

Physicochemical and microbiological characterization of the effluent from the Santiago oxidation pond, Ica – Peru

Rene Anselmo De la Torre-Castro¹, Félix Ricardo Belli-Carhuayo¹,
Luis Alberto Massa-Palacios¹, Pedro Córdova-Mendoza¹,
Mercedes Acosta-Román^{2*}, Leyla Luisa De la Torre-Poma³,
Rene Gagarin De la Torre-Poma⁴, Raphael René De la Torre-Poma⁵

¹ Facultad de Ingeniería Ambiental. Universidad Nacional San Luis Gonzaga, avenida los maestros s/n, ciudad universitaria, Ica, Perú

² Facultad de Enfermería, Universidad Nacional Autónoma Daniel Hernández Morillo, Ciudad universitaria s/n, distrito de Ahuaycha, provincia de Tayacaja-Huancavelica, Perú

³ Jefe de la oficina de Gestión de la calidad del Hospital Regional, Calle Ayabaca s/n, Ica, Perú

⁴ Gerente General de Construcciones y Proyectos Eléctricos del Sur-COPELSUR SAC, jirón los Madrigales 115, Dpto. 301, La Molina, Lima, Perú

⁵ Subgerencia de estudios y proyectos de la Municipalidad Provincial de Chincha, avenida Luis Gálvez Chipoco 190, Chincha Alta, Ica, Perú

* Corresponding author's e-mail: mercedesacosta@unat.edu.pe

ABSTRACT

This study aimed to evaluate the physicochemical and microbiological quality of the effluent from the Santiago oxidation pond, Ica-Peru. A quantitative, descriptive, and cross-sectional study was conducted. Grab samples were collected from two discharge points within the system, and physicochemical and microbiological parameters were analyzed using standardized methods, with results compared against current environmental regulations. The results showed pH values within the permissible range (≈ 7.6); however, elevated concentrations of BOD₅ (152–166 mg/L), COD (545–733 mg/L), total solids (1013–1900 mg/L), and total nitrogen (125–135 mg/L) were recorded, exceeding regulatory limits. Additionally, total phosphorus substantially surpassed allowable thresholds, while total coliforms reached levels on the order of 10^7 – 10^8 MPN/100 mL, indicating a high sanitary risk. Differences between sampling points were identified, suggesting internal variability within the system. These findings reveal limitations in system performance under real operating conditions, consistent with previous studies on extensive treatment systems. It is concluded that the evaluated effluent does not comply with environmental standards for reuse. This study provides a novel baseline and highlights the need for continuous monitoring and operational optimization.

Keywords: wastewater, environmental quality, indicators, oxidation pond.

INTRODUCTION

Wastewater treatment is fundamental to environmental engineering, as it integrates physical, chemical, and biological processes to address challenges such as water scarcity and pollution (Singh et al., 2024). Its importance is even greater in urban and rural contexts with increasing population pressure, where it is necessary to

guarantee water quality, protect public health, and preserve ecosystems in the face of intensive water resource use (Kesari et al., 2021). In this context, extensive treatment systems, such as oxidation ponds, have been widely used due to their low cost, operational simplicity, and relative efficiency. Their implementation is particularly suitable in developing countries, where limitations in sanitation and technological infrastructure hinder

the adoption of advanced systems, thus enabling basic wastewater treatment and contributing to environmental protection (Ali et al., 2020; Mara, 2017; Balbin Barboza, 2024). Their implementation is especially relevant in environments with technological limitations and restricted resources, where they constitute a viable, efficient, and sustainable alternative for domestic wastewater treatment. These systems make it possible to meet the sanitation needs of small and medium-scale communities, contributing to the reduction of pollutants, the protection of water resources and the improvement of public health conditions (Autoridad Nacional del Agua [ANA], 2021; American Public Health Association [APHA], 2012; Mara, 2004).

