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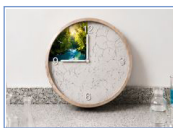
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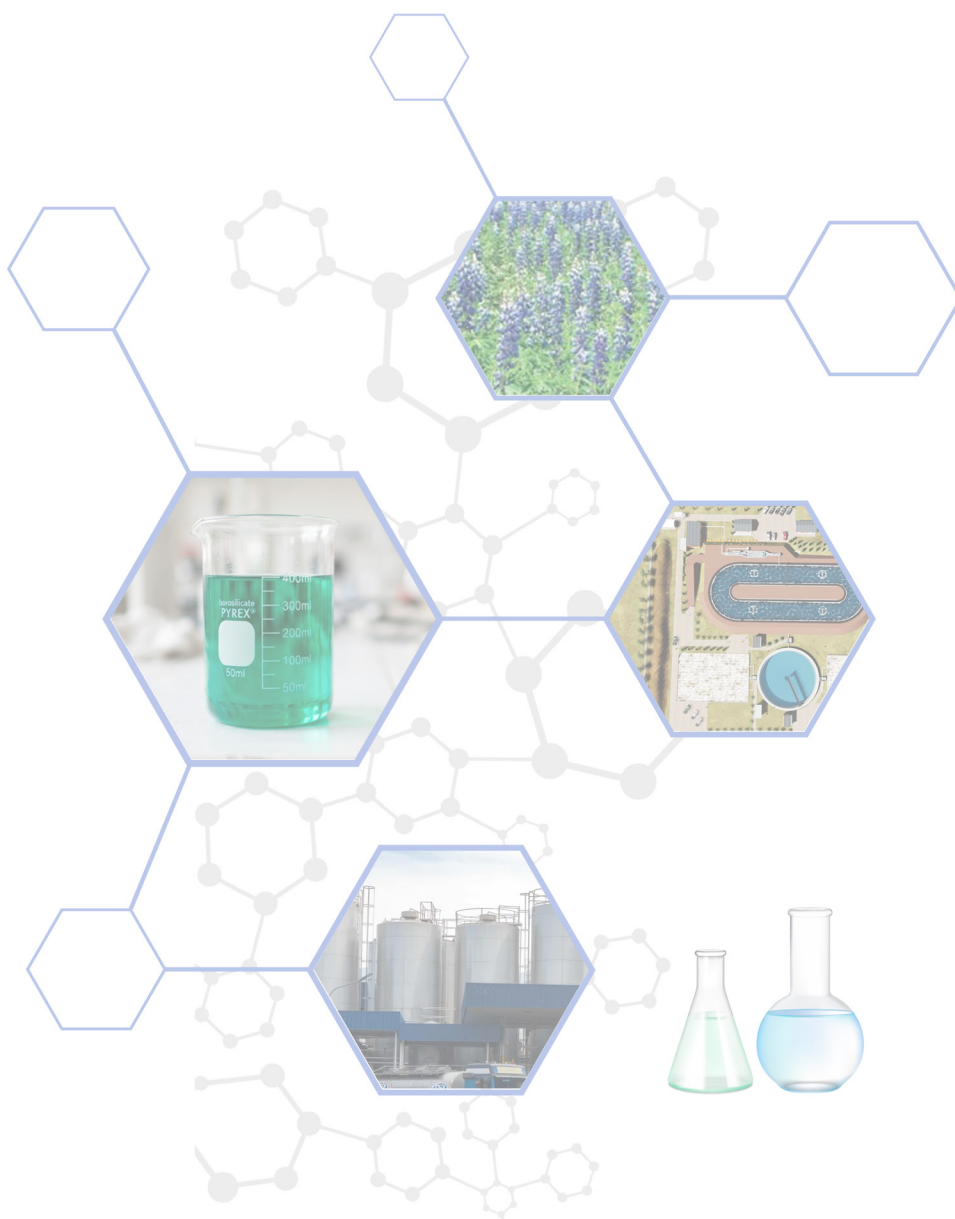
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IIDEPROQ
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In my capacity as Director of the Chemical Engineering Program, and on behalf of the Environmental, Food, Petrochemical, and Biotechnology Engineering Programs, I extend my sincere recognition and support to IIDEPROQ for the publication of the third issue of its Scientific Journal. This new volume represents a sustained effort to strengthen applied research and the dissemination of scientific knowledge, and it deserves our full institutional and academic support.

This edition brings together nine papers that, from diverse perspectives, converge on a common concern: generating evidence, methodologies, and technological alternatives to address productive, environmental, and social challenges of particular relevance to Bolivia and the Andean region. Taken together, these articles demonstrate the breadth and interdisciplinary nature of the research promoted by IIDEPROQ, linking chemical process engineering, environmental management, climatology, data science, agroindustry, and territorial analysis around real-world problems.

The Programs under my direction greatly value this journal as a space for dialogue among research, territory, and society, and that the published works do not aim to close complex problems, but rather to provide data, methodologies, and perspectives that can be contrasted, used, and developed in future research. This cumulative and open-ended nature is an essential part of science and of our students' academic training.

We would also like to express our gratitude to the authors, reviewers, professors, researchers, students, and collaborators who made this edition possible. We invite readers to approach its contents with a critical and constructive spirit, understanding that the value of a scientific publication extends and grows when its results generate discussion, new questions, and knowledge. May this third issue help strengthen, from Bolivia and the Andean region, research that is rigorous, relevant, and committed to technically, socially, and environmentally responsible solutions.



Eng. Jorge Vasquez Peñaranda, Ph.D.
Director of the Chemical Engineering Program
and its Environmental Engineering,
Food, Petrochemical, and Biotechnology Programs.



It is with great satisfaction that we present the third issue of the IIDEPROQ Scientific Journal, a new contribution to strengthening applied research and disseminating scientific knowledge. This issue brings together nine papers that, through diverse approaches, share a common purpose: generating evidence, methodologies, and technological alternatives to address environmental, productive, and social challenges of particular relevance to Bolivia and the Andean region.

Taken together, the articles reveal a central feature of this issue: research is directed toward concrete problems and seeks to connect scientific results with practical needs. The papers address recovery of nickel and cobalt from spent batteries, wastewater treatment, disaster risk management, climate variability, air quality, agroindustrial use of tarwi, waste-to-energy pathways, dairy production in the Altiplano, and changes in high-Andean wetlands.

In the field of the circular economy, electrochemical recovery of nickel and cobalt from spent Ni-MH batteries illustrates the potential to transform waste into secondary sources of valuable materials. The study of natural adsorbents for wastewater from Viacha provides experimental evidence on limonite and orange peel, showing both the possibilities and limitations of these alternatives under treatment conditions.

Environmental management is further addressed through the disaster risk management guide applied to FONABOSQUE, incorporating tools for hazard identification, vulnerability assessment, and project planning. The ENSO study examines its possible implications for the northern and central Bolivian Altiplano and appropriately emphasizes that the relationship between the ocean-atmosphere phenomenon and local impacts is not linear, requiring multiple information sources and early warning systems.

The climate and territorial dimension continues in the study of factors limiting forage availability for dairy production in the Central Altiplano and in the multitemporal analysis of high-Andean wetlands in Antofagasta. From different scales and methodologies, both studies demonstrate the importance of relating climate variables, water availability, vegetation, and productive systems. The use of NDVI, NDWI, and NDMI also illustrates the growing value of remote sensing for monitoring vulnerable ecosystems.

Urban environmental quality is addressed through a platform for visualizing and analyzing PM10 time series. The integration of Tableau® with Python/TabPy and procedures for data cleaning, missing-data treatment, and temporal analysis demonstrate how data-science tools can strengthen environmental monitoring. In parallel, lecithin production from tarwi oil represents a pathway for adding value to national agro-food resources through extraction, degumming, and experimental optimization.

Finally, the modeling study of hydrogen production from biogas generated by municipal solid waste in La Paz connects waste management, reactor modeling, energy production, and CO₂ capture. Its results provide an estimate of theoretical valorization potential while appropriately distinguishing it from industrial production, whose future assessment should include collection, purification, sorbent regeneration, compression, and auxiliary energy requirements.

Overall, the nine papers demonstrate the breadth and interdisciplinary character of the research promoted by IIDEPROQ. Chemical process engineering, environmental management, climatology, data science, agroindustry, and territorial analysis converge around real-world problems. This convergence is a strength, while also requiring consistently high scientific standards: clear objectives, transparent methods, reproducible results, evidence-based discussion, and verifiable references.

This issue is therefore more than a collection of results; it is a space for dialogue between research, territory, and society. The published studies do not seek to close complex problems, but to contribute data, methodologies, and perspectives that can be tested, applied, and developed through subsequent research. This cumulative and open character is an essential part of science.

Deep acknowledge the authors, reviewers, faculty members, researchers, students, and collaborators who made this issue possible. In other hand invite readers to approach its contents with a critical and constructive perspective, recognizing that the value of a scientific publication continues when its findings generate discussion, new questions, and knowledge. May this third issue contribute, from Bolivia and the Andean region, to rigorous, relevant research committed to technically, socially, and environmentally responsible solutions.



Eng. Waldo Vargas Ballester
Master in Environmental Engineering
Director of IIDEPROQ

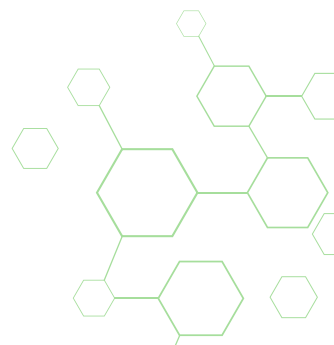




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RECOVERY OF NICKEL AND COBALT FROM SPENT NI-MH BATTERIES BY ELECTROCHEMICAL PROCESS IN THE CITY OF LA PAZ

Jhosep Lendy Aliaga Luque¹, Boris Párraga Andrade^{1,*}

ABSTRACT

Global demand for electronic devices is growing rapidly due to the need to keep pace with technological advancements. These devices rely on batteries with limited lifespans, resulting in significant quantities of electronic waste. The increasing generation of nickel-metal hydride (Ni-MH) battery waste in the city of La Paz poses an environmental problem due to the presence of potentially polluting metals, such as nickel and cobalt. Consequently, there is a need to develop sustainable recycling methods. This research involved recovering nickel and cobalt through a combination of leaching and electrodeposition. Used batteries were collected, discharged, dismantled, and ground. The resulting powders were then leached, purified to remove contaminants, and processed in a two-compartment electrochemical cell separated by an ion-exchange membrane (F-9010), using a platinum anode and a stainless steel cathode. The effects of temperature, voltage, and operating time were evaluated. An electrodeposit with nickel and cobalt concentrations exceeding 97 % was obtained. The optimal parameters identified were a temperature of 45 °C, a voltage of 8 V, and an operating time of 5 hours.

Keywords: Electronic waste, Electrowinning, Nickel, Cobalt.

1. INTRODUCTION

The rapid growth of the electronics industry and energy storage technologies has significantly increased the production and consumption of rechargeable batteries worldwide. In Bolivia, each person generates six kilograms of technological waste per year, totaling almost 80,000 tons annually (Bolrec, 2024). Among these, nickel-metal hydride (Ni-MH) batteries continue to be widely used in electronic devices, portable tools, energy backup systems, and hybrid vehicles due to their high storage capacity, operational safety, and long lifespan (Panasonic s.f.; Allied market research, 2023). However, once their life cycle is complete, these spent batteries become hazardous waste containing potentially toxic metals, such as nickel and cobalt, capable of contaminating soils, surface waters, and ecosystems when disposed of without adequate treatment. Several studies have pointed out that the improper disposal of electronic waste represents a growing environmental challenge, especially in developing countries where recycling systems are still limited (Hariprakash, 2009; Riswan et al.2024). Concurrently, the global demand for nickel and cobalt continues to rise due to their application in rechargeable batteries, special alloys, aerospace industries, and renewable energy technologies. According to international market reports, the sustained growth of these sectors is generating increasing pressure on primary mineral resources, the extraction of which involves high economic, energetic, and environmental costs (Mordor Intelligence, 2026; USGS, 2022).

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The importance of recovering these metals lies not only in mitigating the environmental impacts associated with electronic waste but also in the possibility of reincorporating them into productive cycles under the principles of the circular economy. In this context, hydrometallurgy and electrochemical processes have attracted growing interest due to their capacity to recover high-value metals with lower energy requirements and less secondary waste generation compared to conventional pyrometallurgical processes (Yu et al., 2018).

Addressing this issue has economic, technological, environmental, and scientific implications. From an economic perspective, the valorization of hazardous waste can contribute to reducing the dependence on raw materials from conventional mining. In the technological field, the study provides elements for the development and optimization of electrochemical processes applied to the recycling of electronic waste. Likewise, the implementation of sustainable management alternatives can reduce the environmental risks associated with the improper disposal of batteries. From a scientific standpoint, the research generates experimental information on the joint recovery of nickel and cobalt through electrodeposition and contributes to the knowledge related to the valorization of strategic metals.

Consequently, this research is framed within the principles of sustainability, the circular economy, and the efficient use of resources, evaluating a treatment alternative for spent Ni-MH batteries generated in the city of La Paz, with potential application in similar contexts.

Ni-MH batteries contain valuable metals: approximately 44% nickel, 5% cobalt, 2% zinc, and 9% light and rare earth metals (Shin et al., 2015). The elements present in the highest proportions are K, Ni, Co, and Zn. Nickel is found in both the cathode and the anode, whereas cobalt is primarily located in the anode.

There are few articles on hydrometallurgical and electrochemical processes for the recycling of Ni-MH batteries; leaching in each case is performed with acids such as H_2SO_4 at 90 °C for 4 h (Bertoul et al., 2012), 3N HCl at 90 °C for 3 hours (Rabah et al., 2008), 4M HCl at 95 °C for 3 hours (Tzanetakis et al. 2004), 5% v/v Acetic Acid (Zambrano et al., 2018), and in Lupi et al (2002), a comparison is made between HCl, H_2SO_4 , and HNO_3 , concluding that H_2SO_4 is the most suitable option for this process.

Because the leachate solution contains impurities (Mn, Al, Zn, Cu, rare earths) in its composition, it undergoes a purification step as indicated by (Tzanetakis et al. 2004), to remove rare earths, a 25% bis(2-ethylhexyl) phosphoric acid (D2EHPA) solvent in kerosene is used, separating into an organic phase and a raffinate (Hernandez et al. 2016), or, as indicated by Bertoul et al., (2012), by increasing the pH to 1.2 through the addition of 5 M sodium hydroxide, rare earths are removed as sulfates. Selective precipitation is one of the simplest and, therefore, most widely used methods, achieving efficiencies above 90% for metal recovery. The precipitation order of the metals is specific and depends on the value of the solubility product constant (pKs) (Pagani, 2021).

The solution obtained after rare earth recovery undergoes a second precipitation stage at pH 6 to remove Fe, Zn, and Mn, leaving Ni and Co in solution. The results demonstrated that Fe could be completely removed. As for Mn, only a poor removal efficiency of around 2.3% was achieved. For the complete precipitation of Mn, a pH of approximately 10 was required. Zn could be removed by approximately 24.0%. The precipitation of Ni usually begins at around pH 6.5, but in this case, probably due to a higher quantity of Ni compared to other metals, it was observed that at pH 6, about 0.5% of Ni co-precipitated. Regarding Co, about 2.2% was lost during precipitation (Bertoul et al., 2012).

Electrodeposition is carried out in an electrochemical cell with two compartments separated by an ion-exchange membrane. The process is based on the differences between the reduction potentials of the metals present, which favors their recovery with high purity. One of the advantages of this method is that it does not require external agents to recover the metals and can achieve yields close to 99% (Pagani, 2021).

Finally, considering the need to develop sustainable alternatives for the management of electronic waste and the utilization of strategic metals, the main objective of this research is to recover nickel and cobalt from spent nickel-metal hydride (Ni-MH) batteries through an electrochemical process based on acid leaching, solution purification, and electrodeposition. To achieve this purpose, the characterization of the active materials presents in the batteries, the evaluation of the leaching efficiency of the metals contained in the electrodes, and the determination of the most suitable operating conditions for electrodeposition were proposed.

Additionally, this study sought to analyze the influence of process variables such as temperature, applied voltage, and operating time on the recovery of nickel and cobalt, in order to establish optimal parameters that maximize the system's efficiency. Complementarily, it was proposed to evaluate the purity and composition of the obtained products to determine their reuse potential in industrial applications.

As an additional contribution, the research aims to demonstrate the technical and environmental viability of using electrochemical processes for the valorization of spent Ni-MH battery waste, promoting a recycling alternative that contributes to the circular economy and the reduction of dependence on primary sources of nickel and cobalt. In this context, the hypothesis posed is that optimizing the electrodeposition conditions allows for obtaining high-purity metal deposits and high recovery percentages, establishing it as an efficient solution for the treatment and utilization of this type of electronic waste.

2. MATERIALS AND METHODS

2.1. Materials

We used spent AA and AAA batteries, which were dismantled under a fume hood. A heating system with magnetic stirring was used for the leaching process.

We conducted the electrochemical tests using two peristaltic pumps, a direct current (DC) power supply, an electric heater, stainless steel electrodes as the cathode, and platinum as the anode, in addition to a Flemion-type ion-exchange membrane (F-9010).

The measurement instruments included an analytical balance, a digital thermometer, a pH meter, and a digital multimeter.

We monitored the process using atomic absorption spectrophotometry (AAS), X-ray diffraction (XRD), and X-ray fluorescence (XRF).

The X-ray diffraction (XRD) equipment is a PANalytical X'Pert-3 Powder model, operating with a Cu tube and generating X-ray radiation at 40 kV and 40 mA. We performed a scan between 3° and 60° under fully automated

conditions. We conducted this analysis on the collected and milled initial product for all heavy and light elements, yielding relative abundance estimation data, as shown in Table 2.

The X-ray fluorescence (XRF) equipment is a Rigaku GeigerFlex model, operating with a Cr tube at 50 kV and 30 mA. The recording process consists of two parts: an automatic run covering a range from 10° to 65° to determine the presence of heavy elements, and a manual run at specific ranges corresponding to light elements. We performed this analysis for heavy and light elements present in the initial sample, specifically, the cathodic and anodic powder from the batteries, yielding relative abundance estimation data.

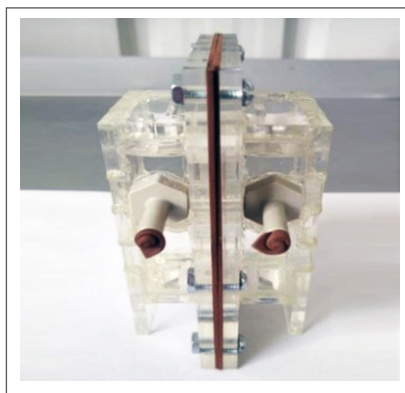
For atomic absorption spectroscopy (AAS) analysis, a Hitachi Model 180-30 instrument was used. The analyses were performed to determine nickel and cobalt concentrations in the recovered product, both in its solid form and after dissolution. The leachate solution was analyzed for nickel, cobalt, manganese, potassium, and zinc, while the battery powder was analyzed for nickel and cobalt.

2.1.1. Electrochemical Cell

We designed the electrochemical cell aiming to: reduce the compartment volume without impeding the solution flow (50 mL per compartment), utilize the maximum possible electrode surface area (15 cm²), and minimize the distance between the electrodes as much as possible (2.5 cm). For the cell's construction, we used high-strength transparent acrylic and dielectric adhesive, as shown in 1.

The system operated continuously and hermetically, featuring polymeric gaskets designed to prevent liquid leaks.

Figure 1. Electrochemical Cell



Source: Prepared by the authors

2.1.2. Flemion 9010 Membrane

The membrane plays a fundamental role in electrolysis systems by separating the reaction compartments and controlling ion transport. Its use favors the separation of the cathodic and anodic reactions and reduces rapid pH variations, which can improve process efficiency (Moets et al., 2014).

Table 1 presents the normal and maximum operating values of the Flemion F-9010 membrane, within which it can operate without sustaining damage.

Table 1. Flemion F-9010 Membrane

Item	Normal	Max. Value	Unit
Current density	1<6	6 <7	kA/m ²
Voltage	0 a 6	<10	V
Temperature	60	80	°C

Source: Adapted from Rabah & Farghaly (2008)

2.2. Methods

2.2.1. STAGE 1 Battery pretreatment

Before dismantling, the batteries were discharged in a 1% w/w NaCl solution to reduce the risks associated with residual energy. This procedure has been reported to achieve battery discharge without compromising the integrity of the casing. (Lu et al., 2013).

After discharging the batteries and separating their components, the cathodic and anodic materials were milled, as shown in Figure 2.

Figure 2. Battery pretreatment



Source: Prepared by the authors

Figure 2 shows: A) the metallic casing, the anodic powder, the cathodic powder, the support mesh for the anodic material, and the separator containing the battery electrolyte; and B) the anodic and cathodic powders after milling.

2.2.2. STAGE 2 Leaching and purification

After pretreatment, we subjected the cathodic and anodic materials to leaching to solubilize the metals present. We used a 2 M H₂SO₄ solution at 90 °C for 4 h, with constant stirring and a solid-to-liquid ratio of 1:30.

Figure 3. Left: the leaching system, and Right: the leachate



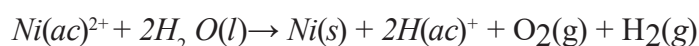
Source: Prepared by the authors

We separated the rare earths present in the leachate through selective precipitation. To achieve this, we adjusted the pH to 1.2 by adding sodium hydroxide. To purify the solution obtained after rare earth recovery, a second precipitation stage at pH 7 removes practically all the iron and over 70% of the total zinc (Bertoul et al., 2012).

2.2.3. STAGE 3 Electrodeposition of nickel and cobalt

This process utilizes two electrodes and relies on electrochemical oxidation and reduction reactions. The separation of the metals depends on the differences in their reduction potentials, enabling the recovery of high-purity products.

