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Article

Metals, sulfur content, and biochemical composition of macrocolonies of *Nostoc* sp. in different geographical locations in Ecuador

Ever Morales Avendaño [1], Jhonny Correa-Abril [2], Elvia V. Cabrera [2], Nilo M. Robles Carrillo [2,3], Andrés Arevalo Moreno [4], Mabel Cadena Zumárraga [5]*

[1] Escuela Superior Politécnica Agropecuaria de Manabí ESPAM MFL/ Manabí / Ecuador.
[2] Universidad Central del Ecuador, Facultad de Ingeniería Química, Grupo de Investigación en Alimentos, Compuestos Orgánicos, Materiales, Microbiología Aplicada y Energía (ACMME) / Quito / Ecuador; jgcorrea@uce.edu.ec.
[2] Universidad Central del Ecuador, Facultad de Ingeniería Química, Grupo de Investigación en Alimentos, Compuestos Orgánicos, Materiales, Microbiología Aplicada y Energía (ACMME) / Quito / Ecuador; evcabreram@uce.edu.ec.
[2] Universidad Central del Ecuador, Facultad de Ingeniería Química, Grupo de Investigación en Alimentos, Compuestos Orgánicos, Materiales, Microbiología Aplicada y Energía (ACMME) / Quito / Ecuador; nmrobles@uce.edu.ec.
[3] Instituto de Investigación Geológico y Energético IIGE / Pichincha / Ecuador; nilo.robles@geoenergia.gob.ec.
[4] Investigador Independiente / Pichincha / Ecuador; andresare_bio@hotmail.com.
[5] Universidad Metropolitana del Ecuador / Pichincha / Ecuador; fcadena@umet.edu.ec.
*Correspondence: edmorales@espam.edu.ec

ABSTRACT

Nostoc sp. is a cyanobacterium identified in several localities of Ecuador, and it exhibits significant potential in the pharmaceutical, food, and environmental sectors, which urges the exploration of its possible applications in the country. Macrocolonies of *Nostoc* sp. were collected at different seasons, and the content of metals, sulfur, and biochemical composition was analyzed according to altitude and geographic position. The results showed that the average carbohydrate content corresponds to 30.34% dry biomass, 27.38% ash, 25.33% protein, 7.66% crude fiber, and 0.71% fat. Regarding the content of metals and elements, it was found that Aluminum presented the highest value of 2049.23 mg/kg, followed by 1786.74 mg/kg, 1364.08 mg/kg, and 443.12 mg/kg of Fe, Mg, and S, respectively, and with the lowest for Cu, Ni, Pb, and Cd of 7.34 mg/kg, 5.62 mg/kg, 3.99 mg/kg and 0.74 mg/kg; respectively; with the following descending order: Al>Fe>Mg>S>Cu>Ni>Pb>Cd at all sites sampled and regardless of altitude and period of rain or drought. Consequently, its potential to adsorb these elements from the environment is preliminarily demonstrated, showing that it could be used in applications for bioremediation of contaminated soils and waters or be an essential bioindicator of environmental pollution.

Keywords: *Nostoc* sp., biochemical composition, bioremediation, metals, sulfur

INTRODUCTION

Cyanobacteria represent a diverse group of photosynthetic microorganisms, recognized as some of Earth's oldest and most versatile organisms. They exhibit various morphologies, nutritional characteristics, and ecological roles, allowing them to adapt to multiple terrestrial and aquatic habitats. Certain species, such as *Leptolyngbya, Oscillatoria*, and *Spirulina,* are of biotechnological interest. Others, including *Anabaena*, *Calothrix*, *Cylindrospermum*, *Nodularia*, *Scytonema*, and *Nostoc*, are environmentally significant due to their capacity to bioindicate metals and their diazotrophic ability, which provides a competitive advantage under nitrogen-limited conditions[1.4].

Cyanobacteria often face stressors such as herbicides, salinity, temperature, and pH fluctuations, alongside heavy metal contamination. In such conditions, they can adsorb, detoxify, or volatilize metals in their growth substrate[5,6]. Among these mechanisms, adsorption is an effective technique for removing contaminants from water bodies[7,8]. Cyanobacterial strains outperform other microorganisms with their unique biochemical composition and exopolysaccharides, facilitating efficient adsorption processes[9].

Most cyanobacteria quickly adapt to adverse abiotic conditions and can even thrive. They utilize waste materials as a nutrient source and eliminate environmental contaminants through enzymatic activities[10]. In many cases, the abundant proliferation of cyanobacterial colonies in these environments suggests their practical use as biosorbents for removing chemical compounds from wastewater and other contaminated substrates[11,12]. This highlights their ecosystem services, which remain to be studied in greater depth in the field and laboratory.

Like many other cyanobacteria, the genus *Nostoc* shows remarkable resilience to extreme environments and metal contamination, dehydration, and repeated freeze-thaw cycles, aiding its adaptation to terrestrial habitats[13,14]. This adaptability to environmental changes, such as drought and rainfall, is attributed to its high exopolysaccharide content, which acts as a protective barrier. These compounds also shield against ultraviolet radiation and function as chelating agents in the bioabsorption of metals, including Cd, Cr, Pb, Fe, Ni, Cu, and Zn[15-20]. *Nostoc linckia*, for instance, has demonstrated the ability to bioaccumulate these metals via atmospheric, aquatic, and soil pathways[21]. Additionally, exopolysaccharides contribute to biocrust formation and support soil recovery under water stress conditions[22,23].

In Ecuador, only one study has documented the identification of various *Nostoc* morphotypes and isolating and cultivating a strain from Napo province[24]. However, specific and detailed information on this *Nostoc* strain is lacking, despite its macrocolonies being observed at altitudes ranging from 19 to 4,000 meters above sea level in Pichincha, Napo, Orellana, Morona Santiago, Zamora-Chinchipe, Sucumbíos, Tungurahua, and Manabí provinces. In these regions, *Nostoc* can occupy extensive areas of soil and cement, with its aerial biomass decreasing during drought periods and growing visibly during the rainy season. This indicates notable adaptability despite limited nutrient accessibility, as this species is nitrogen-fixing.

This study is therefore significant in exploring whether altitude and latitude alter the biochemical properties of *Nostoc* sp. and its bioaccumulation capacity for various chemical elements, as well as its potential as a bioindicator of metals. The research aims to propose possible applications for *Nostoc* sp. in environmental biotechnology, emphasizing its ability to fix atmospheric nitrogen, its potential as a biofertilizer for nitrogen-depleted soils, and its efficiency in adsorbing chemical elements from soil or water.

MATERIAL AND METHODS

Collection Areas

Colonies of *Nostoc* sp. with wet biomass of 4–5 kg were collected from eight locations across six provinces in Ecuador (Figure 1) during different seasons from 2012 to 2021. These collection sites belonged to páramo ecosystems, coastal deciduous forests, and Amazonian tropical rainforests. All fresh samples were transported to the Faculty of Chemical Engineering - Universidad Central del Ecuador laboratory, where they were washed and cleaned to remove impurities. Finally, the samples were air-dried for subsequent biochemical studies and analysis of metal and sulfur content.