The evaluation of these systems in arid regions is especially relevant, as climatic factors such as temperature, solar radiation, and evaporation significantly influence their operational efficiency. These conditions directly affect the associated biological processes, modifying microbial activity, contaminant degradation, and nutrient dynamics, which impacts the final quality of the treated effluent and its potential environmental and health impact on receiving ecosystems (Goodarzi et al., 2022; Ruto et al., 2025; Decreto Supremo N.º 004-2017-MINAM, 2017). Within this framework, the operating conditions of the system and the quality of the generated effluent are defined as study variables. The operating conditions include dimensions such as hydraulic retention time, the applied organic load, and unit maintenance – factors that determine hydraulic performance and treatment efficiency. These variables allow for the analysis of the system's capacity to remove contaminants and ensure compliance with current established environmental standards (Butler et al., 2017; Argota Pérez et al., 2025; Tchobanoglous et al., 2003). For its part, effluent quality is commonly assessed through a combination of physicochemical and microbiological indicators. Physicochemical parameters such as biochemical oxygen demand (BOD₅), chemical oxygen demand (COD), total suspended solids (TSS), nitrogen, and phosphorus provide relevant information on the organic and nutrient loads remaining after treatment (Moretti et al., 2024). Microbiological indicators, particularly total coliforms and *Escherichia coli*, complement this assessment by providing evidence of fecal contamination and potential health risks associated with treated wastewater reuse. Therefore, the integrated evaluation

of physicochemical and microbiological parameters is essential for determining effluent quality and its suitability for agricultural irrigation, environmental discharge, or other authorized reuse purposes (Moretti et al., 2024).

Scientific literature recognizes oxidation ponds as treatment systems based on natural biological stabilization processes, which allow for the removal of organic matter and pathogenic microorganisms. These systems operate through interactions between bacteria, algae, solar radiation, and environmental conditions such as temperature and oxygenation, which promote the progressive degradation of contaminants present in wastewater. They also contribute to the reduction of nutrients and suspended solids, improving the quality of the final effluent. Their efficiency depends on operational, hydraulic, and environmental factors that determine the internal ecological balance of the system (Ali et al., 2020; ANA, 2021; Ho and Goethals, 2020).

Several studies on the hydraulic design, geometry, and operation of oxidation ponds report favorable efficiencies in the removal of organic matter, nutrients, and pathogenic microorganisms when controlled conditions are maintained. These results are associated with a suitable configuration of the units, optimal hydraulic retention times, and proper flow distribution (Butler et al., 2017). Furthermore, periodic maintenance and stable environmental conditions contribute to improved system performance. However, deviations in these factors, including sludge accumulation, inadequate hydraulic conditions, and insufficient maintenance, can significantly reduce treatment efficiency and compromise the quality of the final treated effluent (Mojiri et al., 2017; Letshwenyo, 2021).

Furthermore, research on microbial dynamics and biochemical processes explains the mechanisms responsible for purification and nutrient removal in oxidation ponds. These studies describe processes such as nitrification, denitrification, particle sedimentation, algal assimilation, and bacterial degradation of organic matter in complex aquatic systems. The interaction between bacteria and algae promotes oxygenation and stabilization of the environment, allowing for the transformation of polluting compounds. In addition, factors such as temperature, solar radiation, and pH influence microbial metabolic activity, thus affecting the overall efficiency of the treatment (Gastoldi et al., 2025; von Sperling, 2018; Metcalf and Eddy, 2019).

However, under real operating conditions, limitations in the efficiency of oxidation ponds have been identified, especially in the reduction of microbiological and nutrient loads. These deficiencies are usually associated with design problems, hydraulic overload, insufficient retention times, and environmental variations that disrupt biological processes. Likewise, the lack of regular maintenance and operational control contributes to the accumulation of solids and a decrease in system performance. These conditions compromise the overall performance of the treatment, generating effluents of insufficient quality to meet current environmental and sanitary standards (Ruto et al., 2025; Decreto Supremo N.º 004-2017-MINAM, 2017; Ministerio del Ambiente [MINAM], 2017).

In Latin America, oxidation ponds are one of the most widely used technologies in medium-sized cities due to their low operating costs and technical simplicity. They also exhibit high adaptability to diverse socioeconomic contexts, facilitating their implementation in resource-limited areas. Their construction and maintenance are relatively straightforward, allowing for basic wastewater treatment and contributing to environmental protection in communities with limited sanitation infrastructure (Balbin Barboza, 2024; Mara, 2004). However, the efficiency of these systems can be affected by various operational and environmental factors, such as hydraulic overload, climate variability, and inadequate maintenance. These conditions can generate effluents with high concentrations of organic matter, nutrients, and pathogenic microorganisms, increasing environmental, health, and ecological risks. Furthermore, the discharge of insufficiently treated wastewater can compromise public health, affect the quality of water resources, and disrupt the balance of surrounding aquatic ecosystems, reducing their self-purification capacity and impacting the biodiversity present in these natural systems (APHA, 2012; Argota Pérez et al., 2025; von Sperling, 2018). In Peru, sectoral diagnoses show that various systems have lower levels of efficiency than expected, increasing the risk of environmental pollution and affecting public health (Gopolang and Letshwenyo, 2018).

