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RESEARCH ARTICLE

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Characterization of influent and effluent at a wastewater treatment plant with trickling filters in the high Andean region of Peru

Caracterización de afluente y efluente en una planta de tratamiento de aguas residuales con filtros percoladores en la región altoandina del Perú

Caracterização do afluente e do efluente em uma estação de tratamento de águas residuais com filtros de percolação na região andina do Peru

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ABSTRACT

Introduction: The Yauli wastewater treatment plant, located in the high Andean region of Huancavelica, Peru (~3,383 m), faces environmental conditions that limit the efficiency of biological processes. **Objective:** To determine the concentrations of key parameters in the influent and effluent of the Yauli WWTP, including oils and fats (O&F), thermotolerant coliforms (TC), BOD_5, chemical oxygen demand (COD), total suspended solids (TSS), pH, and temperature. **Materials and methods:** Using a descriptive cross-sectional design, 8 sampling campaigns were conducted for influent and effluent between October 2019 and February 2020. O&F, TT, BOD_5, COD, TSS, pH, and temperature were analyzed. The results were compared with the Maximum Permissible Limits (MPLs) established by Peruvian regulations. Normality tests and Student's t-tests ($p < 0.05$) were applied, with 95% confidence intervals and effect size (Cohen's d). **Results:** The effluent complied with the MPLs for BOD_5, COD, TSS, pH, and temperature. However, BOD_5 exceeded the limit (732.9 mg/L vs. 100 mg/L). Higher removal efficiency was observed for SST (73.15%), and lower for BOD_5 (3.95%). Organic overload was also evident, which affected the system's efficiency. **Conclusion:** The study highlights the limitations of biological treatment in high-Andean conditions. It is necessary to adapt technologies to local environmental and operational conditions to protect water resources and ensure effluent quality.

Keywords: Wastewater treatment plants; Altitude; Environmental monitoring; Peru. (Source: DeCS, Bireme).

Sustainable development objectives: Good health and well-being; Clean Water and Sanitation. (Source: SDG, WHO).

RESUMEN

Introducción: La planta de tratamiento de aguas residuales de Yauli, ubicada en la región altoandina de Huancavelica, Perú (~3383 m), y enfrenta condiciones ambientales que limitan la eficiencia de los procesos biológicos. **Objetivo:** Determinar las concentraciones de parámetros fundamentales en el afluente y efluente de la PTAR de Yauli, incluyendo aceites y grasas (AyG), coliformes termotolerantes (CT), (DBO_5), demanda química de oxígeno (DQO), sólidos suspendidos totales (SST), pH y temperatura. **Materiales y métodos:** Mediante un diseño descriptivo transversal se realizaron 8 campañas por afluente y efluente entre octubre de 2019 y febrero de 2020. Se analizaron AyG, CT, DBO_5, DQO, SST, pH y temperatura. Los resultados se compararon con los Límites Máximos Permisibles (LMP) de la normativa peruana. Se aplicaron pruebas de normalidad y *t* de Student ($p < 0,05$), con intervalos de confianza al 95 % y tamaño del efecto (Cohen's d). **Resultados:** El efluente cumplió con los LMP en AyG, CT, DQO, SST, pH y temperatura. Sin embargo, la DBO_5 excedió el límite (732,9 mg/L vs. 100 mg/L). Se observó mayor eficiencia de remoción en los SST (73,15 %), y menor en la DBO_5 (3,95 %). Se evidenció además una sobrecarga orgánica que afectó la eficiencia del sistema. **Conclusión:** El estudio evidencia limitaciones del tratamiento biológico en condiciones altoandinas. Es necesario adaptar tecnologías a las particularidades ambientales y operativas locales para proteger los recursos hídricos y garantizar la calidad del efluente.

Palabras clave: Plantas de tratamiento de aguas residuales; Altitud; Monitoreo del ambiente; Perú. (Fuente: DeCS, Bireme).

Objetivos de desarrollo sostenible: Salud y bienestar; Agua limpia y saneamiento. (Fuente: ODS, OMS).

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It is hereby stated that the authors are responsible for the content and its accuracy.

