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# Presence of potentially toxigenic cyanobacteria and characterization of the aquatic environment in the irrigation system of the Arequipa countryside, Peru

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## ABSTRACT

Cyanobacteria are organisms distributed worldwide and capable of adapting to various environmental conditions. They are known for their ability to produce toxins. The water bodies where they thrive are often sources of drinking water and are used for productive activities such as agriculture and recreation, representing risks to both the environment and human health. The objective of this study was to determine the presence of potentially toxigenic cyanobacteria and characterize the aquatic environment they inhabit within the irrigation system of the Arequipa countryside, Peru. Three sampling campaigns were conducted in November 2021 and in May and October 2022. The campaigns included the analysis of a reservoir, a river, and 14 ponds. The physicochemical characterization of the water was performed both in situ and in the laboratory. Additionally, phytoplankton and periphyton samples were collected and qualitatively analyzed in the laboratory. The results revealed the presence of 13 cyanobacteria genera: *Anabaena, Anabaenopsis, Aphanocapsa, Arthrospira, Calothrix, Chroococcus, Gloeothece, Leptolyngbya, Nostoc, Oscillatoria, Phormidium, Nodularia*, and *Microcystis*, of which 10 are considered potentially toxigenic. The recorded environmental characteristics included temperatures ranging from 8.56 °C to 22.68 °C, pH values between 7.59 and 9.80, electrical conductivity from 191 µS/cm to 1953 µS/cm, dissolved oxygen levels from 1.22 mg/L to 20.50 mg/L, and turbidity between 1.3 FNU and 291 FNU. The highest chlorophyll concentration, recorded at sampling point LM6, was 682.6 µg/L. The results indicate that the environmental conditions of the water bodies within the Arequipa irrigation system are suitable for the development of cyanobacteria, with a significant percentage of these genera previously reported as toxin producers. This study contributes valuable data for the implementation of monitoring plans focused on managing the risks associated with the presence of cyanobacteria and cyanotoxins in waters used for recreation, agriculture, and livestock activities.

**Keywords:** Arequipa, irrigation system, aquatic environment, toxigenic cyanobacteria.

## INTRODUCTION

Cyanobacteria are a highly diverse group of prokaryotic organisms with widespread distribution in aquatic ecosystems around the world, as well as in soils, biological soil crusts, snow, and cryoconites. This adaptability is attributed to their ability to tolerate extreme conditions (Gaysina et al., 2019; Jaskulska & Mankiewicz-Boczek, 2020). Traditionally, they have been classified based on their morphological characteristics observed through optical microscopy. However, the current polyphasic classification also incorporates ecological data, electron microscopy, and molecular biology tools, in addition to morphology (Komárek et al., 2014). The environmental conditions required for cyanobacteria development essentially include light and nutrients such as nitrogen and phosphorus. Cyanobacteria can thrive in a wide variety of environments, including saline, brackish, and freshwater bodies, and at both high and low temperatures. The optimal temperature for their growth is around 25 °C (Mur et al., 1999).

Cyanobacteria are of great importance due to their ability to form large algal blooms, which deteriorate water quality. Water bodies affected by algal blooms often become unsuitable for recreational and human consumption purposes, mainly due to the cyanobacteria's capacity to produce toxins that pose a public health risk. Cyanotoxins can cause liver damage, neurotoxicity, cytotoxicity, and dermatotoxicity in humans (Huisman et al., 2018; Igwaran et al., 2024). In agriculture, their presence affects plant growth and seed germination by increasing oxidative stress, reducing mineral absorption rates, and decreasing photosynthetic efficiency (Weralupitiya et al., 2022). Between 2000 and 2019, approximately 295 cyanobacterial blooms were reported across lakes, reservoirs, and rivers in Latin America. Countries such as Guatemala, Nicaragua, Colombia, Ecuador, Chile, Brazil, Paraguay, Argentina, and Uruguay have documented the presence of cyanotoxins (Aguilera et al., 2023). In Peru, scientific publications on cyanobacterial blooms and cyanotoxins are scarce. The few reports available indicate the presence of cyanobacteria and cyanotoxins in several water bodies, with genera such as *Dolichospermum* and *Microcystis* being prominent (Salazar-Torres et al., 2023). These genera were recently reported in the El Pañe reservoir (Arequipa, Peru), where they were detected using morphological and molecular methods (Rodríguez Uro et al., 2024).

The city of Arequipa, due to its environmental conditions, is an ideal location for the proliferation of cyanobacteria. Situated at an altitude of 2335 meters above sea level, it experiences semi-arid to desert climates, with precipitation occurring from December to May and annual temperatures averaging between 10 °C and 25 °C. Arequipa is one of the most important agricultural regions in Peru, with significant export potential (Quiroz, 2019). Additionally, it offers a variety of tourist and recreational attractions, including activities such as fishing, rafting, and boating. This study aims to document the presence of cyanobacteria and characterize the aquatic environments they inhabit within the irrigation system of the Arequipa countryside.