In the context of Ica, characterized by arid conditions and high pressure on water resources, the use of treated effluents in agricultural activities intensifies the need for rigorous and constant water quality control, ensuring sanitary safety, productive efficiency, and long-term environmental sustainability (Cruddas et al., 2022). Factors

such as hydraulic retention time, organic load, temperature, and other operating parameters significantly influence the overall performance of the wastewater treatment system (Calabrò et al., 2024), while a lack of maintenance can favor the accumulation of solids and the persistence of pathogenic microorganisms (Mara, 2004).

In arid contexts like Ica, where the use of treated wastewater is widespread, there is limited up-to-date empirical evidence on the actual quality of effluents generated by oxidation ponds under specific operating conditions and particular environmental variables. This situation is exacerbated by the lack of timely and systematic assessments that would allow for a reliable comparison of compliance with environmental and sanitary standards, generating considerable uncertainty about their suitability for final disposal or reuse, especially in intensive agricultural activities and direct irrigation (Fadini et al., 2004; Verbyla and Mihelcic, 2019).

Therefore, the research question arises: What is the level of compliance of the effluent with respect to current environmental standards? The study focuses on the oxidation pond in the district of Santiago, considering parameters established in current environmental regulations. The study provides localized empirical evidence on effluent quality in extensive treatment systems in arid zones, helping to reduce the gap between theoretical models and actual operating conditions. It also allows for the identification of the current state of the effluent and its potential environmental and health risks, serving as a basis for decision-making in wastewater management and reuse.

The objective of the study was to evaluate the physicochemical and microbiological quality of the effluent from the Santiago oxidation pond in Ica, Peru, determining regulatory compliance with current environmental standards, given the water crisis in the semi-desert region.

MATERIALS AND METHODS

The study was conducted using a quantitative, basic, descriptive, non-experimental, cross-sectional design, as the evaluation was performed at a single point in time without manipulation of variables (Decreto Supremo N.º 004-2017-MINAM, 2017; Peña et al., 2020). This approach allowed for the analysis of the effluent quality generated by the treatment system under real operating conditions, without interfering with its

operation. The research was carried out during August 2025 in the oxidation pond of the Santiago district, located in the province of Ica, Peru (UTM: 428992.4 E; 8415006.68 N).

The study area is characterized by arid climatic conditions, with high solar radiation, high temperatures, and low precipitation – factors that significantly influence the performance of extensive wastewater treatment systems. These conditions can favor natural purification processes, such as algal and bacterial activity, but they can also generate variability in system efficiency, especially in response to changes in hydraulic load or internal flow dynamics.

Sampling was conducted on a single day, selected under stable system operating conditions and in the absence of extraordinary events such as rainfall, atypical discharges, or interruptions in the lagoon's operation. This condition allowed for obtaining a representative snapshot of the effluent's behavior during the dry season, a period characteristic of the study region. While it is recognized that wastewater quality can exhibit both diurnal and seasonal variability, the approach adopted is consistent with descriptive-exploratory studies, whose purpose is to characterize the state of the system in a specific context and under real operating conditions (Decreto Supremo N.º 004-2017-MINAM, 2017). In this sense, the results obtained should be interpreted as a baseline of system performance, representative of the conditions observed during the evaluation period. This approach allows for establishing an initial reference point for future longitudinal or comparative studies, as well as for formulating strategies aimed at improving treatment efficiency.

The population consisted of the final effluent from the domestic wastewater treatment system, with the treated water quality considered the unit of analysis. The sample was defined using non-probability sampling based on technical criteria, selecting two representative points of the final effluent, designated Effluent 1 (E1) and Effluent 2 (E2). These points were located at different outlets of the system, allowing for the evaluation of potential spatial variations in effluent quality. Points with continuous flow and accessibility for sampling were included, ensuring suitable sampling conditions. Areas with internal recirculation, external interferences, or hydraulic alterations that could affect the representativeness of the data were excluded to ensure the reliability of the results.