Studies on nickel recovery from nickel-metal hydride batteries establish the following reaction:



As well as the electrowinning reaction for cobalt:

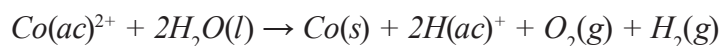
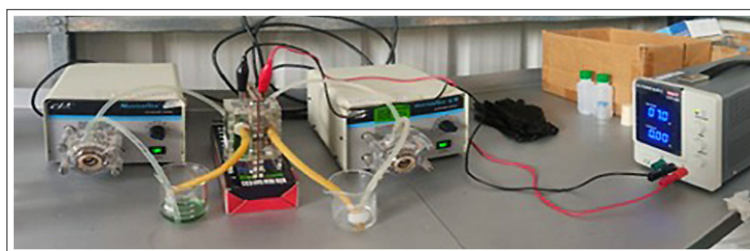


Figure 4. Electrolysis System

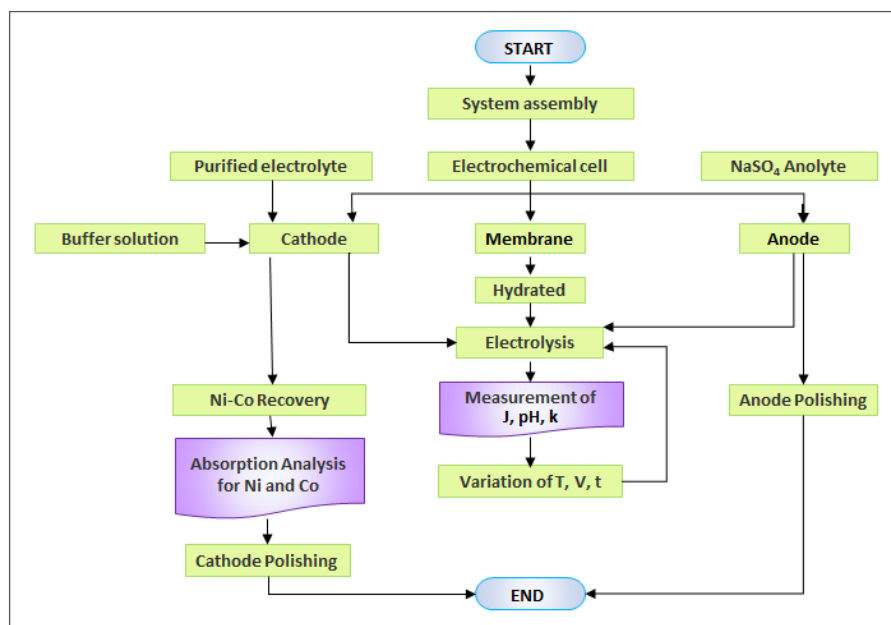


Source: Prepared by the authors

Figure 4 shows the system used for electrodeposition. The anode was platinum and the cathode was stainless steel; both had an active area of 15 cm². After electrodeposition, the deposit was collected for subsequent analysis.

Experiments were conducted at different temperatures, voltages, and operating times. For these tests, we kept the concentration of the purified electrolyte used as the catholyte constant (1,688 mg/L of cobalt and 9,625 mg/L of nickel), as well as the concentration of the Na_2SO_4 anolyte (1 M), reaching a current density of 250 A/m². The continuous process is shown in Figure 5.

Figure 5. Schematic of the process carried out for the objective of the project



Source: Prepared by the authors

3. RESULTS AND DISCUSSION

3.1 Battery dismantling

We performed an X-ray fluorescence (XRF) analysis to identify the elements present in the cathodic and anodic powders obtained from the dismantled batteries and used in the study.

Table 2. Battery powder components

Components	Elements
Major	K, Ni, Co, Zn
Minor	La, Nb, Mn
Trace	Na, Fe, Y, Pb

Source: XRD Laboratory Report (IGEMA)

We also conducted an atomic absorption analysis for nickel and cobalt; the results are shown in Table 3. The analyses indicate that the initial battery powders contain 6.5% cobalt and 50% nickel.

Table 3. Nickel and cobalt concentration in battery powder

Elements	Concentration
Cobalt	6.5%
Nickel	50%

Source: AAS Laboratory Report (LCA)

3.2. Leaching

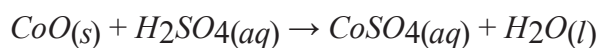
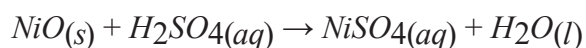
For the leaching process, we added 33.33 g of battery powder to 1 L of 2 M sulfuric acid and subjected it to leaching at 89 °C for 4 h with constant stirring (Bertuol et al., 2012). We used a reflux condenser to prevent the loss of leachate volume due to the prolonged duration of this process. Upon initial contact between the powder and the acid, we observed a black effervescent reaction; after 15 minutes, this phenomenon ceased, and the solution turned green, as shown in Figure 6.

Figure 6. Battery leachate



Source: Prepared by the authors

The reaction that takes place during this process is as follows:



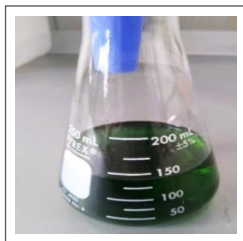
At the end of the leaching process, the suspension was filtered to separate the unleached solid residue from the solution.

Table 4. Unleached mass

	Values	Unit
Total mass	2.792	g
Filter paper mass	1.322	g
Unleached mass	1.470	g

Source: Prepared by the authors

Figure 7. Leachate solution



Source: Prepared by the authors

The pH measured after this process was 1, and this solution was designated as the unpurified electrolyte. Following this process, an atomic absorption analysis was performed to measure the concentration of the various elements present in the unpurified electrolyte, yielding the following results.

Table 5. Concentrations of the main components of the leachate solution

Parameter	Method	Unit	Determination Limit	Leachate 50 - 1
Cobalt	EPA 219.2	mg/l	0.050	1688
Manganese	EPA 243.1	mg/l	0.020	574
Nickel	EPA 249.1	mg/l	0.040	9625
Potassium	EPA 258.1	mg/l	0.210	75
Zinc	EPA 289.2	mg/l	0.038	95

Source: AAS Laboratory Report (LCA)

The results show the presence of several elements in the leachate solution, with a predominance of nickel and cobalt.

We can calculate the leaching % with the following equation:

$$\%X_{Lix} = \frac{C_M * V_{sol}}{m_M} * 100\% \quad (1)$$

$\%X_{Lix}$: Leaching yield (%)

C_M : Metal concentration (g/L)

V_{sol} : Volume of the leachate solution (L)

m_M : Mass of the leached metal (g)

Table 6. Leaching yield

	Values	Unit
Vol. of leaching solution	1.00	L
Mass in the material	33.33	g
%Co powder	6.50	%
% Ni powder	50.00	%
%Co leached	77.92	%
%Ni leached	57.76	%

Source: Prepared by the authors

The percentage of leached nickel was lower than that of cobalt. This behavior can be attributed to the higher solubility of cobalt sulfates compared to nickel sulfates, and to the adhesion of a fraction of the material to the magnet of the magnetic stirring system. Compared to the use of other acids that yield less than 40% (Zambrano et al., 2018), H_2SO_4 proves to be ideal for this process.

3.3. Removal of rare earths

The removal of rare earths was carried out by selective precipitation. The pH was adjusted to 1.2 by adding 5 M NaOH; the solution was kept under constant stirring for 30 min and subsequently filtered to separate the precipitate.

Table 7. Precipitated mass of rare earths

	Valuees	Unit
Total mass	3.486	g
Filter paper mass	1.251	g
Rare earth mass	2.235	g

Source: Prepared by the authors

3.4. Precipitation of impurities

The solution was adjusted to pH 6 by adding 5 M NaOH to precipitate impurities and keep the nickel and cobalt in solution

Table 8. Precipitated mass of impurities

	Valuees	Unit
Total mass	3.217	g
Filter paper mass	1.405	g
Impurities mass	1.812	g

Source: Prepared by the authors

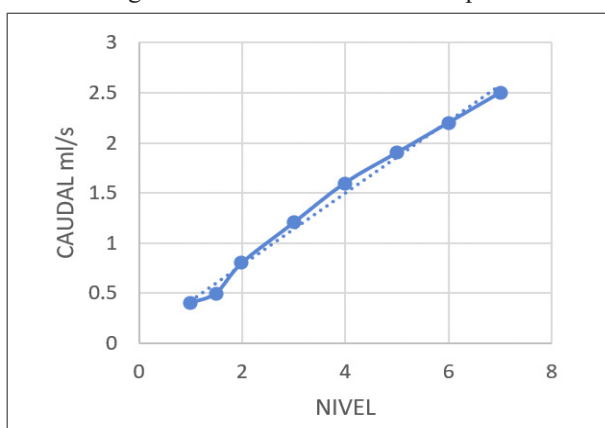
3.5. Electrodeposition

Before establishing the experimental design, preliminary tests were performed to identify the variables with the greatest influence on the electrodeposition.

3.5.1. Flow rate

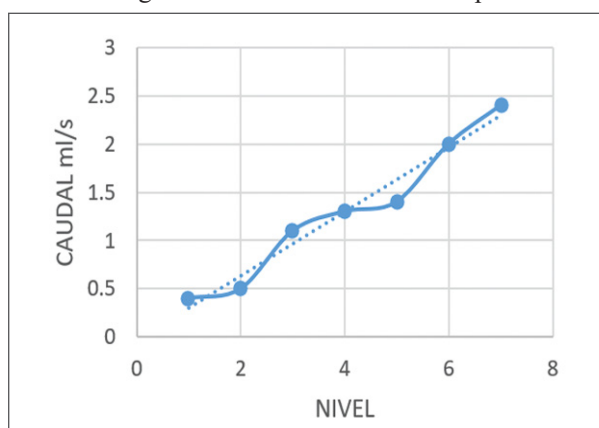
For this variable, the flow rate levels of the peristaltic pumps had to be measured. A time of 10 seconds was used for all measurements.

Figure 8. Level vs. flow rate Pump 1



Source: Prepared by the authors

Figure 9. Level vs. flow rate Pump 2



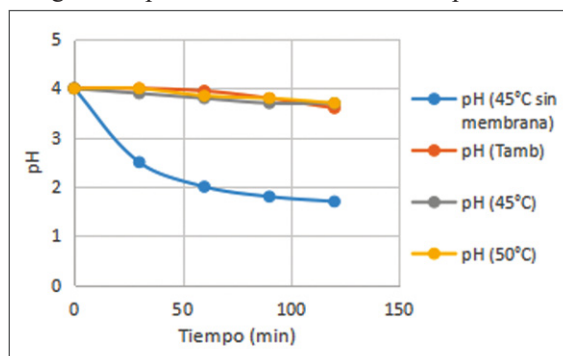
Source: Prepared by the authors

A flow rate of 0.5 mL/s was selected for both pumps, because at this rate, the liquid level in the electrochemical cell remained stable and allowed the maximum possible active area of the electrodes to be utilized.

3.5.2. pH

A pH of 4 was established as a suitable value for the process. To prevent acidification caused by oxidation-reduction reactions, a membrane was used to separate the cathodic and anodic reactions and to reduce sudden variations in pH.

Figure 10. pH variation at different temperatures



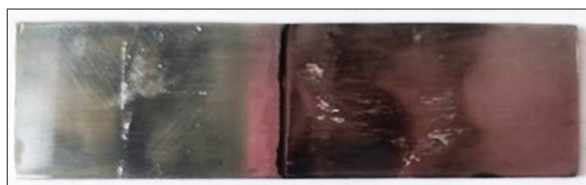
Source: Prepared by the authors

3.5.3. Time

Initial tests were performed with an operating time of 1 h; under this condition, no evidence of electrodeposition was observed on the cathode of the electrochemical cell. The first changes were observed at approximately 1 h and 25 min. For this reason, the experimental tests were started at 2 h, a time at which a minimum amount of deposit suitable for measurement and analysis was obtained.

A maximum time of 5 h was established, since at around 5 h and 30 min the deposited solids began to detach, making it difficult to collect the electrodeposit and causing variations in current intensity.

Figure 11. Detachment of the deposit



Source: Prepared by the authors

3.5.4. Temperature

The temperature variable was taken into account for the experimental design, starting from a room temperature of approximately 17 °C up to a maximum value of 45 °C; this second value was chosen because at higher temperatures, solid oxides tend to precipitate in the electrolytic solution.

Figure 12. Electrolyte precipitate



Source: Prepared by the authors

3.5.5. Voltage

$$V_{total} = 6.530 \text{ V}$$

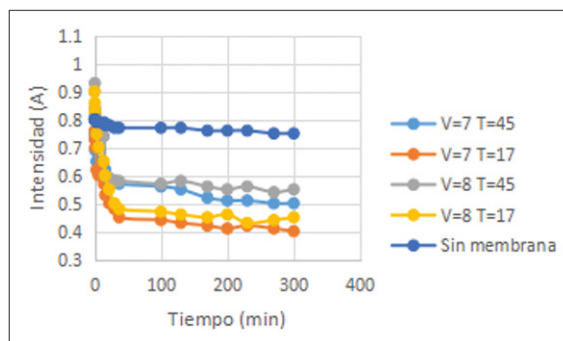
The voltage range was defined based on the electrochemical requirements of the system and preliminary tests.

Preliminary tests were started at 6 V; at this voltage, the formation of the deposit required a prolonged time. Therefore, 7 V was selected as the lower level and 8 V as the upper level. This range was kept within the operating limit of the membrane, whose maximum specified voltage is less than 10 V.

3.5.6. Current intensity

During electrodeposition, the current intensity tended to decrease over time due to the formation of a solid product layer on the cathode surface.

Figure 13. Current intensity vs. time



Source: Prepared by the authors

3.6. Experimental design (Total concentration)

A 2^3 factorial design was applied, supplemented with a center point and an external point. The lower and upper levels of the factors are presented in Table 9.

Table 9. Total concentration design

	Unit	Type	Std. Dev.	Low	High
Temperature	°C	Factor	0	17	45
Time	h	Factor	0	2	5
Voltage	V	Factor	0	7	8
Concentration	%	Response	3.56706	72.82	99.04

Source: Prepared by the authors

The experimental results were analyzed using Design-Expert software, which was used for the statistical analysis of the experimental design and the optimization of the studied variables.

A design 2^3 was applied, with 8 experimental tests and a replica (the duplicate of the experiments), obtaining 16 tests, additionally a test was performed for the central point (experiment 17) and another test for the external point (experiment 18), being 18 final experiments shown in Table 10.

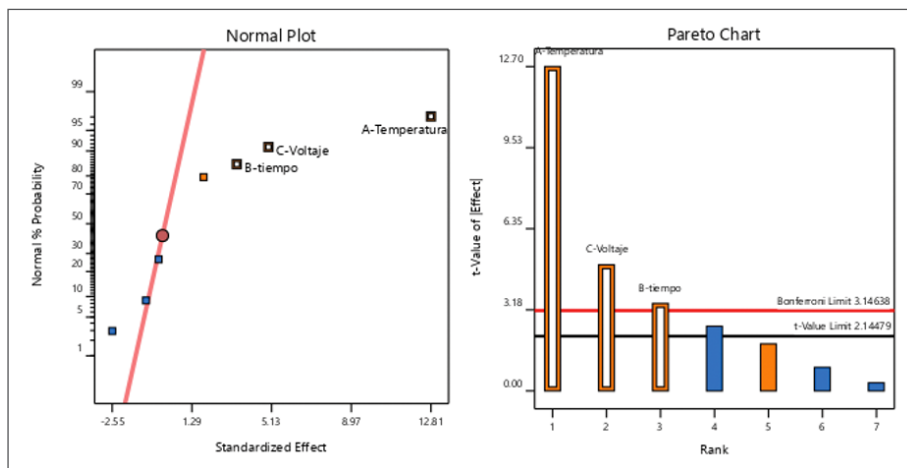
Table 10. Actual Total concentration design

Experiment	Run	Factor 1 A: temperature °C	Factor 2 B: time h	Factor 3 C: voltage V	Response 1 concentration %
1	6	17	2	7	72.82
2	10	17	2	7	75.70
3	13	45	2	7	90.86
4	11	45	2	7	89.70
5	18	17	5	7	83.46
6	5	17	5	7	83.14
7	14	45	5	7	94.28
8	3	45	5	7	93.12
9	1	17	2	8	82.94
10	16	17	2	8	85.49
11	12	45	2	8	95.23
12	17	45	2	8	96.46
13	7	17	5	8	83.89
14	9	17	5	8	83.81
15	8	45	5	8	99.04
16	15	45	5	8	98.21
17	4	30	5	8	91.90
18	2	50	5	8	98.48

Source: Based on the report of the AAS laboratory analysis (IGEMA)

The response variable presented values between 72.82 and 99.04%. The ratio between the maximum and minimum values was 1.36007; since it was less than 3, a data transformation was not considered necessary.

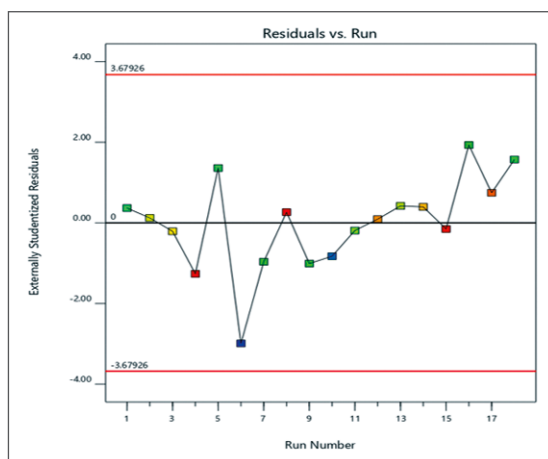
Figure 14. Pareto chart for Total concentration



Source: Design-Expert software

Figure 14 allows for the identification of the variables with the greatest significance in the process.

Figure 15. Residuals for Total concentration



Source: Design-Expert software

The residuals plot shows a data distribution without anomalous observations outside the considered limits.

Table 11. Analysis of variance ANOVA Total concentration

Source	Sum of squares	df	Mean square	F-value	p-value	
Model	969.58	3	323.19	72.13	< 0.0001	significant
A-temperature	722.98	1	722.98	161.36	< 0.0001	
B-time	52.51	1	52.51	11.72	0.0041	
C-voltage	109.21	1	109.21	24.37	0.0002	
Residual	62.73	14	4.48			
Lack of fit	52.83	6	8.80	7.12	0.0071	significant
Pure error	9.90	8	1.24			
Cor Total	1032.31	17				

Source: Design-Expert software

The model F-value of 72.13 implies that the model is significant. There is only a 0.01% chance that an F-value this large could occur due to noise. P-values less than 0.05 indicate statistical significance. In this case, temperature (A), time (B), and voltage (C) were significant factors.

Terms with p-values greater than 0.10 are considered not significant, except for those necessary to maintain model hierarchy.

Table 12. Statistics for Total concentration

Std. Dev.	2.12	R ²	0.9392
Mean	88.81	Adjusted R ²	0.9262
C.V. %	2.38	Predicted R ²	0.8964
		Adeq Precision	23.60

Source: Design-Expert software

The predicted R² of 0.8964 is in reasonable agreement with the adjusted R² of 0.9262; that is, the difference is less than 0.2. The Adeq Precision parameter evaluates the signal-to-noise ratio; values greater than 4 are considered adequate. The obtained value of 23.60 indicates an adequate signal and supports the use of the model to explore the experimental space.

The coefficient values of the equation corresponding to the concentration of the nickel and cobalt alloy are shown.

$$\%(Ni - Co) = 32.23 + 0.457 * T + 1.153 * t + 4.99 * V$$

3.6.1. Optimization

The values of the variables obtained by maximizing the concentration are:

Table 13. Optimized results Total concentration

Temperature	Time	Voltage	Conc%	Desirability
45.000	5.000	8.000	98.511	0.980
44.998	4.986	8.000	98.494	0.979
45.000	5.000	7.995	98.486	0.979
45.000	4.970	8.000	98.476	0.978
45.000	5.000	7.990	98.461	0.978

Source: Design-Expert software

Therefore, the optimal operating conditions determined were:

Table 14. Optimized values for Total concentration

Temperature	°C	45
Time	h	5
Voltage	V	8
Concentration	%	98.511

Source: Prepared by the authors

4. CONCLUSIONS

- A collection, selection, and pretreatment procedure for end-of-life Ni-MH batteries was established. 30 batteries were processed: 20 AA type, with an average mass of 19.889 g, and 10 AAA type, with an average mass of 11.545 g.
- Manual dismantling allowed the recovery of 148.779 g of anodic material and 171.801 g of cathodic material, equivalent to a total of 320.580 g of active material. For the leaching tests, 33.330 g were used.
- XRF analysis of the battery powder showed that these contain major concentrations of nickel, cobalt, zinc, and potassium, followed to a lesser extent by rare earths and manganese, confirming that they are a viable secondary source of strategic metals.
- AAS analysis shows that the cathodic and anodic powders are composed of 6.5% cobalt and 50% nickel.
- Leaching with 2 M sulfuric acid at 89 °C for 4 h, allowed the metals present in the battery powder to be solubilized, reaching a leaching percentage of 57.76% for nickel and 77.92% for cobalt.
- The applied membrane electrochemical method proved to be viable for the recovery of nickel and cobalt from spent Ni-MH batteries, reaching concentrations higher than 97% (Ni-Co) in the obtained deposits.
- The 2³ factorial design allowed determining that the optimal combination of conditions to reach total concentrations higher than 97% corresponds to 45 °C, 8 V, and 5 h.
- The F-9010 membrane favored pH control around 4 in the cathodic compartment and contributed to obtaining more uniform deposits with a lower presence of impurities.