## METHODOLOGY

The study area includes the Aguada Blanca reservoir (AB) and ponds belonging to the irrigation system of the Arequipa countryside. These water bodies were divided into two groups corresponding to the right margin (RM) and left margin (LM) of the Chili River. In the Aguada Blanca reservoir, the sampling points were located in the central region of the reservoir body and near the dam (Figure 1). In the irrigation system, a total of 15 sampling points were selected, including the Chili River, as well as natural and artificial ponds distributed across the Arequipa countryside (Figure 2).

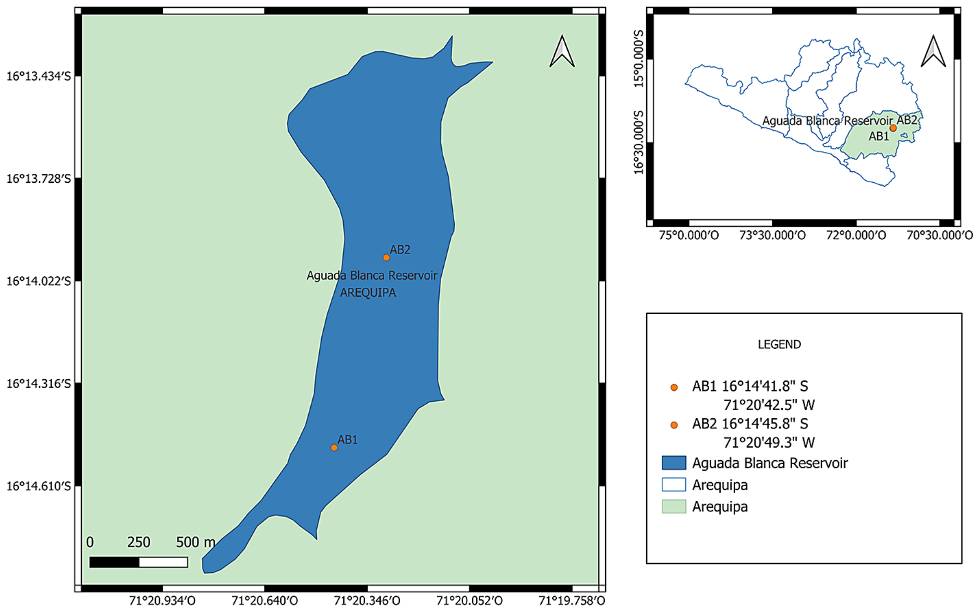


**Figure 1.** Map of the Aguada Blanca reservoir and sampling point locations

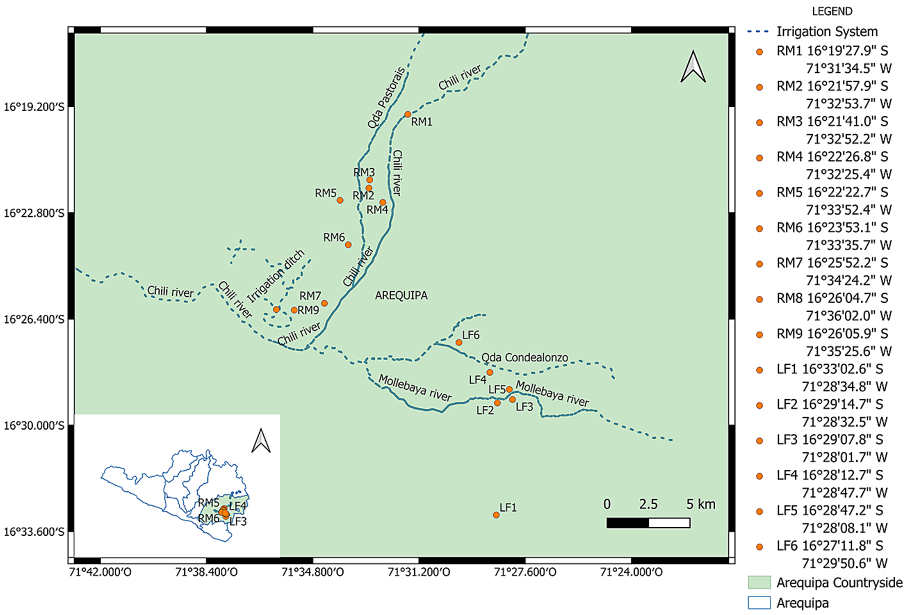


**Figure 2.** Map of the ponds sampled in the irrigation system of the Arequipa countryside

## Field methodology

Three sampling campaigns were conducted: during the dry season in November 2021, and during the wet and dry seasons in May and October 2022, respectively. Phytoplankton samples were collected through horizontal and vertical drags using a plankton net with a 20 µm mesh size. Periphyton samples were obtained by brushing and scraping surfaces. All samples were collected in 200 mL flasks and preserved with 4% formaldehyde (Samanez et al., 2014). Physicochemical parameters were measured in situ using a Hanna Instruments HI 9829 multiparameter probe (Romania, Hanna Instruments). The recorded parameters included temperature (°C), pH, electrical conductivity (µS/cm), dissolved oxygen (mg/L), and turbidity (FNU). At sampling points AB1, AB2, and LM6, surface water samples were directly collected in 1 L amber flasks for the analysis of chlorophyll (µg/L), total nitrogen (mg/L), and total phosphorus (mg/L). These samples were sent to an accredited laboratory for analysis.

### *Laboratory methodology*

The samples were analyzed qualitatively using optical microscopy. A Panthera C2 microscope (Motic, China) with an integrated camera (Motic Cam, China) was used. Observations were made at magnifications of 10×, 40×, and 100×, and Chinese ink was added to improve the visualization of colony mucilage (Mendoza, 2016). The identification of genera was based on the works of Komárek & Anagnostidis (1999, 2005) and Komárek (2013), and classification followed Komárek et al. (2014). The reported cyanobacteria were categorized as potentially toxic based on the genera described in scientific publications (Huisman et al., 2018; Igwaran et al., 2024).