RESUMO

Introdução: A estação de tratamento de águas residuais de Yauli, localizada na região andina de Huancavelica, no Peru (~3.383 m), enfrenta condições ambientais que limitam a eficiência dos processos biológicos. **Objetivo:** Determinar as concentrações de parâmetros fundamentais no afluente e no efluente da ETAR de Yauli, incluindo óleos e gorduras (OG), coliformes termotolerantes (CT), DBO_5, demanda química de oxigênio (DQO), sólidos suspensos totais (SST), pH e temperatura. **Materiais e métodos:** Por meio de um desenho descritivo transversal, foram realizadas 8 campanhas no afluente e no efluente entre outubro de 2019 e fevereiro de 2020. Foram analisados óleos e gorduras (AyG), coliformes termotolerantes (CT), DBO_5, DQO, SST, pH e temperatura. Os resultados foram comparados com os Limites Máximos Permissíveis (LMP) da regulamentação peruana. Foram aplicados testes de normalidade e t de Student ($p < 0,05$), com intervalos de confiança de 95% e tamanho do efeito (Cohen's d). **Resultados:** O efluente cumpriu os LMP em AyG, CT, DQO, SST, pH e temperatura. No entanto, a DBO_5 excedeu o limite (732,9 mg/L vs. 100 mg/L). Observou-se maior eficiência de remoção na SST (73,15 %) e menor na DBO_5 (3,95 %). Evidenciou-se, além disso, uma sobrecarga orgânica que afetou a eficiência do sistema. **Conclusão:** O estudo evidencia limitações do tratamento biológico em condições de alta montanha. É necessário adaptar as tecnologias às particularidades ambientais e operacionais locais para proteger os recursos hídricos e garantir a qualidade do efluente.

Palavras-chave: Estações de tratamento de águas residuárias; Altitude; Monitoramento ambiental; Peru. (Fonte: DeCS, Bireme).

Objetivos de desenvolvimiento sustentável: Saúde e bem-estar; Água potável e saneamento. (Fonte: MDS, OMS).

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INTRODUCTION

The management of wastewater is a global challenge due to its impact on public health, environment and sustainable development. In 2022, UN-Water[1] reported that only 76% of the wastewater obtained any treatment, thus, showing gaps in less developed regions. In Latino America the World Bank[2] estimated that only between 30% to 40% of the wastewater collected is treated. Substantial disparities exist across the region: Chile achieves treatment coverage of approximately 71%, whereas Paraguay reports a rate as low as 4%, and Peru reaches approximately 39%, reflecting inequalities in sanitation infrastructure and wastewater management.

In Peru, geographic and socioeconomic conditions exacerbate sanitation challenges. Studies conducted in Lima, as Ramirez *et al.*[3] assessed artificial wetlands with efficiency of removal of DQO between 55% and 71%, showing not only advances but also the need to optimize existing systems. Difficulties are intensified in high altitudes where lower atmospheric pressure can affect oxygen transfer and aeration efficiency. Baquero *et al.*[4] indicated that, at an altitude of 2,550 m above sea level, oxygen requirements may increase by a factor of 1.5. At Yauli, located at an altitude of 3,385 m above sea level, these effects may be even more pronounced. Guo *et al.*[5] also demonstrated that microbial community composition differs in alpine environments, potentially influencing carbon and nitrogen degradation processes. Studies conducted on the Qinghai-Tibet Plateau[6] and in Ecuador[7] further indicate that altitude, temperature, and hydraulic retention time can influence the treatment performance of wastewater treatment plants (WWTPs) in high-altitude environments.

The Wastewater Treatment Plant (WWTP) of Yauli, placed in the region of the same name in the region of Huancavelica, Peru, combines primary and secondary treatment processes by the use of a trickling filter. This system faces questionings about its capacity to remove key pollutants, such as five-day biochemical oxygen demand BOD_5, which could be affecting the quality of the river Ichu: its receptor waterbody. The extreme highness of the region enlarges the working limitations, because the biological processes depend on the oxygenation conditions that are seen affected by the less atmospheric pressure. Haque[8] underlines that the technological challenges vary according to local environmental conditions, underscoring the importance of site-specific assessments.

Accordingly, this study aimed to determine the concentrations of key parameters in the influent and effluent of the Yauli Wastewater Treatment Plant (WWTP), including oil and grease (O&G), thermotolerant coliforms (TC), five-day biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), total suspended solids (TSS), pH, and temperature. These parameters were compared with the maximum permissible limits (MPLs) established by Peruvian regulations to assess whether the plant complies with the applicable discharge requirements. The removal efficiency of each parameter was also evaluated to provide a quantitative assessment of the treatment system's performance. The study hypothesized that the plant would fail to meet the regulatory limits for at least some parameters, particularly BOD_5, owing to the technological and operational constraints associated with high-altitude environments.