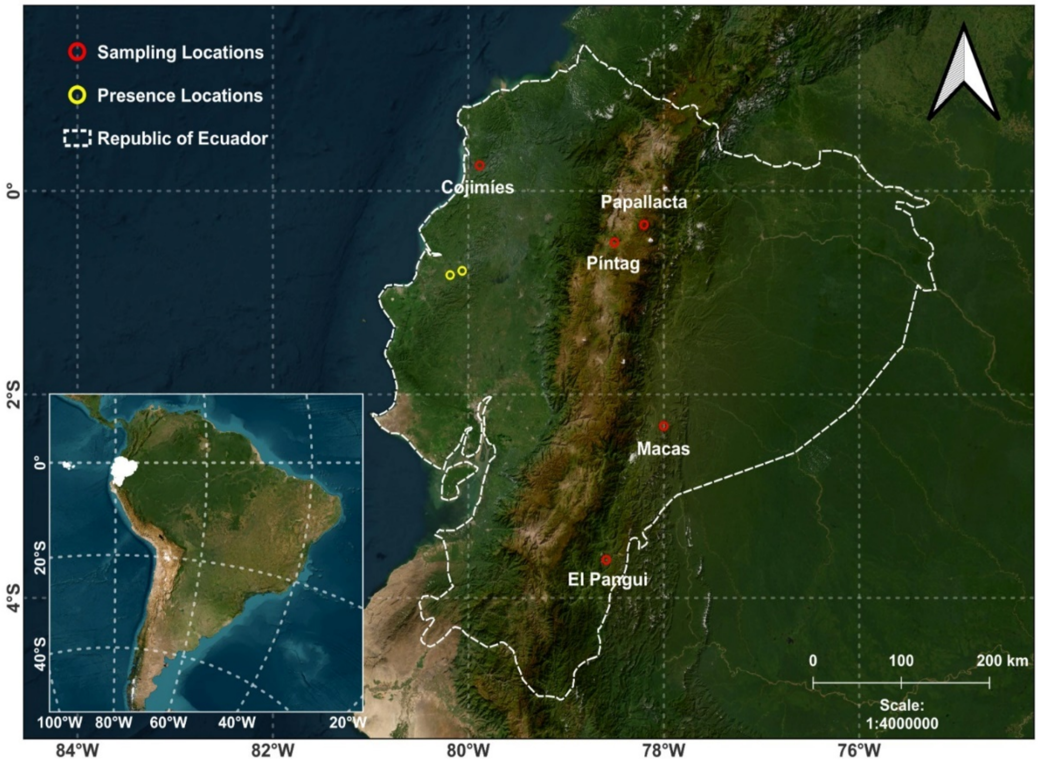


Figure 1. Geographical location of *Nostoc* sp. sampling sites.

Biochemical Composition Analysis

Protein content was evaluated using the Kjeldahl nitrogen determination method with a Behr-Labor behrotest® Kjeldahl analyzer, employing dried biomass as described by López et al.[25]. Lipid quantification followed the ICA 37/1990 method using 30 g of dried, ground sample[26]. Total Dry matter (TDM) and ash content were measured using a METTLER TOLEDO TGA 1 Star thermogravimetric balance, heating samples from 25 °C to 700 °C at 5 °C/min in an inert atmosphere, followed by 20 minutes in an oxidizing atmosphere at 700 °C. Carbohydrate content was determined using the standard volumetric method by Ramzija Cvrk[27,28]. Crude fiber (Fiber C) was determined using the Kűrschner-Hanak method, which consists of weighing 1000 g of the crushed sample, placing it in a 100 mL flask, adding 25 mL of 80% acetic acid and 2.5 mL of concentrated nitric acid, keeping the mixture under reflux for 30 minutes. Subsequently, the solution was filtered, and the precipitate was washed with a hot blend of acetic and nitric acid, hot water, ethanol, and petroleum ether, then dried at 105 °C for 30 minutes in an oven. Total digestible nutrients (TDN) were determined following the Lofgreen protocol[29].

Metals and Sulfur Content Analysis

Cadmium (Cd), copper (Cu), iron (Fe), magnesium (Mg), Lead (Pb), Aluminum (Al), and nickel (Ni) concentrations were analyzed using flame atomic absorption spectrophotometry with a Perkin Elmer AAnalyst 400. Samples were previously subjected to digestion, following the protocol described in the Application Book of the Milestone SK-10 microwave digester. 0.5 g of sample was used, which was digested with 6 mL of 65% nitric acid (HNO_3) and 2 mL of 30% hydrogen peroxide (H_2O_2). Heating was carried out from 25 °C to 200 °C for 15 min, maintained at 200 °C for 15 min.

The sulfur content was determined by elemental analysis using an Elementar equipment model Vario MACRO Cube. In this procedure, the sample is combusted in the presence of a catalyst, and the combustion gases are transported by an inert gas (helium) to selective sensors for each gas. Subsequently, the gases are thermally desorbed and analyzed by a thermal conductivity detector, which provides a signal proportional to the concentration of each component of the sample[30].

Statistical Analysis

The coefficient of variation assessed variability in *Nostoc* sp. biomass in terms of biochemical composition and metal and sulfur content. Pearson's correlation coefficient established relationships between biochemical composition, metal and sulfur concentrations, and sample collection altitudes.

Box-and-whisker plots visualized data distribution, aiding in identifying outliers and comparative analysis of element concentrations and biochemical composition. All statistical analyses and visualizations were performed using Origin 2024 and Microsoft Excel.

RESULTS

Figure 9 presents critical data on altitude, seasonality, location, and other crucial aspects of the sampling sites for *Nostoc* sp., facilitating the characterization of environmental conditions in which the samples were collected. For biochemical characterization, Figure 2 visually compares the various biochemical components analyzed across the sampling sites. Additionally, Figure 3 illustrates the relationship between water-soluble biomolecular carbohydrates (CBHs) and the altitude of collection. This analysis is based on the data in Figure 10, which details the biochemical composition of *Nostoc* sp. samples and includes descriptive statistics for parameters such as total dry matter (TDM), ash, proteins, lipids, CBHs, crude fiber (C.F.), and total digestible nutrients (TDN). The figure data indicate that TDN constitutes the most significant proportion of the dry weight of this cyanobacterium, followed by CBHs, ash, and proteins in order of abundance. Lipid content was the lowest, followed by crude fiber, suggesting notable nutrient utilization efficiency in these organisms.

Figure 4 compares the concentrations of various elements analyzed in *Nostoc* sp. samples. The heatmap (Figure 5) provides a detailed visual representation, facilitating the comparison of element distributions across sampling sites. Additionally, Figure 6 analyzes the linear relationships between different elements and the altitude of the collection. This analysis relies on data from Figure 11, which summarizes the metal and sulfur content of the samples, along with descriptive statistics. Aluminum (Al) was identified as the most abundant metal, followed by iron (Fe) and magnesium (Mg).

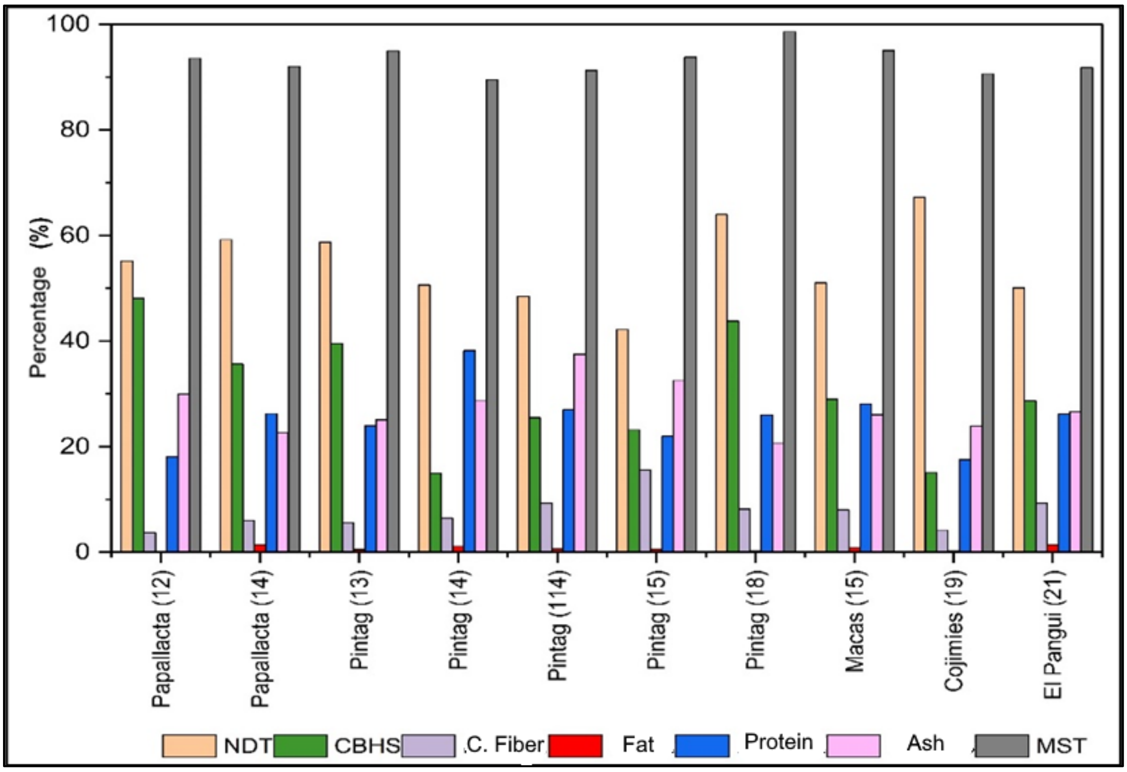


Figure 2: Grouped bars comparing biochemical composition based on Nostoc sp. sampling sites.