5. ACKNOWLEDGMENTS

We thank the Universidad Mayor de San Andrés, in particular the Faculty of Engineering and the Department of Chemical, Petrochemical, Environmental, and Food Engineering, for the facilities provided for the development of this project. Likewise, special recognition is given to the Chemical Processes Research and Development Institute (IIDEPROQ) for its support in the study and development of projects within its different research lines.

6. LIST OF SYMBOLS AND ABBREVIATIONS

Ni - MH: Metallic Nickel Hydride, or Nickel Metal Hydride

F - 9010: Flemion ionic membrane

T: Temperature °C

V : Voltage V

t : Time h

%Ni - Co: Nickel and Cobalt concentration

AAS: Atomic Absorption Spectrophotometry

DRX: X-Ray Diffraction

FRX: X-Ray Fluorescence

kA/m^2 : Kiloamperes per square meter

M : Molarity mol/Litro

% X_{Lix} : Leaching yield (%)

C_M : Metal concentration (g/L)

V_{sol} : Leached solution volume (L)

m_M : Mass of leached metal (g)

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EVALUATION OF NATURAL ADSORBENTS IN THE REMOVAL OF AMMONIA AND OTHER NITROGEN COMPOUNDS IN WASTEWATER FROM THE VIACHA WASTEWATER TREATMENT PLANT

Beimar Arturo Ticona^{1,3,*}, Cristhian Carrasco¹, Paula Cecilia Soto²

ABSTRACT

This study evaluated the adsorption capacity of natural materials, namely limonite and orange peel, for the removal of ammonium and nitrogen compounds from wastewater at the Viacha Wastewater Treatment Plant (WWTP). Water physicochemical parameters were analyzed from August 2022 to November 2023, in a collaboration between IIDEPROQ and EMAPAV under the COSUDE CVG415 project. The results revealed high concentrations of ammoniacal nitrogen, with an average IQR of 119.5 ppm in the influent and 75.5 ppm in the effluent, alongside irregularities in the oxygen supply of the oxidation ditch. Orange peel exhibited limited adsorption, whereas limonite achieved a maximum removal of 45.5% under optimal conditions (pH 5.7, particle size 2.36 mm, and equilibrium time of 99.4 minutes). These findings support the implementation of a trickling biofilter as a tertiary treatment to enhance nitrification. Although natural adsorbents show potential for removing nitrogenous contaminants, their use at the Viacha WWTP is constrained by the high concentrations of these compounds. This study provides key data on non-conventional technologies for wastewater treatment in local contexts, emphasizing the importance of exploring innovative and sustainable solutions.

Keywords: Adsorption, sustainable solutions, ammonium removal, nitrification percolating filter, WWTP (Viacha).

1. INTRODUCTION

Water is an essential natural resource for life and socioeconomic development, especially in rural communities and growing cities, where access to basic services such as drinking water and sanitation is limited. In many regions of Bolivia, including rural and peri-urban areas, the lack of adequate wastewater treatment infrastructure has generated significant water pollution problems. This situation not only affects water quality but also poses a risk to public health and local ecosystems (INE, 2012).

Viacha, a municipality located in the province of Ingavi, department of La Paz, exemplifies this problem. With an estimated population of over 80,000, Viacha faces challenges related to wastewater management, particularly due to the discharge of domestic and industrial effluents into nearby water bodies, such as the Pallina River and Cohana Bay, which flows into Lake Titicaca. Recent studies have documented the enrichment of nutrients, especially nitrogen compounds, in these water bodies, leading to trophic changes, reduced biodiversity, and eutrophication events (Duwig et al., 2014; Archundia et al., 2016; Lazzaro et al., 2016).

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Figure 1. Wastewater inlet and outlet



Source: Author's own work, photographs taken during water sampling

Nitrogen pollution, in the form of ammonium (NH_4^+), nitrites (NO_2^-), and nitrates (NO_3^-), is particularly concerning due to its environmental and human health impacts. Ammonium, for example, can transform into nitrites and nitrates, compounds that, in high concentrations, are associated with diseases such as methemoglobinemia (known as "blue baby syndrome") and potential cancer risks due to the formation of nitrosamines (Mohseni-Bandpi et al., 2013; Battas et al., 2019). Furthermore, the presence of these compounds in surface and groundwater, such as the Purapurani and Viacha aquifers, poses an additional challenge to the sustainable management of water resources in the region (MMAyA/VRHR, 2016).

In this context, the effluent discharge, as shown in Figure 1, exhibits a characteristic green color associated with eutrophication processes, indicating high concentrations of ammonium, nitrites, and nitrates discharged into the Pallina River. This exacerbates eutrophication problems in Cohana Bay and Lake Titicaca. In this scenario, the Viacha Wastewater Treatment Plant (WWTP), shown in Figure 2, plays a crucial role in mitigating water pollution. However, the plant faces technical limitations, such as the high organic load of the effluent, the presence of fats, and the inhibition of nitrifying bacteria due to the wide temperature variations characteristic of the Bolivian Altiplano. These factors hinder the efficient removal of nitrogen compounds.

Figure 2. Plan view of the WWTP (Viacha)



Source: Extracted from Consultoría y Construcción Gómez Dants (2015). Estudio TESA PTAR Viacha [Technical drawing No. 4]

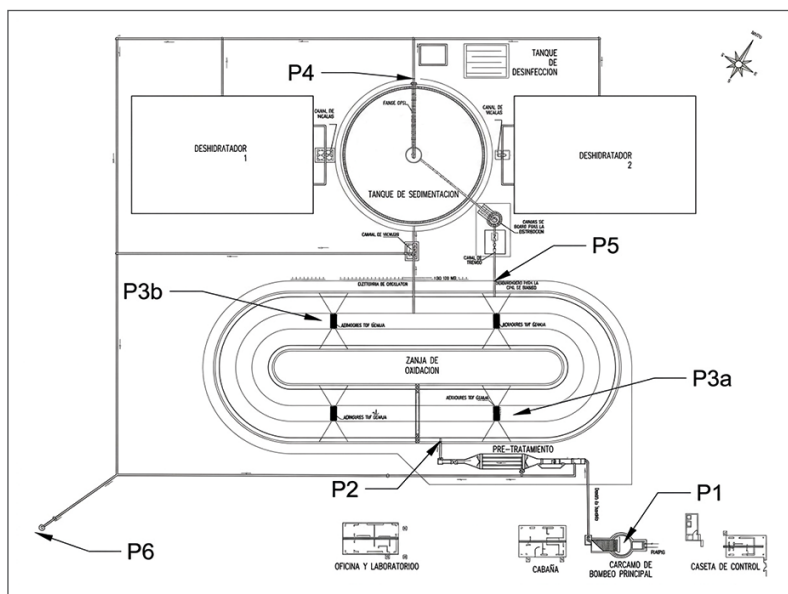
Given this problem, the main objective of this research is to evaluate the adsorption capacity of natural materials (limonite and orange peel) to remove ammonium and other nitrogen compounds from the wastewater of the Viacha Wastewater Treatment Plant. The results of this study aim to lay the groundwork for the development of innovative and sustainable technologies, thus contributing to improving the efficiency of wastewater treatment in the region, protecting local ecosystems, and safeguarding the health of surrounding communities.

2. MATERIALS AND METHODS

2.1. Wastewater monitoring at the Viacha WWTP

Wastewater monitoring is essential to ensure the quality of treated water and protect the environment. Specific monitoring points, shown in Figure 3, were established to collect accurate data on nitrogen compounds, pollutants, and other water quality indicators. Monitoring was conducted weekly from August 2022 to November 2023, ensuring continuous and detailed tracking.

Figure 3. Wastewater monitoring points



Source: Adapted from Manual de operación y mantenimiento: Planta de tratamiento de aguas residuales y emisarios (PTAR) - Viacha (p. 106), by ECOBLAD S.R.L., 2022.

The samples were collected following standardized procedures based on the Bolivian Standard NB/ISO 5667-10:2019 – Water Quality - Sampling of Wastewater, guaranteeing the consistency and reliability of the data.

2.2. Determination of physicochemical parameters

The physicochemical parameters of the wastewater were analyzed both in situ and in the laboratory; a summary is shown in Table 1.

Table 1. Parameters and methods used

Parameter	Method
Ammoniacal Nitrogen	SM-4500B
	SM-4500E
	HACH 8155
	HI93733
Nitrate	HI93728
Nitrite	HI93708
Biochemical Oxygen Demand	SM 5210 D
Chemical Oxygen Demand	SM 5220 B
pH	
Temperature	
Turbidity	HI 9828
Electrical Conductivity	
Oxidation-Reduction Potential	
Dissolved Oxygen	

Source: List of parameters in APHA (2017). Analytical procedures from HACH (DR890) and Hanna (HI 9828) spectrophotometer manuals.

2.3. Methods for analysis

In the adsorption experiments and wastewater analysis at the Viacha Wastewater Treatment Plant (WWTP), both standardized methods (Standard Methods) and abbreviated methods (HACH, Hanna) were used. Wastewater analyses were performed at the Viacha WWTP using abbreviated methods, while adsorption analyses were carried out at IIDEPROQ using standardized methods, due to the availability of specialized materials and reagents.

2.3.1. Determination of Ammoniacal Nitrogen ($\text{NH}_3\text{-N}$)

2.3.1.1. Distillation Method

The SM-4500B method (distillation) followed by the SM-4500E method (titration) was used to determine the concentration of $\text{NH}_3\text{-N}$, the arrangement can be seen in Figure 4.

Figure 4. Working distillation equipment arrangement (IIDEPROQ)



Source: Author's own work, photograph taken at IIDEPROQ laboratories.

The process involved distilling a 100 mL sample of wastewater with borate buffer solution (pH 9) and boiling chips. The distillate was collected in boric acid and titrated with sulfuric acid (0.02 N H₂SO₄) to determine the concentration of NH₃-N using the formula:

$$N - NH_3 \left[\frac{mg}{L} \right] = \frac{(a - b) * 280}{V}$$

Where:

a= mL de H₂SO₄ 0.02N used to titrate the sample

b= mL de H₂SO₄ 0.02N used to titrate the sample

v= volume of the analyzed sample

280=14 x normality H₂SO₄ x 1000ugN

2.3.1.2. Rapid methods (HACH and Hanna)

Two spectrophotometric methods were used to determine ammonium. Using the HACH instrument, the 385 N, Ammonia, Salic program was used, preparing samples with salicylate and ammonium cyanurate reagents and measuring the absorbance after 15 minutes. Using the HANNA instrument, the Ammonium HR method was applied, adding reagents HI93733A-0 and HI93733B-0 and taking the measurement after 3 minutes and 30 seconds.

2.3.2. Determination of nitrates (NO₃⁻)

The HANNA method for nitrates was used. The HI93728-0 reagent was added to the sample and the absorbance was measured after 4 minutes and 30 seconds.

2.3.3. Statistical analysis (Interquartile Range - IQR)

Interquartile Range (IQR) analysis was applied to assess the variability of the data for the analyzed parameters. This analysis allowed for the identification of outliers and predominant concentrations of nitrogenous pollutants.

2.4. Operational analysis of the Viacha Wastewater Treatment Plant

The performance of the activated sludge system was evaluated using a mass balance, considering the oxidation ditch and the settling tank as complete mixing reactors.

2.4.1. Adsorption study with biosorbents

2.4.1.1. Preparation of biosorbents

Two natural adsorbents were prepared: orange flavedo (*Citrus sinensis*), which was washed, dried at 60 °C, crushed and sieved (#100 mesh ASTM), and limonite, used in granule form and dried at 60 °C until a constant weight was reached.

2.4.1.2. Adsorption tests

Preliminary Tests: The adsorption of $\text{NH}_3\text{-N}$ in synthetic solutions (10-100 mg/L) was evaluated with orange peel and limonite, varying pH, particle size, adsorbent mass and stirring time.

Experimental studies in batch reactors: Experiments were performed with limonite to evaluate the adsorption kinetics, varying the contact time (0.5, 1, 2, 4 and 8 hours).

2.5. Design of a percolating biofilter

A trickling biofilter was designed based on the Albertson and Okey model (1988, as cited in Water Environment Federation, 2010), using limonite as the packing material. The design considered zero-order and first-order kinetics, with an $\text{NH}_3\text{-N}$ flux of $1.2 \text{ g/m}^2\cdot\text{dy}$ and temperature corrections. (Water Environment Federation, 2010).

3. RESULTS AND DISCUSSION

3.1. Characterization of wastewater (Influent)

Wastewater from Viacha exhibits medium to high levels of contamination, indicating a municipal origin with a significant nutrient and solids load. The presence of emerging contaminants such as pharmaceuticals and surfactants was identified, which are not efficiently removed by conventional systems. Furthermore, the need for continuous monitoring of fats and oils, which can affect the efficiency of biological treatment, is highlighted; the results are shown in Table 2.

Table 2. Comparison of wastewater characterization

Parameter	High (Metcalf-Eddy)	High-Medium (Viacha)
BOD5 (mg/L)	400	246.9
COD (mg/L)	1000	377.8
ammoniacal N (mg $\text{NH}_3\text{-N/L}$)	50	119.5
N nitrate mg (mg $\text{NO}_3\text{-N/L}$)	0	11.3
PT (mg P/L) (*)	15	14.25
Total Solids (TS)	1200	1219.2
Total Dissolved Solids (TDS)	850	802.3
Fixed Solids (mg/L)	525	530.7
Volatile Solids (mg/L)	325	549.7
Suspended solids (SS) (mg/L)	350	421.8
Total coliforms (MPN/100 mL) (*)	$10^7\text{-}10^9$	3.5×10^5

Reference: values from Metcalf & Eddy, (1998)

3.1.1. Evaluation of oxygen supply in the oxidation ditch

The oxygen supply provided by rotary aerators is insufficient to meet the demand for the degradation of organic and nitrogenous matter. The four aerators operating continuously would supply 1161.6 kg O₂/day, while the demand is 1231.8 kg O₂/day, resulting in a deficit of 70.2 kg O₂/day. Considering the recommended operating regime, the available oxygen is even lower, which negatively impacts the nitrification and ammonia removal processes.

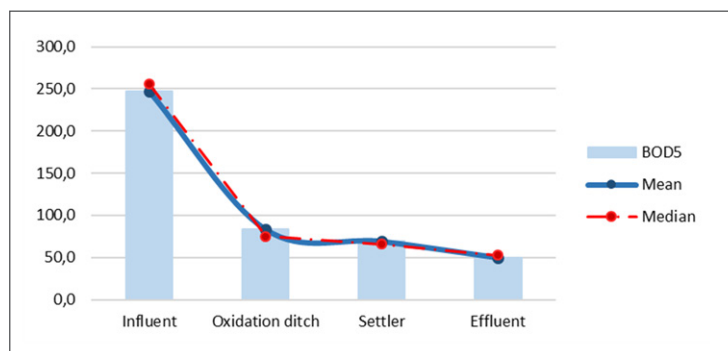
Improvement in the aeration system

To optimize oxygen transfer and improve treatment efficiency, the implementation of an aeration system with fine bubbles and mechanical agitators is recommended, which can increase oxygen dissolution efficiency to 6.6 kg O₂/h. Furthermore, considering the population growth of Viacha (113,453 inhabitants, INE 2024), the expansion of the wastewater treatment plant and the implementation of carousel-type oxidation ditches are suggested to guarantee future treatment capacity.

3.1.2. Catabolism of carbon and nitrogen compounds

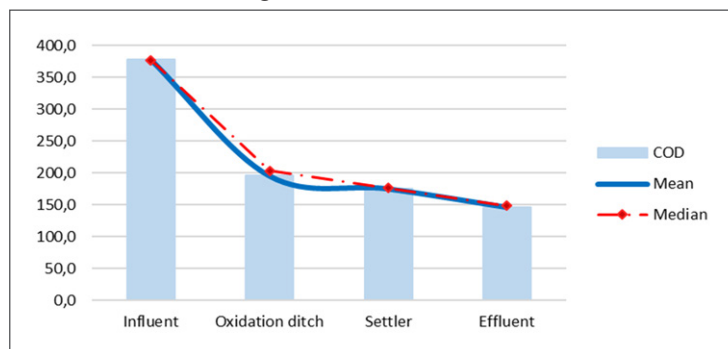
The degradation of pollutants in wastewater was assessed by measuring the reduction of BOD and COD, the variations of which are shown in Figures 5 and 6. However, insufficient oxygen in the process limits removal efficiency, suggesting the need to increase the hydraulic retention time. The lack of flow data prevented the calculation of system efficiencies, although trends in water quality were identified. The oxidation ditch showed the greatest reduction in organic matter due to the oxygen supply.

Figure 5. DBO5 Trend line



Source: From Ticona (2025, p. 91)

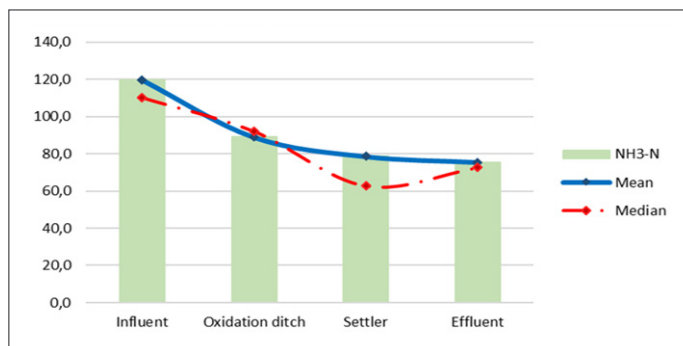
Figure 6. COD Trend line



Source: From Ticona (2025, p. 91)

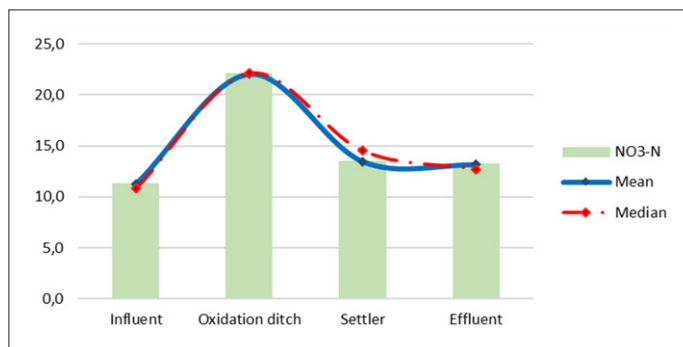
Nitrification was observed in two stages: conversion of NH_3 to NO_3^- , as shown in Figures 7 and 8, with low detection of NO_2^- due to its immediate conversion. Denitrification occurred in anoxic zones within the oxidation ditch. The activated sludge process exhibited limited nitrification due to the metabolic priority of carbonaceous compound degradation.

Figure 7. $\text{NH}_3\text{-N}$ Trend line



Source: From Ticona (2025, p. 91)

Figure 8. $\text{NO}_3\text{-N}$ Trend line



Source: From Ticona (2025, p. 91)

Reported optimal conditions for nitrification include temperature ($\sim 30^\circ\text{C}$), pH (7.2-8.5), and adequate oxygenation. However, the average temperature in the ditch was $\sim 13^\circ\text{C}$, affecting the efficiency of the process. Hydraulic problems were identified in the settling tank, where the lateral inlet creates dead zones with solids accumulation, affecting contaminant removal and turning some areas into anaerobic reactors. Furthermore, inadequate control of the hydraulic level between the oxidation ditch and the sedimentation tank could allow the discharge of untreated water.

3.2. Preliminary tests with orange peel

The orange peel biosorbent showed an equilibrium time of 60 minutes, with rapid adsorption in the first 30 minutes due to the high surface area available. However, the adsorption capacity was limited, reaching a maximum removal of 7.9% for 0.15 mm particles (ASTM #100) and only 1.3% for 2.36 mm particles (ASTM #8).

These low values are attributed to the reduced surface area in larger particles and the material's permeability limitations, especially under acidic pH conditions (pH 5.5), which are incompatible with the neutral to basic pH of Viacha wastewater.

3.3. Experimental tests with limonite

The highest amount of ammonia adsorbed by limonite was reached at 240 minutes; however, from 90 minutes onwards, the capacity remained constant, reaching equilibrium. The experimental conditions are summarized in Table 3.

Table 3. Experimental kinetic conditions

Parameter	Value	Unit
pH	5.7	
Particle size	2.36	mm
Dose	4.1	g
Time	99.4	min
% Removal	45.4	%

Source: From Ticona (2025, p. 91)

The adsorption kinetics of limonite fit the pseudo-second-order model (Ho & McKay, 1999), with a correlation coefficient ($R^2 = 0.989$). The equilibrium adsorption capacity was 3.39 mg NH_3/g , confirming the material's effectiveness. The selected kinetic equation was:

$$q_t = \frac{t}{0.15 + \frac{t}{3.39}}$$

Donde:

q_t : Total amount of biosorbate adsorbed at any time (mg/g)

t : time (min)

Regarding the adsorption isotherm, the Langmuir model (Langmuir, 1918) showed a maximum adsorption capacity (q_{max}) of 49.75 mg NH_3/g , with moderate affinity (Langmuir constant $b = 0.342 \text{ L/mg}$). The fit was optimal ($R^2 = 0.9859$), validating its use to describe the process. The selected Langmuir equation was:

$$q_e = \frac{17.01 * C_e}{1 + 0.34 * C_e}$$

Donde:

q_e : amount of adsorbate in the adsorbent at equilibrium (mg/g)

C_e : equilibrium concentration in the liquid phase (mg/L)

3.4. Design of a percolating filter

Calculations were performed for different filter media in the trickling biofilter, following the Albertson and Okey (1988, as cited in Water Environment Federation, 2010) kinetic model for nitrification. This model allows the determination of the surface area of the media required for zero-order nitrification, using a kinetic constant $k_n=1.2$. The calculations were based on the characteristics of each material, considering its specific surface area and average density.