# RESULTS AND DISCUSSION

## Characterization of sampling points

The irrigation system of the Arequipa countryside primarily consists of the Chili River, which is the most important river in the city. This river divides the city into two sections, prompting this study to separate the sampling zones into right and left margins. Additionally, the Aguada Blanca reservoir was included because a significant portion of the Chili River's water originates from this reservoir. A total of 14 ponds, both artificial and natural, were sampled (Table 1).

Most of the water bodies sampled are used for agricultural and livestock purposes, except for points AB, RM1, and LM6. The first (AB) serves as the main water source for the Arequipa population, while the latter two (RM1 and LM6) are used for recreational activities, including rafting and boating.

**Table 1.** Main characteristics and uses of the irrigation system in the Arequipa countryside

| Irrigation system | Water body | Use |
|---|---|---|
| Aguada Blanca reservoir (AB) | Reservoir | Source of water for drinking, agriculture, and livestock |
| RM1 | River | Agriculture, livestock, and recreational use |
| RM2 | Artificial pond | Agriculture and livestock |
| RM3 | Natural pond | Agriculture |
| RM4 | Artificial pond | Agriculture |
| RM5 | Natural pond | Agriculture |
| RM6 | Artificial pond | Agriculture and livestock |
| RM7 | Artificial pond | Agriculture |
| RM8 | Natural pond | Agriculture and livestock |
| RM9 | Natural pond | Agriculture and livestock |
| LM1 | Artificial pond | Agriculture and livestock |
| LM2 | Artificial pond | Agriculture |
| LM3 | Natural pond | Agriculture and livestock |
| LM4 | Artificial pond | Agriculture and livestock |
| LM5 | Artificial pond | Agriculture |
| LM6 | Natural pond | Agriculture and recreational use |

## Physicochemical parameters

The data for the physicochemical parameters are presented in Tables 2, 3, and 4, which show differences across the sampling seasons. During the dry season of 2021, the minimum temperature was 13.09 °C, and the maximum was 22.68 °C, the highest recorded across all campaigns. In the wet season of 2022, the minimum temperature was 8.56 °C, the lowest recorded for all sampling campaigns, while the maximum was 20.18 °C. Lastly, in the dry season of 2022, the minimum temperature was 9.62 °C, and the maximum was 21.54 °C. Regarding pH, all environments were alkaline, with values ranging from 7.59 to 9.80. Regarding the conductivity and total solids levels, elevated levels can be observed