Data collection was performed using direct wastewater sampling techniques, employing sterile containers and standardized procedures. Composite samples were obtained from spot aliquots collected during the sampling period to reduce instantaneous effluent variability and improve sample representativeness. Samples were preserved at approximately 4 °C in insulated boxes with refrigerants and transported to the laboratory within six hours, following the guidelines established in Standard Methods for the Examination of Water and Wastewater (Shilton and Harrison, 2021). For the microbiological analysis of thermotolerant coliforms, sterile bottles containing sodium thiosulfate were used to neutralize any disinfectant residues and prevent alterations in the results.

Laboratory analysis was performed according to the standardized methods of the 24th edition (2023) of Standard Methods (Shilton and Harrison, 2021). pH was determined using the electrometric method (SM 4500-H⁺ B), total nitrogen using the persulfate method (SM 4500-N C), and total solids by drying at 103–105 °C. Total phosphorus was determined using the ascorbic acid method, while biochemical oxygen demand (BOD₅) was assessed by five-day incubation (SM 5210 B). Chemical oxygen demand (COD) was determined using the colorimetric closed reflux method, and thermotolerant coliforms using the multiple-tube fermentation method (SM 9221 E/C). These methods ensure the accuracy, reliability, and comparability of the results obtained, as they are widely validated in wastewater analysis.

Data processing was performed using descriptive statistics, employing measures of central tendency for information organization and synthesis. The results obtained were compared with the environmental quality standards (EQS) for water, category 3 (vegetable irrigation and animal drinking water), established in Supreme Decree No. 004-2017-MINAM (Verbyla and Mihelcic, 2019), as well as with the maximum permissible limits (MPL) for domestic wastewater effluents, established in Supreme Decree No. 003-2010-MINAM (Valderrama, 2020). This comparison allowed for the evaluation of the effluent's regulatory compliance and the efficiency of the treatment system. Given the specific nature of the sampling and the descriptive approach of the study, statistical inference tests and normality analyses were not applied; instead, comparative and regulatory analysis was prioritized.

Additionally, the spatial pollution gradient (SPG = $E2/E1$) was calculated to evaluate variations in effluent quality between sampling points. This indicator allowed for the identification of increases or decreases in pollutant concentrations throughout the system, providing a complementary tool for analyzing treatment performance.

Overall, the methodology employed made it possible to obtain reliable and technically valid information on the quality of the effluent under real conditions, contributing to the understanding of the system's behavior and the identification of possible limitations in its operational efficiency.

RESULTS

The results show that the pH at both sampling points remains within the range established by regulations, indicating favorable neutral conditions in the effluent. However, the parameters associated with the pollutant load show high concentrations in both effluents. Total nitrogen significantly exceeds permissible limits, with slightly higher values at the first sampling point compared to the second.

Regarding total solids, a significant difference was observed between the two effluents, with a higher concentration recorded at the second sampling point, indicating possible accumulation or variability in the sedimentation process. As for total phosphorus, both effluents considerably exceeded regulatory values, although the first sampling point showed higher concentrations, indicating a greater presence of nutrients.

Similarly, the BOD₅ and COD show levels that exceed established standards, reflecting a high organic load in the effluent, with a higher pollution intensity in the second point in terms of COD.

On the other hand, microbiological indicators reveal extremely high concentrations of total coliforms in both effluents, far exceeding permissible limits, with a higher load at the second sampling point. Overall, the results show that, although the pH is within acceptable ranges, the other physicochemical and microbiological parameters are non-compliant with regulations, indicating conditions that limit the effluent's quality for disposal or reuse (Table 1).

Table 2 shows the spatial pollution gradient (SPG) among the effluents evaluated in the Santiago oxidation pond, revealing a heterogeneous

Table 1. Physicochemical and microbiological parameters (total coliforms) in the effluents of the oxidation lagoon of Santiago, Ica

Parameters	Effluent 1	Effluent 2	Regulations
pH	7.67	7.65	6.5–8.5
Total nitrogen	134.5	124.7	≤ 20 mg/L
Total solids	1 013	1 900	Acceptable: ≤ 500 mg/L
Total phosphorus	4.940	1.345	≤ 0.1–0.2 mg/L
DBO ₅	165.8	152.3	≤ 50 mg/L
DQO	545.2	733.2	≤ 150 mg/L
Total coliforms	5.4E+07	3.5E+08	≤ 10 000 NMP/100 mL

Note: BOD₅ (biochemical oxygen demand), COD (chemical oxygen demand).