Given the significantly high concentration of $\text{NH}_3\text{-N}$ in the Viacha WWTP effluent, a recalculation was performed for a scenario in which the treatment reduces the $\text{NH}_3\text{-N}$ by half, reaching a value of 25 ppm. This value represents a more realistic intermediate condition for the biofilter design. The initial data used for this calculation were:

Flow rate (Q): 50 L/s
NTK-Ni: 32 ppm
NTK-Ne: 1.5 ppm
 $\text{NH}_3\text{-Ni}$: 25 ppm
DBO: 25 ppm
sDBO: 5 ppm
Temperature: 15°C

The results are summarized in Table 4:

Table 4. Calculated values for percolating biofilter

	River rock	Crossflow PVC Plastic	Granular limonite	Units
SAA	62.3	138	1791	m^2/m^3
D	10.58	10.58	10.58	m
P	1574	7.11	0.55	m
WHL	0.57	0.57	0.57	$\text{L}/\text{m}^2\cdot\text{s}$
TOL	0.08	0.17	2.24	$\text{kg}/\text{m}_3\cdot\text{d}$

Where: SAA, Specific Surface; D, Filter Diameter; P, Depth of the filter medium; V, Total volume of the filter medium; WHL, Wet hydraulic loading; TOL, Total organic loading.

The results showed that, under these conditions, the biofilter dimensions can be optimized. For example, for limonite, a diameter of 10.58 m and a depth of 0.55 m were obtained. These dimensions allow for the implementation of two smaller biofilters, each 5.3 m in diameter and of the same depth, which simplifies their construction and operation.

This approach not only improves treatment efficiency, but also offers design flexibility, adapting to the specific needs of the Viacha WWTP and contributing to the effective reduction of nitrogen compounds in the effluent.

4. CONCLUSIONS AND RECOMMENDATIONS

- The physicochemical characterization of the water from the Viacha Wastewater Treatment Plant (WWTP), conducted from August 2022 to November 2023, shows a high load in the wastewater compared to international literature standards. The average ammonia nitrogen value is excessively high (119.5 ppm) compared to the high ammonia nitrogen range of 50 ppm to 75 ppm, indicating that the inflow should be controlled by identifying the source of this high quantity of nitrogenous nutrients.
- According to the analysis of data from report LAB-042-2023 EMAPAV, the oxygen supplied to the wastewater in the oxidation ditch is insufficient for the inflow rate, the concentration of contaminants, and the volume of water treated. The required amount is 1231.8 kg O₂/day, but the aerator brushes only provide 1161.6 kg O₂/day at maximum operating capacity. This deficiency prevents the nitrogen compounds from being oxidized.
- Water quality analysis of the effluent revealed average BOD and COD values of 49.6 mg O₂/L and 146 mg O₂/L, respectively, while historical minimums have been recorded at 8 mg O₂/L and 23 mg O₂/L. These results do not reflect the treatment of the entire incoming water flow, as a deficiency in the oxygen parameter required during operation was detected. This deficiency prevents achieving the reported values, which are expected to result in high efficiencies when all the water is treated. To confirm this situation, rigorous monitoring of both the water entering the reactor and the untreated water discharged via the bypass into the Pallina River is essential.
- Hydraulic and sanitary systems are inextricably linked in wastewater treatment plant design. If the hydraulics are not functioning properly, wastewater quality is compromised, as observed in hydraulic system observations involving the removal of nitrogen compounds from wastewater. Hydraulic head and the design of the sedimentation tank in the wastewater treatment plant (WWTP) negatively impact operation, increasing nitrogen compounds and potentially turning the sedimentation tank into an anaerobic reactor before the water even leaves the WWTP.
- The natural biosorbent orange peel exhibits very low adsorption capacity even under optimal conditions, hindering scalability despite its low cost. Its application in wastewater is more complex, as wastewater contains microorganisms that adhere to and degrade the material, increasing the water's organic load.
- The limonite biosorbent showed a good removal result, which had a maximum of 45.5%, whose optimal operating parameters are pH 5.7, particle size 2.36mm, equilibrium time 99.4 min and it was determined to be useful for performing the removal of ammonia nitrogen under the optimal adsorption conditions.
- The effectiveness of natural adsorbents is influenced by pH, as the best ammonia adsorption results are achieved under acidic conditions. However, the wastewater treated at the Viacha Wastewater Treatment Plant tends to be alkaline. Furthermore, the small particle size, when chosen for a filter medium, must ensure permeability and cross-flow of air and wastewater. These considerations complicate the implementation of non-conventional technologies.
- Implementing a trickling biofilter as a tertiary treatment process in wastewater is a viable alternative due to its compact design and the use of efficient materials such as limonite, which not only adsorbs nitrogen compounds

but also promotes biofilm formation thanks to its high specific surface area. With a flow rate of 50 L/s and an intermediate concentration of 25 mg/L of ammonia nitrogen ($\text{NH}_3\text{-N}$), and a filter medium 10.58 m in diameter and 0.55 m deep, this unit is designed to progressively reduce the concentration of ammonia nitrogen and, after decreasing the carbonaceous organic load, enhance biological activity, achieving more efficient removal of nitrogenous pollutants.

- It is recommended to adjust the frequency of monitoring parameter analyses, prioritizing an operational approach. Parameters such as solids, which are inexpensive to measure, provide key information for the daily operation of the system, allowing for optimized control and performance.
- It is recommended to implement additional oxygenation equipment to improve the process at the Viacha Wastewater Treatment Plant, as the current mechanical aeration is superficial and insufficient. Furthermore, homogenization using mixers submerged in the oxidation ditch is inefficient, as evidenced by the low dissolved oxygen levels, which decrease drastically at depths greater than 0.5 m.

5. ACKNOWLEDGMENTS

I thank Eng. Cristhian Carrasco Villanueva, PhD, and Eng. Paula Cecilia Soto Rios, PhD, from the Faculty of Engineering (UMSA), for their guidance and support. I also thank IIDEPROQ for facilitating the analytical development in the laboratory, and EMAPAV for granting me access to their laboratories to establish the baseline analysis of the Viacha Wastewater Treatment Plant. Finally, I thank COSUDE for the initial financial support within the framework of project CVG415.

6. ABBREVIATIONS

BOD₅, Biochemical Oxygen Demand at 5 days, (mg O₂/L)
COD, Chemical Oxygen Demand, (mg O₂/L)
 NH_4^+ , Ammonium ion, key nitrogenous pollutant, (mg/L)
 NO_2^- , Nitrite ion, intermediate in nitrification (mg/L)
 NO_3^- , Nitrate ion, nitrification product (mg/L)
N-NH₃, Ammoniacal nitrogen, main contaminant analyzed, (mg/L)
O₂, Dissolved oxygen, essential for nitrification, (mg/L or kg/d)
pH, Potential of hydrogen
qe, Amount of adsorbate in the adsorbent at equilibrium (mg/g)
SAA, Specific surface area of the filter material, m²/m³

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DISASTER RISK MANAGEMENT GUIDE CASE STUDY: APPLIED TO FONABOSQUE

Carla Siles^{1,*}, Waldo Vargas Ballester², Romina Sánchez Calle¹

ABSTRACT

The National Forest Development Fund (FONABOSQUE) is an autonomous public entity in Bolivia, created on July 12, 1996, under Forestry Law N° 1700. It operates under the Ministry of Environment and Water, and its mission is to finance initiatives for sustainable forest management, integrated watershed management, soil conservation, and fire management. Over the years, it has promoted various forestry projects, but without a clear Disaster Risk Management (DRM) approach, which has resulted in vulnerability to forest fires, floods, and droughts. This gap also implied non-compliance with Law N° 602 and Ministerial Resolution N° 115 of 2015, which require risk analysis in public investment projects.

Focusing to this need, a technical DRM guide was developed containing methodologies to identify hazards, assess vulnerabilities, and reduce risks. The guide was validated through FONABOSQUE-funded projects, and as an application example, the Pre-Investment Technical Design Study (EDTP by its Spanish acronym) of the project “Strengthening Sustainable Productive Associations” in Apolo is presented, where analytical methodologies such as the Saaty matrix and Bayesian analysis were applied. This guide is a valuable tool to strengthen future projects, promoting safer and more sustainable planning aligned with the Sendai Framework for Disaster Risk Reduction and the Sustainable Development Goals (SDGs).

Keywords: Disaster Risk Management (DRM), vulnerability, risk analysis, Saaty matrix, Bayesian analysis

1. INTRODUCTION

Disaster Risk Management (DRM) is an essential component for ensuring the sustainability of projects, particularly in contexts with high exposure to natural hazards such as forest fires, floods, droughts, and others. In the case of the National Forest Development Fund (FONABOSQUE), although current regulations—specifically Ministerial Resolution No. 115 of May 12, 2015, establish the obligation to include the analysis and design of prevention and risk management measures in the Preliminary Conditions Technical Report (ITCP by its Spanish acronym) and in the Pre-Investment Technical Design Studies (EDTP by its Spanish acronym).

In addition to exposing projects to material, environmental, and social impacts, this institutional the lack of the DRM carries the risk of regulatory non-compliance, which may affect the legality and eligibility of funded initiatives. In this context, a DRM guide adapted to FONABOSQUE’s requirements was developed, establishing a methodology for carrying out the four key steps of the process: hazard analysis, vulnerability analysis, risk assessment, and the formulation of intervention measures. This guide proposes the complementary use of two

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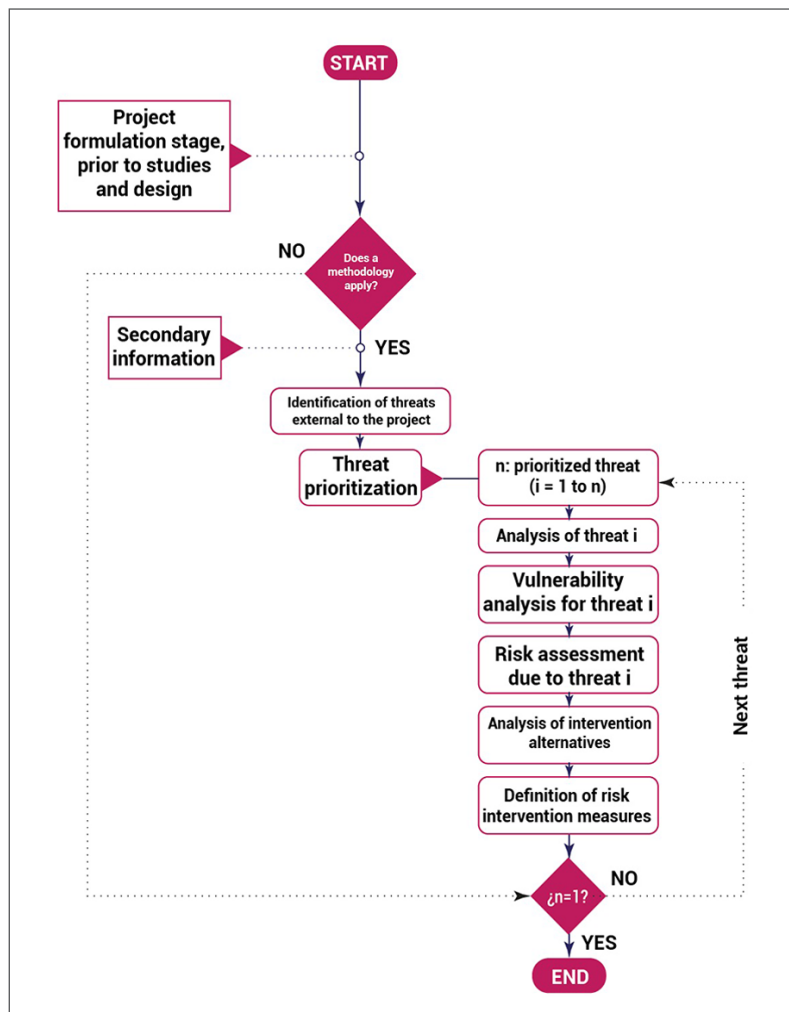
approaches: an analytical one, which incorporates tools such as the Saaty matrix (Saaty, 1980) and Bayesian analysis (UDAPE, 2024), and another based on digital platforms, which facilitates the processing of informational data.

The guide was applied in projects funded by FONABOSQUE, and in this work the following example was used: the Pre-Investment Technical Design Study TPDS of the project “Strengthening Sustainable Productive Associations: Promoting Conservation, Livelihoods, and Market Consolidation in the Municipality of Apolo” (FONABOSQUE, 2024). The analysis identified forest fires, floods, and droughts as the priority hazards.

2. MATERIALS AND METHODS

The flowchart of the proposed methodological procedure is presented. The guide proposes a structured process composed of four fundamental steps: (1) hazard analysis, (2) vulnerability analysis, (3) risk assessment, and (4) formulation of intervention measures (see Figure 1).

Figure 1. General methodological process



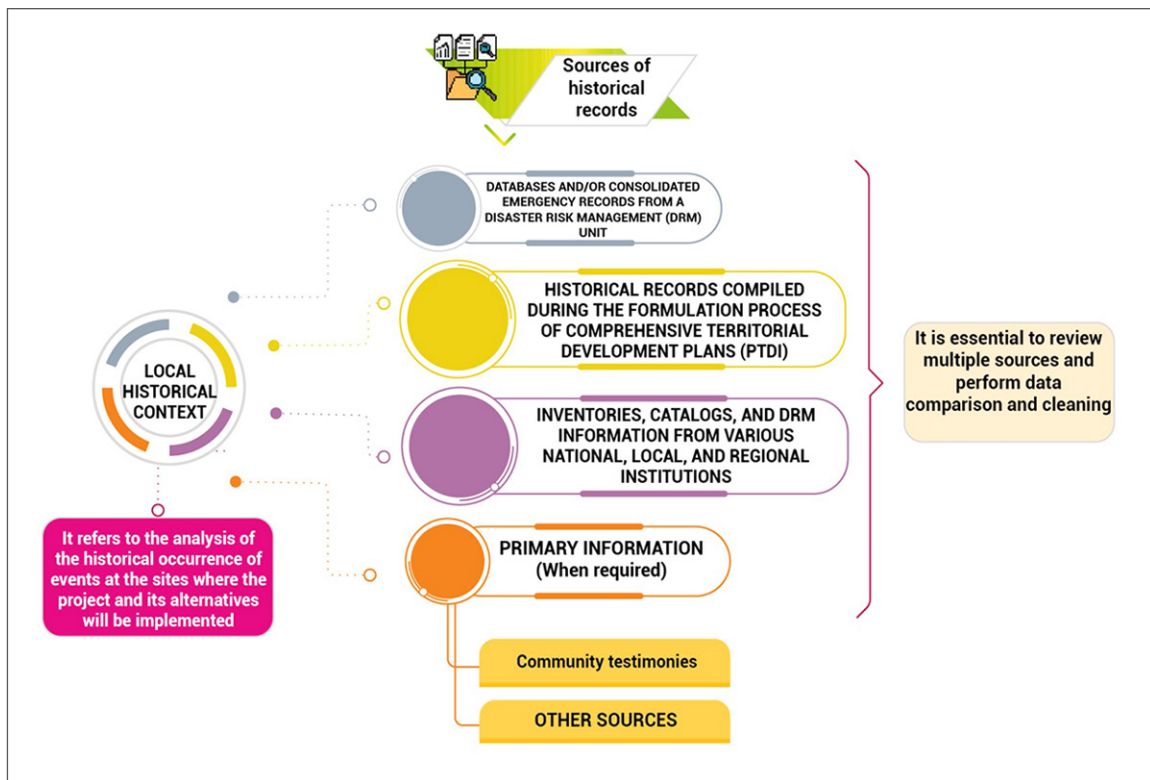
Source: Siles C., (2025)

a) Input information

The process begins with the project data, which must have the appropriate level of detail according to the formulation phase it is in. Having accurate information is essential to carry out the work effectively. Within the framework of this methodology, it is recommended to use the most detailed information available.

Once the project is placed within its general hazard context, it is crucial to investigate and analyze past events recorded at the local level. The study of these historical records is key to understanding the hazards, as it provides the essential information needed and, in many cases, the only available source to conduct an accurate assessment (see Figure 2).

Figure 2. Analysis of the local historical event context



Source: Siles C., (2025)

b) Hazard Analysis

A hazard is defined as “the probability that a natural, socio-natural, or anthropogenic event will occur at a specific time or place” (Law No. 602/2014).

To properly understand and manage the hazards a project may pose, either to its surroundings or within its own structure, it is essential to analyze the historical context of similar projects. This allows learning from past situations by identifying relevant events and the damage they caused.

These hazards should be classified according to their priority level (high, medium, or low), taking into account factors such as frequency and potential damage. It is recommended to focus the analysis on hazards considered high or medium priority. However, if the necessary resources are available, ideally all possible hazards should be assessed.

Tables 1 and 2 provide criteria to evaluate the frequency and potential damage of each hazard, which facilitates their prioritization in a clearer and more structured manner.

Table 1. Frequency criteria for hazard prioritization

Description	Frequency criterion
It occurs frequently, once every 1 to 5 years	HIGH
Limited possibility of occurrence or happens sporadically; once every 5 to 20 years	MEDIUM
Expected to occur rarely, once or less in 20 years	LOW

Source: Siles C., (2025)

Table 2. Damage potential criteria for hazard prioritization

Description	Damage potential criterion
Can severely affect physical elements (destruction) and people (deaths), as well as disrupt activities in the area	HIGH
Can moderately affect physical elements, activities, and people, without causing human deaths	MEDIUM
Only minor physical damages would occur	LOW

Source: Siles C., (2025)

Figure 3 visually presents the suggested combination of these criteria to establish the priority order in the analysis.

Figure 3. Combination of criteria for hazard prioritization

		DAMAGE POTENTIAL		
		HIGH	MEDIUM	LOW
FREQUENCY	HIGH	High Risk	High Risk	Medium Risk
	MEDIUM	High Risk	Medium Risk	Medium Risk
	LOW	Medium Risk	Medium Risk	Low Risk

Source: Siles C., (2025)

c) Vulnerability Analysis

Vulnerability refers to the conditions of elements exposed to a hazard that make them susceptible to damage. It can occur:

- Due to exposure to the hazard.
- Due to fragility when in contact with the hazard, which reflects intrinsic conditions such as the fragility of people, communities, activities, relationships, and functions.
- Due to resilience, that is, the ability to absorb or recover from the impact of the hazard.

Vulnerability varies depending on the hazard being analyzed. Therefore, it is necessary to conduct a specific analysis for each prioritized hazard.

Depending on the information available, there are various methodologies for vulnerability analysis. The guide provides some methodologies based on secondary information analysis. However, a more detailed analysis involving community participation would allow for a more accurate assessment of vulnerability.

If the technical team deems it necessary, primary data can be collected to achieve a more precise evaluation.

d) Risk Assessment

Risk is defined as “The estimated magnitude of loss of life, injured persons, affected property, damaged environment, and paralyzed economic activities, as well as affected goods and services in a given location, during a defined period of exposure to a particular hazard, considering the vulnerability conditions of the threatened sectors and population” (Law No. 602, Risk Management Law, November 14, 2014).

Risk analysis comprises two essential elements: Hazard and vulnerability. This analysis focuses on evaluating how both factors interact to estimate the potential impact that could result from the occurrence of a hazard in a vulnerable environment.

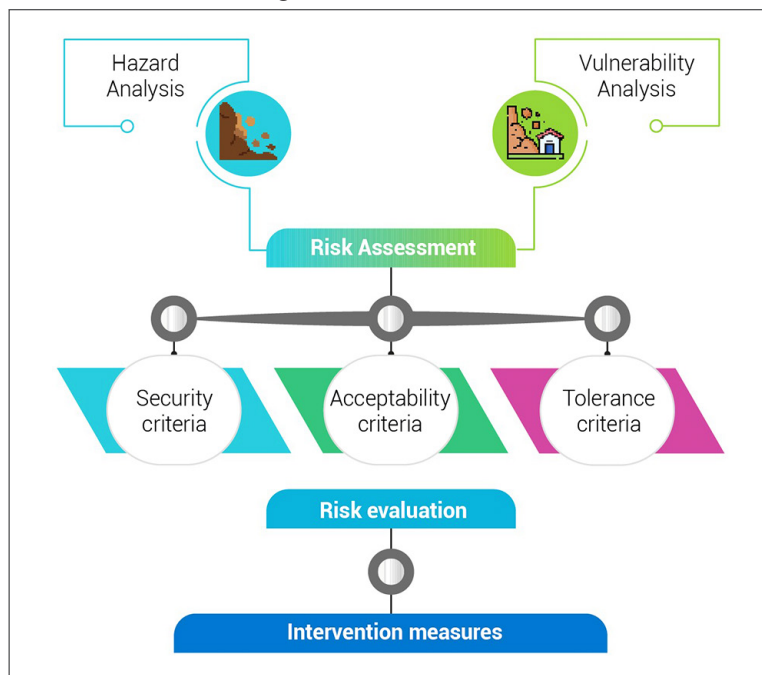
To do this, it is necessary to categorize the risk, which is based on the interaction between the hazard and vulnerability. The following matrix is suggested for this purpose (see Figure 4).

Figure 4. Risk criteria

		VULNERABILITY		
		HIGH	MEDIUM	LOW
THREAT	HIGH	High Risk	High Risk	Medium Risk
	MEDIUM	High Risk	Medium Risk	Medium Risk
	LOW	Medium Risk	Medium Risk	Low Risk

Source: Siles C., (2025)

Figure 5. Risk evaluation



Source: Siles C., (2025)

e) Formulation of Intervention Measures

After assessing the risk, it is essential to integrate the necessary DRM actions into the project and recommend those appropriate for the specific context. In this regard, intervention measures may differ in nature, following a process such as the one described below:

- Analysis of alternatives for risk reduction and climate change adaptation.
- Evaluation of the alternatives and selection of the most suitable intervention or mitigation measures.