**Table 2.** Physicochemical parameters during the dry season of 2021. C° (temperature), EC (electrical conductivity), TDS (total dissolved solids), D.O. (dissolved oxygen), turbidity

| Sample point | Temperature [°C] | pH | EC [µS/cm] | TDS [ppm] | D.O. [mg/L] | Turbidity FNU |
|---|---|---|---|---|---|---|
| AB1 | 12.48 | 8.49 | 211 | 105 | 5.90 | 5.7 |
| AB2 | 12.61 | 8.40 | 211 | 105 | 5.67 | 1.3 |
| RM1 | 12.45 | 7.76 | 246 | 123 | 6.79 | 3.5 |
| RM2 | 14.40 | 7.72 | 252 | 126 | 5.62 | 2.2 |
| RM3 | 13.73 | 7.96 | 249 | 125 | 7.91 | 2.5 |
| RM4 | 17.00 | 9.06 | 252 | 126 | 8.42 | 1.9 |
| RM5 | 16.49 | 8.33 | 248 | 124 | 7.35 | 2.3 |
| RM6 | 15.08 | 9.34 | 215 | 108 | 9.93 | 6.1 |
| RM7 | 19.09 | 9.50 | 636 | 318 | 20.50 | 7.0 |
| RM8 | 19.62 | 7.59 | 585 | 293 | 2.85 | 1.9 |
| RM9 | 17.93 | 7.72 | 583 | 292 | 1.22 | 26.8 |
| LM1 | 16.03 | 8.14 | 1664 | 832 | 5.99 | 0.5 |
| LM2 | 15.98 | 8.37 | 1209 | 604 | 7.47 | 0.5 |
| LM3 | 19.73 | 9.28 | 561 | 281 | 9.18 | 2.5 |
| LM4 | 22.68 | 8.17 | 674 | 337 | 5.97 | 1.3 |
| LM5 | - | - | - | - | - | - |
| LM6 | 21.06 | 9.27 | 913 | 457 | 14.04 | 39.3 |

**Note:** (-) pond without presence of water.

**Table 3.** Physicochemical parameters during the wet season of 2022. C° (temperature), EC (electrical conductivity), TDS (total dissolved solids), D.O. (dissolved oxygen), turbidity

| Sample point | Temperature [°C] | pH | EC [µS/cm] | TDS [ppm] | D.O. [mg/L] | Turbidity FNU |
|---|---|---|---|---|---|---|
| AB1 | 10.25 | 9.11 | 268 | 134 | 5.66 | 1.4 |
| AB2 | 10.56 | 8.37 | 279 | 139 | 5.15 | 12.6 |
| RM1 | 8.56 | 7.97 | 307 | 154 | 5.54 | 1.6 |
| RM2 | 9.92 | 7.97 | 316 | 158 | 6.23 | 1.0 |
| RM3 | 9.68 | 7.97 | 313 | 157 | 6.06 | 1.3 |
| RM4 | 12.55 | 9.43 | 308 | 154 | 9.40 | 7.3 |
| RM5 | 12.31 | 8.29 | 322 | 161 | 7.27 | 0.9 |
| RM6 | 12.04 | 8.77 | 322 | 161 | 8.66 | 15.3 |
| RM7 | 20.18 | 9.34 | 507 | 254 | 11.06 | 12.0 |
| RM8 | 19.93 | 9.12 | 652 | 326 | 10.29 | 2.5 |
| RM9 | - | - | - | - | - | - |
| LM1 | 13.06 | 8.15 | 1953 | 977 | 6.61 | 0.0 |
| LM2 | 13.64 | 8.06 | 1311 | 655 | 6.63 | 2.7 |
| LM3 | 14.74 | 9.07 | 622 | 311 | 9.52 | 3.4 |
| LM4 | - | - | - | - | - | - |
| LM5 | 15.47 | 8.38 | 676 | 338 | 7.23 | 0.0 |
| LM6 | 16.66 | 9.08 | 967 | 483 | 11.70 | 15.1 |

**Note:** (-) pond without presence of water.

**Table 4.** Physicochemical parameters during the dry season of 2022. C° (temperature), EC (electrical conductivity), TDS (total dissolved solids), D.O. (dissolved oxygen), turbidity

| Sample point | Temperature [°C] | pH | EC [µS/cm] | TDS [ppm] | D.O. [mg/L] | Turbidity FNU |
|---|---|---|---|---|---|---|
| AB1 | 10.76 | 8.00 | 191 | 95 | 8.77 | 1.9 |
| AB2 | 12.26 | 8.29 | 191 | 95 | 8.37 | 1.1 |
| RM1 | 9.71 | 7.78 | 229 | 115 | 8.30 | 2.3 |
| RM2 | 9.62 | 8.08 | 230 | 115 | 8.23 | 1.3 |
| RM3 | 12.17 | 8.66 | 230 | 115 | 10.09 | 291 |
| RM4 | 14.86 | 8.60 | 242 | 121 | 9.63 | 2.2 |
| RM5 | 16.88 | 8.36 | 249 | 124 | 7.45 | 1.6 |
| RM6 | - | - | - | - | - | - |
| RM7 | 21.54 | 9.13 | 424 | 212 | 11.36 | 7.8 |
| RM8 | 17.14 | 8.31 | 484 | 242 | 9.37 | 10.6 |
| RM9 | - | - | - | - | - | - |
| LM1 | 15.73 | 8.23 | 1675 | 838 | 2.55 | 0.0 |
| LM2 | 18.12 | 8.33 | 1103 | 551 | 9.99 | 0.0 |
| LM3 | 20.81 | 9.29 | 533 | 266 | 7.79 | 2.1 |
| LM4 | - | - | - | - | - | - |
| LM5 | 19.83 | 8.34 | 533 | 267 | 7.84 | 0.0 |
| LM6 | 20.33 | 9.00 | 806 | 403 | 10.73 | 21.3 |