MATERIALS AND METHODS

Field of study

The study was carried out in the district of Yauli, province and department of Huancavelica, Peru, at an altitude of approximately 3,383 m above sea level (m a.s.l.), in the central Andes. The district borders Paucará (Acobamba Province) to the east, Huancavelica to the west, Acoria to the north, and Ccochaccasa (Angaraes Province) to the south.

The Yauli Wastewater Treatment Plant (WWTP) receives an average influent flow rate of 8.2 L/s (705.89 m^3/day) and discharges an average effluent flow rate of 2.8 L/s (241.92 m^3/day). Its infrastructure includes a pretreatment system comprising a wastewater collection system, pumping facilities, a screening chamber, and a grit chamber. Subsequently, the wastewater passes through two primary sedimentation tanks and a grease trap, which facilitate the initial removal of settleable solids and oil and grease. Biological treatment is performed using trickling filters arranged in series, after which the treated

effluent is discharged directly into the receiving river. The sludge generated in the sedimentation tanks and trickling filters is conveyed to a drying bed for subsequent disposal.

The plant does not incorporate chemical disinfection, ultraviolet (UV) disinfection, or tertiary filtration. Consequently, effluent quality depends primarily on the physical and biological treatment processes described above.

The sampling points were georeferenced using Universal Transverse Mercator (UTM) coordinates, as follows:

1. **Influent:** Northing (N) 8,588,737 m; Easting (E) 516,232 m; altitude 3,404 m a.s.l.
2. **Effluent:** Northing (N) 8,588,702 m; Easting (E) 516,203 m; altitude 3,383 m a.s.l.

These coordinates identify the locations of the influent and effluent sampling points and provide a spatial reference for contextualizing the environmental conditions under which sampling was conducted.

Design and Unity of analysis

The research was carried out using a descriptive cross sectional design[9], directed to characterize the wastewater at the Yauli Wastewater Treatment Plant (WWTP). Sampling campaigns were carried out under normal operative conditions with stable flow rates and safe access to the facility. Sampling periods affected by operational failures or heavy rainfall were excluded. The study was conducted between October 2019 and February 2020, during the rainy season in the Andean region. The units of analysis consisted of wastewater samples collected from the plant's influent and effluent. The following physicochemical and microbiological parameters were evaluated: oil and grease (O&G), total coliforms (TC), biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), total suspended solids (TSS), pH, and temperature. The results were compared with the maximum permissible limits (MPLs) established under Supreme Decree No. 003-2010-MINAM[10]. These indicators were used to characterize wastewater quality and assess the performance of the treatment system in relation to applicable national and international standards.

Sampling

Eight sampling campaigns were conducted between October 2019 and February 2020, yielding eight samples per sampling location (influent and effluent; total $n = 16$). During each campaign, a 24-hour composite sample was collected at both the inlet and outlet of the WWTP, following the protocol established by Ministerial Resolution No. 273-2013-VIVIENDA[11], which regulates effluent monitoring in Peru. The average daily flow rates were 8.2 L/s (705.89 m^3/day) at the influent and 2.8 L/s (241.92 m^3/day) at the effluent. Sampling was performed during daytime hours and avoided periods of heavy rainfall to minimize the effects of dilution. Samples were collected in sterile, 1-L polyethylene containers for the analysis of each parameter (O&G, TC, BOD_5, COD, and TSS) and transported to the laboratory under refrigerated conditions at 4 °C. Microbiological analyses were performed within a maximum of six hours after sample collection, whereas physicochemical samples were stored for 24-48 hours before analysis, in accordance with the *Standard Methods for the Examination of Water and Wastewater*[12].

