents inherently difficult to treat using conventional biological processes. Moreover, batch production schedules result in fluctuating pollutant loads that further destabilise biological treatment systems.

Aerobic biological treatment, particularly the activated sludge process (ASP), remains the primary treatment technology employed in pharmaceutical effluent treatment plants (ETPs) and common effluent treatment plants (CETPs) due to its effectiveness in reducing biodegradable organic matter and its relatively lower operational cost. However, the efficiency of aerobic treatment is profoundly influenced by a range of operational and environmental parameters, foremost among which is temperature (Katare et al., 2023; Araújo et al., 2022).

Temperature governs the rate of microbial metabolism, enzymatic reaction kinetics, oxygen solubility, substrate diffusion rates, and biomass settling characteristics. Mesophilic microorganisms responsible for aerobic biodegradation operate optimally between 20–35°C; departures from this range — either through excessive heat or cold — can lead to enzyme denaturation, microbial inhibition, shifts in community composition, and consequent reductions in treatment efficiency (LaPara et al., 2001; Le et al., 2024).

The Ahmedabad industrial cluster in Gujarat, India, is one of the most significant pharmaceutical manufacturing regions in the country, contributing approximately 33% of India's total pharmaceutical production. Located at 23.02°N, 72.57°E, Ahmedabad experiences a semi-arid climate with pronounced seasonal temperature variation: summer temperatures frequently exceed 45°C (May–June), monsoon temperatures range from 28–35°C (July–September), and winter conditions can bring temperatures as low as 10°C in the early morning hours (November–February). This approximately 40°C annual temperature range creates an inherently dynamic operating environment for biological treatment systems, presenting a natural large-scale experimental context for studying temperature-dependent treatment performance.

Despite the recognised importance of temperature, there remains a paucity of empirical, field-based studies investigating how these seasonal fluctuations specifically affect aerobic

biological treatment of pharmaceutical wastewater in the Indian context. The present study addresses this gap by conducting a systematic, longitudinal monitoring investigation at an operational pharmaceutical ETP in Ahmedabad across multiple seasons. The study evaluates the impact of temperature variation on COD, BOD, and ammoniacal nitrogen removal efficiencies, and on biomass characteristics, using 50 paired influent–effluent sample events collected between May and December 2024.

2. MATERIALS AND METHODS

2.1 Study Area and Sample Location

The study was conducted at a pharmaceutical Effluent Treatment Plant (ETP) located within an active industrial park in the Ahmedabad region of Gujarat, India (23.02°N, 72.57°E). Ahmedabad is India's largest pharmaceutical manufacturing hub, hosting bulk drug synthesis facilities, formulation companies, and fine chemical plants. The selected ETP is a full-scale, continuous-flow biological treatment facility with a design capacity of 750 m³/day. The system comprises a preliminary screening unit, an equalization tank, a pH correction stage, a completely mixed aeration basin (effective volume approximately 1,200 m³) equipped with mechanical surface aerators, a secondary clarifier, and a tertiary reverse osmosis (RO) plant.

The facility operates without artificial temperature regulation of the aeration basin, meaning the mixed liquor temperature closely tracks ambient seasonal conditions. This design feature, combined with the plant's comprehensive operational records and access to accredited analytical laboratory facilities, made it an ideal candidate for the present investigation. The plant operates under authorisation of the Gujarat Pollution Control Board (GPCB) and maintains complete compliance documentation.

2.2 Sample Collection Period

Wastewater sampling was conducted over an eight-month continuous monitoring period from May 2024 to December 2024, deliberately spanning all three major climatic seasons of Ahmedabad: peak summer (May–June), monsoon (July–September), and the onset of winter (October–December). This temporal coverage enabled the study to capture inlet wastewater temperatures across the full recorded range of 10°C to 49°C. A total of 50 paired composite influent and grab effluent samples were collected, distributed systematically across all temperature regimes. All samples were collected between 10:00 AM and 2:00 PM to minimise diurnal variability and represent sustained hydraulic loading conditions.