**Note:** (-) pond without presence of water.

on the left margin during all three sampling campaigns, likely due to the water supplying this area coming from underground water seepage.

According to data from SENAMHI (National Meteorology and Hydrology Service of Peru), the Arequipa countryside experienced scarce precipitation between January and March 2021, which increased in 2022. Regarding temperature, the maximum recorded was 26.8 °C and the minimum was 7.2 °C during the dry season of 2021.

For the wet season of 2022, the maximum was 26.2 °C and the minimum 5.2 °C, while for the dry season of 2022, the maximum was 26 °C and the minimum 6.4 °C. The temperature variation in the region highlights the remarkable adaptability of cyanobacteria to grow and thrive under diverse conditions, especially considering Arequipa's altitude. According to Beaulieu et al. (2013), temperature is one of the primary factors influencing the growth of cyanobacteria, both on the water's surface and within the water column, along with nutrient and nitrogen levels.

Additionally, during the dry seasons of 2021 and 2022, total phosphorus, total nitrogen, and chlorophyll were analyzed at the Aguada Blanca reservoir and sampling point LM6. These analyses were conducted only at these locations due to the reservoir's importance as the primary water source for the city of Arequipa and the detection of the Microcystis genus at point LM6 in previous studies. These parameters are critical for understanding the trophic state of the water body and determining whether conditions favor or indicate the presence of cyanobacterial blooms. At the Aguada Blanca reservoir, a significant increase in chlorophyll levels was observed during the dry season of 2022, while extremely high chlorophyll levels were recorded at point LM6 during both seasons (Table 5). Chlorophyll is directly related to the biomass of microalgae. At point LM6, it reflects the abundant presence of microalgae, including cyanobacteria, recorded at this site.

## Morphological identification

A total of five orders, 10 families, and 13 genera of cyanobacteria were identified. During the dry season of 2021, five genera were recorded (Table 6), while seven genera were recorded during the wet season of 2022 (Table 7), and 11 genera during the dry season of 2022 (Table 8). Throughout the sampling campaigns, *Oscillatoria* was the most frequently recorded genus, appearing at most sampling points along with

**Table 5.** Levels of total phosphorus (Pt), total nitrogen (Nt), and chlorophyll *a* during the dry seasons of 2021 and 2022

| Sample point | Dry season 2021 | | | Dry season 2022 | | |
|---|---|---|---|---|---|---|
| | Pt [mg/L] | Nt [mg/L] | Chlorophyll *a* [µg/L] | Pt [mg/L] | Nt [mg/L] | Chlorophyll *a* [µg/L] |
| AB1 | 0.003 | 0.39 | 3.5 | 0.021 | 0.21 | 3.2 |
| AB2 | 0.009 | 0.31 | 2.2 | 0.019 | 0.21 | 16.5 |
| LM6 | 0.12 | 1.81 | 28.4 | 0.163 | 1.11 | 682.6 |

**Table 6.** Cyanobacteria present at the sampling points during the dry season of 2021

| Cyanobacteria | Dry season 2021 | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Aguada B. | | Right margin | | | | | | | | | Left margin | | | | | |
| | AB1 | AB2 | RM1 | RM 2 | RM 3 | RM 4 | RM 5 | RM 6 | RM 7 | RM 8 | RM 9 | LM1 | LM2 | LM3 | LM4 | LM5 | LM6 |
| *Aphanocapsa sp.* | | | | | | | | | | | | | | | | | |
| *Leptolyngbya sp.* | | | | | | | P | | | | | P | | | | | |
| *Arthrospira sp.* | | | | | | | | | | | | | | | | | |
| *Microcystis sp.* | | | | | | | | | | | | | | | | | F |
| *Gloeothece sp.* | | | | | | | | | | | | | | | | | |
| *Chroococcus sp.* | | | | | | | | | | P | | | | | P | | |
| *Oscillatoria sp.* | F | F | P | P | P | P | | | A | P | | A | A | | P | | |
| *Phormidium sp.* | | | | | | | | | | | | | | | | | |
| *Calothrix sp.* | | | | | | | | | | | | | | | P | | |
| *Anabaenopsis sp.* | | | | | | | | | | | | | | | | | F |
| *Nodularia sp.* | | | | | | | | | | | | | | | | | |
| *Anabaena sp.* | | | | | | | | | | | | | | | | | |
| *Nostoc sp.* | | | | | | | | | | | | | | | | | |