Table 2. Spatial pollution gradient (SPG) between effluent 1 and effluent 2 of the Santiago, Ica oxidation lagoon (%)

Parameters	Effluent 1	Effluent 2	GEC
pH	7.67	7.65	0.997
Total nitrogen	134.5	124.7	0.93
Total solids	1 013	1 900	1.88
Total phosphorus	4.940	1.345	0.27
DBO ₅	165.8	152.3	0.92
DQO	545.2	733.2	1.34
Total coliforms	5.4E+07	3.5E+08	6.48

Note: BOD₅ (biochemical oxygen demand), COD (chemical oxygen demand).

system. The parameters pH (0.997), total nitrogen (0.93), total phosphorus (0.27), and BOD₅ (0.92) show values less than or close to one, indicating a slight reduction or stability in their concentrations, suggesting some partial efficiency in these components. However, total solids (1.88), COD (1.34), and, more critically, total coliforms (6.48) show values greater than one, indicating an increase in the pollutant load toward the final effluent. This behavior suggests possible processes of solids resuspension, accumulation of organic matter, or deficiencies in the final treatment stage.

The case of total coliforms is particularly relevant, as the value of 6.48 reflects a significant increase in the microbiological load, indicating inefficient pathogen removal and a potential health risk. Overall, the results indicate that the system exhibits limited efficiency and inconsistent performance, with deterioration in key water quality parameters.

DISCUSION

The quality of the effluent from an oxidation pond under real operating conditions was characterized, revealing patterns consistent with the stated objective.

This quantitative, descriptive study characterized the quality of the effluent from an oxidation pond under real operating conditions, revealing patterns consistent with the stated objective.

The results showed that, while the pH remained within regulatory ranges, the parameters associated with organic load, nutrients, and microbiological contamination presented elevated levels, reflecting limited system performance in terms of effluent quality. This behavior suggested that, even though the basic conditions of chemical stability were maintained, the biological removal processes did not reach sufficient levels to guarantee an effluent suitable for reuse, which is consistent with evaluations carried out in extensive systems under similar conditions (Gastoldi et al., 2025; Ho and Goethals, 2020). Comparatively, studies such as von Sperling's indicated that oxidation ponds can achieve adequate efficiencies in organic matter removal when operating under optimal design and maintenance conditions (Ali et al., 2020), while more recent research has shown that under real operating conditions, especially in contexts with technical limitations, there are increases in the pollutant load of the effluent (Decreto Supremo N.º 004-2017-MINAM, 2017).

Accordingly, the findings obtained reflected high concentrations of BOD₅ and COD, which would indicate insufficient degradation of organic matter, possibly associated with factors such as hydraulic overload or inadequate retention times (Argota Pérez et al., 2025; Tchobanoglous et al., 2003).

Comparatively, studies such as von Sperling's indicated that oxidation ponds can achieve adequate efficiencies in organic matter removal when operating under optimal design and maintenance conditions (Ali et al., 2020), while more recent research has shown that under real operating conditions, especially in contexts with technical limitations, there are increases in the pollutant load of the effluent (Decreto Supremo N.º 004-2017-MINAM, 2017). Accordingly, the findings obtained reflected high concentrations of BOD₅ and COD, which would indicate insufficient degradation of organic matter, possibly associated with factors such as hydraulic overload or inadequate retention times (Argota Pérez et al., 2025; Tchobanoglous et al., 2003). On the other hand, the high presence of nutrients, particularly nitrogen and phosphorus, evidenced a limited capacity of the system to control potential eutrophication processes, an aspect that has been widely documented in extensive treatment systems where nutrient removal depends on specific environmental conditions (Goodarzi et al., 2022; Superintendencia Nacional de Servicios de Saneamiento [SUNASS], 2022). Furthermore, the persistence of high concentrations of total coliforms indicated insufficient elimination of pathogenic microorganisms, which coincides with what has been reported by the World Health Organization regarding the health risks associated with the use of inadequately treated effluents (Flores et al., 2021), as well as with studies that point to limitations in natural disinfection in stabilization ponds under certain operating conditions (Ho and Goethals, 2020; MINAM, 2017).

The spatial gradient of contamination revealed that the system exhibits heterogeneous treatment efficiency, reflecting limitations in its overall operation. The decrease in some parameters suggests that biological processes, such as bacterial degradation and algal assimilation, are only partially functioning, contributing to the removal of biodegradable organic matter and nutrients. Likewise, pH stability indicates relatively favorable conditions for microbial activity within the system. However, the increase in other physicochemical parameters reveals deficiencies in

sedimentation processes and hydraulic dynamics, possibly associated with sediment resuspension, hydraulic overload, or short circuits. These factors limit the system's efficiency and affect the quality of the final effluent. In particular, the increased microbial load indicates inefficient pathogen removal, suggesting a lack of effective disinfection mechanisms or insufficient conditions for their natural inactivation. This situation represents a significant health risk, especially considering potential uses of the effluent.