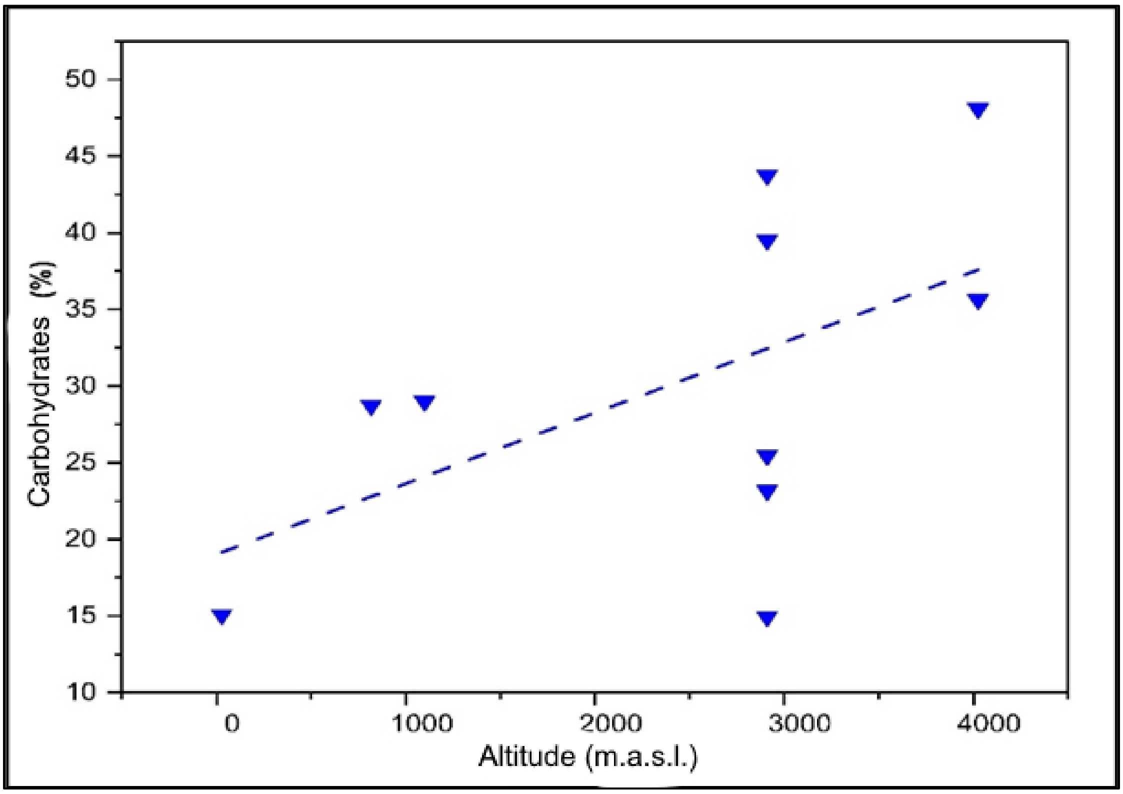
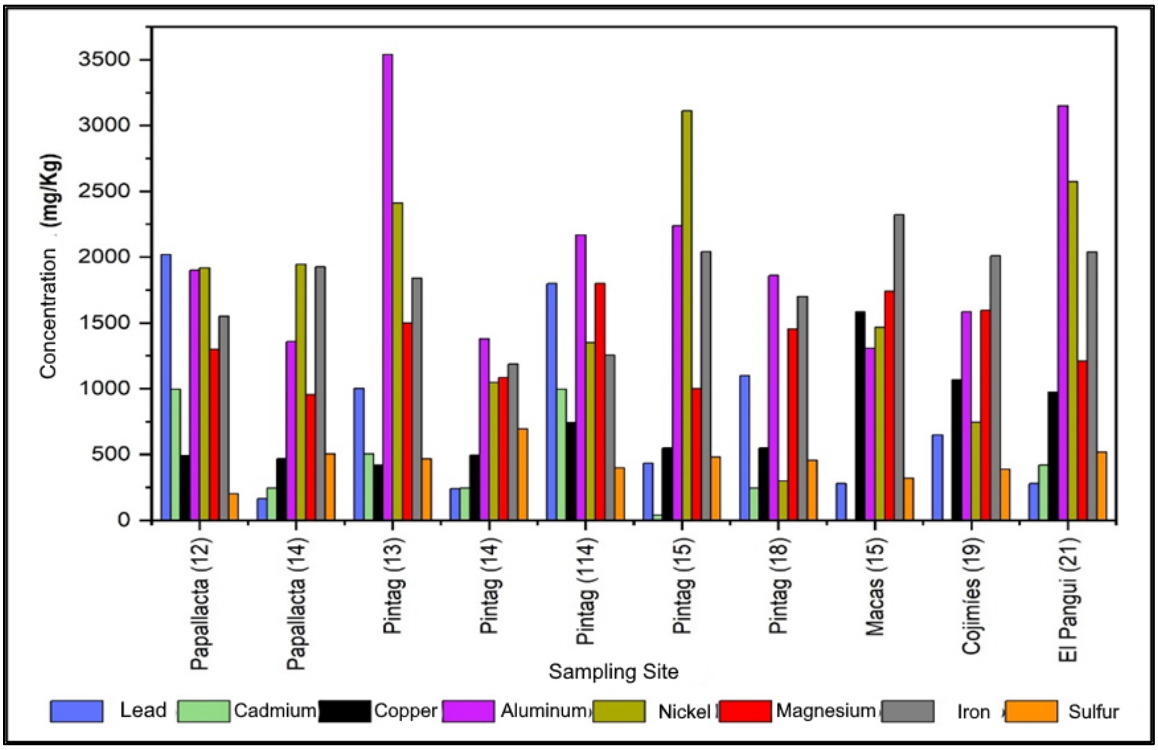
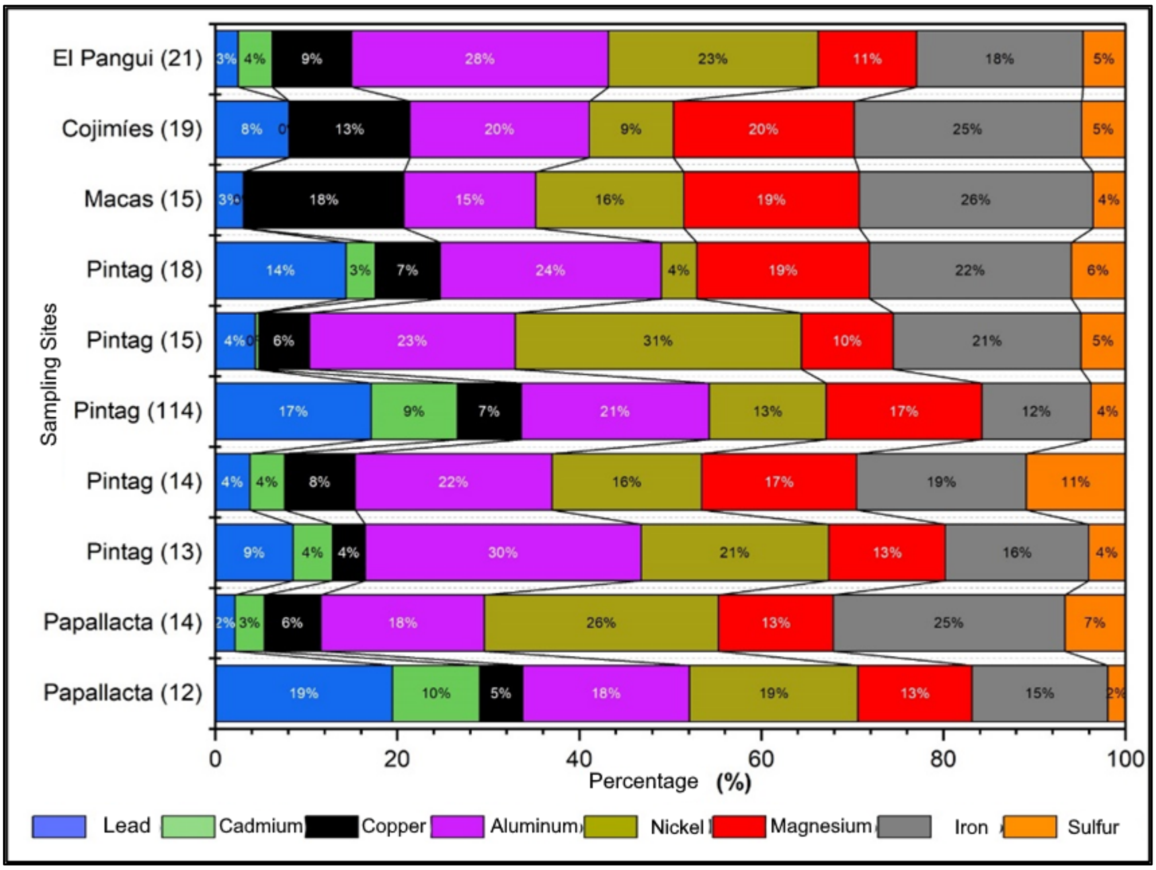


Figure 3: Relationship between carbohydrate percentage and the altitude of *Nostoc* sp. sample collection.