Safety, acceptability, and tolerance criteria

i) Safety criterion

Involves protecting lives and property against disasters, ensuring that the measures adopted are effective in mitigating risks.

ii) Acceptability criterion

Defines the level of loss a community is willing to tolerate without compromising its economic or social integrity. this includes considering local expectations and needs.

iii) Tolerance criterion

Related to a community's capacity to recover after a disaster. This involves evaluating not only the immediate impact but also how pre-existing conditions can be restored or long-term resilience improved.

3.1. Analysis of Historical Records

3.1.1. Climate Risks

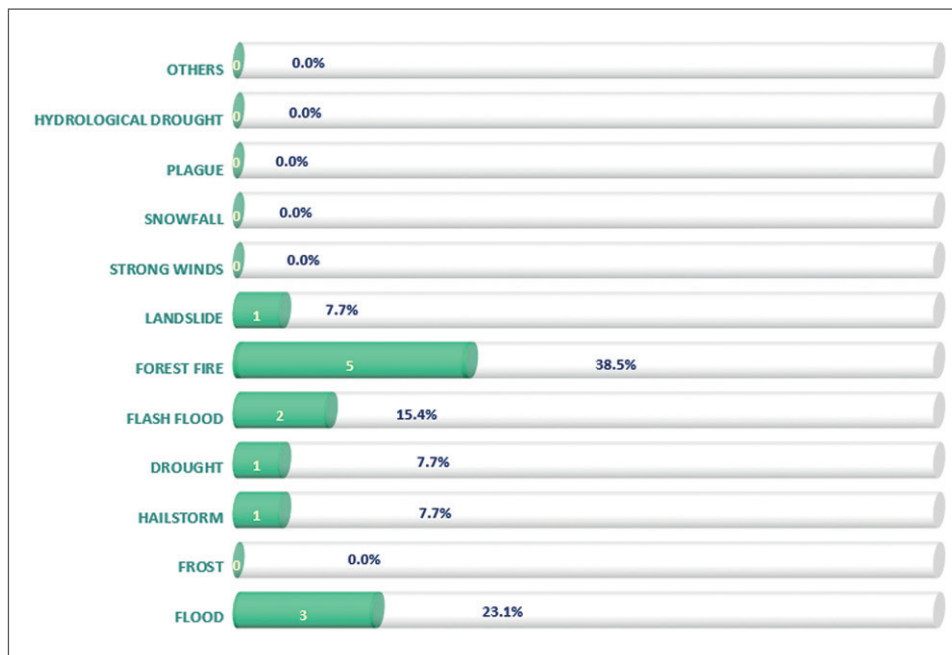
i. Relevant Adverse Events Recorded in Apolo

The events recorded during the period 2013 - 2023 include floods, frosts, hailstorms, droughts, landslides, forest fires, and others (thunderstorms, heavy rains, overflows, epidemic quarantines, human avalanches, collapses, mudflows, explosions, drownings).

During the study period, 13 events were recorded. Regarding disaster events, 38.5% corresponded to forest fires (5), ranking first among the most frequent events in Apolo; the second place with 23.1% corresponds to floods (3); and the third place with 15.4% corresponds to landslides (2).

Figure 6 shows the events that occur most frequently, which have a negative impact on various socioeconomic activities in the region.

Figure 6. Cumulative records by type of event occurring in Apolo (2013–2023)



Source: Siles C., based on information provided by SINAGER, 2024

ii. Impact of Disasters in the Municipality of Apolo

For the period 2013–2023, disaster activity shows an irregular pattern, with a total of 13 events concentrated in the years 2014, 2018, 2019, 2020, 2021, and 2022. Affected population. include a total of 2,003 people affected and 3,956 impacted, although there were no reported cases of injuries or missing persons, and only one death was reported in 2020.

Regarding material damage, 21 homes were affected, with the biggest losses recorded in the agricultural sector, where 15340.148 hectares were affected and 1846 hectares lost, mainly in 2019 and 2021.

Years without events indicate possible variability in disaster incidence, with significant peaks in specific years, which could be linked to particular climatic or social phenomena (see Table 3).

Table 3. Events and damages recorded in the Municipality of Apolo, period 2013 - 2023

YEAR	N° OF EVENTS	PERSONAL DAMAGES					MATERIAL DAMAGES			
		VICTIMS	AFFECTED	MISSING	INJURED	DECEASED	HOUSING		CROPS [Ha]	
							AFFECTED	DESTROYED	AFFECTED	LOST
TOTAL	13	2003	3956	0	0	1	3	18	15340.15	1846
2013	0	0	0	0	0	0	0	0	0	0
2014	1	0	486	0	0	0	0	0	1600	0
2015	0	0	0	0	0	0	0	0	0	0
2016	0	0	0	0	0	0	0	0	0	0
2017	0	0	0	0	0	0	0	0	0	0
2018	1	278	278	0	0	0	0	0	0	0
2019	3	599	300	0	0	0	3	18	8500	0
2020	4	0	1	0	0	1	0	0	0	0
2021	2	726	2491	0	0	0	0	0	4740.15	1296
2022	2	400	400	0	0	0	0	0	500	550
2023	0	0	0	0	0	0	0	0	0	0

Source: Siles C., based on information provided by SINAGER, 2024

Table 4. Damages recorded by type of event in the Municipality of Apolo, period 2013 - 2023

EVENT	N° OF EVENTS	PERSONAL DAMAGES					MATERIAL DAMAGES			
		VICTIMS	AFFECTED	MISSING	INJURED	DECEASED	HOUSING		CROPS [Ha]	
							AFFECTED	DESTROYED	AFFECTED	LOST
Total	13	2003	3956	0	0	1	3	18	15340.15	1846
Flood	3	1004	3255	0	0	0	0	0	3627.73	1296
Frost	0	0	0	0	0	0	0	0	0	0
Hailstorm	1	199	0	0	0	0	0	0	0	0
Drought	1	400	400	0	0	0	0	0	500	500
Flash flood	2	0	1	0	0	1	0	0	0	0
Forest fire	5	0	0	0	0	0	0	0	2712.42	50
Landslide	1	400	300	0	0	0	3	18	8500	0
Strong winds	0	0	0	0	0	0	0	0	0	0
Snowfall	0	0	0	0	0	0	0	0	0	0
Plague	0	0	0	0	0	0	0	0	0	0
Hydrological drought	0	0	0	0	0	0	0	0	0	0
Others	0	0	0	0	0	0	0	0	0	0

Source: Siles C., based on information provided by SINAGER, 2024

3.2. Hazard Analysis

It can be observed that the results of the analysis conducted using two approaches—one based on the database provided by SINAGER (SINAGER, 2024) in the analytical approach—coincide with those obtained by UDAPE (UDAPE, 2024) in the platform-based approach, despite using different methodologies.

Once the hazards are identified and prioritized according to the presented methodology, the following events are considered: flood, landslide, forest fire, landslide, and hailstorm. On the other hand, droughts will not be included in the subsequent analysis, as they have been classified as LOW priority (see Table 5).

Table 5. Project hazards

EVENT HAZARD	HAZARD IDENTIFICATION AND PRIORITIZATION			HAZARD	
	Frequency Criterion	Ptential Criterion	Analysis Criterion	Analysis with SINAGER Database	UDAPE
Forest fire	MEDIUM	MEDIUM	MEDIUM RISK	HIGH	
Flood	HIGH	MEDIUM	HIGH RISK	HIGH	HIGH
Drought	LOW	LOW	LOW RISK	LOW	LOW
Landslide	MEDIUM	MEDIUM	MEDIUM RISK	MEDIUM	
Flash flood	MEDIUM	HIGH	HIGH RISK	HIGH	
Hailstorm	MEDIUM	MEDIUM	MEDIUM RISK	MEDIUM	LOW

Source: Siles C., based on information provided by SINAGER and UDAPE, (2024)

3.3. Vulnerability Analysis

At this stage, the vulnerability of the previously prioritized hazards is analyzed. This analysis is carried out using two approaches: an analytical approach and a platform-based approach, both of which have databases and provide a result or vulnerability range.

Depending on the available information and the chosen approach, there are various methodologies for vulnerability analysis; the guide suggests several, and the choice will depend on the designer's criteria. For the analysis presented below, two methodologies were used: an analytical approach using the Saaty matrix for multicriteria evaluation, and the Bayesian Method, used in the UDAPE platform (UDAPE, 2024).

Table 6. Vulnerability analysis results for floods, droughts, and hailstorms

Hazard	Population Vulnerability
Flood	HIGH
Drought	VERY LOW
Hailstorm	VERY LOW

Source: Siles C., based on information provided by SINAGER and UDAPE, (2024)

3.3.1. Site analysis based on exposure (micro-location)

This analysis consists of assessing the exposure of the site where the project is intended to be implemented. Project exposure is closely related to its location within the territory and the type of project.

The following components are evaluated: bioclimatic, geological, ecosystem, built environment, pollution, and institutional–social. For each of these components, Tables 7 through 12 must be completed, considering the variables for each component.

3.3.1.1. Bioclimatic Component

Table 7. Multicriteria Evaluation Matrix (Saaty Method) for the Bioclimatic Component

Nº	VARIABLES	N/A	1	2	3
1 Hygrothermal comfort		X			
	1. The land has good thermal conditions for human habitat				
	2. The land has unfavorable but not extreme comfort conditions for human habitat				
	3. The land has very unfavorable thermal comfort conditions, with temperatures, relative humidity and heat waves greater than normal conditions				
2 Orientation		X			
	1. The longitudinal axis of the land is oriented east-west				
	2. When the land is rectangular or irregular, but its longitudinal axis is oriented north-east or north, up to 22 degrees from north				
	3. When the land is rectangular or irregular but its longitudinal axis is oriented north-south, southeast or southwest				
3 Wind					
	1. Winds with average annual speeds below 5.5 m/s (20 km/h)				
	2. Winds with average annual speeds between 5.5 and 7.9 m/s (28 km/h)			X	
	3. Winds with average annual speeds above 10.8 m/s (36 km/h) that may affect the project				
4 Precipitation					
	1. Dry regime or normal precipitation with occasional effects				
	2. Rigorous precipitation or drought regime not exceeding the territory's average, with distinct periods and non-significant effects				
	3. Severe precipitation regime exceeding the territory's average, with poorly differentiated periods during the year; precipitation may cause significant effects on the project or environmental factors				X
5 Noise		X			
	1. Insignificant noise below 40 decibels, a quiet urban environment				
	2. Acceptable noise, between 40 and 60 decibels, isolated noise sources that do not affect the project				
	3. High noise levels, above 65 decibels, or the land is located less than 60 meters from: industries, airports, heavily trafficked roads, churches, markets, etc.				
6 Air quality					
	1. Little or no effect from air pollution		X		
	2. Moderate effect from air pollution, presence of some sources (bad odors or suspended dust may occasionally occur) between 20 and 40 meters away				
	3. Strong effect from high air pollution (bad odors and suspended dust are permanently present), pollution sources less than 20 meters away				

Source: Siles C., based on the methodology of SEGEPLAN, (2013)

3.3.1.2. Geological component

Table 8. Multicriteria Evaluation Matrix (Saaty Method) for the Geological Component

N°	VARIABLES	N/A	1	2	3
7	Seismicity 1. The land is located in a low-hazard area on rocky ground, with no tall buildings nearby or slopes close to the site 2. The land is not close to seismic faults, but there are tall buildings nearby, transformer banks, rotten trees within 20 to 30 meters, and slopes under 2 meters in height 3. The land is located on one or more seismic faults, or faults exist less than 20 meters away; or tall buildings, transformer banks, rotten trees, etc. are within 1/3 of their height				
			X		
8	Erosion 1. There is no visual evidence of erosion on the land 2. The land shows signs of a moderate erosion process with vegetation cover predominant over most of the area (presence of small gullies at 2-meter intervals or numerous drainage lines) 3. The land shows signs of a pronounced erosion process (no vegetation cover, exposed roots, gullies 7 to 15 cm deep, numerous drainage lines)				
				X	
9	Landslide or Collapse 1. There is no risk of landslide or collapse on the land 2. There is a landslide risk on the land, but no effects on the site are expected due to the position of the slope 3. The land is located in zones of high danger from partial or mass landslides (due to loose soils, slopes greater than 15%)				
				X	
10	Volcanism 1. There are no nearby volcanoes, or if any exist, they are far enough that their activity would not affect the project 2. There are active volcanoes near the site and their volcanic activity could damage the project 3. The land is very close to inactive volcanoes and/or volcanoes with frequent activity that could seriously affect the project (ash, gases, lava, lahars, earthquakes, pyroclastics, etc.)		X		
11	Slope ranges 1. The land has slopes between 1 and 5%, or optimal ranges for the type of project 2. The land's slopes are between 5 and 15% 3. The land's slopes are greater than 15%				
				X	
12	Soil quality (field test, laboratory, or expert opinion) 1. Soils with strength or bearing value greater than 1.5 kg/cm ² (fine dry sand, hard clay, coarse dry sand, gravel, cemented gravel and sand, medium rock, solid rock) or a water table deeper than 6 meters 2. Soils with strength or bearing value between 1 and 1.5 kg/cm ² or a water table shallower than 5 meters, or without plastic or expansive clays 3. Soils with strength or bearing value equal to or less than 1 kg/cm ² or a water table at or above the depth of the foundations, or presence of clays with a high plasticity index or expansive clays		X		
13	Land use 1. The zoning plan indicates that land use is compatible with the type of project proposed 2. Land use is compatible with the type of project proposed, even though the zoning plan does not indicate it 3. Land use is not compatible with the type of project proposed		X		
14	Geological formation (review Bolivia's geological map and verify in the field with weathering, consolidation, and fragmentation tests) 1. The site is located on a geological formation of rock and deposits (sound rock and consolidated deposit) 2. The site is located on a moderately consolidated and weathered geological formation (sandy formation - slightly eroded ash) 3. The site is located on a rocky geological formation or deposits (poorly consolidated, highly weathered and fractured)		X		

Source: Siles C., based on the methodology of (SEGEPLAN, 2013)

3.3.1.3. Ecosystem Component

Table 9. Multicriteria Evaluation Matrix (Saaty Method) for the Ecosystem Component

N°	VARIABLES	N/A	1	2	3
15	Agricultural soils				
	1. There are nearby agricultural lands but farming techniques are not harmful, or there are no agricultural lands within a 400-meter radius				
	2. Burning or fumigation farming practices are used nearby, but the effect on the proposed project is minor			X	
	3. Nearby (less than 20 meters from the land) there are agricultural lands where burning or pesticide fumigation practices are used, which may affect people's health or the activities of the proposed project				
16	Surface hydrology				
	1. Due to its location, the land is not susceptible to flooding according to historical records				
	2. Flooding may exceptionally occur, but without the possibility of damage to the proposed project			X	
	3. The flood hazard is evident due to the existence of nearby water bodies, historical records, or the project encroaching on the natural right-of-way of a water body				
17	Groundwater hydrology				
	1. There is no historical evidence of groundwater flows in the land's area that could affect the project				
	2. Near the land, within less than 20 meters, there are groundwater sources at depths between 10 and 40 meters. Soils with low infiltration rates.			X	
	3. Near the land there are significant groundwater flows at depths less than 10 meters (soils with high infiltration rate)				
18	Lakes				
	1. The land is located more than 3 meters above the overflow elevation		X		
	2. The altitude difference is equal to or less than 1.50 m				
	3. The land is within the natural right-of-way elevation				
19	Fragile areas				
	1. The land is far from environmentally fragile areas, at distances greater than 1 km				
	2. The land is between 250 and 500 m from environmentally fragile areas			X	
	3. The land is within or very close to (less than 200 meters) environmentally fragile areas				
20	Sedimentation				
	1. There is no risk of deposit accumulation on the land where the project will be located				
	2. On the land where the project will be located, deposit accumulation may occasionally occur in insignificant amounts that do not affect the project and/or alter the land's topography			X	
	3. The land is within zones of deposit or soil accumulation, which may alter the site's topography or affect the proposed project during intense rains				

Source: Siles C., based on the methodology of (SEGEPLAN, 2013)

3.3.1.4. Built Environment Component

Table 10. Multicriteria Evaluation Matrix (Saaty Method) for the Built Environment Component

N°	VARIABLES	N/A	1	2	3
21 Range of action					
	1. Less than 25% of the population using the proposed project is located more than 5 km on foot or one hour by bus				
	2. Between 25 and 49% of the population using the project is more than 5 km on foot or one hour by bus			X	
	3. More than 50% of the population using the project is more than 5 km on foot, or one hour by bus, from the project's area of action				
22 Accessibility					
	1. There is no difficulty accessing the site at any time of year				
	2. There are roads usable only in certain seasons, or access construction is required for certain types of transport			X	
	3. Accessibility is difficult at certain times and impossible during the rains due to lack of infrastructure, means of transport (land and water)				
23 Access to services					
	1. Basic services exist at the site where the project will be located and it is possible to connect to them				
	2. At the site where the project will be located, at least two of the four services exist, or it is at least possible to connect to two of them			X	
	3. At the site where the project will be located, the services do not exist or the project cannot connect to them due to insufficiency or incapacity of the service systems				
24 Urban and rural considerations					
	1. When a territorial development plan (urban-rural) exists at the site where the project will be located and is compatible with the population growth and services it will require				
	2. When there is no development plan (urban and rural) for the land where the project will be located, or if it exists it is elementary, but there are alternatives to integrate the site with population growth and the services it requires			X	
	3. When there is no territorial development plan (urban and rural) at the site where the project will be located, and the project is not compatible with existing population growth and services, which hinders its future integration into urban or rural growth				
25 Land uses and pollution sources					
	1. The land is far from pollution sources		X		
	2. The land is moderately close to pollution sources, and historically pollution sources existed at the site				
	3. The land is close to pollution sources or shows evidence of contamination				
26 Urban and rural regulations					
	1. Municipal regulations or ordinances exist and the site is compatible with urban and rural development				
	2. There are no municipal regulations or ordinances, or if they exist they are not enforced, or the proposed project will moderately affect urban and rural development			X	
	3. There are no municipal regulations or ordinances, or if they exist they are not enforced, and the site where the project will be located will considerably affect urban and rural development				
27 Communal areas					
	1. There is coverage of services and communal areas				
	2. There are no communal areas or basic facilities, but these will be provided by the project			X	
	3. There are no communal areas or basic facilities				
28 Waste treatment facilities					
	1. There is appropriate space at the site and the soils are suitable for treating liquid and solid waste		X		
	2. There is the possibility of applying preliminary treatment, but on a restricted basis				
	3. There is no space and/or the soils are not suitable for building adequate treatment systems. There is no final effluent disposal system, or effluents are discharged into the watercourse				
29 Project dimensionality					
	1. The land's dimensions are sufficient to meet the type of project		X		
	2. The land's dimensions are just enough for the project but will not allow its expansion or modification				
	3. The land's dimensions are insufficient				

Source: Siles C., based on the methodology of SEGEPLAN, (2013)

3.3.1.5. Pollution Component

Table11. Multicriteria Evaluation Matrix (Saaty Method) for the Pollution Component

N°	VARIABLES	N/A	1	2	3
30 Solid and liquid waste					
	1. The land is more than 1000 meters from open-air solid and liquid waste dumps in the same wind direction, or opposite the wind direction but with tree masses that filter the polluted air.		X		
	2. The land is between 800 and 1200 meters from pollution sources (500-800 m, sanitary landfills; 800-1000 m, open-air solid waste dumps; 1200 m from cemeteries.)				
	3. The land is at distances of less than 100 to 800 meters from pollution sources (less than 500 m, sanitary landfills; less than 800 m, open-air solid waste dumps; less than 100 m from cemeteries)				
31 Polluting industries					
	1. The land is located more than 1000 meters from polluting industries (paint factories, nitrogen acids, leather processing); 500 m from polluting industries (construction material yards and asphalt plants); 300 m from slaughterhouses and plant fiber processing plants; and 100 m from glass, dairy, canned fish, gypsum, and clay factories		X		
	2. The land is located below the above standards, but very close to the limit of the standard, and there are mitigating factors such as tree masses				
	3. The land is located less than 1000 m from the limit of the standards and there are no tree masses				
32 High-voltage lines or electromagnetic equipment					
	1. The land is located more than 80 meters from high-voltage power transmission lines, electrical or electronic equipment (telephone antennas), etc.		X		
	2. The land is between 70 and 80 meters from high-voltage power transmission lines, electrical or electronic equipment (telephone antennas), etc.				
	3. The land is less than 70 meters from high-voltage power transmission lines, electrical or electronic equipment (telephone antennas), etc.				
33 Danger of explosions and fires					
	1. The land is more than 25 m from flammable structures (wood, straw, wattle-and-daub buildings) and/or more than 180 m from structures with explosion hazards (gas stations, material warehouses, explosive gas warehouses). At distances of less than 60 m from underground or above-ground fuel storage and gas plants		X		
	2. The land is at or below the limits of the above standards				
	3. The land is well below the above standards or adjacent to flammable structures or structures with explosion hazards				
34 Vice establishments					
	1. There are no nearby vice establishments to the land		X		
	2. The land is located at a sufficient distance from vice establishments				
	3. The land is adjacent to or extremely close to vice establishments (bars, nightclubs, etc.)				
35 Solid and liquid waste collection services					
	1. The land has coverage of these services and there is capacity to collect solid and liquid waste				
	2. The land is located in an area where solid and liquid waste collection services are planned to be provided			X	
	3. Strong effect from high air pollution (bad odors and suspended dust are permanently present), pollution sources less than 20 meters away				

Source: Siles C., based on the methodology of SEGEPLAN, (2013)

3.3.1.6. Institutional and Social Component

Table 12. Multicriteria Evaluation Matrix (Saaty Method) for the Institutional and Social Component

Nº	VARIABLES	N/A	1	2	3
36 Territorial conflicts	1. There are no territorial conflicts or disputes in the area where the proposed project will be located		X		
	2. There are territorial claims, but there is consensus among the population on the legitimacy of the site for the proposed project				
	3. There are territorial conflicts or disputes in the area where the proposed project will be located, and/or the project's location at the site may trigger or intensify territorial disputes				
37 Public safety	1. There is security near the land where the proposed project will be located		X		
	2. In the surroundings of the land where the proposed project will be located, common criminal behavior has occurred, but it is isolated and infrequent				
	3. The land where the project will be located is in areas with high rates of common crime, armed confrontations, kidnappings, or vandalism				
38 Legal framework	1. The land complies with the provisions of the legal framework (registered with a property title)		X		
	2. The land is in the process of being legalized				
	3. The land does not comply with legal regulations				
39 Citizen participation	1. There are communal organizations that actively participate in the proposal, planning, execution, and maintenance of the proposed project		X		
	2. There is organization but it does not actively participate in all phases of the project				
	3. There is no community organization, or one exists but is not taken into consideration				
40 Socioeconomic importance	1. The project is the main source of socioeconomic accessibility		X		
	2. Other routes exist, but the project is necessary				
	3. The project has low economic and social significance				
41 Quality of life	1. The project seeks to improve the quality of life of the population in impoverished neighborhoods		X		
	2. The project affects a sector of the population, but does not positively impact their quality of life				
	3. The project does not represent a significant contribution to quality of life				
42 Local conduct	1. The population has habits of using public space				
	2. There are limitations that can be overcome through education and citizen participation			X	
	3. The population does not have habits of using public space				

Source: Siles C., based on the methodology of SEGEPLAN, (2013)

This rating represents the site exposure index in relation to the proposed project and the threats that could affect it. It also allows for decisions to be made regarding whether the analyzed site location is appropriate for the implementation of the proposed project.