Sampling was conducted in coordination with the Yauli Wastewater Treatment Plant (WWTP), with the corresponding operational authorization. During the sampling campaigns, site conditions were recorded. Water temperatures ranged from 17 to 19.6 °C at the influent (mean = 18 °C) and from 19 to 22.4 °C at the effluent (mean = 21 °C). The average daily flow rates were 8.2 L/s at the influent and 2.8 L/s at the effluent. Operational records were also collected, including information on percolating filter maintenance and variations in hydraulic loading, to contextualize the results. Only 24-hour composite samples collected from the influent and effluent under controlled storage and transportation conditions were included in the analysis. Samples taken during heavy rains or those that didn`t fill the maximum times in the established processes by the reference protocols were discarded.

Instrumentation and analytical procedures

Physicochemical and microbiological analyses were performed in accordance with the procedures described in *Standard Methods for*

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the Examination of Water and Wastewater[12].

- **Oil and grease (O&G):** Method 5520B. Oil and grease were extracted using a Soxhlet apparatus with benzene for 4 hours from a 250-mL sample. The residual material was then weighed using a calibrated digital balance.
- **Thermotolerant coliforms (TC):** Method 9222D. A 100-mL sample was filtered through a 0.45-μm membrane, incubated at 44.5 °C for 24 hours, and the resulting colonies were counted using a colony counter (MEL/MF total kit).
- **Biochemical oxygen demand (BOD_5):** Method 5210B. Samples were incubated in the dark for five days at the temperature specified by the analytical protocol, using designated bottles. Dissolved oxygen consumption was measured using an ME-98 instrument.
- **Chemical oxygen demand (COD):** Method 5220D. A 1-mL sample was subjected to closed reflux digestion with potassium dichromate in an acidic medium at 150 °C for 2 hours using a DBR-125 reactor. The resulting COD was measured directly using a DR-125 portable colorimeter (Hach).
- **Total suspended solids (TSS):** Method 2540D. A 250-mL sample was filtered under vacuum using Whatman filter paper and a Kitasato flask connected to a vacuum pump. The filter was dried at 106 °C for 60 minutes and weighed using a calibrated digital balance.

In situ measurements of pH, temperature, dissolved oxygen, and electrical conductivity were performed using an Ezodo portable multiparameter meter, which was calibrated with standard solutions and accepted only when deviations were ≤ 5%. The sampling points were georeferenced using a Garmin eTrex 10 handheld GPS receiver, with a stated positional accuracy of ± 5 m. Flow rates were measured using the velocity-area method at the influent and the volumetric method at the effluent.

All equipment was calibrated in accordance with the manufacturers' instructions before each series of measurements, with an acceptance criterion of ≤ 5% deviation.

Evaluation of the organic loading of the biological filter

The organic loading rate applied to the biological filter was calculated as a criterion of diagnostic of the performance of the unit of treatment, following the recommendations of the technical literature[13,14]. This parameter was used to asses whether the system operated within the recommended organic loading ranges for trickling filters and to contextualize the observed treatment performance.

The organic loading rate was calculatedusing the following equation:

$$\text{Organic load} = \frac{Q \times C}{V}$$

Where (Q) is the daily influent flow rate, (C) is the influent biochemical oxygen demand (BOD_5) concentration, and (V) is the effective volume of the filter. The treatment plant has two biological filters operating in parallel, each containing a 3-m-high gravel bed[15]. Since no official technical documentation was available, the volume of each filter was estimated based on typical dimensions reported in the literature, assuming a 6 m diameter, which corresponds to an approximate volume of 85 m^3 per unit. The plant's average influent flow rate was 705.89 m^3/day, distributed between the two units. Influent BOD_5 concentrations ranged from 648.6 to 774.3 mg/L, with an average of approximately 700 mg/L, according to the analyses performed on the influent.

Statistical analysis and quality control

Data were analysed in orderto compare influent and effluent concentrations and validate their distribution. Normality tests were applied (Kolmogorov-Smirnov and Shapiro-Wilk tests), which are suitable for small samples ($n = 8$), as a preliminary step before conducting parametric analyses. Subsequently, Student's t-test ($p < 0.05$) was used, along with 95% confidence intervals and the effect size (Cohen's d), to complement the statistical interpretation and assess the practical magnitude of the differences. Calculations were performed using SPSS v.25, which was used to conduct the statistical analyses of the environmental data.

The removal efficiency was estimated using the following formula:

$$\text{Efficiency} = \left(1 - \frac{\text{Concentration in effluent}}{\text{Concentration in influent}}\right) \times 100\%$$

Expressing the plant's contaminant removal efficiency as a percentage. The results were presented as means and standard deviations.