**Note:** (F) phytoplankton, (P) periphyton, (A) phytoplankton and periphyton.

**Table 7.** Cyanobacteria present at the sampling points during the wet season of 2022

| Cyanobacteria | Wet season 2022 | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Aguada B. | | Right margin | | | | | | | | | Left margin | | | | | |
| | AB1 | AB2 | RM1 | RM 2 | RM 3 | RM 4 | RM 5 | RM 6 | RM 7 | RM 8 | RM 9 | LM1 | LM2 | LM3 | LM4 | LM5 | LM6 |
| *Aphanocapsa sp.* | | | | | | | | | | | | | | | | | |
| *Leptolyngbya sp.* | | | | | | | P | | P | | | P | | | | | |
| *Arthrospira sp.* | | | | | | | | | | | | | | | | | |
| *Microcystis sp.* | | | | | | | | | | | | | | | | | F |
| *Gloeothece sp.* | | | | | | | | | | | | | | | | | |
| *Chroococcus sp.* | | | | | | | | | | P | | | | | P | | |
| *Oscillatoria sp.* | F | F | P | P | P | P | | | P | P | | A | A | P | P | P | |
| *Phormidium sp.* | | | | | | | | | | | | | P | | | | |
| *Calothrix sp.* | | | | | | | | | | | | | | | P | | |
| *Anabaenopsis sp.* | | | | | | | | | | | | | | | | | F |
| *Nodularia sp.* | F | F | | | | | | | | | | | | | | | |
| *Anabaena sp.* | | | | | | | | | | | | | | | | | |
| *Nostoc sp.* | | | | | | | | | | | | | | | | P | |

**Note:** (F) phytoplankton, (P) periphyton, (A) phytoplankton and periphyton.

**Table 8.** Cyanobacteria present at the sampling points during the dry season of 2022

| Cyanobacteria | Dry season 2022 | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Aguada B. | | Right margin | | | | | | | | | Left margin | | | | | |
| | AB1 | AB2 | RM1 | RM 2 | RM 3 | RM 4 | RM 5 | RM 6 | RM 7 | RM 8 | RM 9 | LM1 | LM2 | LM3 | LM4 | LM5 | LM6 |
| *Aphanocapsa sp.* | | | | | | | | | | | | P | | | | | A |
| *Leptolyngbya sp.* | | | P | P | P | | P | | P | P | | | P | P | | | |
| *Arthrospira sp.* | | | | | | | | | | | | F | | | | | |
| *Microcystis sp.* | | | | | | | | | | | | | | | | | F |
| *Gloeothece sp.* | | | | | | | | | | | | P | | | | | |
| *Chroococcus sp.* | P | | | | | | | | | P | | | | | | | |
| *Oscillatoria sp.* | F | | P | P | P | P | | | A | A | | A | A | P | | P | |
| *Phormidium sp.* | | | | | P | | | | | P | | | P | | | | |
| *Calothrix sp.* | | | | | | | | | | | | | | | | | |
| *Anabaenopsis sp.* | | | | | | | | | | | | | | | | | F |
| *Nodularia sp.* | | | | | | | | | | | | | | | | | |
| *Anabaena sp.* | P | | P | | A | | | | | | | | | | | | |
| *Nostoc sp.* | | | | | P | | | | | | | | | | | | |

**Note:** (F) phytoplankton, (P) periphyton, (A) phytoplankton and periphyton.

*Leptolyngbya*. Some genera were only observed at specific sampling sites, such as *Nodularia* at the Aguada Blanca reservoir, *Arthrospira* and *Gloeothece* at point LM1, and *Microcystis, Aphanocapsa* and *Anabaenopsis* at point LM6.

Regarding the presence of cyanobacteria, a total of 13 genera were recorded during the 2021 and 2022 seasons. At the Aguada Blanca reservoir, *Nodularia* was the only genus recorded exclusively during the wet season of 2022 (Table 7). Additionally, *Anabaena* was reported only during the dry season of 2022 (Table 8). Both genera are known for forming algal blooms, with the former being the only genus reported to produce the hepatotoxin nodularin (Catherine et al., 2016), while the latter can produce microcystins, cylindrospermopsins, anatoxin-a, and saxitoxins (Salomón et al., 2020). Although these genera were recorded during specific periods, continuous monitoring is necessary to prevent potential blooms, especially considering that chlorophyll levels at point AB2 increased during the dry season of 2022 compared to 2021 (Table 5).