The site exposure rating was calculated, and the weights were determined using the Saaty method (see Table 13).

Table 13. Determination of Weights Using the Saaty Method

	C1	C2	C3	C4	C5	C6	Ci
C1	1	1	1	3	5	1	0.24
C2	1	1	3	3	3	1	0.26
C3	1	1/3	1	5	1	1	0.17
C4	1/3	1/3	1/5	1	1	1	0.08
C5	1/5	1/3	1	1	1	1	0.10
C6	1	1	1	1	1	1	0.15

The summary of the ratings, taking into account the variables of each component and their relative weights, is presented in the following table (see Table 14).

Table 14. Structure of Vulnerability Analysis by Exposure

Site exposure					
Component/variable	Rating	Relative weight	Component/variable	Rating	Relative weight
Bioclimatic Component	2	0.24	Built Environment Component	2	0.08
1 Hygrothermal comfort	N/A		21 Range of action	2	
2 Orientation	N/A		22 Accessibility	2	
3 Wind	2		23 Access to services	2	
4 Precipitation	3		24 Urban considerations	2	
5 Noise	N/A		25 Land uses and pollution sources	1	
6 Air quality	1		26 Urban regulations	2	
Geology Component	1	0.26	27 Communal areas	2	
7 Seismicity	1		28 Waste treatment facilities	1	
8 Erosion	2		29 Project dimensionality	1	
9 Landslides	2		Pollution Component	1	0.10
10 Volcanism	1		30 Solid and liquid waste	1	
11 Slope ranges	2		31 Polluting industries	1	
12 Soil quality	1		32 High-voltage lines or electromagnetic equipment	1	
13 Land use	1		33 Danger of explosions and fires	1	
14 Geological formation	1		34 Vice establishments	1	
Ecosystem Component	2	0.17	35 Waste collection services	2	
15 Agricultural soils	2		Institutional and Social Component	1	0.15
16 Surface hydrology	2		36 Territorial conflicts	1	
17 Groundwater hydrology	2		37 Public safety	1	
18 Lakes	1		38 Legal framework	1	
19 Fragile areas	2		39 Citizen participation	1	
20 Sedimentation	2		40 Socioeconomic importance	1	
			41 Quality of life	1	
			42 Local conduct	2	

Source: Siles C., based on the methodology of SEGEPLAN, (2013)

3.4. Site Exposure Vulnerability Rating

Next, the site exposure rating is estimated, which is the result of the sum of the products obtained by multiplying the rating of each component by its respective relative weight, according to the methodology proposed by SEGEPLAN, (2013). The formula to follow is:

$$C_{VES} = (C_{CB} * PR_{CB}) + (C_{CG} * PR_{CG}) + (C_{CE} * PR_{CE}) + (C_{CMC} * PR_{CMC}) + (C_{CC} * PR_{CC}) + (C_{CIS} * PR_{CIS})$$

Where:

C: Rating, **PR:** Relative Weight, **ES:** Site Exposure, **CB:** Bioclimatic Component, **CG:** Geological Component, **CE:** Ecosystem Component, **CMC:** Built Environment Component, **CC:** Pollution Component, **CIS:** Institutional and Social Component.

The site exposure rating is used to make decisions, as suggested in the weighting scale for the level of vulnerability by site exposure of the proposed project.

By applying the indicated formula and analyzing the data from Table 7, it was determined that the Site Exposure Vulnerability is:

$$C_{VES} = 1.49$$

Which corresponds to a medium vulnerability

According to the weighting scale, this value places the site in the medium exposure category (see Table 15).

Table 15. Weighting Scale for Site Exposure Level

Exposure level	Range	Recommendation
Highly exposed sites	2:00 to 3:00	Look for a new site, or in special cases where a new site is not an option, an in-depth analysis of fragility and resilience should be carried out, considering the exposure elements
Moderately exposed sites	1:00 to 1:99	Continue the vulnerability analysis of the proposed project, considering the exposure elements that could affect the project
Sites with low exposure	0:0 to 0:99	Continue the vulnerability analysis of the proposed project

Source: Siles C. Based on the Saaty methodology, (1980)

3.5 Risk Analysis and Evaluation

Risk analysis considers two fundamental components: hazard and vulnerability. Based on the analyses and results obtained in the previous sections, step 3 is carried out: risk evaluation, which includes completing the risk matrix. Using the risk criteria table, the corresponding rating for each hazard was determined (see Table 16).

Table 16. Risk Evaluation

Event	Hazard	Vulnerability	Risk Evaluation
Forest fire	MEDIUM	MEDIUM	MEDIUM RISK
Flood	HIGH	HIGH	HIGH RISK
Drought	LOW	LOW	LOW RISK
Landslide	MEDIUM	MEDIUM	MEDIUM RISK
Flash flood	HIGH	MEDIUM	HIGH RISK
Hailstorm	MEDIUM	LOW	MEDIUM RISK

Source: Siles C., based on information provided by SINAGER, VIDECI, and SEGEPLAN, (2024)

The table shows the identified risks. Various types of threats were analyzed (natural, socio-natural, and anthropogenic), highlighting events such as forest fires, floods, droughts, landslides, flash floods, and hailstorms.

High Risk: Floods and flash floods present a high risk due to the combination of a high hazard level and high or medium vulnerability. This suggests that these events are a priority for mitigation and adaptation actions.

Medium Risk: Threats such as forest fires, landslides, and hailstorms have a medium risk rating, indicating that although they are not the highest priority, they require monitoring and control measures to reduce potential impacts.

Low Risk: Drought is classified as low risk, as both the hazard and vulnerability are low. However, monitoring remains important due to potential climate changes that could alter these conditions.

3.6. Formulation of Intervention Measures

- Floods and flash floods should be addressed through specific action plans, such as strengthening infrastructure, implementing early warning systems, and promoting community awareness.
- Forest fires and landslides require preventive management strategies, including reforestation, soil management, and contingency plans.
- For hailstorms, it is recommended to work on agricultural protection systems and insurance mechanisms to reduce impacts on communities.
- Continuous monitoring of droughts is essential to detect potential upward trends in the level of hazard.

This risk prioritization is essential for allocating resources efficiently and minimizing impacts in the region.

4. CONCLUSIONS

- The project “Development of a Disaster Risk Management (DRM) Guide for FONABOSQUE” successfully met all the established objectives.
- A DRM guide was designed that can be implemented throughout the life cycle of projects financed by FONABOSQUE, strengthening their focus on sustainability and resilience.
- The guide was applied to FONABOSQUE projects, and in this work the following was used as an example: the Technical Pre-Investment Design Study (TPDS) of the project “Strengthening Sustainable Productive Associations: Promoting Conservation, Livelihoods, and Market Consolidation in the Municipality of Apolo.”
- The results obtained from the practical case were evaluated, allowing for adjustments and improvements to ensure its applicability and efficiency in future projects.
- Clear objectives were established, aligned with FONABOSQUE’s mission, and current legal and international regulations were identified, ensuring regulatory compliance.
- Historical data, common risks, and best practices were compiled, grounding the guide in solid evidence and real-world context.
- During the vulnerability analysis carried out in the municipality of Apolo, the results obtained were significant:
 - The main risks associated with the project were identified, including forest fires, deforestation, and droughts, which are the most frequent threats in the region.
 - Using tools such as the Saaty Matrix and the Bayesian method, vulnerability levels were quantified in key areas, which made it possible to propose concrete mitigation and prevention measures.
 - The case analysis demonstrated that the implementation of measures based on the guide can significantly reduce the risks to which projects and beneficiary communities are exposed.
- Impact of the Guide on FONABOSQUE’s Risk Management
 - The guide provided a structured and systematic approach to risk identification, analysis, and mitigation, strengthening FONABOSQUE’s capacity to address disaster-related challenges.
 - Its application in FONABOSQUE projects made it possible to validate the relevance and usefulness of the guide, demonstrating its potential to be integrated into project selection, evaluation, and monitoring processes.
 - The results of the practical case showed that the guide not only complies with national regulations, such as Ministerial Resolution No. 115, but is also aligned with international commitments such as the Sendai Framework and the Sustainable Development Goals (SDGs).
- Institutional Strengthening and Benefits for Projects. The implementation of the guide in projects financed by
- FONABOSQUE will make it possible to:
 - Significantly reduce vulnerability to natural disasters, decreasing the risk of economic, environmental, and human losses.

- Ensure regulatory compliance, enhancing FONABOSQUE's credibility as a financing entity for sustainable projects.
 - Promote a culture of prevention and resilience, both within the institution and among beneficiary communities.
- This project represents a significant advancement in disaster risk management within the context of projects financed by FONABOSQUE. The developed guide is a comprehensive, adaptable, and effective tool that not only improves project planning and implementation, but also strengthens their sustainability, contributing to the conservation of natural resources and the well-being of the communities involved. Its implementation will continue to generate tangible and sustainable benefits in the long term.

5. RECOMMENDATIONS

- It is recommended to incorporate Disaster Risk Management (DRM) as a subject or cross-cutting content within the Environmental Engineering curriculum, considering that this topic is currently not formally addressed, despite its importance for comprehensive and context-based training.
- FONABOSQUE should institutionalize the use of the Technical Guide, ensuring that all projects it finances apply DRM criteria from the design phase onward.
- It is suggested to train technical staff from FONABOSQUE and implementing entities in the use of analytical methodologies for vulnerability and risk analysis, such as the Saaty Matrix and Bayesian analysis.
- It is advisable to promote agreements with universities and research centers to update and enhance the technical guide with new approaches, geospatial tools, and case studies.
- It is strongly encouraged to integrate risk monitoring and evaluation processes throughout the project life cycle, thereby strengthening the sustainability and resilience of investments.

6. REFERENCES

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ENSO PHENOMENON PERSPECTIVES AND MONITORING FOR THE NORTH AND CENTRAL ALTIPLANO OF BOLIVIA: THE 2026-2027 EL NIÑO

Katherine Rojas Murillo^{1,*}, Magali Garcia Cardenas¹, Gavi Alavi Murillo¹, Alex Blanco¹

ABSTRACT

The El Niño-Southern Oscillation (ENSO) is an irregular ocean-atmosphere interaction that develops, on average, every 3 to 7 years in the Pacific Ocean and is one of the main drivers of interannual climate variability in the Andean region. This work synthesizes the ENSO monitoring and classification criteria used by the Japan Meteorological Agency (JMA) and the United States National Oceanic and Atmospheric Administration (NOAA), reviews the available evidence on its relationship with the climate of the North and Central Altiplano of Bolivia, and contrasts this historical evidence with the forecast outlooks available for the 2026-2027 El Niño event. To this end, monthly series of precipitation, maximum temperature, and minimum temperature (1976-2025) from seven stations of the National Meteorology and Hydrology Service (SENAMHI) were analyzed. Monthly synoptic classification of sea surface temperature (SST) anomalies of Kung and Chern (1995) for the developing event was compared with that of previous very strong El Niño events. As of May 2026, SST anomalies close to 2 °C were recorded in the Niño 1+2 region and close to 1 °C in the other regions; by July, these anomalies exceeded 3 °C in the Niño 1+2 region and reached 2 °C in Niño 3.4, with more than a 90% probability, according to NOAA, that the event will reach the very strong category between September and December 2026. The synoptic classification of the event (type C) coincides with that of 1982-1983 and 2015-2016, years in which the Altiplano recorded seasonal drought between December and March, cold anomalies of minimum temperature between December and January, and wet anomalies toward April. It is concluded that the ENSO-precipitation relationship in the Altiplano is weak and indirect, and is influenced by other factors such as the Pacific Decadal Oscillation (PDO) and the North Atlantic Oscillation (NAO), among others; therefore, monitoring of the developing event must integrate synoptic analysis, multi-model ensembles, and ancestral knowledge within early warning systems, particularly given the absence of a simple relationship between the magnitude of the forcing and the magnitude of the local impact.

Keywords: ENSO, Bolivian Altiplano, PDO, NAO, climate risk management.

1. INTRODUCTION

The El Niño-Southern Oscillation (ENSO) is an ocean-atmosphere interaction that occurs, on average, every 3 to 7 years in the Pacific Ocean. This irregular cycle typically begins between March and July, lasts about 12 to 18 months, and reaches its peak intensity between October and January. Although ENSO was previously defined as a continuous, self-sustained cyclical oscillation (Gu & Philander, 1995), this view was superseded by several later studies, including Kessler (2002), which posits ENSO events as a succession of independent episodic events.

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Conceptually, ENSO is not a strictly regular cycle, owing to its asymmetric evolution between its El Niño and La Niña phases. This asymmetry is evident in the disparity of sea surface temperature (SST) anomaly intensities and spatial patterns, as well as in the temporal development of the events. This variability reflects nonlinear ocean-atmosphere coupling dynamics and stochastic forcings such as westerly wind bursts (An et al., 2020). Its warm phase (El Niño) is associated with a weakening of the trade winds, the displacement of warm water masses to the eastern Pacific, suppression of the thermocline (the boundary between cold deep water and warm surface water) in the eastern Pacific, and weakening of the Walker Circulation, which in turn exponentially fuels further weakening of the winds; its cold phase (La Niña) shows the opposite behavior (Bjerknes, 1969; Gu & Philander, 1995).

The study of this phenomenon has a long history. It originated with empirical observations by fishermen in northern Peru and southern Ecuador, who identified a warm ocean current that tended to appear around December — near Christmas — and called it El Niño, in reference to the Christ Child (Martinez, 2020). Walker (1920) described the Southern Oscillation and, together with Bliss (1932), documented its link to the Indian monsoon. Bjerknes (1969) established the physical relationship between the two phenomena, linking the oceanic and atmospheric components and giving rise to the concept of ENSO (Cane, 1983). The 1982-1983 event consolidated the phenomenon's scientific and media relevance owing to the unprecedented magnitude of its impacts — at the time — on infrastructure, agriculture, and fishing activity in Peru, Ecuador, Bolivia, and the rest of South America (Glantz, 2001; Quinn et al., 1987).

1.1. ENSO classification and monitoring

Because ENSO involves the ocean and atmosphere, its monitoring began with the Southern Oscillation Index (SOI), defined as the sea-level pressure difference between Tahiti and Darwin. Currently, SSTs are monitored in four regions of the equatorial Pacific, defined through various studies (NCAR, 2026): Niño 1+2 (used to track the coastal Niño that impacts Peru and Ecuador), Niño 3, Niño 3.4, and Niño 4. The JMA (Japan Meteorological Agency) uses the Niño 3 region to define ENSO, while NOAA (National Oceanic and Atmospheric Administration) uses the Niño 3.4 region; both institutions consider the ± 0.5 °C threshold to classify an event as Neutral, El Niño, or La Niña. Classification indices have been redefined over time: NOAA recently incorporated the RONI (Relative Oceanic Niño Index) to replace the ONI (Oceanic Niño Index), to remove the influence of long-term global warming and improve the ability to track the phenomenon.

Table 1. Conceptual differences in the definition of an El Niño/La Niña event

Criterion	(JMA) Japan	(NOAA) United States
Index used	JMA Index	RONI Index (formerly ONI)
Monitoring zone	Niño 3 (Eastern Pacific)	Niño 3.4 (Central Pacific)
Time window	5 months (moving average). Seeks very stable changes.	3 months (moving average). More sensitive to abrupt changes.
Effect of Climate Change	Does not account for global warming.	Accounts for global-warming noise by subtracting the warming of the entire tropics, to ensure that the anomaly is solely due to El Niño.
Months required for classification	6 consecutive months	5 consecutive months

Source: Prepared by the authors

Using a different approach, Takahashi et al. (2011) defined the E and C indices through an empirical orthogonal function (EOF) analysis of monthly SST anomalies from the HadISST database, based on the two main modes of variability. The E-index is primarily associated with extreme warming events concentrated in the eastern Pacific, whereas the C-index relates to moderate cold or warm events in the central Pacific. Using these indices, Cai et al. (2020) identified the 1982-1983 and 1997-1998 events as very strong El Niño episodes, expressed mainly in the E-index, while the 2015-2016 event manifested simultaneously in both the E-index and the C-index.

Kung & Chern (1995), for their part, developed a classification of SST anomalies based on cluster analysis, identifying seven synoptic patterns (A through G) that group the spatial behavior of such anomalies and allow for their visual identification, albeit with a certain degree of subjectivity. Types C, D, and F are related to El Niño events; C and F are the most similar to each other, although type F is associated with greater coverage of warm anomalies — generally between 1 and 3 °C — extending also into the North Pacific and the Atlantic Ocean. Type C is characterized by more intense warm anomalies concentrated along the equatorial Pacific, typically exceeding 3 °C (Lupo et al., 2008).

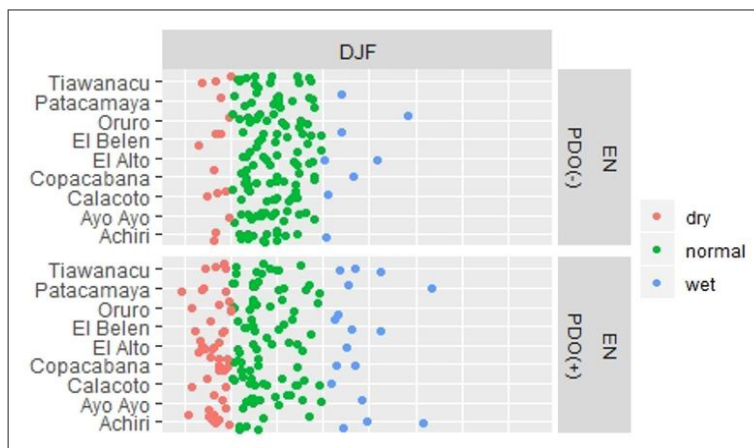
1.2. Precipitation climatology in the Altiplano and its relationship with ENSO

Around 80% of the Altiplano's annual precipitation falls between December and March (Andrade et al., 2018); this “wet season” depends strongly on the position and intensity of an upper-level anticyclone (200 hPa) known as the Bolivian High (BH). This high-pressure system is typically associated with divergent flows aloft, sustained by ascent linked to a surface low-pressure system (Krishnamurti et al., 2013). A more northerly position of the BH increases westerly wind anomalies and the occurrence of dry events, whereas a more southerly position favors precipitation in the region (Garreaud et al., 2003; Vuille & Keimig, 2004), owing to the BH's role in transporting moisture from the interior of the continent toward the Altiplano (Cai et al., 2020).

The relationship between ENSO and precipitation during the wet season in the Altiplano — located in the central Andes of South America — has been previously studied (Canedo-Rosso et al., 2019; Garreaud & Aceituno, 2001; Segura et al., 2019; Vuille & Keimig, 2004). These studies agree that the relationship between El Niño/La Niña phases and dry/wet anomalies is not direct and generally weak (Garreaud et al., 2003; Perry et al., 2017). Although dry anomalies in the Altiplano are associated with strengthened westerly winds at mid and upper levels of the atmosphere — which inhibit moisture transport from the east — and these winds tend to intensify during El Niño events, the relationship between ENSO and Altiplano precipitation remains weak (Garreaud & Aceituno, 2001). This is confirmed in the work of Canedo-Rosso et al. (2019), who evaluated the relationship between precipitation and the Niño 3 and Niño 3.4 indices, the NAO, and the Atlantic Meridional Mode (AMM), among others, through a Maximum Covariance Analysis (MCA); this study shows that the Niño 3, Niño 3.4, and NAO indices together explain the largest proportion of the covariance of Altiplano precipitation during Dec-Jan-Feb. Additionally, forcings such as the PDO (Pacific Decadal Oscillation) modulate ENSO impacts. Rojas-Murillo et al. (2022) show a greater number of dry standardized monthly precipitation anomalies during the positive phase of the PDO combined with El Niño during Dec-Jan-Feb. As of 2026, the PDO is in a negative phase, which, although also a scenario for dry anomalies, shows fewer of them; the same study shows that the BH is positioned, on average, farther north during El Niño events in the positive phase of the PDO, and shifts southward during the negative phase (Figure 1).