In order to ensure data reliability, quality control procedures were implemented, including periodic equipment calibration, duplicate analyses, and verification using certified reference standards, in accordance with APHA guidelines[12] and ISO/IEC 17025:2017[16]. The analyses were conducted at RCJ Labs Universal, accredited under NTP-ISO/IEC 17025:2006 (accreditation code: 00RCJLE 096), which supports the validity of the analytical procedures. During sample collection, sterile gloves were used, and the sampling materials were properly prepared and handled to minimize potential contamination and interference, reduce systematic errors, and ensure reproducibility.

RESULTS

Organic load applied to the biological filters

The average influent flow rate of the plant was 705.89 m^3/day, distributed between two biological filters operating in parallel (approximately 352.95 m^3/day per unit). Given an average influent biochemical oxygen demand (BOD_5) concentration of 700 mg/L (0.7 kg/m^3) and an estimated volume of approximately 85 m^3 per filter (6 m in diameter and 3 m in height), the applied organic loading rate was calculated as 2.91 kg BOD_5/(m^3·day) per unit.

This value exceeds the organic loading ranges reported in the literature for trickling filters, which are classified as follows:

- Low rate load : 0,08 - 0,32 kg DBO_5/(m.day).
- High rate load : 0,32-1,12 kg DBO_5/(m.day)[13,14].

This comparison indicates that the biological filters at the Yauli wastewater treatment plant (WWTP) operate under conditions of excessive organic loading.

Concentrations of parameters in influent and effluent

The average concentrations of the evaluated parameters in the influent and effluent, along with their respective standard deviations (SD), are summarized in Table 1. These values reflect the initial pollutant load and the water quality after treatment, respectively. A general reduction in effluent concentrations compared with influent concentrations is observed for most parameters, except for temperature, which remains relatively stable. The most pronounced differences are observed for total suspended solids (TSS), whereas BOD_5 exhibits only a limited reduction.

Table I.
Averages and standard deviations of concentrations in influent and effluent

Parameter	M inflow	DE inflow	M Effluent	SD Effluent	MPLs
O&G (mg/L)	27.9	3.2	16.6	2.8	20
TC (NMP/100 mL)	15,412.5	1,200	8,562.5	950	10,000
BOD_5 (mg/L)	763.2	45.6	732.9	40.3	100
COD (mg/L)	125.1	10.2	114.8	9.5	200
TSS (mg/L)	390.6	25.4	105.0	15.6	150
pH (Units)	7.6	0.1	7.5	0.1	6-9
Temperature (°C)	21.2	0.5	21.1	0.4	35

Comparison with maximum permitted limits (MPLs)

Compliance with regulatory standards was evaluated by comparing effluent concentrations with the maximum permissible limits (MPLs) established by Peruvian regulations. The results show that parameters such as total coliforms (TC), oils and fats (O&G), chemical oxygen demand (COD), total suspended solids (TSS), pH,

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and temperature comply with the applicable limits after treatment. In contrast, BOD_5 substantially exceeds the maximum permissible limit, indicating a limitation in the wastewater treatment plant's (WWTP's) capacity to remove biodegradable organic matter. These results are illustrated in Figure 1.



Figure 1.
Comparison of effluent parameters with the maximum permissible limits (MPLs) established by Peruvian regulations

A: Total coliforms (TC).
B: Oils and fats (O&G).
C: Chemical oxygen demand (COD)..
D: Biochemical oxygen demand (BOD_5).
E: Total suspended solids (TSS).
F: pH.
G: Temperature.

Removal efficiency

The capacity of the wastewater treatment plant (WWTP) to remove contaminants was quantified using removal efficiency, expressed as a percentage (Table 2). The results show substantial variability in removal efficiency across the evaluated parameters. TSS exhibited the highest removal efficiency, whereas BOD_5 and COD showed considerably lower efficiencies. These findings highlight differences in treatment performance depending on the type of contaminant.

Table 2.
Removal efficiencies of the WWTP

Parameter	Removal efficiency (%)
O&G	40.61
TC	44.48
BOD_5	3.95
COD	8.2
TSS	73.15

Statistical analysis

The results of the normality tests applied to the effluent data (Table 3) indicated that most of the analyzed parameters were consistent with a normal distribution. For oils and fats (O&G), total coliforms (TC), BOD_5, TSS, pH, and temperature, the *p*-values obtained from the Kolmogorov-Smirnov and Shapiro-Wilk tests were greater than the significance level ($\alpha = 0.05$), providing insufficient evidence to reject the null hypothesis of normality. For COD and temperature, the p-values were closer to the significance threshold; nevertheless, the results were considered acceptable for the subsequent parametric analyses, based on methodological consistency.