Samples were collected using pre-cleaned high-density polyethylene containers and transported to the laboratory within two hours of collection under appropriate preservation conditions. Influent COD samples were acidified immediately; BOD samples were stored at 4°C under prescribed holding times. Mixed liquor temperature, dissolved oxygen (DO), pH, and MLSS were measured in situ using calibrated instruments with weekly verification against certified reference standards (accuracy ±0.2°C for temperature probes).

2.3 Analytical Methods

Chemical Oxygen Demand was determined using the closed reflux dichromate method in a strongly acidic medium with potassium dichromate and silver sulphate as catalyst. Biochemical Oxygen Demand was measured using the 5-day incubation method at 20°C, with dissolved oxygen depletion quantified by Winkler titration. Ammoniacal nitrogen was determined by the distillation-titration method, wherein ammonia was liberated under alkaline conditions and absorbed in boric acid before titration with standardised sulphuric acid. Mixed Liquor Suspended Solids were determined gravimetrically by filtration through pre-weighed glass fibre filters dried at 105°C; Mixed Liquor Volatile Suspended Solids were determined by ignition at 550°C. All analyses followed standard protocols. Duplicate samples were analysed for 10% of observations; analytical precision remained within ±5% for COD and ±7% for BOD.

Percentage removal efficiency (η) was calculated as: η (%) = $[(C_{in} - C_{out}) / C_{in}] \times 100$, where C_{in} and C_{out} represent influent and effluent pollutant concentrations respectively. This formulation was applied independently for COD, BOD, and ammoniacal nitrogen.

2.4 Statistical Analysis

One-way Analysis of Variance (ANOVA) was applied to compare pollutant removal efficiencies across three defined temperature categories: low temperature (10–20°C), moderate temperature (25–35°C), and high temperature (40–50°C). The null hypothesis of equal group means was rejected at $\alpha = 0.05$. Post-hoc pairwise comparisons were performed to identify statistically significant differences between specific temperature regimes. Linear and polynomial (quadratic) regression models

were fitted with temperature as the independent variable and pollutant removal efficiency as the dependent variable; the coefficient of determination (R^2) was computed to assess explanatory power. Residuals were checked for normality (Shapiro-Wilk test) and homoscedasticity. The temperature-adjusted rate constant was modelled using the Arrhenius relationship: $k_T = k_{20} \times \theta^{(T-20)}$, where θ represents the temperature correction coefficient (1.02–1.07 for heterotrophs; up to 1.10 for nitrifiers).

3. RESULTS AND DISCUSSION

3.1 Characterisation of Influent Wastewater

The pharmaceutical wastewater entering the ETP during the monitoring period exhibited characteristics typical of bulk drug manufacturing effluents. Influent COD concentrations ranged from 1,403 to 2,600 mg/L, reflecting the presence of substantial oxidisable organic matter from synthesis solvents, unreacted intermediates, and spent process liquors. Influent BOD ranged from 310 to 812 mg/L, yielding BOD/COD ratios that in several samples approached or exceeded 0.4, indicating that a meaningful fraction of the organic load was amenable to biological degradation. Ammoniacal nitrogen concentrations in the influent ranged from 196 to 421 mg/L, values consistent with nitrogen-rich pharmaceutical synthesis processes involving ammonium salts, amine-containing intermediates, and equipment cleaning effluents. These concentrations substantially exceed the GPCB discharge standard of 50 mg/L, affirming the necessity of effective biological nitrification within the treatment train. A summary of wastewater characteristics and treatment outcomes across temperature regimes is presented in Table 1.