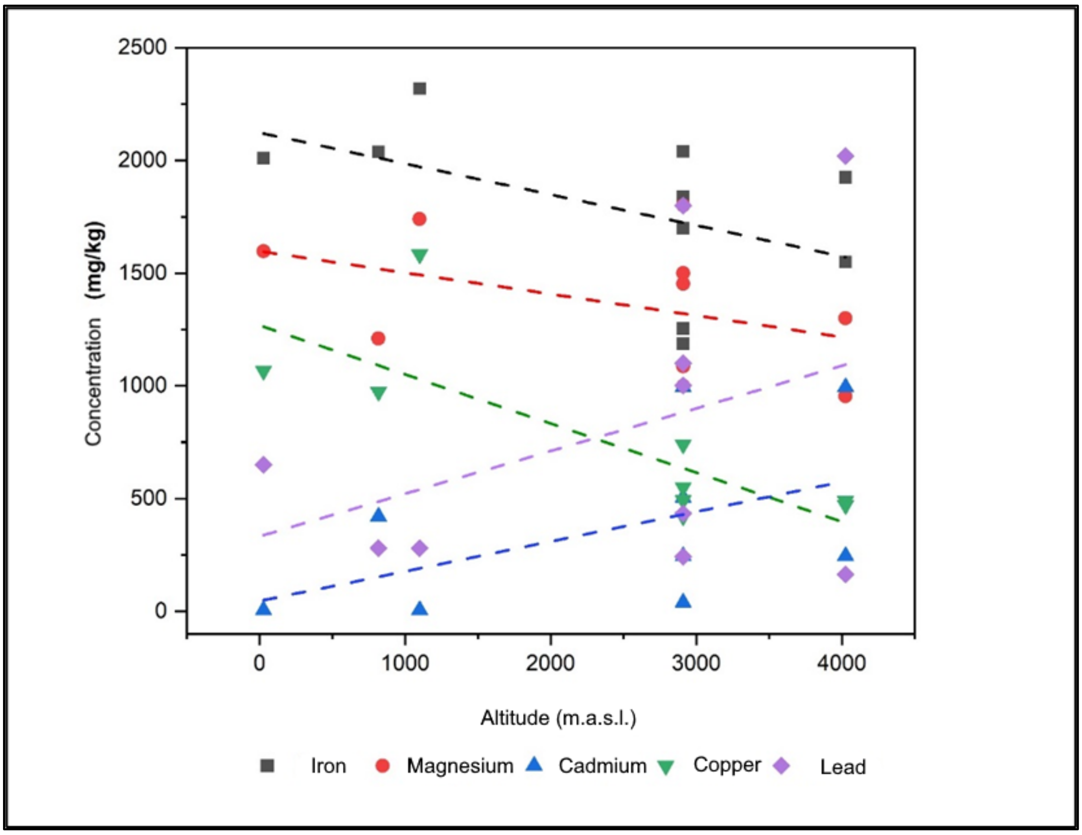
Nickel *300, Cadmium *500, Copper *100, Lead *200.

Figure 4: Grouped bars showing elemental concentrations based on *Nostoc* sp. sampling sites.



Nickel *300, Cadmium *500, Copper *100, Lead *200.

Figure 5: Heatmap of elemental concentrations by sampling site for *Nostoc* sp.



Nickel *300, Cadmium *500, Copper *100, Lead *200.

Figure 6: Linear relationships of elemental concentrations with sample collection altitude for *Nostoc* sp.

The detailed analysis of Figure 7 (box-and-whisker plot for biochemical composition) reveals that the TDN component has a wide distribution, with a median of around 70%. CBHs exhibit a more compact box, indicating a homogeneous distribution, with a median near 55%. Crude fiber (C.F.) shows a slightly lower median, just under 40%, with relatively low dispersion. Lipids, on the other hand, display more variability, with a median of around 25%. Proteins have the highest median, close to 90%, with minimal dispersion, while ash shows a highly compact distribution, with a median near 10%. Finally, TDM exhibits significant dispersion, with a median of around 90%. This detailed biochemical composition analysis identifies concentration and variability patterns in the studied components, which is crucial for the characterization and quality control of the materials.

The distribution of elemental concentrations, presented in Figure 8 (box-and-whisker plot for chemical elements), highlights exciting patterns. Some elements, such as Aluminum (Al) and iron (Fe), display more excellent dispersion, while others, like sulfur (S), show a more concentrated distribution. The presence of individual points outside the whiskers indicates outliers or extreme values for specific elements, such as Lead (Pb), copper (Cu), and sulfur (S). Additionally, comparing the medians reveals that Al has the highest central concentration. Conversely, the size of the boxes reflects the interquartile range, indicating the range in which the central 50% of the data is concentrated. Elements such as Cadmium (Cd) and copper (Cu) show a narrower interquartile range, indicating more homogeneous distributions.

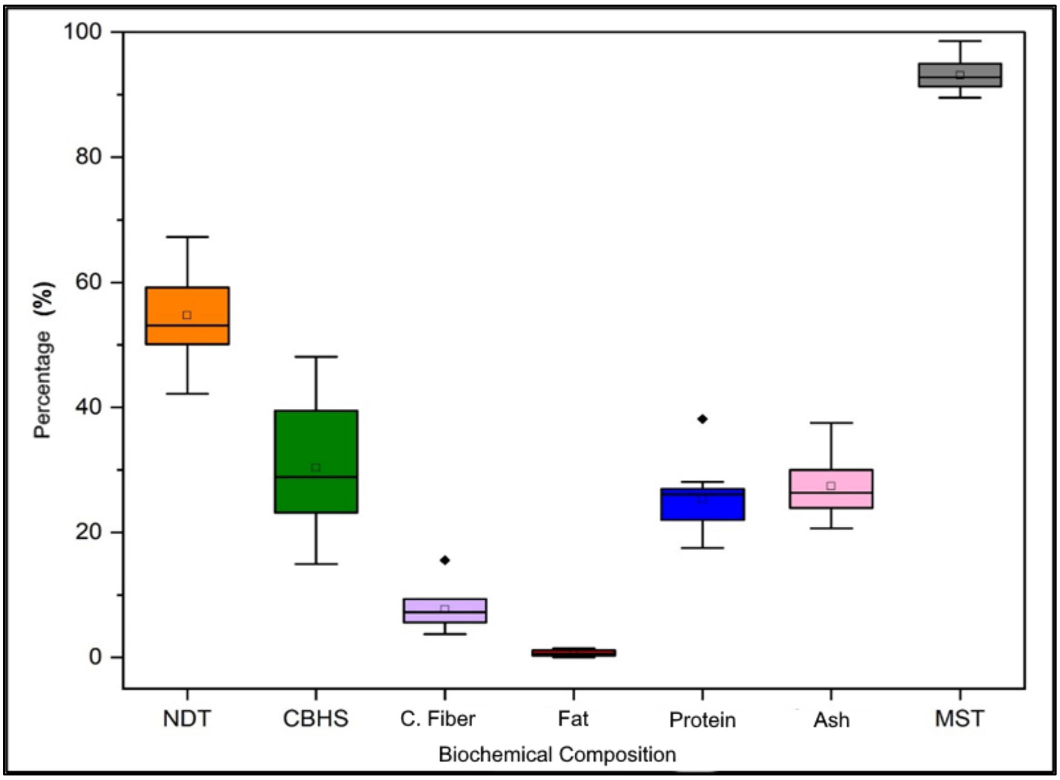


Figure 7: Box-and-whisker plot for biochemical composition in *Nostoc* sp.