Table 3.
Results of the Kolmogorov-Smirnov and Shapiro-Wilk normality tests applied to the effluent parameters

Parameter	Kolmogorov–Smirnov (*p*)	Shapiro–Wilk (*p*)	Normality
O&G	0.200	14.26	18.94
TC	0.200	7,768.29	9,356.71
BOD_5	0.142	699.21	766.59
COD	0.061	106.86	122.74
TSS	0.027	91.96	118.04
pH	0.200	7.42	7.58
Temperature	0.057	20.77	21.43

Decision criterium: $p \geq 0.05 \rightarrow$ accepted normality.

After normality was assessed, the paired-samples Student's t-test was applied at a significance level of $p < 0.05$ to compare the mean values of each parameter in the influent and effluent. This procedure was used to determine whether the observed reductions were statistically significant and to assess the treatment plant's performance.

The results of the paired-samples Student's t-tests and Cohen's *d* effect size analyses (Table 4) indicate that the treatment plant achieved statistically significant reductions in oils and fats (O&G), total coliforms (TC), and total suspended solids (TSS), with large to very large effect sizes. Although BOD_5 and COD did not show statistically significant differences, their moderate to large effect sizes suggest potential reduction trends that warrant further investigation with a larger sample size. In contrast, pH and temperature remained relatively stable, consistent with their roles as operational or monitoring parameters rather than direct indicators of treatment efficiency (Table 4).

Table 4.
Comparison of influent and effluent parameters using paired-samples Student's *t*-tests, 95% confidence intervals, and Cohen's *d*.

Parameter	*p*-value	Lower IC 95 %	Upper IC 95 %	Cohen´s d
O&G	0.001	14.26	18.94	3.76
TC	0.003	7,768.29	9,356.71	6.33
BOD_5	0.120	699.21	766.59	0.70
COD	0.085	106.86	122.74	1.05
TSS	< 0.001	91.96	118.04	13.55
pH	0.320	7.42	7.58	1
Temperature	0.450	20.77	21.43	0.22

* $p < 0.05$ indicates meaningful differences between influent and effluent.
** IC 95% confidence interval 95%.
*** Cohen`s d: effect size (0.2 = small, 0.5 = medium, ≥ 0.8 = big).

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DISCUSSION

The results showed statistically significant differences in parameters such as oils and fats (O&G), total coliforms (TC), and total suspended solids (TSS), with high removal efficiencies and large effect sizes. In contrast, BOD_5 and COD did not show statistically significant differences, although their effect sizes suggested potentially meaningful trends. These differences in statistical significance and effect size across the evaluated parameters provide a basis for contextualizing the findings from Yauli in relation to other high-Andean wastewater treatment experiences, where organic matter removal efficiencies have varied according to altitude, technological design, and operating conditions.

At the Yauli WWTP in Peru (3,404 m above sea level), removal efficiencies were minimal, reaching only approximately 3.95% for BOD_5 and 8% for COD, with no statistically significant differences observed. Although the final COD concentration complied with Peruvian regulatory standards (< 200 mg/L), the low removal efficiencies suggest limitations in the performance of trickling filters under high-altitude conditions and excessive organic loading.

In contrast, at the Pucará WWTP in Bolivia (2,455 m above sea level), Echeverría *et al.*[17] reported high removal efficiencies of 79.3% for BOD_5, 88.5% for COD, and 95.2% for TSS. This higher treatment performance may be associated with the lower altitude, which potentially reduces oxygen transfer limitations, as well as the greater robustness of the treatment train, which includes an upflow anaerobic sludge blanket (UASB) reactor, trickling filters, clarifiers, grit filters, and UV disinfection. However, nutrient removal (nitrogen and phosphorus) remained low, confirming that even more comprehensive treatment systems may have limitations in removing certain contaminants.