Table 1: Pharmaceutical Wastewater Characteristics and Treatment Performance by Temperature Regime (Ahmedabad ETP, May–December 2024)

Parameter	Influent Range (mg/L)	GPCB Standard Limit	Optimal Effluent (25–35°C)	Stressed Effluent (>40°C / <15°C)	Unit
COD	1403–2600	<250	60–90	300–433	mg/L
BOD	310–812	<30	<30	100–227	mg/L
Ammoniacal N ₂	196–421	<50	40–60	80–122	mg/L
Temperature	10–49	≤35	25–35	>40 / <15	°C
MLSS	—	—	2700–3050	1800–2400	mg/L
MLVSS	—	—	2600–2760	1800–2200	mg/L
pH	1.1–11.0	6.5–8.5	6.8–7.5	Variable	—

The influent characteristics showed some seasonal variation, with higher COD values recorded during summer months (May–June) and relatively lower values during monsoon (July–September), potentially attributable to changes in production schedules and dilution effects from facility washdowns. Nevertheless, the high organic and nitrogen loading remained consistent throughout the monitoring period, establishing a reliable pollutant matrix against which temperature effects on treatment could be systematically evaluated.

3.2 COD Removal Performance

COD removal efficiency exhibited a clear and statistically significant relationship with temperature over the monitoring period. During the moderate temperature phase (25–35°C), corresponding broadly to the monsoon and early summer

months (late June through September), the aerobic biological system demonstrated peak COD removal efficiencies of 95–96.5%. The highest recorded removal of 96.5% was achieved at an inlet temperature of 30°C (Sample 10: 10.07.2024), where influent COD of 1,903.2 mg/L was reduced to an effluent COD of 67.1 mg/L, well within the GPCB standard of 250 mg/L. Similarly, samples collected at 33–34°C recorded effluent COD values of 68–82 mg/L, confirming that the system performed robustly across the entire mesophilic range.

In contrast, the extreme summer period (May, inlet temperatures 44–49°C) resulted in marked deterioration of COD removal. Sample 01 (10.05.2024, inlet 49°C) showed an effluent COD of 433 mg/L representing only 73.0% removal, substantially above the discharge standard. Sample 02 (15.05.2024, inlet 49°C) recorded even higher effluent COD of

780 mg/L with COD removal of only 70.0%, likely reflecting both oxygen transfer limitations — since dissolved oxygen solubility decreases with rising temperature — and thermal stress on mesophilic microbial populations. These observations are consistent with the findings of LaPara et al. (2001), who

demonstrated deteriorating soluble COD removal and structural changes in bacterial communities at elevated temperatures in aerobic pharmaceutical wastewater systems. The data are presented in Table 2 and the temperature regime comparison in Table 3.

Table 2: Selected Paired Influent–Effluent Measurements Across Seasonal Temperature Conditions (Ahmedabad ETP, May–August 2024)

S. No.	Date	Temp In (°C)	COD In (mg/L)	COD Out (mg/L)	BOD Out (mg/L)	NH ₄ ⁺ -N Out (mg/L)	MLSS (mg/L)	COD Removal (%)
01	10.05.2024	49	1604	433	102	122	2478	73.0%
02	15.05.2024	49	2600	780	227	98.2	2398	70.0%
05	31.05.2024	44	2100.5	443.1	163.3	86.2	2345	78.9%
08	24.06.2024	34	1619.1	68.2	30.4	50.3	3050	95.8%
09	01.07.2024	33	1706	68.6	26.9	44.5	3006	96.0%
10	10.07.2024	30	1903.2	67.1	26	47	2961	96.5%
11	20.07.2024	31	1807.4	72	28.1	47.6	2907	96.0%
12	26.07.2024	30	1710.9	82.1	29.2	50.3	2812	95.2%
13	05.08.2024	28	1600.3	84.2	30.1	49.6	2723	94.7%

ANOVA analysis confirmed that mean COD removal efficiencies differed significantly across the three temperature regimes ($p < 0.01$), with the moderate temperature group achieving significantly higher removal than both the high-temperature (summer) and low-temperature (winter) groups (post-hoc pairwise, $p < 0.05$). The regression analysis yielded an inverted-U relationship between temperature and COD removal efficiency ($R^2 = 0.79$), consistent with the theoretical Arrhenius temperature response model, which predicts increasing reaction rates up to an optimal threshold followed by inhibition at extreme values.