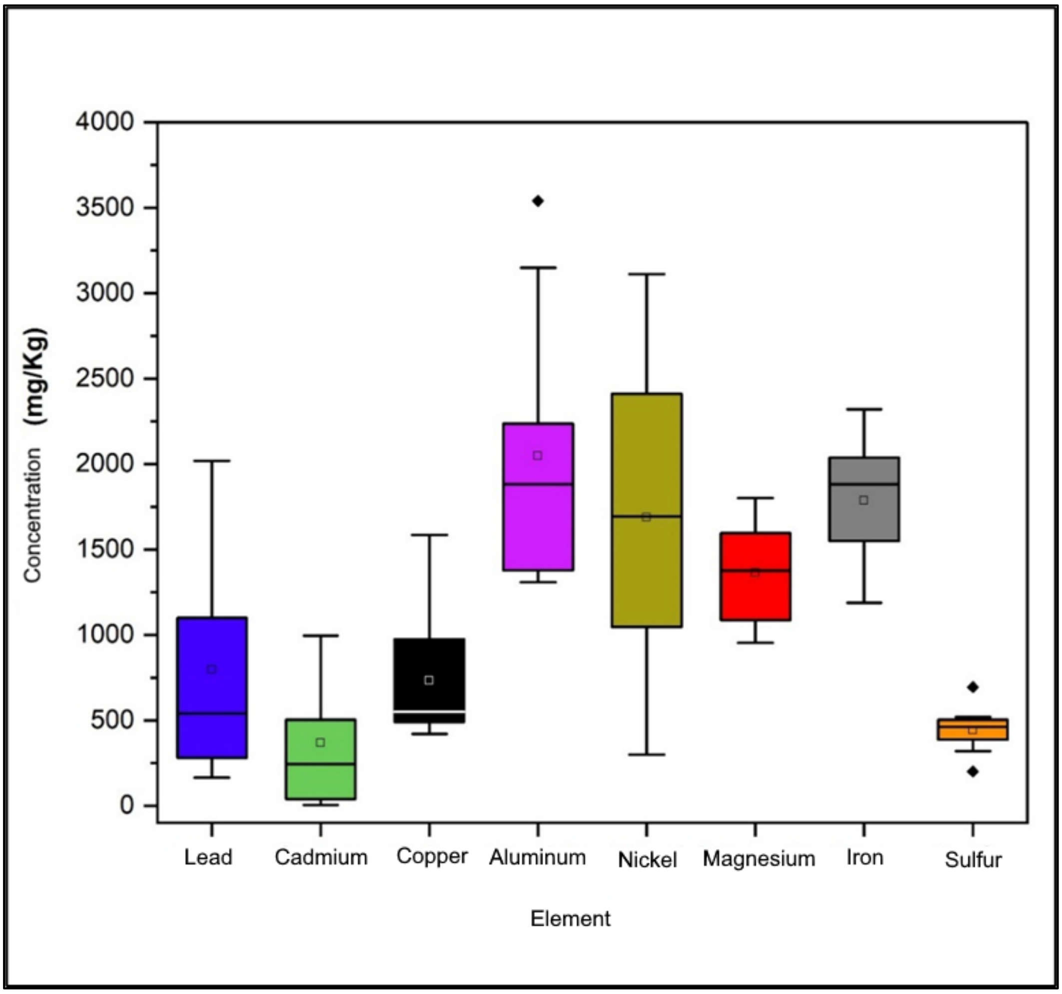


Figure 8: Box-and-whisker plot for chemical element content in *Nostoc* sp.

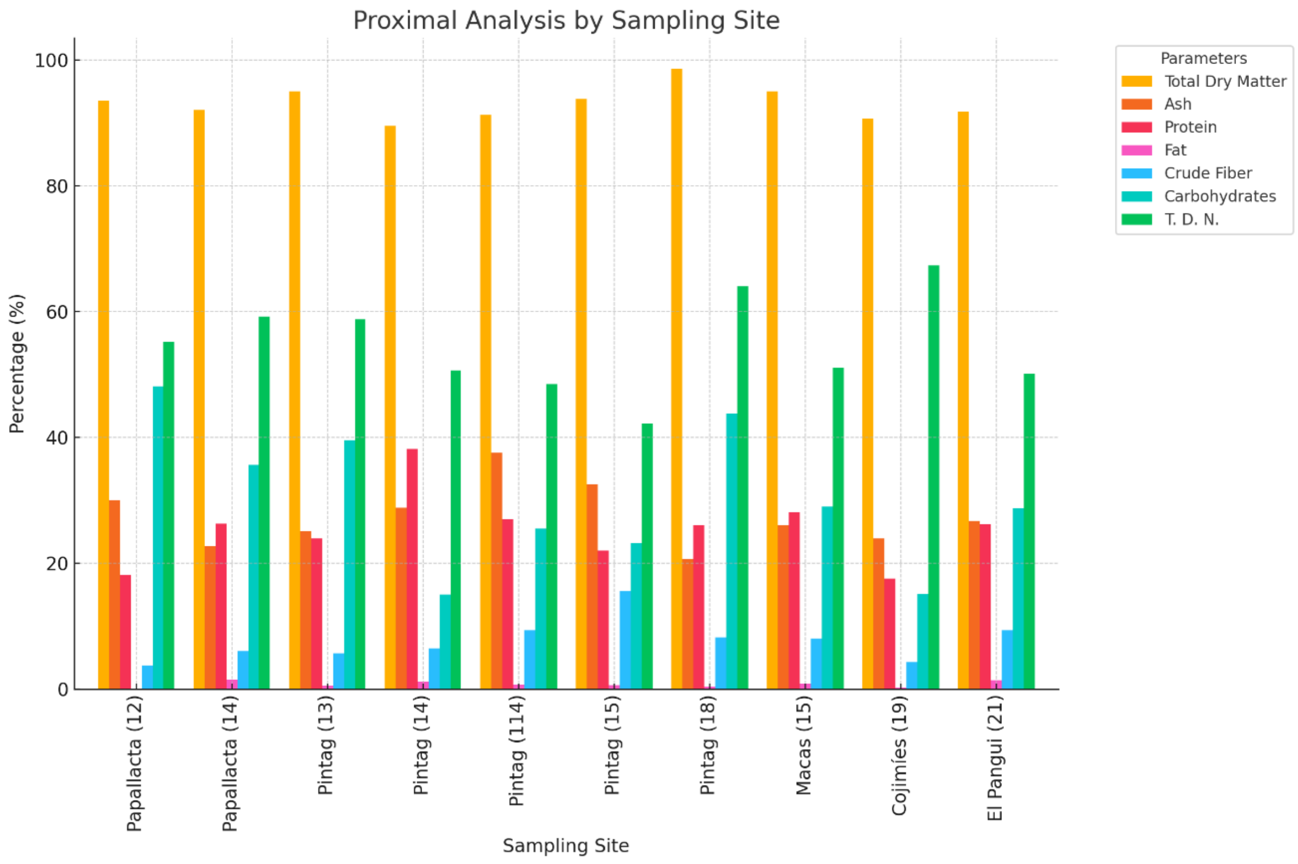


Figure 9. Bar chart representing the proximal analysis across various sampling sites. The evaluated parameters include Total Dry Matter, Ash, Protein, Fat, Crude Fiber, Carbohydrates, and TDN (Total Digestible Nutrients), expressed as percentages (%). Sampling sites cover Papallacta, Pintag, Macas, Cojimíes, and El Pangui.