Additionally, Echeverría *et al.*[18] evaluated four other wastewater treatment plants (WWTPs) in Bolivia—Villa El Carmen, Ucureña, Tolata, and Colquerrancho—all located at approximately 2,700 m above sea level. The results showed variability in effluent COD concentrations (93-333 mg/L) and TSS concentrations (18-460 mg/L), indicating substantial operational differences among plants employing similar technologies. In all cases, ammoniacal nitrogen ($N\text{-}NH_3$) concentrations (41-74 mg/L) exceeded the reference limit of 30 mg/L, highlighting the limited nutrient removal capacity of these treatment systems under high-Andean conditions. Furthermore, salinity and electrical conductivity constrained the potential agricultural reuse of the treated effluent, extending the identified limitations beyond organic matter removal.

Finally, in Ecuador, Jerves-Cobo *et al.*[7] reported initial removal efficiencies of 60%-74% for BOD_5 and 48.9%-68.4% for COD in conventional constructed wetlands located in Acchayacu (2,689 m above sea level) and Churuguzo (2,628 m above sea level). Following the technological upgrade to vertical subsurface-flow constructed wetlands (VSSF-CWs) and surface-flow constructed wetlands (SF-CWs), removal efficiencies increased substantially, reaching 83%-95% for BOD_5 and 82.8%-89.4% for COD, with TSS removal efficiencies of approximately 95%. Although nutrient removal remained limited (total phosphorus: 53%-57%; ammoniacal nitrogen: 30%-40%), these findings demonstrate the potential of technological upgrades to improve treatment performance and overcome some of the limitations of conventional systems at high altitudes.

Although successful treatment outcomes have been reported at high Andean altitudes, regional comparisons reveal substantial variability in WWTP performance, largely depending on the robustness of the treatment systems and their operating conditions. Nevertheless, nutrient removal remains a persistent challenge; therefore, the suitability of treated effluent for irrigation remains an important unresolved issue in the management of high-Andean WWTPs. The extreme environmental and operational conditions in Yauli highlight some of the most pronounced treatment limitations. To understand the plant's limited treatment performance, it is necessary to consider the environmental and operational factors that influence its efficiency.

In Yauli, altitude-related environmental conditions may partly explain the low removal

efficiencies observed. Lower oxygen availability can hinder organic matter degradation because the driving force for oxygen dissolution decreases, requiring higher airflow rates to maintain adequate dissolved oxygen levels[4]. Low temperatures can also alter microbial community composition, resulting in more vulnerable microbial ecosystems that are sensitive to environmental fluctuations[5]. Xu *et al.*[19] reported that, at high altitudes, the biodegradable fraction of influent wastewater tends to be lower ($BOD_5/COD < 0.4$), while the abundance and diversity of active biomass may decrease, thereby reducing treatment capacity. Furthermore, Zhang *et al.*[20] found that WWTPs at higher altitudes may receive influent with elevated COD concentrations (147.9-340.2 mg/L), increasing the organic load requiring treatment. In Yauli, however, influent COD concentrations were comparatively moderate (97-168 mg/L). Nevertheless, removal efficiency remained minimal, suggesting that the limited treatment performance cannot be attributed solely to altitude or influent characteristics but may also reflect operational constraints and technological limitations.

Organic overloading at the Yauli WWTP may partly explain the low removal efficiencies observed. Braz *et al.*[21] demonstrated that overloading in anaerobic reactors directly affects active biomass: volatile fatty acids accumulate, microbial communities become altered, and methanogenesis may be inhibited when the pH falls below 6. Similarly, Jwara *et al.*[22] reported that hydraulic overloading at the Darvill WWTP in South Africa reduced biological nutrient removal efficiency, with average removal efficiencies of 40% for nutrients and 64% for soluble reactive phosphorus, while ammonia removal was particularly affected. Although the overloading in Yauli was organic, whereas that in Darvill was hydraulic, both cases demonstrate that operating outside the design parameters can compromise treatment system performance. Zhang *et al.*[23] further noted that excessively low organic loading can also pose risks, including increased dissolved organic nitrogen accumulation, the formation of disinfection by-products during chlorination, and an increase in antibiotic resistance genes. Overall, these findings indicate that both excessive and insufficient loading can destabilize WWTP performance, potentially compromising effluent quality and sanitary safety.