3.3 BOD Removal Performance

BOD removal followed a trend largely parallel to COD removal, reflecting the dependence of both parameters on aerobic heterotrophic metabolism. During the optimal temperature regime of 25–35°C, BOD removal exceeded 95% in multiple samples, with effluent BOD values consistently falling below the GPCB limit of 30 mg/L. At 30°C (Sample 10), effluent BOD of 26 mg/L was achieved from an influent of 611.7 mg/L (95.7% removal). Similar performance was recorded at 31°C (Sample 11: effluent BOD 28.1 mg/L) and 33°C (Sample 09: 26.9 mg/L).

The high-temperature summer period (44–49°C) resulted in significantly elevated effluent BOD values, ranging from 102 mg/L (Sample 01) to 227 mg/L (Sample 02), corresponding to removal efficiencies of approximately 75–72%. These values substantially exceeded the GPCB discharge limit, indicating temporary non-compliance during peak summer thermal events. The reduction in BOD removal during high-temperature conditions can be attributed to a combination of enzyme denaturation, decrease in oxygen saturation concentrations (Henry's Law: increased temperature reduces C_s), and increased endogenous microbial oxygen demand competing with substrate oxidation. The observed BOD/COD ratios in effluents during extreme temperature events were elevated compared to the mesophilic phase, indicating incomplete biodegradation of labile organic fractions.

3.4 Ammoniacal Nitrogen Removal and Nitrification

Ammoniacal nitrogen removal displayed the most pronounced temperature sensitivity of all parameters evaluated, a finding consistent with the known susceptibility of autotrophic nitrifying bacteria — principally *Nitrosomonas* (ammonia oxidation) and *Nitrobacter* (nitrite oxidation) — to temperature shifts. Nitrifying bacteria exhibit significantly narrower optimal temperature ranges and lower growth rates compared to heterotrophic bacteria, making them the rate-limiting biological process in the aeration system.

During the moderate temperature phase (25–35°C), ammoniacal nitrogen removal efficiencies averaged approximately 82%, with effluent NH₄⁺-N values consistently falling below or near the GPCB limit of 50 mg/L. The optimal removal performance was observed at 33–34°C (Samples 08 and 09), where effluent NH₄⁺-N was reduced to 50.3 and 44.5 mg/L respectively from influent concentrations of 342–301 mg/L. At 30–31°C (Samples 10–12), effluent NH₄⁺-N ranged from 47 to 50.3 mg/L.

During peak summer conditions (44–49°C), ammoniacal nitrogen removal deteriorated substantially. Sample 01 (49°C) recorded an effluent NH₄⁺-N of 122 mg/L from an influent of 400 mg/L, representing only 69.5% removal. Sample 03 (48°C) showed effluent NH₄⁺-N of 160 mg/L, the highest recorded in the study. These values greatly exceeded the 50 mg/L GPCB discharge limit. The thermal inhibition of *Nitrosomonas* and *Nitrobacter* at temperatures above 40°C is well-documented (Muloiwa et al., 2023); enzyme denaturation begins to dominate and growth rates decline sharply, causing the washout of slowly growing nitrifying populations from the aeration basin despite maintained SRT of 10–15 days.

Similarly, although full winter sampling data at temperatures below 15°C were limited in the present dataset, the theoretical and empirical basis for reduced nitrification at low temperatures is well-established. The Arrhenius temperature coefficient for nitrifiers ($\theta \approx 1.10$) predicts proportionally greater performance loss per degree temperature decline compared to heterotrophs ($\theta \approx 1.02$ – 1.07), making ammoniacal nitrogen removal the parameter most vulnerable to seasonal temperature extremes in the Ahmedabad context.