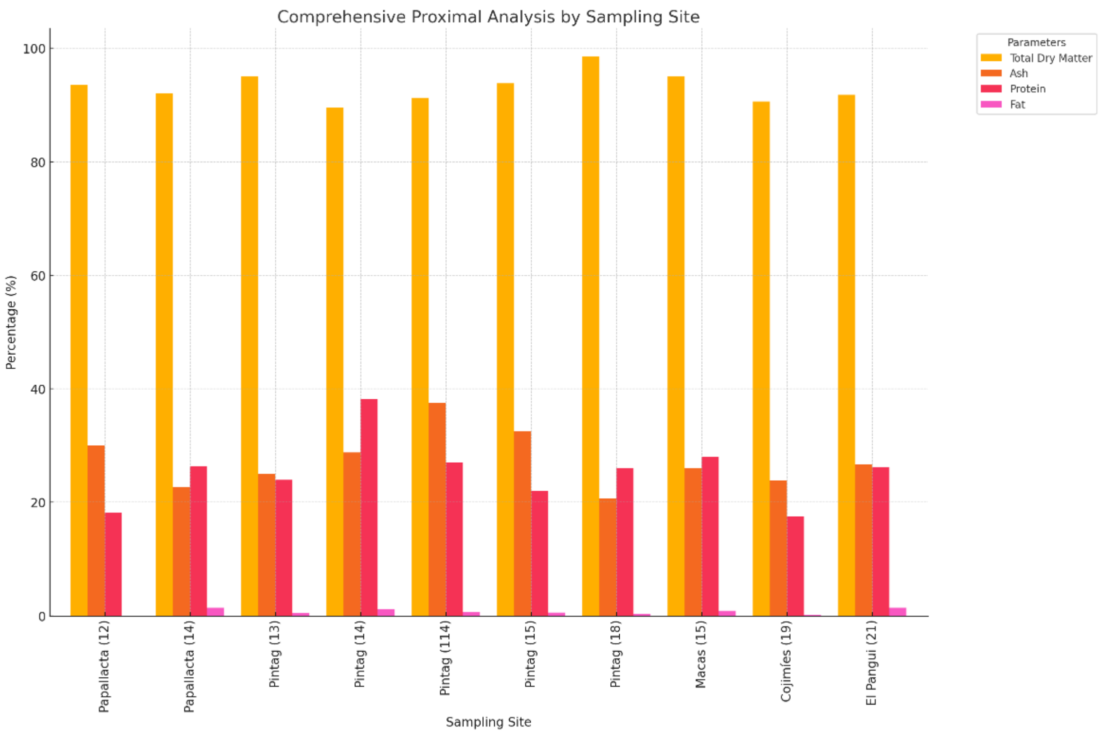


Figure 10. Bar chart showing the proximal analysis of different parameters at various sampling sites: Papallacta, Pintag, Macas, Cojimíes, and El Pangui. The parameters evaluated include Total Dry Matter, Ash, Protein, Fat, Crude Fiber,

Carbohydrates, and TDN (Total Digestible Nutrients), expressed as percentages (%). The values for Mean, Standard Deviation, and Coefficient of Variation are excluded from the main chart to focus on comparisons between the sites.

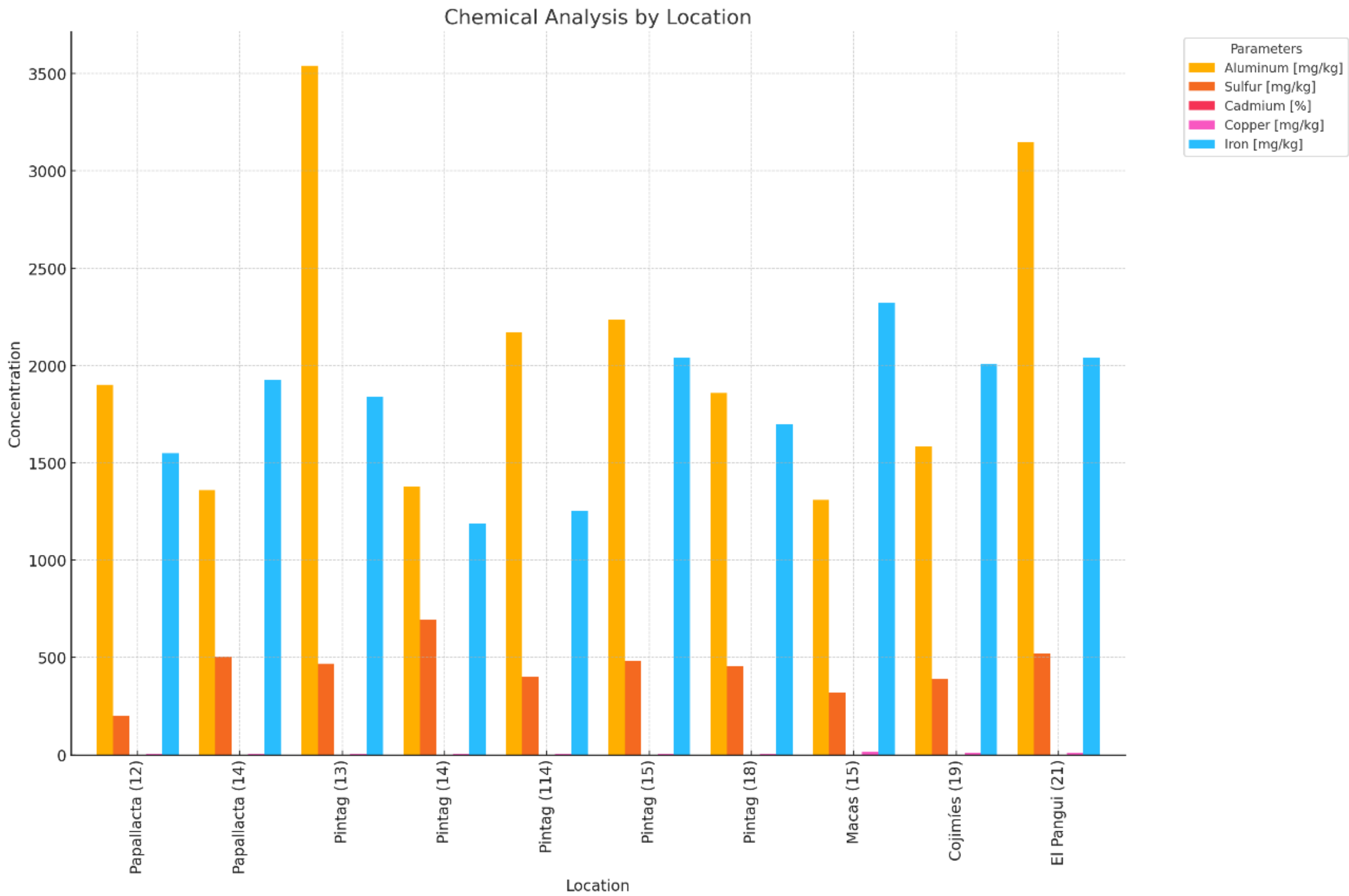


Figure 11. Bar chart showing the concentrations of various chemical elements (Aluminum, Sulfur, Cadmium, Copper, Iron, Magnesium, Lead, and Nickel) at different locations: Papallacta, Pintag, Macas, Cojimíes, and El Pangui. Concentrations are expressed in mg/kg, except Cadmium, which is in percentage (%). The values for Mean, Standard Deviation, and Coefficient of Variation are excluded to focus on the specific location.