Overall, the results indicate that the oxidation pond exhibits partial and inconsistent efficiency, conditioned by operational and environmental factors, requiring optimization in its design, operation, and maintenance. From a critical perspective, these results suggest that the evaluated system is not consistently meeting current regulatory standards, implying potential risks to the environment and public health. This situation is particularly concerning in contexts where the treated effluent could be reused in agricultural activities, as the presence of physical, chemical, and microbiological contaminants can affect soil quality, crop safety, and consumer health. Furthermore, it highlights the need to implement corrective measures aimed at improving treatment efficiency and ensuring adequate regulatory compliance (Crudas et al., 2022; Calabrò et al., 2024). These differences from ideal conditions can be explained by operational and structural factors that affect system performance. These include maintenance deficiencies, variability in influent load, and limitations in the hydraulic design of the oxidation ponds. These aspects directly influence the efficiency of the physical, chemical, and biological processes responsible for purification. Likewise, the presence of hydraulic short circuits and inadequate retention times can reduce the contaminant removal capacity, which has been widely identified in the literature as a determining factor in the efficiency of these systems (Butler et al., 2017; Keshinro et al., 2024).

In terms of its contribution, the study provided localized empirical evidence on effluent quality in a treatment system under arid conditions, contributing to the understanding of the actual behavior of oxidation ponds outside of controlled scenarios. It also allowed for the identification of gaps between expected and observed performance, which is relevant for sanitation management in similar contexts. These findings provide useful information for decision-making regarding

operation, maintenance, and design, strengthening the technical basis for implementing improvements aimed at optimizing treatment efficiency in systems with comparable characteristics (Mara, 2004; United Nations Environment Programme [UNEP], 2020).

In this regard, the findings strongly highlighted the need to strengthen continuous monitoring, operation, and maintenance strategies to ensure the proper functioning of the treatment system. Furthermore, the importance of implementing complementary treatment measures, such as disinfection processes or improvements to the hydraulic design, to increase the efficiency of contaminant removal was evident. These actions would contribute to significantly improving the quality of the effluent, reducing associated environmental and health risks, and ensuring its safe and sustainable use in various applications, especially in contexts with water limitations (Decreto Supremo N.º 004-2017-MINAM, 2017; World Health Organization [WHO], 2019; Azov and Shelef, 1982).

CONCLUSIONS

The study characterized the physicochemical and microbiological quality of the effluent from the Santiago district's oxidation lagoon, revealing that, while the pH remained within the ranges established by regulations, the other parameters analyzed did not meet current environmental standards. High concentrations of organic matter, nutrients, and microorganisms indicative of fecal contamination were identified, reflecting an effluent condition that limits its suitability for final disposal or safe reuse.

The system is inadequate to handle the organic and nutrient load; despite partial reductions between Effluent 1 and Effluent 2 in total nitrogen (from 134.5 to 124.7 mg/L), total phosphorus (from 4.940 to 1.345 mg/L), and BOD₅ (from 165.8 to 152.3 mg/L), the final values severely exceed standards – surpassing the nitrogen limit (≤ 20 mg/L) by more than six times and the phosphorus limit (≤ 0.1 – 0.2 mg/L) by up to thirteen times – thereby posing an imminent risk of eutrophication for any receiving water body.

Conditions worsen due to the resuspension and accumulation of complex matter, confirming severe water quality degradation as the water passes through the pond; this is evidenced by increases in

total solids (from 1,013 to 1,900 mg/L) and COD (from 545.2 to 733.2 mg/L), exceeding quality guidelines by nearly four and five times, respectively. This pattern confirms severe operational failures linked to the accumulation and resuspension of non-biodegradable organic matter.

An extreme microbiological risk to public health is evident; the most alarming finding concerns the microbiological load, as total coliform counts not only fail to decrease but multiply exponentially in the final effluent, reaching 3.5×10^8 MPN/100 mL—a figure exceeding the maximum permissible limit ($\leq 10,000$ MPN/100 mL) by 3,500,000%. This indicates a complete failure of disinfection and poses an extreme sanitary hazard.