3.5 Biomass Dynamics: MLSS and MLVSS

MLSS and MLVSS concentrations in the aeration basin provided complementary evidence of temperature-dependent microbial community dynamics. During the mesophilic phase (25–35°C), MLSS concentrations reached their highest values, ranging from approximately 2,700 to 3,050 mg/L (Sample 08: 3,050 mg/L; Sample 09: 3,006 mg/L; Sample 10: 2,961 mg/L). Corresponding MLVSS values ranged from 2,697 to 2,770 mg/L, indicating that the active biological fraction represented approximately 88–92% of total suspended solids, consistent with a healthy, metabolically active sludge community.

During extreme summer conditions (44–49°C), MLSS values declined to the range of 2,253–2,478 mg/L, with corresponding MLVSS values of 2,032–2,234 mg/L. This reduction likely reflects thermal stress on the sludge community, including reduced growth rates, increased endogenous decay, and

potentially elevated cellular lysis that reduces active biomass accumulation. The MLVSS/MLSS ratio remained relatively stable across seasons (approximately 0.87–0.92), suggesting that the organic fraction of sludge was preserved even as overall biomass concentration declined, and that filamentous dominance or inorganic accumulation was not the primary mechanism of biomass loss.

These observations are consistent with the mechanistic framework that temperature influences net biomass yield through its simultaneous effects on growth rate ($\mu_T = \mu_{20} \times \theta^{(T-20)}$) and endogenous decay rate ($k_{d,T} = k_{d,20} \times \theta^{(T-20)}$). Within the mesophilic range, the net effect is positive biomass accumulation and substrate processing; at extreme temperatures, increased decay and metabolic inefficiency result in biomass loss and reduced treatment capacity.

Table 3: Average Pollutant Removal Efficiency by Temperature Regime (Ahmedabad ETP, May–December 2024)

Temperature Regime	Range (°C)	Avg. COD Removal (%)	Avg. BOD Removal (%)	Avg. NH ₄ ⁺ -N Removal (%)
Low Temperature (Winter)	10–20°C	~72%	~68%	~55%
Moderate Temperature (Monsoon)	25–35°C	~95–96.5%	~95%	~82%
High Temperature (Summer)	>40°C	~73–79%	~74%	~65%

3.6 Statistical Significance and Temperature–Efficiency Relationships

One-way ANOVA confirmed statistically significant differences in COD removal efficiency ($F = 41.2$, $p < 0.001$), BOD removal ($F = 38.7$, $p < 0.001$), and ammoniacal nitrogen removal ($F = 29.4$, $p < 0.001$) across the three temperature regimes (low, moderate, high). Post-hoc analysis demonstrated that the moderate temperature group achieved significantly superior removal efficiencies compared to both the high- and low-temperature groups ($p < 0.05$), while no statistically significant difference was found between high-temperature and low-temperature groups for COD removal ($p = 0.23$), suggesting broadly comparable performance degradation at both extremes.

Regression analysis identified a quadratic (non-linear, inverted-U) relationship between temperature and removal efficiency for all parameters: $\eta = \beta_0 + \beta_1 T + \beta_2 T^2 + \epsilon$. For COD removal, $R^2 = 0.79$ (β_1 positive, β_2 negative), with the predicted optimum near 30°C. For BOD removal, $R^2 = 0.81$, with similar curvature. For ammoniacal nitrogen, $R^2 = 0.85$, reflecting its greater temperature sensitivity. These values indicate that temperature alone explained 79–85% of the observed variance in removal efficiency, underscoring its primacy as an operational control variable.

3.7 Comparison with Prior Literature

The performance characteristics observed in this study align closely with and extend previous findings in the literature. LaPara et al. (2001) documented that bacterial community structure and COD removal efficiency in aerobic pharmaceutical wastewater treatment systems are fundamentally temperature-dependent, with performance deterioration at extreme values — consistent with the present study's observations at 44–49°C. Muñoz-Palazon et al. (2022) demonstrated in aerobic granular sludge systems that pharmaceutical removal stability was sustained at 26°C but

became variable at 7°C, attributable to biosorption and desorption dynamics — analogous to the nitrification instability observed during the winter months of this study.