At point LM6, the presence of *Microcystis* was recorded during all sampling campaigns. This genus is particularly significant as it is one of the most prevalent bloom-forming cyanobacteria, reported in at least 108 countries, 79 of which have also documented the presence of microcystins (Harke et al., 2016; Le et al., 2022). Constant monitoring is recommended, as Table 5 data show high chlorophyll levels in this area, with 28.4 µg/L recorded during the dry season of 2021 and excessively high levels of 682.6 µg/L during the dry season of 2022. These values indicate a fully eutrophic environment, where the presence of *Anabaenopsis* and *Aphanocapsa*—both capable of producing microcystins was also recorded. These findings are concerning, as this natural pond is used for both agricultural and recreational purposes, posing risks to nearby crops and public health for those who come into contact with its water, which is heavily frequented. In other regions of Peru, the *Microcystis* genus includes species such as *M. aeruginosa*, reported in Lake Chinchaycocha (Junín), Puerto Viejo (Lima), Lake Titicaca (Puno), and Lake Lagunillas (Puno), and *M. wesenbergii*, reported in Huacachina Lagoon (Ica) (Mendoza, 2016; Salazar-Torres et al., 2023). The most frequently observed genera across all sampling campaigns were *Oscillatoria* and *Leptolyngbya*, cyanobacteria commonly found in freshwater environments in both planktonic and benthic forms due to their wide variety of species (Hameed & Buniya, 2024; Komárek & Johansen, 2015). This explains their presence at most sampling points. *Oscillatoria* has been reported to produce microcystins, homoanatoxin-a, and saxitoxins, while *Leptolyngbya* has only been associated with microcystins (Salomón et al., 2020). These genera were found attached to various substrates, rocks, and canal walls originating from the ponds, emphasizing the need for better care and maintenance of irrigation systems.

*Phormidium* and *Nostoc* were minimally recorded across the sampling campaigns. *Nostoc* was found in its colonial form even in ponds that were beginning to dry up. Dodds et al. (1995) note that this genus is one of the most successful cyanobacteria due to its ability to survive extreme climates, including completely dry environments. Currently, *Nostoc* is extensively studied by pharmaceutical companies for its therapeutic properties, although it has also been reported to produce microcystins (Fidor et al., 2019). On the other hand, *Phormidium* has been increasingly reported worldwide, particularly in rivers, and is capable of producing microcystins, anatoxin-a, and homoanatoxin-a (McAllister et al., 2016).

Currently, there is no evidence that the genera *Chroococcus*, *Calothrix*, or *Gloeothece* can produce toxins, so they were not given much emphasis in this study. However, *Arthrospira* has been reported to contain microcystins in derived products, as noted by Rhoades et al. (2023) (Figure 3).

In recent years, the presence of cyanobacteria associated with the formation and duration of algal blooms due to the increase in global warming has caused great concern worldwide (Kim et al., 2024). A wide variety of studies exist regarding the risks posed by the presence of cyanobacteria and cyanotoxins to human health in recreational and drinking water. However, there are few reports concerning the presence of cyanobacteria in waters used for irrigation and the risks they pose to agriculture, livestock, and human health. The results obtained show the presence of cyanobacteria in the irrigation system, the small, shallow water bodies sampled in this study are sensitive to eutrophication, anthropogenic activity, and global warming, creating ideal conditions for the growth and blooming of cyanobacteria (Kuczyńska-Kippen et al., 2024).

Therefore, further studies on this genus are necessary, considering its commercial use as a dietary supplement for many people. As noted by Salazar-Torres et al. (2023), regulatory and control measures for cyanobacteria in Peru are virtually non-existent, with only a legal framework establishing a maximum limit of 0.001 mg/L of microcystin-LR in water bodies designated for human consumption. This regulation, however, excludes recreational and agricultural water use, among others, and is outlined in the Environmental Quality Standards (ECA) for Water (Supreme Decree No. 004-2017-MINAM). In Arequipa, the reservoir system within the Chili River basin is interconnected, with the Aguada Blanca reservoir collecting water from six upstream reservoirs. As of October 2023, the Majes Autonomous Authority (AUTODEMA) reported monitoring results for the region's main reservoirs, including Aguada Blanca. These assessments follow the World Health Organization (WHO) alert levels (1999), which consist of initial surveillance (200 cells/mL), Alert I (2,000 cells/mL), and Alert II (100,000 cells/mL), and the WHO guidelines (2021), which include