Another study also shows that a meridional temperature gradient at 400 hPa between 16° and 20° S could explain part of the precipitation variability during extreme drought events (Segura et al., 2019).

Figure 1. Classification of standardized precipitation anomalies (dry, normal, wet) at the North and Central Altiplano stations (SENAMHI) during the El Niño phase and the positive and negative phases of the PDO, for the December-January-February (DJF) quarter. The red dots show the number of years with dry anomalies, the green dots show years with little anomaly (normal), and the light-blue dots represent years with wet anomalies, by station.



Source: Adapted from Rojas-Murillo et al. (2022)

For the Bolivian Altiplano, understanding ENSO is critical because the region concentrates agricultural and livestock activities that are highly sensitive to precipitation variability and extreme events such as droughts, frosts, and floods. Knowing that the relationship between Pacific SST anomalies and Andean precipitation is neither simple nor direct, and that it is modulated by other climatic forcings (Canedo-Rosso et al., 2019; Rojas-Murillo et al., 2022), the objective of this article is to synthesize ENSO monitoring criteria, review its historical effects on the climate of the North and Central Altiplano, and contrast this evidence with the outlooks available for the 2026-2027 El Niño event.

2. METHODOLOGY

Monitoring of the development of the 2026-2027 El Niño event was conducted using official monitoring and forecasting sources (NOAA, JMA) as well as alternative statistical forecasting sources (International Research Institute for Climate and Society, Columbia Climate School-IRI). At the time of this review, these sources agreed that a very strong El Niño phase was expected toward the end of 2026.

Based on this, we analyzed previous events identified by NOAA as very strong El Niño events, also referred to by Cai et al. (2020): 1982-1983, 1997-1998, and 2015-2016. As a comparative baseline, monthly time series of precipitation, maximum temperature, and minimum temperature covering 49 years (1976-2025) were obtained from the database of Bolivia's National Meteorology and Hydrology Service (SENAMHI). The dataset includes seven stations located in the Northern and Central Altiplano, five of which provide records for all three variables, while the remaining two provide precipitation data only (Table 1). Monthly anomalies were calculated and standardized by dividing each anomaly by the corresponding climatological standard deviation for that month. This procedure removes the effect of differences in variability among months and expresses the magnitude of each anomaly relative to its typical seasonal variability (IRI, 2019). For each month, the 1991-2020 period was used as the climatological reference (WMO, 2017) to calculate the corresponding monthly mean and standard deviation. This approach allowed the identification of unusually warm, cold, or dry behavior compared with the 1991-2020 reference climatological conditions.

Table 2. Weather stations used in the analysis, available variables, and coordinates

Station	Tmax/Tmin	Precipitation	Lat. (°)	Lon. (°)	Altitude (m)
Achiri	—	X	-17.212	-69.002	3880
El Alto (Aeropuerto)	X	X	-16.510	-68.198	4037
Ayo Ayo	X	X	-17.093	-68.007	3888
El Belén	X	X	-16.019	-68.712	3833
Calacoto	X	X	-17.283	-68.634	3826
Copacabana	—	X	-16.169	-69.088	3815
Oruro (Aeropuerto)	X	X	-17.966	-67.079	3719

After reviewing the impacts associated with the selected very strong El Niño events, their monthly correspondence with the synoptic classification of Kung & Chern (1995) was examined, based on the archives of Lupo et al. (2008), classifying the anomalies recorded through 2016 and the months of 2026. This classification was used because of its application in lines of research on regional climate variability and seasonal forecasting: Lupo et al. (2007, 2008) extended the monthly classification archive through 2007 and linked it to the PDO; Birk et al. (2010) analyzed its relationship with temperature and precipitation in the Midwestern United States; and Henson et al. (2017) applied it to agricultural yield series.

Finally, a literature review of the impacts of El Niño events in the study region was carried out, identifying the work of Poma (2018), who — to analyze the factors influencing change in production systems — built timelines together with producers from communities in the North and Central Altiplano, to determine milestone events, including those of climatic origin, in the history of these communities.

3. RESULTS

3.1. Status and forecast of the 2026-2027 El Niño event

Regarding the ongoing monitoring of the 2026 ENSO event, forecasts from the major operational climate centers consistently indicate the development of a Strong to Very Strong El Niño event. In May 2026, NOAA's Climate Prediction Center (CPC) reported sea surface temperature (SST) anomalies of approximately 2 °C in the Niño 1+2 region and around 1 °C across the remaining Niño regions (CPC, 2026). By July, SST anomalies in the Niño 1+2 region had exceeded 3 °C, while anomalies in the Niño 3.4 region had reached approximately 2 °C. Based on these observed conditions and model projections, NOAA's August 2026 assessment indicated a probability exceeding 90% that the event would meet the Very Strong El Niño criterion (≥ 2 °C) during the September–October–November (SON) and October–November–December (OND) seasons. Similarly, the IRI plume forecasts (2026), which integrate projections from a range of statistical and dynamical models, indicated mean SST anomalies of approximately 2.5–3.0 °C for the OND season. Forecasts issued by the Japan Meteorological Agency (JMA, 2026) were broadly consistent with these projections, supporting the expectation of an exceptionally strong El Niño event during the latter part of 2026.

As an independent source of ENSO predictability, the statistical forecasting framework developed by Ham et al. (2019) was additionally considered. This framework employs convolutional neural networks (CNNs) to predict ENSO-related SST variability and provides forecasts through the Seoul National University AI Climate platform (aiclimete.snu.ac.kr/enso). The model projects an evolution broadly consistent with the operational forecasts issued by NOAA, with Niño 3.4 SST anomalies reaching approximately 3 °C during November–December 2026. Figure

2 shows the Niño 3.4 SST anomaly time series spanning 2024–2027. Observations are indicated by the black line, while the red line represents the forecast initialized in September 2025. The shaded envelope denotes the model's correlation skill as evaluated during the 1984–2017 validation period, thereby illustrating the model's predictive performance as a function of forecast lead time.

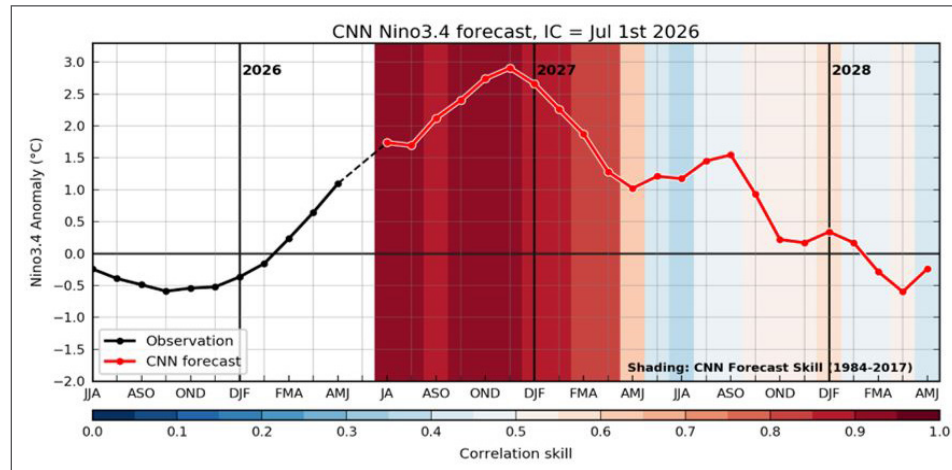


Figure 2. Forecast of the SST anomaly in the Niño 3.4 region using a convolutional neural network (CNN)

Source: ACE LAB (2026)

3.2. Synoptic classification of the developing event

Monthly mean SST anomaly maps for January–July 2026 were examined using the NCEP/NCAR (National Center for Environmental Prediction/National Center for Atmospheric Research) reanalysis dataset¹. In addition, SST anomaly maps from the Optimum Interpolation Sea Surface Temperature (OISST) dataset² were examined using the interactive animations provided by IRI³. The spatial evolution of the SST anomalies indicates that, during June and July 2026, the developing ENSO event exhibited a pattern broadly resembling synoptic type C described by Kung and Chern (1995), characterized by intense warm anomalies concentrated in the equatorial Pacific, exceeding 3 °C. To place the 2026 event in a historical context, monthly warming patterns from previous ENSO years were subsequently examined. A partially comparable spatial pattern was identified during the 1982–1983 and 2015–2016 events (Figure 3).

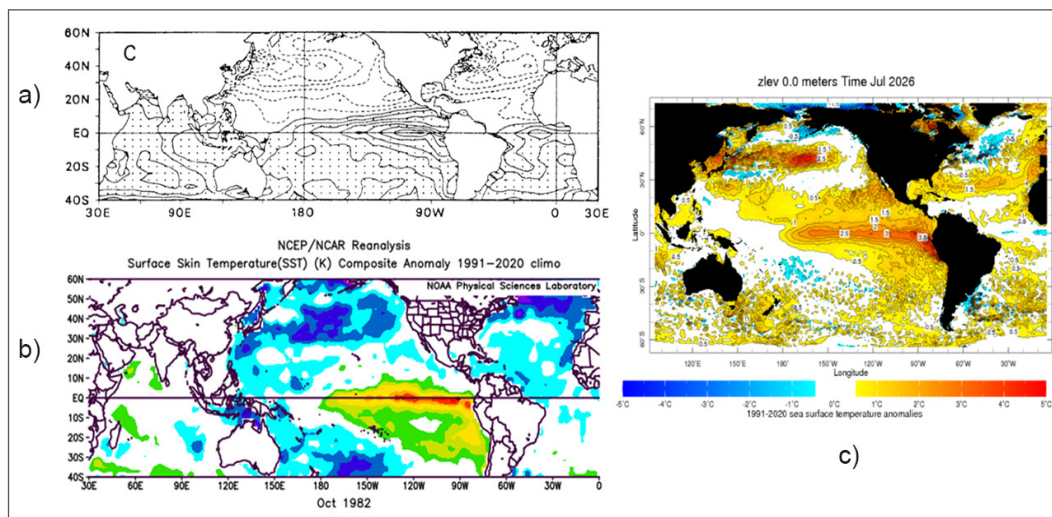


Figure 3. Comparison of SST anomalies: (a) October 1982 (NCEP/NCAR Reanalysis, relative to the 1991–2020 climatology); (b) reference type C synoptic pattern (Kung & Chern, 1995); (c) July 2026 (1991–2020 climatology).

Source:
a) Kung Chern (1995),
b) NCEP/NCAR Reanalysis, c) IRI

¹ Available at <https://psl.noaa.gov/cgi-bin/data/composites/printpage.pl> ²NOAAs 1/4-degree Daily Optimum Interpolation Sea Surface Temperature Version 2.1

³ Available at https://iridl.ldeo.columbia.edu/maproom/Global/Ocean_Temp/Anomaly_Loop.html

Table 3 summarizes the monthly synoptic classification for the 1970–2016 period, compiled based on Lupo et al. (2008) and Kung and Chern (1995). In this classification scheme, types C, D, and F are associated with El Niño–type conditions. Type C occurs during several major El Niño events, including 1976–1977, 1982–1983, and 2015–2016. In contrast, the 1997–1998 event is predominantly classified as types E and F, with no occurrence of type C. For 2026 (Table 4), the classification indicates a rapid transition from types G and D, associated with negative SST anomalies, during the first quarter of the year to type C beginning in May and persisting through June. This transition coincides with the development of pronounced positive SST anomalies concentrated in the eastern equatorial Pacific, consistent with the spatial characteristics of type C.

Table 3. Monthly synoptic classification of SST anomalies (types A to G of Kung and Chern, 1995) for the 1970–2026 period, where types C, D, and F correspond to the El Niño classification. Type-C months and the reference years analyzed in this study are highlighted in color (prepared from Lupo et al., 2008).

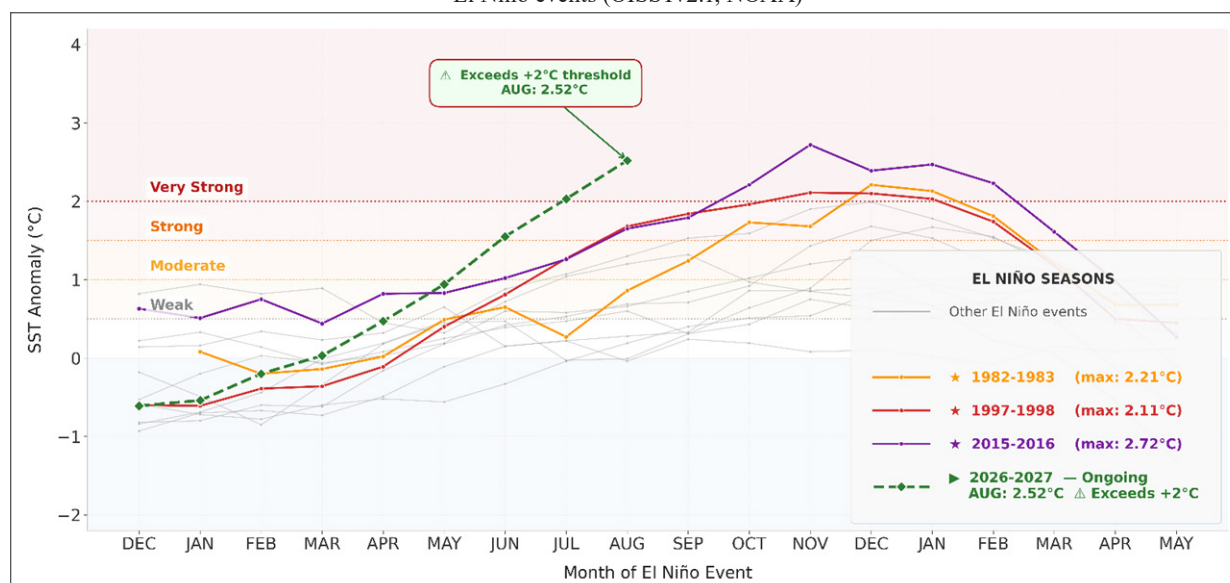
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1970	C	C	C	C	C	C	C	B	B	B	B	B
1971	B	B	B	C	B	B	B	B	B	B	B	B
1972	B	B	B	C	C	C	C	F	C	C	C	C
1973	C	C	C	B	B	B	B	B	B	B	B	B
1974	B	B	B	B	B	B	B	B	B	B	B	B
1975	B	B	B	B	B	B	B	B	B	B	B	B
1976	B	B	B	B	B	B	B	C	C	C	F	F
1977	C	C	C	B	B	E	E	E	E	E	C	F
1978	F	F	F	E	E	B	C	E	E	C	F	F
1979	C	C	C	C	C	C	F	F	F	F	F	F
1980	F	F	F	F	F	E	E	E	E	E	E	E
1981	F	F	F	C	C	E	E	E	E	E	E	E
1982	E	E	E	E	C	F	F	C	C	C	C	F
1983	C	F	F	F	F	F	F	E	E	C	E	E
1984	E	E	F	B	E	B	E	E	E	E	B	B
1985	B	B	B	B	B	E	E	E	E	E	E	E
1986	E	E	F	E	E	F	F	F	F	F	F	F
1987	F	F	E	E	F	C	F	E	F	E	F	F
1988	E	E	E	E	E	E	E	E	E	A	A	G
1989	G	G	G	G	F	F	E	E	E	E	F	F
1990	A	E	E	F	F	F	F	F	D	D	D	D
1991	D	F	F	C	C	E	E	E	E	F	F	F
1992	F	F	F	F	F	F	F	F	F	F	F	F
1993	F	F	F	F	F	F	F	F	D	F	F	F
1994	D	D	F	E	F	F	D	E	D	D	D	D
1995	E	E	E	E	E	E	E	E	E	E	E	E
1996	E	E	E	E	E	E	E	E	E	E	E	E
1997	E	E	E	E	E	E	E	E	E	E	F	F
1998	F	F	F	F	F	F	F	G	G	G	G	G
1999	G	G	G	G	G	G	G	G	G	G	G	G
2000	G	G	B	B	B	G	G	A	A	A	A	G
2001	G	B	B	B	G	G	G	G	G	A	A	A
2002	B	A	A	A	A	D	D	D	D	D	D	D
2003	D	D	D	B	B	A	A	A	E	E	A	A
2004	A	A	A	B	B	D	D	D	D	D	D	D
2005	D	D	D	B	B	B	B	A	A	A	A	A
2006	A	B	B	B	B	B	B	D	D	D	D	D
2007	D	A	G	G	G	G	G	G	G	A	A	G
2008	G	G	G	G	G	B	B	B	B	B	B	B
2009	B	G	G	B	B	F	F	F	F	D	D	D
2010	D	D	D	D	B	B	G	G	G	G	G	G
2011	G	G	B	B	B	G	G	G	G	G	G	G
2012	G	G	G	B	F	F	F	F	F	G	G	A
2013	A	B	B	B	B	B	G	G	G	G	A	A
2014	A	A	G	G	F	F	F	F	E	E	F	F
2015	E	G	G	D	F	C	C	C	C	C	C	C
2016	F	F	F	F	F	G	G	G	G	G	G	G

Table 4. Monthly synoptic classification of SST anomalies (according to Kung and Chern, 1995) for 2026

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2026	G	D	D	D	C	C						

A comparison of the SST anomalies observed during 2026 with those recorded during previous Very Strong El Niño events indicates a marked intensification of the current event. By August 2026, the SST anomaly had reached 2.52 °C according to NOAA OISSTv2.1 (Figure 4), exceeding the anomaly values recorded in July during the 1982–1983 and 2015–2016 Very Strong El Niño events. The increase in SST anomalies has been particularly pronounced since May 2026, indicating a sustained intensification of the warming signal throughout the end of the year.

Figure 4. Evolution of the SST anomaly (Niño 3.4 region) during 2026 compared with historical very strong El Niño events (OISSTv2.1, NOAA)



Source: Prepared by the authors

3.3. Precipitation, minimum temperature, and maximum temperature anomalies in analogous events

Given the similarity between the 2026 SST anomaly patterns and the type-C configuration, together with the classification of the ongoing event as Strong to Very Strong El Niño as of August 2026 (Table 2), the standardized anomalies of precipitation, minimum temperature, and maximum temperature were analyzed for the 1982–1983 and 2015–2016 events. The analysis was based on 24-month time series from meteorological stations located in the Northern and Central Altiplano (Table 1; Figures 5–7).

For both events, precipitation exhibited a recurring seasonal pattern characterized by negative anomalies from December through March (Figure 5), coinciding with the local wet season, followed by a transition toward positive anomalies in April. However, the magnitude and spatial distribution of the precipitation deficits varied substantially among stations and between events. In April, six of the seven stations with available precipitation records exhibited positive anomalies, indicating above-normal monthly precipitation. These positive anomalies may have resulted from intense precipitation events capable of producing surface erosion or degradation in areas previously affected by drought; however, this interpretation is beyond the scope of the present analysis.

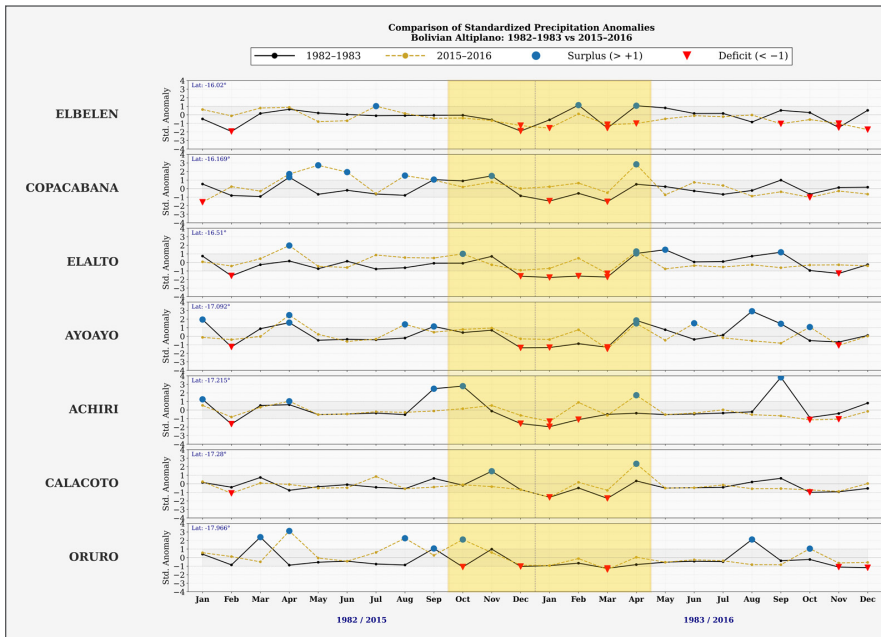
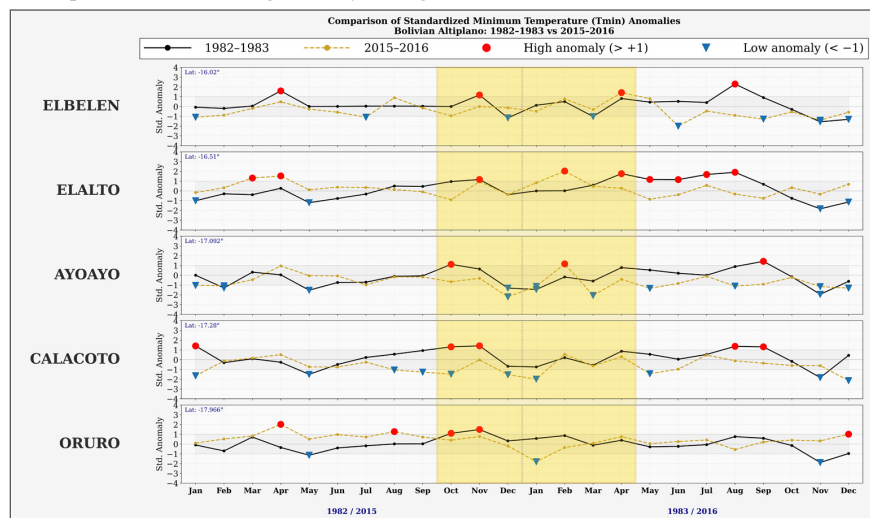


Figure 5. Standardized monthly precipitation anomalies at the North and Central Altiplano stations during the very strong El Niño events of 1982-1983 and 2015-2016. Red (blue) dots denote negative (positive) standardized anomalies below (above) one standard deviation, indicating a precipitation deficit (surplus) relative to the mean.