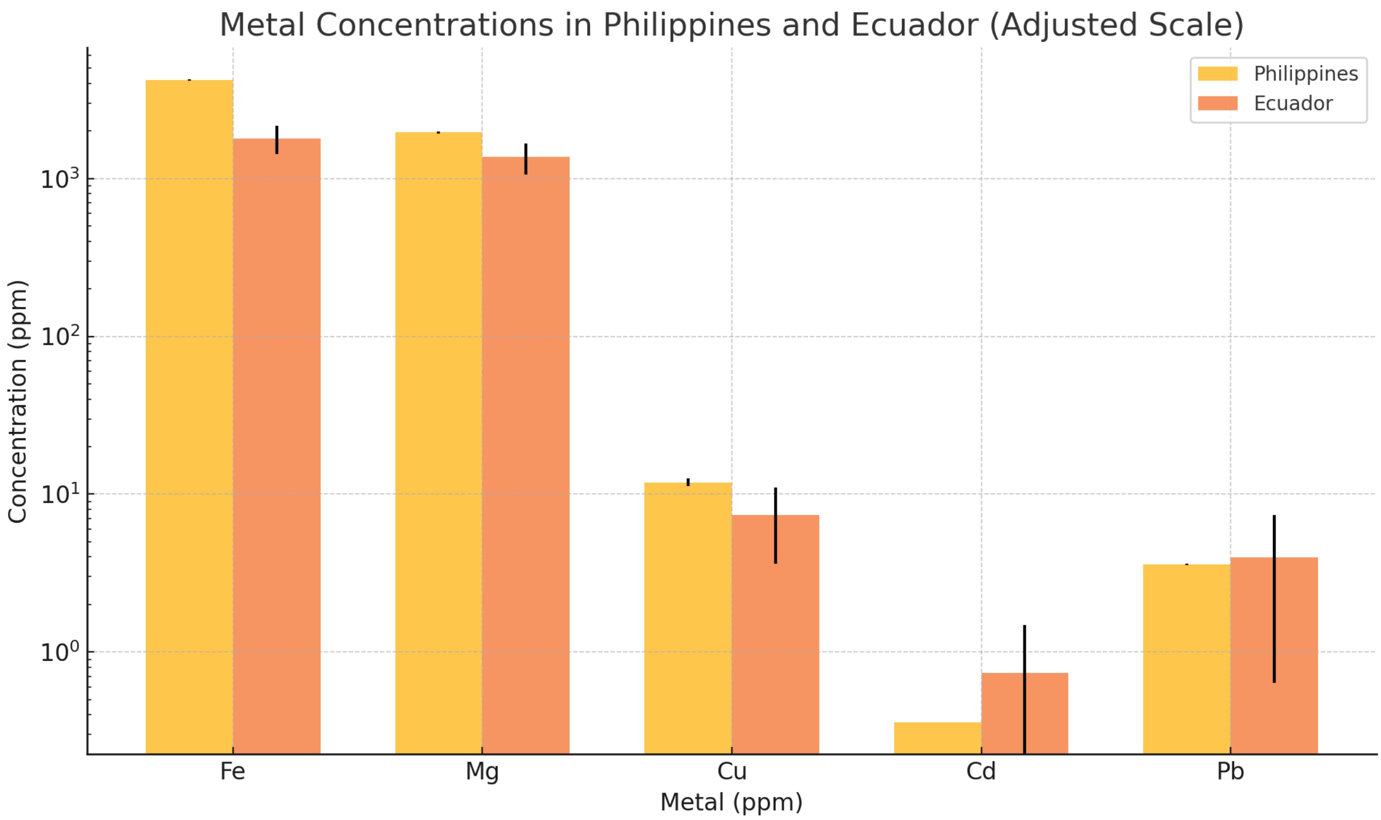


Figure 12. Bar chart showing the concentrations of metals (Fe, Mg, Cu, Cd, and Pb) in the Philippines and Ecuador, with error bars representing standard deviations. The scale has been adjusted to a logarithmic scale to enhance the visualization of metals with lower concentrations, such as Cu, Cd, and Pb, alongside metals with higher concentrations.

This study compares the concentrations of key metals (Fe, Mg, Cu, Cd, and Pb) in environmental samples from the Philippines and Ecuador. The results highlight significant differences in metal concentrations between the two regions, which could be attributed to variations in geological characteristics, anthropogenic activities, and environmental factors.

DISCUSSION

This study evaluated the biochemical composition of *Nostoc* sp., observing variations based on the altitude of the collection site. Figures 9, 10, and 11 present results from ten samples collected simultaneously, focusing on the metal, sulfur, and biochemical composition concerning geographic position and altitude. The findings indicate that the average carbohydrate content represents 30.34% of the total dry matter, followed by ash (27.38%), protein (25.33%), crude fiber (7.66%), and fat (0.71%). Statistical analysis shows no linear relationship between altitude and total dry matter (r=0.03, p=0.18), ash (r=0.04, p=0.189), protein (r=0.02, p=0.12), fat (r=0.00, p=-0.03), crude fiber (r=0.00, p=-0.01), or digestible nutrients (r=0.02, p=-0.16). However, carbohydrate content (r=0.30, p=-0.55) exhibited a weak but direct linear relationship with altitude.

The obtained values for protein, carbohydrates, digestible nutrients, and crude fiber highlight significant nutritional potential. These components vary depending on geographic altitude, suggesting that solar irradiance influences biochemical composition by affecting photosynthetic capacity and atmospheric exposure. In their natural habitat, *Nostoc* sp. experiences total solar irradiance. Previous studies demonstrate that UV-A radiation positively enhances *Nostoc*'s carbon and nitrogen fixation capacity, influencing its metabolism. This is evidenced by increased sugar, fatty acid, citrate accumulation, and higher biomass production[30].

Figure 3 reveals interesting patterns: at low altitudes near sea level, carbohydrate concentration is around 15%. As altitude increases, carbohydrate concentration exhibits a linear upward trend, rising progressively between 1000 and 3000 m.a.s.l. Beyond 3000 m.a.s.l., carbohydrate concentration rises more steeply, reaching approximately 45% at 4000 m.a.s.l. These results suggest that factors associated with altitudinal gradients—such as climate conditions, nutrient availability, or vegetation composition—significantly influence carbohydrate accumulation or distribution in this system. This pattern has critical implications for the ecology and physiology of organisms inhabiting mountainous environments and the dynamics of biogeochemical cycles.

A comparison of carbohydrate levels during dry and rainy periods revealed a slight increase in samples collected during drought conditions in both Papallacta and Pintag. Specifically, 54.9% and 45.1% values were recorded in Papallacta during drought and rainfall, respectively, and 66.26% during drought compared to 33.74% in the rainy season in Pintag. These findings align with studies on filamentous cyanobacteria of the *Scytonema* and *Tolypothrix* genera, which show extracellular polysaccharide production under temperature (8–40°C) and irradiance (3–21 W/m^2) gradients. Increased exopolysaccharide (EPS) production at higher temperatures may represent an adaptive mechanism to heat/drought stress[31].

Additional studies on EPS characterization in *Nostoc sphaericum* and *Nostoc commune* samples from Junín, Ancash, Cajamarca, and Pachacamac (Peru) have identified that *N. sphaericum* produces EPS with superior physicochemical properties. These include its potential as a nutritional raw material and protective barriers formed by anionic heteropolysaccharides, sulfate groups, amphiphilic behavior, and cation-chelating capacity [32].

When comparing the average values of ash, protein, crude fiber, and fat from the proximal analysis in this study (figure 9), the results are similar to those found in *Nostoc sphaericum* ("cushuro") in Huaraz, Peru, which reported 7.77 ± 0.01% ash, 26.68 ± 0.01% protein, 5.77 ± 0.11% crude fiber, and 0.21 ± 0.03% fat[33,34]. These findings suggest biochemical similarities despite differences in species and habitat, as the studied species is aerophytic, whereas *Nostoc sphaericum* is aquatic and ancestrally edible[35].

Regarding metal and sulfur content, Aluminum showed the highest concentration (2049.23 mg/kg), followed by iron (1786.74 mg/kg), magnesium (1364.08 mg/kg), and sulfur (443.12 mg/kg). Copper (7.34 mg/kg), nickel (5.62 mg/kg), Lead (3.99 mg/kg), and Cadmium (0.74 mg/kg) had significantly lower concentrations, resulting in the following elemental composition order: Al > Fe > Mg > S > Cu > Ni > Pb > Cd, consistent across all sampled sites, regardless of altitude or season. This order aligns with a study conducted in the Philippines on *Nostoc commune*, which reported a similar descending order: Fe > Mg > Cu > Cd > Pb, with elemental profiles comparable to those observed in this study in Ecuador[36]. Differences in elemental profiles could be attributed to variations in edaphic, hydrological, or climatic characteristics between the sampling sites in the Philippines and Ecuador.

Figure 6, which examines element concentration as a function of altitude, reveals multimodal distribution patterns for most studied elements, indicating complex transport, deposition, and accumulation processes along the altitudinal gradient. For iron (Fe) and magnesium (Mg), a clear negative linear trend between their concentrations and altitude is evident, suggesting leaching, erosion, and transport mechanisms that favor their accumulation in lower-altitude areas. This could relate to higher organic matter availability, weathering rates, and redox conditions in low-altitude soils. Conversely, copper (Cu) displays a more homogeneous and stable distribution across the altitudinal range, indicating geochemical equilibrium processes and mechanisms of retention and recycling, which are likely influenced more by edaphic factors and speciation than by altitude itself.

The greater dispersion and variability observed in Cadmium (Cd) and Lead (Pb) distributions may be linked to external contributions such as atmospheric deposition, anthropogenic activities, or local geological factors introducing heterogeneity in the concentrations of these elements. The elevated Aluminum and iron content in the biomass of *Nostoc* sp. could correlate with the soil acidification theory in Ecuador, which suggests that temperature and precipitation regimes have contributed to the aging of tropical clay soils. This process removes silica, predominating kaolinite, and Fe and Al oxides in current soils[37]. Consequently, the high Al and Fe concentrations in all sampled areas may be associated with these acidic soils. According to Ecuador's environmental quality standards for soil resources, the average cadmium content of 0.74 mg/kg slightly exceeds the maximum allowable limit of 0.5 mg/kg by 0.24 mg/kg. In contrast, the average lead content of 5.62 mg/kg remains well below the maximum permissible limit of 19 mg/kg[38,39].

The studied of this *Nostoc* species categorized as a terrestrial aerophytic cyanobacterium that thrives on soil surfaces (Manabí) rocky soils (Napo, Pichincha, Morona Santiago, and Zamora Chinchipe) and has been found forming abundant macro colonies on cement (Cojimíes, Manabí), unlike aquatic species such *Nostoc sphaericum* ("Murmunta"), which depends on waterborne nutrients for growth, and this species many times does not have direct soil contact.