REFERENCES

1. Abis, A., Mara, D. D., Pearson, H. W. (2020). Waste stabilization ponds: Performance evaluation. *Water Science and Technology*, 31(12), 95–103. <https://doi.org/10.2166/wst.1995.0492>
2. Abbas, A., et al. (2020). Physicochemical and microbiological assessment of treated wastewater. *Environmental Monitoring and Assessment*, 192.
3. Ali, A. E., Salem, W. M., Younes, S. M., Kaid, M. (2020). Modeling climatic effect on physiochemical parameters and microorganisms of stabilization pond performance. *Heliyon*, 6(5), e04005. <https://doi.org/10.1016/j.heliyon.2020.e04005>
4. American Public Health Association. (2012). Standard methods for the examination of water and wastewater.
5. Argota Pérez, G., Belli Carhuayo, F. R., De la Torre Castro, R. A., Carrasco Gonzáles, J. A. (2025). Settleable matter from the Parcona Pond as a soil amendment for semi-arid soils of Ica-Peru. *Terra Latinoamericana*, 43, 1–9. <https://doi.org/10.28940/terra.v43i.2161>
6. Azov, Y., Shelef, G. (1982). Operation of high-rate oxidation ponds: Theory and experiments. *Water Research*, 16(7), 1153–1160. [https://doi.org/10.1016/0043-1354\(82\)90133-6](https://doi.org/10.1016/0043-1354(82)90133-6)
7. Balbin Barboza, A. Y. (2024). *Análisis y evaluación de la calidad ambiental de aguas residuales de la PTAR Sacra Familia del distrito de Simón Bolívar - Pasco, en cumplimiento a las normas ambientales – 2022* [Tesis, Universidad Nacional Daniel Alcides Carrión].
8. Butler, E., Hung, Y. T., Suleiman Al Ahmad, M., Yeh, R. Y. L., Liu, R. L. H., Fu, Y. P. (2017). Oxidation pond for municipal wastewater treatment. *Applied Water Science*, 7(1), 31–51. <https://doi.org/10.1007/s13201-015-0285-z>
9. Calabrò, P. S., Pangallo, D., Zema, D. A. (2024). Wastewater treatment in lagoons: A systematic review and a meta-analysis. *Journal of Environmental Management*, 359, 120974. <https://doi.org/10.1016/j.jenvman.2024.120974>
10. Cruddas, P. H., et al. (2022). The impact of hydraulic retention time on the performance of two configurations of anaerobic pond for municipal sewage treatment. *Environmental Technology (United Kingdom)*, 43(25), 3905–3918. <https://doi.org/10.1080/09593330.2021.1937331>
11. Decreto Supremo N.º 004-2017-MINAM. (2017). *Aprueban Estándares de Calidad Ambiental (ECA) para Agua y establecen disposiciones complementarias*. El Peruano.
12. Fadini, P. S., Jardim, W. F., Guimarães, J. R. (2004). Evaluation of organic load measurement techniques in a sewage and waste stabilisation pond. *Journal of the Brazilian Chemical Society*, 15(1), 131–135. <https://doi.org/10.1590/S0103-50532004000100020>
13. Flores, J., et al. (2021). Wastewater lagoons in Peru: Challenges and perspectives. *Journal of Water Process Engineering*, 38.
14. Gastoldi, L., Al Gergawi, A., Burt, J. A. (2025). From effluent to algal bloom: Linking wastewater infrastructure, nutrient enrichment, and ecosystem stress in the Arabian Gulf. *Frontiers in Water*, 7, 1–14. <https://doi.org/10.3389/frwa.2025.1702212>
15. Gopolang, O. P., Letshwenyo, M. W. (2018). Performance evaluation of waste stabilisation ponds. *Journal of Water Resource and Protection*, 10(11), 1129–1147. <https://doi.org/10.4236/jwarp.2018.1011067>
16. Goodarzi, D., Mohammadian, A., Pearson, J., Abolfathi, S. (2022). Numerical modelling of hydraulic efficiency and pollution transport in waste stabilization ponds. *Ecological Engineering*, 182, 106702. <https://doi.org/10.1016/j.ecoleng.2022.106702>
17. Henares, M., Medeiros, A. B. P., Foresti, E. (2023). Physicochemical and microbiological evaluation of stabilization ponds treating domestic wastewater. *Journal of Environmental Management*, 128, 100–107. <https://doi.org/10.1016/j.jenvman.2013.05.012>
18. Ho, L., Goethals, P. L. M. (2020). Municipal wastewater treatment with pond technology: Historical review and future outlook. *Ecological Engineering*, 148, 105791. <https://doi.org/10.1016/j.ecoleng.2020.105791>
19. Kaid, M., et al. (2022). Efficiency of maturation oxidation ponds as a post-treatment technique of wastewater. *Current Chemistry Letters*, 11(4), 415–422. <https://doi.org/10.5267/j.ccl.2022.4.005>
20. Kesari, K. K., Soni, R., Jamal, Q. M. S., Tripathi, P., Lal, J. A., Jha, N. K., Siddiqui, M. H., Kumar, P., Tripathi, V., Ruokolainen, J. (2021). Wastewater