The technology employed may also partly explain the low removal efficiencies observed at the Yauli WWTP. Trickling filters have structural and operational limitations that may become more pronounced under high-Andean conditions. Ali *et al.*[24] reported that low temperatures can reduce contaminant degradation rates and compromise biofilm stability, potentially leading to ice formation and clogging of the filter media. Furthermore, organic overloading may cause excessive water retention and reduced oxygen transfer, while hydraulic shock loads during rainy seasons may promote the detachment of active biomass. Oliveira-Avellar *et al.*[25] confirmed that, even under controlled conditions, trickling filters may exhibit limited efficiency in removing nutrients such as ammoniacal nitrogen. Additionally, Abyar and Nowrouzi[26] reported environmental impacts associated with energy consumption and greenhouse gas emissions. Overall, these findings suggest that the low removal efficiency observed at Yauli may result from a combination of environmental constraints, operational factors, and the inherent limitations of the technology in treating complex contaminants while meeting sustainability requirements.

The results obtained at the Yauli WWTP have important practical implications for the management of wastewater treatment systems in high-Andean regions. The low removal efficiencies for BOD_5 and COD, together with the variability observed in parameters such as oils and fats (O&G) and total coliforms (TC), indicate that trickling filters may not consistently ensure compliance with effluent quality standards. From an operational perspective, these findings suggest that treatment systems employing this technology may require redesign or optimization to account for high-altitude environmental conditions, excessive organic loading, and the inherent limitations of biofilm-based processes.

From a management perspective, the findings reinforce the need to evaluate more robust and adaptable treatment technologies capable of maintaining performance under adverse environmental and operational conditions. Comparative evidence from constructed wetland

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systems in Ecuador indicates that technological modifications can substantially improve contaminant removal efficiencies. This suggests that hybrid treatment systems and nature-based solutions may represent promising alternatives for high-Andean settings, although their suitability should be assessed in terms of local environmental conditions, treatment requirements, and operational feasibility.

Finally, the evidence of environmental impacts and energy-related burdens associated with trickling filters[26] highlights the need to consider sustainability as a central criterion in technology selection. Overall, the findings from Yauli indicate that improving WWTP performance at high altitudes requires not only operational adjustments but also strategic investment in more resilient treatment technologies, supported by regulatory and management frameworks that prioritize effluent quality and public health protection, particularly when treated wastewater is intended for agricultural reuse.

This study has somelimitations that should be considered. First, sampling was conducted during the rainy season; therefore, a complete annual cycle was not covered, and potential seasonal variations could not be assessed. Second, the small sample size limits the generalizability of the findings. In addition, nutrient parameters, such as nitrogen and phosphorus, were not evaluated, although they are important for a comprehensive assessment of WWTP performance. The overloading of the trickling filters also represents an operational limitation that directly affects the interpretation of the results, potentially leading to an underestimation of the system's actual treatment efficiency under optimal operating conditions. Finally, samples were collected only at the plant influent and final effluent; consequently, it was not possible to identify the specific treatment stages or internal processes responsible for the observed performance limitations.

CONCLUSIONS

The WWTP in Yauli exhibited low removal efficiency for the biodegradable fraction of the organic load, as evidenced by its failure to meet the maximum permissible limit (MPL) for BOD_5. In contrast, parameters such as COD, oils and fats (O&G), total coliforms (TC), and total suspended solids (TSS) showed satisfactory removal efficiencies and complied with the applicable regulatory limits, while pH and temperature remained within acceptable ranges. These findings indicate that, although the plant achieves satisfactory removal of several parameters, the limitations of trickling filter technology, excessive organic loading, and high-altitude conditions may constrain overall treatment performance and prevent full regulatory compliance. Therefore, improvements are needed to reduce the potential environmental impacts of the treated effluent.

It is recommended to evaluate technological improvements aimed at enhancing aerobic processes and incorporating more resilient systems, such as membrane bioreactors (MBR) or hybrid wetlands, which have demonstrated greater treatment capacity under high-Andean conditions.

For future research, annual monitoring covering seasonal variations is recommended, along with the inclusion of nutrient parameters (nitrogen and phosphorus) and critical operational variables, such as dissolved oxygen and flow rate. A larger sample size should also be considered to strengthen the statistical robustness of the findings. In particular, direct characterization of the trickling filter media and laboratory-based biodegradability tests would help verify the hypothesis of excessive organic loading and strengthen the assessment of the plant's treatment performance.

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