Regarding the relationship between altitude and metal and sulfur concentrations, no linear correlations were observed for Aluminum (r = 0.00, p = -0.06), sulfur (r = 0.00, p = 0.01), and nickel (r = 0.03, p = 0.17). Weak inverse linear relationships were detected for iron (r = 0.26, p = -0.51) and magnesium (r = 0.18, p = -0.43). Conversely, weak direct linear correlations were noted for Cadmium (r = 0.23, p = 0.48) and Lead (r = 0.15, p = 0.38), while Lead also exhibited a separate inverse linear correlation (r = 0.62, p = -0.79). Across an altitudinal range of 27 to 4025 m.a.s.l., *Nostoc* demonstrated significant rehydration capacity during rainfall or irrigation, indicating its versatility in bioaccumulating metals and sulfur across varying temperatures. During the rainy season, greater abundance and development of *Nostoc* macrocolonies were observed in Napo and Pichincha at altitudes between 2910 and 4025 m.a.s.l.

These results indicate no definitive effect of altitude or collection date on metal and sulfur content. Future studies should incorporate monitoring across different collection periods and include proximal and metal analyses. However, a study in Morocco identified nitrogen content, available phosphorus, altitude, humidity, pH, and electrical conductivity as crucial factors influencing cyanobacterial community distribution along an altitudinal gradient[40,41].

In the dry regions of the Himalayan range, altitude, and vegetation type have been found to enhance *Nostoc* biomass production with increasing elevation, likely due to its adaptation to low temperatures and desiccation. This adaptation is attributed to a well-developed mucilaginous EPS sheath that protects against cold and dehydration. Such findings confirm the consistent behavior of *Nostoc* across various habitats where it has been studied[42].

Latitude has also been shown to influence *Nostoc* properties. A study on heavy metal content and biochemical composition of *N. commune* across 16 provinces in China revealed that higher latitudes correlate with increased biomass production and improved nutritional quality while maintaining manageable levels of arsenic, Lead, and chromium in the sampled sites[43].

These findings regarding identifying chemical elements in aerophytic cyanobacteria, particularly *Nostoc* sp., highlight its potential for future research into bioremediation mechanisms and its use as a bioindicator of heavy metals in diverse environments[44-47].

Figure 12 presents a comparative analysis of metal concentrations (Fe, Mg, Cu, Cd, and Pb) in environmental samples from the Philippines and Ecuador, employing a logarithmic scale to enhance the visualization of metals with lower concentrations, such as Cu, Cd, and Pb, alongside those with higher concentrations like Fe and Mg. These results provide insights into regional differences in metal bioavailability, which geological, climatic, and anthropogenic factors may influence.

The data show that the Philippines has significantly higher concentrations of Fe (4202 ppm) than Ecuador (1786.74 ± 363.55 ppm). This difference can be attributed to the volcanic origin of the Philippine soils, which are typically rich in iron oxides due to high weathering rates and mineral deposition. Magnesium (Mg) levels follow a similar pattern, with 1959 ppm in the Philippines and 1364.08 ± 301.38 ppm in Ecuador. These elevated levels in the Philippines suggest that nutrient cycling and geological formation processes are pivotal in Mg availability.

For trace metals, the Philippines exhibits slightly higher concentrations of Cu (11.88 ± 0.69 ppm) compared to Ecuador (7.34 ± 3.72 ppm). This suggests relatively stable natural and anthropogenic inputs in both regions, though the broader variability in Ecuador indicates localized factors, such as mining or agricultural runoff. Conversely, Ecuador shows nearly double the cadmium (Cd) concentration (0.74 ± 0.74 ppm) compared to the Philippines (0.36 ppm). Although both values are within a low range, the elevated Cd levels in Ecuador raise environmental concerns, as Cd is highly toxic even at low concentrations and is often associated with industrial and agricultural activities.

The slightly higher lead (Pb) concentration in Ecuador (3.99 ± 3.35 ppm) compared to the Philippines (3.59 ± 0.05 ppm) suggests potential localized contamination sources, such as industrial emissions or lead-based materials. The variability observed in Pb and Cd concentrations in Ecuador highlights the need for site-specific studies to identify contamination sources and mitigate their impact.

These findings align with the study's broader observations of *Nostoc sp***.** as a bioindicator for environmental pollutants. The cyanobacterium's ability to bioaccumulate metals in varying concentrations underscores its potential for use in environmental monitoring and remediation. Its effectiveness in absorbing metals like Cd and Pb could make it a valuable tool for mitigating soil and water contamination, especially in regions with industrial or agricultural pollutants.

The observed differences in metal concentrations between the Philippines and Ecuador suggest region-specific applications for *Nostoc sp***.**. In the Philippines, the focus may be on mitigating Fe and Mg concentrations in environments affected by volcanic soils. In Ecuador, the emphasis could shift toward remediating Cd and Pb, given their higher and more variable concentrations. Previous studies have demonstrated the potential of cyanobacteria, including *Nostoc sp***.**, for the bioabsorption of heavy metals such as Pb and Cd through their exopolysaccharide-rich surfaces.

The patterns observed in Figure 12 contribute to a growing body of evidence supporting the role of *Nostoc sp***.** in environmental management. Its capacity to adapt to diverse ecological conditions and bioaccumulate metals highlights its utility as a bioindicator and a key organism for bioremediation strategies. The findings suggest that *Nostoc sp***.** could be critical in addressing metal contamination in tropical and subtropical ecosystems.

A deeper understanding of cyanobacteria's response mechanisms to heavy metals could pave the way for their development in producing biologically active natural products. Cyanobacteria's resistance to high copper (Cu) concentrations may explain the enhanced growth rates observed in certain biomass enzymes. In response to varying concentrations of divalent metal ions, some strains express mRNA for the stress protein GroEL and the metal-binding protein metallothionein. These resistance systems likely work in concert to protect the cell from damage. Metallothioneins, cysteine-rich proteins, bind metal ions, reducing their cellular availability and effectively detoxifying them[48.50].

Industrial activities have negatively impacted the environment by releasing large amounts of toxic elements, including heavy metals. Exopolysaccharides (EPSs) are surface-active compounds proposed as a solution to mitigate heavy metal pollution. Microbial EPSs, with notable selectivity for metal adsorption, are particularly valuable for extracting valuable metals from industrial wastewater. In this context, studies have explored the supplementation of culture media with additional sugar sources to enhance exopolysaccharide production and assess their effectiveness in adsorbing various toxic heavy metals, such as copper (Cu), nickel (Ni), and chromium (Cr)[51.53].

CONCLUSIONS

The findings of this study demonstrate that the *Nostoc* sp. strain exhibits a remarkable capacity for bioaccumulation of metals in the following descending order: Al > Fe > Mg > S > Cu > Ni > Pb > Cd. This ability was consistently observed across all sampling sites, regardless of altitude or climatic conditions, including rainy and dry periods. This positions *Nostoc* sp. as a potential bioindicator of heavy metal presence in diverse ecosystems.

The presence of *Nostoc* sp. was documented over a broad altitudinal range, from 27 m.a.s.l. (Manabí) to 4025 m.a.s.l. (Napo). Proximal analysis of the dry biomass revealed the following composition: 30.34%

carbohydrates (the highest proportion), followed by 27.38% ash, 25.33% protein, 7.66% crude fiber, and 0.71% fat. These results underscore the nutritional potential of this cyanobacterium within its habitat. However, further toxicity studies are recommended due to the possible presence of cyanotoxins.

The biological and biochemical aspects of *Nostoc* sp. examined in this study contribute to understanding the species' ecology and providing valuable insights into biomass availability and the concentrations of biochemical components, heavy metals, and sulfur across different geographic locations. This information is crucial for the sustainable management of natural populations and their potential utilization in future applications. Notably, *Nostoc* sp. thrives in environments with high solar irradiation and demonstrates adaptations that enable it to prosper across a wide range of altitudes, temperatures, and climatic variations.

Given their ecological and biotechnological relevance, further studies on the diversity and geographic distribution of *Nostoc* strains in Ecuador are strongly recommended. The bioprospecting of these species could unveil new opportunities for their application in environmental management and mitigating heavy metal contamination.

The comparative analysis presented in Figure 12 underscores the importance of understanding regional variations in metal concentrations to inform environmental management practices. Future research should delve deeper into the mechanisms driving metal bioaccumulation in *Nostoc sp.* and explore its application in bioremediation technologies. Additionally, long-term monitoring across varying environmental gradients could further elucidate the factors influencing metal bioavailability and cyanobacterial adaptation in these regions.

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Additional information Correspondence should be addressed to *edmorales@espam.edu.ec*

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