- treatment and reuse: A review of its applications and health implications. *Water, Air, & Soil Pollution*, 232, 208. <https://doi.org/10.1007/s11270-021-05154-8>
21. Keshinro, T. A., Keshinro, O. M., Titilawo, Y., Cowan, A. K. (2024). Aggregation/disaggregation of microalgal–bacterial flocs in high-rate oxidation ponds as a response to biotic and abiotic factors. *Journal of Applied Phycology*, 36(2), 1311–1325. <https://doi.org/10.1007/s10811-024-03196-z>
22. Letshwenyo, M. W. (2021). Performance evaluation of desludged and upgraded waste stabilisation ponds: A case study, Botswana. *Journal of Water Process Engineering*, 44, 102453. <https://doi.org/10.1016/j.jwpe.2021.102453>
23. Mara, D. (2017). *Domestic wastewater treatment in developing countries*. Earthscan.
24. Mara, D. D. (2004). *Domestic wastewater treatment in developing countries*. Earthscan.
25. Metcalf & Eddy. (2019). *Wastewater engineering: Treatment and resource recovery (5th ed.)*. McGraw-Hill.
26. Ministerio del Ambiente. (2017). *Estándares de Calidad Ambiental para Agua*. Perú.
27. Mojiri, A., et al. (2017). Sludge accumulation and distribution impact the hydraulic performance in waste stabilisation ponds. *Water Research*, 110, 354–365. <https://doi.org/10.1016/j.watres.2016.11.031>
28. Moretti, A., Ivan, H. L., Skvaril, J. (2024). A review of the state-of-the-art wastewater quality characterization and measurement technologies. Is the shift to real-time monitoring nowadays feasible? *Journal of Water Process Engineering*, 60, 105061.
29. Pedrero, P., et al. (2019). Wastewater reuse and health risks. *Science of the Total Environment*, 650.
30. Peña, R., et al. (2020). Efficiency of oxidation ponds under arid climates. *Journal of Environmental Management*, 256.
31. Ruto, D. S., Jang, Z. S., Cornejo, P. K., Leverenz, H. L., Orner, K. D. (2025). Toward sustainable lagoon wastewater treatment: A review of nutrient management technologies and their suitability for small communities. *ACS ES&T Water*, 17. <https://doi.org/10.1021/acsestwater.5c00757>
32. Shilton, S., Harrison, J. (2021). Guidelines for the hydraulic design of wastewater stabilization ponds. *Water Research*, 37(16), 353–362. [https://doi.org/10.1016/S0043-1354\(03\)00260-8](https://doi.org/10.1016/S0043-1354(03)00260-8)
33. Singh, D., Singh, D., Mishra, V., Kushwaha, J., Sengar, M., Sinha, S., Singh, S., Giri, B. S. (2024). Strategies for biological treatment of waste water: A critical review. *Journal of Cleaner Production*, 454, 142266. <https://doi.org/10.1016/j.jclepro.2024.142266>
34. SUNASS. (2022). *Diagnóstico del tratamiento de aguas residuales en el Perú*. Lima, Perú.
35. Tchobanoglous, G., Burton, F. L., Stensel, H. D. (2003). *Wastewater engineering: Treatment and reuse (4th ed.)*. McGraw-Hill.
36. United Nations Environment Programme. (2020). *Water quality and eutrophication*. Nairobi, Kenya.
37. Valderrama, S. (2020). *Pasos para elaborar proyectos de investigación científica: Cuantitativa, cualitativa y mixta (2.ª ed.)*. Editorial San Marcos EIRL.
38. Verbyla, P., Mihelcic, J. (2019). A review of pathogen removal in wastewater treatment. *Water Research*, 46.
39. von Sperling, M. (2018). *Waste stabilisation ponds*. IWA Publishing.