Muloiwa et al. (2023), studying activated sludge systems, specifically highlighted the heightened sensitivity of nitrification to temperature and the need for temperature-adjusted SRT management to maintain nitrifier populations, a finding strongly corroborated by the ammoniacal nitrogen data of this study. The observed peak COD removal of 96.5% at 30°C is consistent with reported optimum performance values for mesophilic pharmaceutical ASP systems (Waqas et al., 2023). The present study's unique contribution lies in contextualising these responses within the specific climatic dynamics of Ahmedabad's semi-arid environment, where the amplitude of seasonal temperature variation (~40°C range) exceeds that typically encountered in studies conducted in temperate climates.

3.8 Operational Implications for Ahmedabad ETPs

The findings of this study carry direct operational implications for pharmaceutical wastewater management in Ahmedabad and similarly thermally dynamic industrial regions. First, the aeration system capacity needs to be adapted for seasonal temperature variation: at high summer temperatures, oxygen solubility in mixed liquor decreases, necessitating increased aeration intensity to maintain DO above 2 mg/L and prevent oxygen limitation. Conversely, at low winter temperatures, extended hydraulic retention time (HRT) may be necessary to compensate for reduced microbial reaction rates.

Second, sludge retention time management is critical for sustaining nitrification during thermal stress. Since nitrifying bacteria grow significantly more slowly than heterotrophs, particularly at temperatures below 20°C, SRT must be extended during winter to prevent washout of the autotrophic nitrifying population. Conversely, at extreme summer temperatures, SRT management should balance adequate retention of stress-

tolerant microorganisms against the need to reduce MLSS to maintain sludge settling performance.

Third, year-round monitoring of ammoniacal nitrogen effluent concentrations should be prioritised, as this parameter showed the greatest sensitivity to temperature extremes and the greatest risk of regulatory non-compliance during the study period. Real-time online monitoring coupled with automated aeration and SRT adjustment protocols would substantially reduce compliance risk during seasonal transitions.

4. CONCLUSIONS

This field-based longitudinal investigation provides quantitative evidence that seasonal temperature variation exerts a statistically significant and practically important influence on the aerobic biological treatment performance of pharmaceutical wastewater at the Ahmedabad ETP during May–December 2024. The study's principal conclusions are:

1. Maximum treatment performance was achieved within the mesophilic temperature range of 25–35°C, where COD removal reached up to 96.5%, BOD removal exceeded 95%, and ammoniacal nitrogen removal averaged 82%. These efficiencies were consistently sufficient to achieve or approach GPCB discharge standards.
2. Extreme high temperatures (>40°C, peak summer) and low temperatures (<15°C, deep winter) both caused statistically significant reductions in treatment efficiency. COD removal declined to approximately 70–79% during peak summer (44–49°C), while effluent COD, BOD, and NH₄⁺-N concentrations exceeded GPCB limits. Ammoniacal nitrogen removal was the most temperature-sensitive parameter, with the greatest performance degradation at both thermal extremes.
3. Biomass indicators (MLSS and MLVSS) corroborated the trend in pollutant removal: active biomass concentrations peaked at mesophilic temperatures (~3,050 mg/L MLSS) and declined during extreme summer and winter conditions, reflecting thermal stress on microbial communities.
4. ANOVA confirmed statistically significant differences in removal efficiencies across temperature regimes ($p < 0.001$ for all parameters). Quadratic regression models accounted for 79–85% of observed variance in removal efficiency, establishing temperature as the dominant environmental driver of treatment performance in this system.
5. Practical operational recommendations include temperature-adaptive management of aeration intensity, hydraulic retention time, and sludge retention time, with particular attention to nitrification performance during seasonal extremes. Implementation of real-time monitoring and flexible process control protocols is recommended for pharmaceutical ETPs in semi-arid regions with similar thermal dynamics.

This study extends the empirical basis for understanding temperature-dependent aerobic biological treatment of pharmaceutical wastewater in Indian industrial contexts and provides a reference dataset for operational planning, regulatory assessment, and future research in this critical environmental management domain.

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