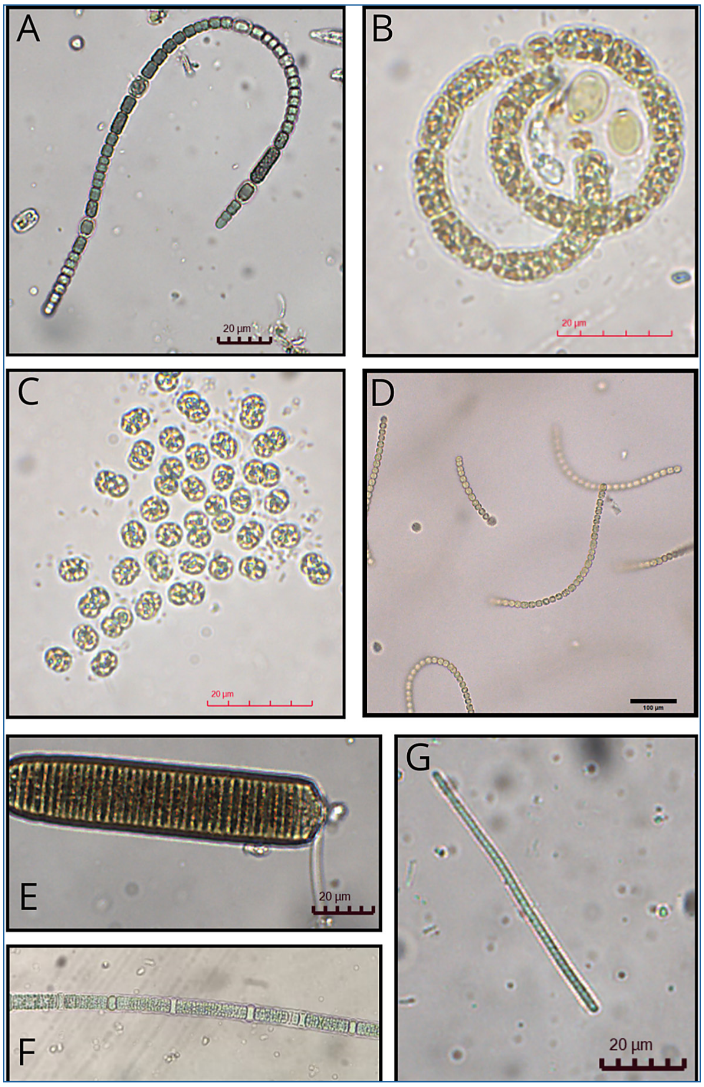


**Figure 3.** Potentially toxic cyanobacteria: (A) *Anabaena* sp. 40x, (B) *Anabaenopsis* sp. 100x, (C) *Microcystis* sp. 100x, (D) *Nostoc* sp. 10x, (E) *Oscillatoria* sp. 40x, (F) *Nodularia* sp. 40x, and (G) *Phormidium* sp. 40x

surveillance (10 colonies/mL or 50 filaments/mL), Alert I (≥ 0.3 $mm^3/L$), and Alert II (≥ 4.0 $mm^3/L$). The monitoring data highlight episodes of cyanobacteria dominance in the El Pañe reservoir, where Rodríguez Uro et al. (2024) reported the presence of the genera *Dolichospermum* and *Microcystis*, as well as microcystin-LR concentrations of 40.60 µg/L and 25.18 µg/L in May and November 2022, respectively. These values exceed the regulatory limits for the El Pañe reservoir. However, for the ponds located in the Arequipa countryside, there are no prior records of cyanobacteria presence. This study identified only the presence of cyanobacteria genera and potentially toxic cyanobacteria in the irrigation system of the Arequipa countryside. Therefore, further in-depth studies are recommended to determine the species-level diversity of cyanobacteria and their toxin-producing capabilities. These studies will assist authorities in managing the risks associated with the presence of cyanobacteria and cyanotoxins in water used for human consumption, recreation, agriculture, and livestock.

## CONCLUSIONS

Under the environmental conditions of the Aguada Blanca reservoir, the Chili River, and the 14 irrigation ponds studied, a total of 13 cyanobacteria genera were recorded, 10 of which are considered potentially toxigenic cyanobacteria. These include *Anabaena, Anabaenopsis, Aphanocapsa, Arthrospira, Leptolyngbya, Nostoc, Oscillatoria, Phormidium, Nodularia*, and *Microcystis*. These cyanobacteria come into contact with the environment and humans through agricultural activities, recreation, or as a water source for human consumption. This study provides valuable knowledge about the presence of cyanobacteria and the environmental conditions under which they develop within the irrigation system of the Arequipa countryside. These results serve as a foundation for managing the risks associated with exposure of the Arequipa population to cyanobacteria and cyanotoxins in water bodies designated for human consumption, agriculture, livestock, and recreational purposes.

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