Source: Prepared by the authors

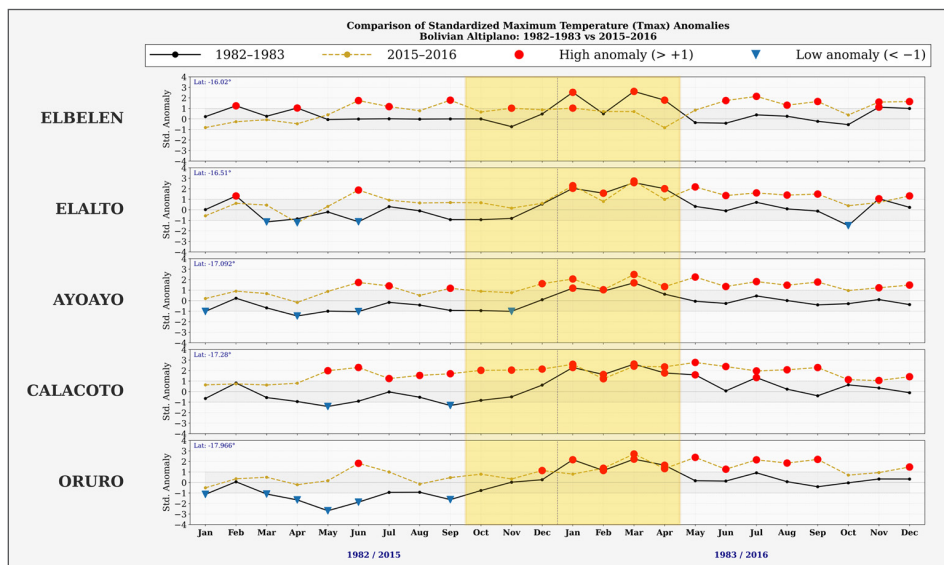
Regarding monthly minimum temperature, Figure 6 indicates negative anomalies between December and January, corresponding to periods of below-normal minimum temperatures that may be associated with an increased likelihood of frost occurrence. These conditions represent a potential environmental and agricultural risk, particularly during the local growing season, although the magnitude of their effects would depend on the intensity, duration, and timing of individual frost events and on the specific crops and phenological stages involved. In contrast, Figure 7 shows a persistent predominance of positive maximum temperature anomalies from October onward, consistently across the stations analyzed and throughout the subsequent year. This pattern indicates a sustained signal of above-normal monthly temperatures following the development of the El Niño events, mainly in 2015-2016.

Figure 6. Standardized monthly minimum temperature anomalies at the North and Central Altiplano stations during the very strong El Niño events of 1982-1983 and 2015-2016.



Source: Prepared by the authors

Figure 7. Standardized monthly maximum temperature anomalies at the North and Central Altiplano stations during the very strong El Niño events of 1982-1983 and 2015-2016.



Source: Prepared by the authors

Taken together, the two Very Strong El Niño events examined show at least two to three months with dry anomalies during the typical rainy season, cold minimum-temperature anomalies between December and January indicative of conditions favorable for frost occurrence, and wet anomalies in April. This latter may increase the potential for localized flooding and erosion following prolonged dry conditions. Since the type-C synoptic pattern has persisted through August 2026, similar precipitation and temperature responses may occur during the current event. However, this should not be interpreted as a deterministic forecast, given the unusually strong SST anomalies observed in 2026 and the inherent variability of the atmospheric response.

3.4. Local perception of historical impacts

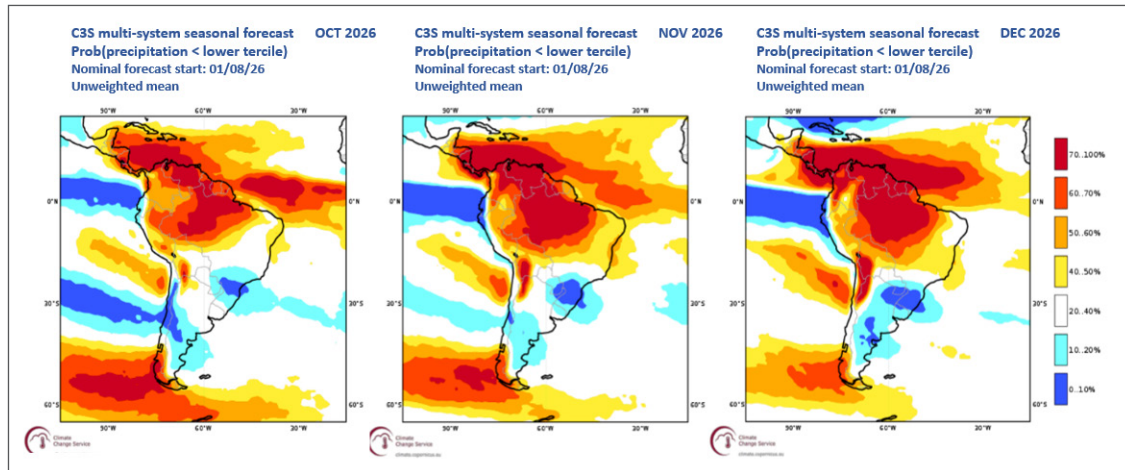
Poma (2018), using a timeline-based approach to assess drivers of change in production systems, reported that producers in the Central Altiplano identified drought conditions in 1983 and 2016, associated with forage losses, reduced potato production, and substantial out-migration. In the Northern Altiplano, respondents reported severe frosts in 1983 and intense drought conditions during 2014–2016. The co-occurrence of drought, frost, and subsequent wet conditions may help explain the magnitude of the impacts reported by producers in both regions, particularly in the context of Very Strong El Niño events and the occurrence of months characterized by the type-C synoptic pattern.

3.5. Multi-model seasonal outlooks for 2026-2027

Multi-model ensemble forecasts from C3S, CCSR/IRI, CIIFEN, and SISSA-NMME¹ show broadly consistent probabilities of below-normal precipitation for the October–November–December (OND) 2026 season. For the Central and Southern Altiplano, the projected probabilities range from 50% to 80%, with a tendency toward higher probabilities in December. In the Northern Altiplano, however, greater uncertainty is evident: C3S projects

a 40–70% probability of below-normal precipitation toward the end of the season, whereas CCSR/IRI indicates probabilities below 50%. For temperature, the models show greater consistency, with high probabilities of above-normal values across the study region (Figures 8 and 9).

Figure 8. Probability (%) of precipitation below the lower tercile according to the ECMWF's C3S multi-model system, for October, November, and December 2026 (forecast issued 08/01/2026).



Source: C3S multi-system precipitation 1-month

https://climate.copernicus.eu/charts/packages/c3s_seasonal/products/c3s_seasonal_spatial_mm_rain_1m?area=area13&base_time=202609010000&type=terc_lo&valid_time=202612010000

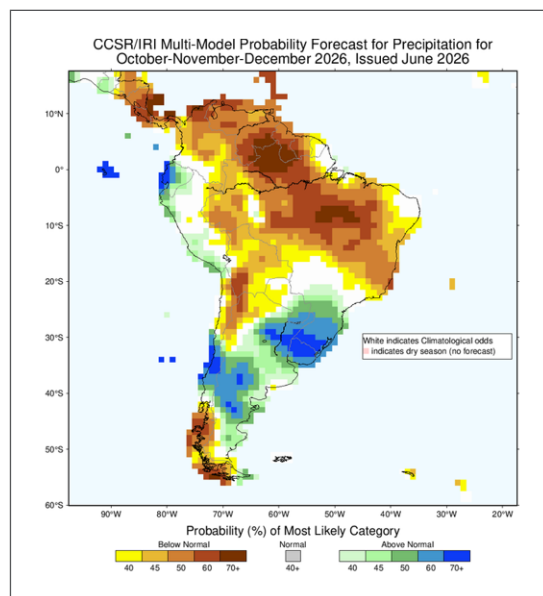


Figure 9. CCSR/IRI multi-model probabilistic precipitation forecast for the October-November-December 2026 quarter, issued in June 2026, for South America with a regional detail of the Bolivian Altiplano

Source: CCSR/IRI Multi-model probability forecast for precipitation

<https://iri.columbia.edu/our-expertise/climate/forecasts/seasonal-climate-forecasts/>

4. DISCUSSION

The results indicate that the relationship between SST anomalies and Altiplano precipitation is complex and non-linear (Garreaud et al., 2003; Perry et al., 2017). Both dry La Niña and wet El Niño conditions may occur, while individual events can also exhibit contrasting dry and wet periods. This variability reflects the strong spatial

heterogeneity of precipitation, changes in the latitudinal position of the Bolivian High, and variations in moisture transport from the east and north (Vuille & Keimig, 2004). Other climate modes, such as the PDO and NAO, may further modulate the regional response to ENSO (Mokhov et al., 2004; Canedo-Rosso et al., 2019).

The recurrence of the type-C pattern during the 1982–1983, 2015–2016, and 2026 events provides a basis for considering potentially analogous hydroclimatic responses, although the similarity in synoptic classification does not necessarily imply comparable impacts.

4.1. Corresponding between the Kung and Chern synoptic type and the E/C indices

Comparison of the Kung and Chern (1995) synoptic classification with the E- and C-indices proposed by Takahashi et al. (2011) suggests a conceptual correspondence, rather than a direct equivalence. Type C, characterized by intense positive SST anomalies concentrated in the central-eastern equatorial Pacific, broadly resembles the spatial structure of extraordinary eastern Pacific events identified by the E-index. In contrast, type F, which exhibits a broader extension toward the North Pacific and Atlantic, shows greater similarity to the spatial characteristics associated with moderate central Pacific events described by the C-index. Importantly, type E in the seven-cluster classification of Kung and Chern, which represents transitional conditions, is conceptually distinct from the E-index of Takahashi et al. (2011), despite the shared nomenclature. This distinction is necessary to avoid potential terminological confusion. Using the E-index, Cai et al. (2020) classified the 1982–1983 and 1997–1998 events as extraordinary eastern Pacific El Niño events of comparable magnitude, whereas the 2015–2016 event exhibited characteristics captured by both the E- and C-indices.

4.2. Why 1982–1983 and not 1997–1998: the weight of the spatial pattern over magnitude

This last point helps to partly explain, at least in part, why 1997–1998 did not reproduce the same impacts in the Bolivian Altiplano as 1982–1983, despite both being among the most intense El Niño events on instrumental record and sharing, in magnitude-based SST indices — such as the E-index (Cai et al., 2020) or the EP/CP scheme (Yu & Kim, 2013) — a classification as an extraordinary eastern Pacific event. In the monthly Kung and Chern archive reproduced in Table 2, the 1982–1983 synoptic pattern predominantly corresponds to types C and F — the same pattern observed in two months of the 2026–2027 event — while 1997–1998 is consistently classified as types E and F, with no expression of type C. This difference in the spatial pattern of the anomaly, rather than in its absolute magnitude, could partly explain why the Altiplano’s drought and frosts in 1982–1983 were not replicated with the same severity in 1997–1998, and reinforces the argument that the Kung and Chern classification provides complementary — and in this case more discriminating — information than conventional ENSO magnitude indices for anticipating potential regional impacts in the Altiplano.

4.3. Limitations of the historical-analogue approach

The historical-analogue approach adopted in this study has several limitations. First, the small number of Very Strong El Niño events in the instrumental record (1982–1983, 1997–1998, and 2015–2016) limits the statistical robustness and generalizability of comparisons based on individual events. Second, the relationship between Pacific SST anomalies and Altiplano climate is potentially non-stationary. Long-term warming alters the SST baseline against which ENSO thresholds are defined, motivating the use of the Relative Oceanic Niño Index (RONI) alongside conventional indices such as the ONI. Consequently, spatial classifications such as that of Kung

and Chern may partly reflect both interannual variability and longer-term changes in the background climate state. Third, the comparison of 2026–2027 with the 1982–1983 and 2015–2016 events is currently based on the similarity of synoptic patterns observed through July. A more robust assessment will require extending the analysis as the event evolves and incorporating forecast-verification products issued by NOAA, JMA, and IRI following the OND season. Finally, the 1997–1998 event warrants further quantitative assessment, particularly through station-level comparisons of standardized precipitation and temperature anomalies with those observed during 1982–1983 and 2015–2016.

4.4. Integrating ancestral knowledge and formal forecasts

Multi-model ensembles provide greater confidence in the projected tendency toward below-normal precipitation and above-normal temperatures during the OND–NDJ seasons over the Central and Southern Altiplano. However, the coarse resolution of global forecasts does not fully capture the region's strong spatial variability associated with topography and regional circulation.

Local observations also reveal contrasting conditions: heavy snowfall on August 17–18 in the Central Altiplano was perceived by producers as favorable for near-average production, whereas limited snowfall in the Northern Altiplano supported a different assessment. These differences highlight the potential value of integrating local and Indigenous knowledge with model-based forecasts, particularly where model signals are weak or spatially inconsistent.

4.5. Implications for risk management and adaptation

The co-occurrence of seasonal drought, frost events, and late-season wet anomalies identified in the analogue events, consistent with the impacts reported by Poma (2018), suggests that climate-risk management in the Northern and Central Altiplano should account for sequences of interacting hazards rather than isolated events. Potential adaptation measures could therefore be phased according to the seasonal progression of risks, including water and livestock-feed management during the December–March dry period, frost protection during December–January, and drainage and water-management measures in response to late-season wet conditions and potential flooding. Integrating these measures into early-warning systems, together with continuous monitoring based on synoptic classifications, multi-model forecasts, and local knowledge, may improve preparedness for compound and sequential hazards. More broadly, agroecological practices such as maintaining soil cover, integrating native tree species, using protected production systems, and applying soil amendments may contribute to strengthening the resilience of agroecosystems to climatic variability and associated economic impacts.

5. CONCLUSIONS

Based on the results presented, the following conclusions are proposed, organized from general to specific:

- The relationship between Pacific Sea surface temperature (SST) anomalies and precipitation variability in the Bolivian Altiplano is complex and not univocal. The regional response to ENSO may be modulated by other modes of climate variability, including the Pacific Decadal Oscillation (PDO) and the North Atlantic Oscillation (NAO), whose influence may vary according to their phase. Their consideration in future analyses may therefore contribute to a more comprehensive understanding of the factors governing precipitation variability over the Altiplano.

- As of July 2026, the ongoing 2026–2027 El Niño event showed a marked intensification, with SST anomalies exceeding those observed during the corresponding period of previous Very Strong El Niño events (1982–1983, 1997–1998, and 2015–2016). NOAA forecasts indicated a probability exceeding 90% that the event would reach the Very Strong category between September and December 2026.
- The synoptic evolution of the 2026 event exhibits characteristics consistent with type C in the classification of Kung and Chern (1995), a pattern also identified during the 1982–1983 and 2015–2016 events. During these historical analogues, the Northern and Central Altiplano experienced negative precipitation anomalies between December and March, negative minimum-temperature anomalies associated with conditions favorable for frost occurrence between December and January, and positive precipitation anomalies toward April, potentially increasing the likelihood of localized flooding and erosion following prolonged dry conditions.
- The comparison with the 1997–1998 event, which was of comparable magnitude but predominantly classified as types E and F, with no occurrence of type C, indicates that the spatial structure of SST anomalies provides complementary information to conventional ENSO magnitude indices when examining potential regional impacts over the Altiplano. However, this interpretation should be further evaluated through quantitative comparisons across a larger set of events and stations.
- Multi-model ensembles from C3S, CCSR/IRI, CIIFEN, and SISSA-NMME indicate probabilities of 50–80% for below-normal precipitation during the October–November–December (OND) 2026 season over the Central and Southern Altiplano, together with a consistent signal of above-normal temperatures across the region. Greater uncertainty is evident in the Northern Altiplano, where the models provide contrasting probabilities of dry conditions. Local observations also indicate regional differences: producers associated the snowfall observed in August with the possibility of delayed rainfall in the Northern Altiplano, whereas in the Central Altiplano it was interpreted as potentially consistent with near-average seasonal conditions. These observations highlight the value of considering local information alongside model-based forecasts, particularly where model signals are spatially inconsistent.
- Taken together, these findings highlight the potential value of strengthening early-warning systems in the Northern and Central Altiplano through an integrated framework combining synoptic classifications, statistical and dynamical forecasts, and local and Indigenous knowledge. Such a framework could support differentiated preparedness and adaptation measures addressing seasonal water deficits, frost occurrence, and late-season wet conditions. Rather than being implemented solely in response to individual El Niño events, these systems should operate continuously to account for the substantial interannual variability and the occurrence of multiple and sequential climate hazards.
- As an immediate research priority, the 1997–1998 event should be incorporated into the comparative analysis through station-by-station standardized precipitation and temperature anomaly series, following the approach applied to the 1982–1983 and 2015–2016 events. This analysis would provide a quantitative basis for testing the hypothesis that the spatial structure of SST anomalies contributes to differences in Altiplano hydroclimatic responses beyond the effect of ENSO magnitude alone.

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DEVELOPMENT OF A PLATFORM FOR VISUALIZATION AND ANALYSIS OF AIR QUALITY TIME SERIES

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ABSTRACT

This study aimed to develop an interactive platform for visualizing and analyzing air-quality time series in Tableau®, using PM10 records from three automatic monitoring stations of the MoniCA network in Cochabamba. The work was intended to strengthen environmental management through a tool integrating data cleaning, statistical analysis, and dynamic visualization.

The methodology comprised the systematization of hourly records for 2019-2023, the removal of negative and outlying values, the assessment of data sufficiency, the treatment of missing values, and time-series decomposition. As an operational acceptance criterion, the proportion of valid data in each series was evaluated, adopting 75% valid data as a reference threshold to support comparable analyzes across periods and stations.

PM10 concentrations from Fuerza Aerea, Parque Kanata, and SEMAPA were obtained through continuous automatic monitoring. The integration of Tableau® with Python/ TabPy enabled imputation routines, descriptive metrics, and graphical outputs aimed at identifying trends, seasonality, and time windows with elevated concentrations relative to the applicable standards.

Results showed marked differences in data completeness among stations and a consistent seasonal pattern, with higher PM10 concentrations during the dry and winter period. Moving averages proved useful for descriptive analysis of short gaps, whereas linear interpolation was used for time-series decomposition because a complete sequence was required. Overall, the platform improved analytical exploration of the data and proved useful as a technical support tool for interpreting air-quality information.

Keywords: air quality, PM10, time series, data visualization, Tableau®.

1. INTRODUCTION

Globally, air pollution is one of the main environmental risks to human health due to its association with respiratory and cardiovascular diseases (WHO, 2024; Röbbel, n.d.). In Bolivia, this problem is particularly relevant in urban centers where vehicle emissions, industrial activities, and weather conditions that limit the dispersion of pollutants converge.

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Air pollution represents one of the main environmental problems in urban centers, particularly in Bolivia, where emissions from the motor vehicle fleet, industrial and commercial activity are the predominant sources (MMAYa, 2021).

In cities like Santa Cruz, La Paz, and Cochabamba, air pollution has become a major public health problem. In Cochabamba, the valley topography and high traffic density contribute to the accumulation of particulate matter, making systematic monitoring of PM₁₀ essential for interpreting changes in air quality over time. Motor vehicles are responsible for approximately 70% of the country's air pollution, exacerbated by forest fires and indiscriminate burning practices (El País, 2021).

In the city of Cochabamba, one in five people owns a vehicle. Motor vehicles are responsible for 92% of particulate matter smaller than 10 microns (PM₁₀) and nitrogen oxides (NO_x), making them the primary source of pollutants. Environmental audit report K2/AP06/Y13 indicates that the Cochabamba Valley is particularly susceptible to pollution due to its topographical and climatic characteristics (Acosta, 2022).

Since 2000, thanks to the Clean Air project financed by COSUDE, the installation of air quality monitoring networks has been promoted, consolidating into the National Network MoniCA Bolivia (MMAYA, 2021).

The MoniCA network is present in eight departments of the country, and employs passive, active, and automatic methodologies for measuring criteria pollutants such as PM₁₀, NO₂, CO and O₃. The objectives of the monitoring include describing the temporal behavior of concentrations, verifying compliance with air quality regulations, generating information for environmental management, and providing input for risk communication and the activation of response measures when appropriate. However, the lack of continuity in the records and the heterogeneity in the cleaning and analysis procedures have limited the technical use of these databases. Sufficient information and high-quality records are essential for time series to be interpretable and comparable across stations and periods.

Although data from the MoniCA network is available in the National Environmental Information System (SNIA), there is no platform that allows for dynamic and interactive analysis of time series. This prevents in-depth analysis of seasonal patterns, long-term trends, and comparisons between periods and seasons. The lack of such a tool limits comprehensible access to information for both decision-makers and the general public.

In this context, tools like Tableau® offer a viable alternative for integrating data cleaning routines, descriptive metrics, time decomposition, and interactive visualization. Rather than simply generating 'intuitive visualizations,' the focus of this study is on structuring a reproducible analytical environment that allows for the examination of trends, seasonality, concentration distribution, and comparison with normative limits.

Finally, the development of a digital air quality analysis platform addresses not only a technical need, but also a social, environmental, and academic one. It facilitates timely decision-making in public health, promotes the use of modern visualization and analysis methodologies, and contributes to building analytical capacity in the field of environmental management. Furthermore, it lays the groundwork for future research in predictive modeling and environmental monitoring.

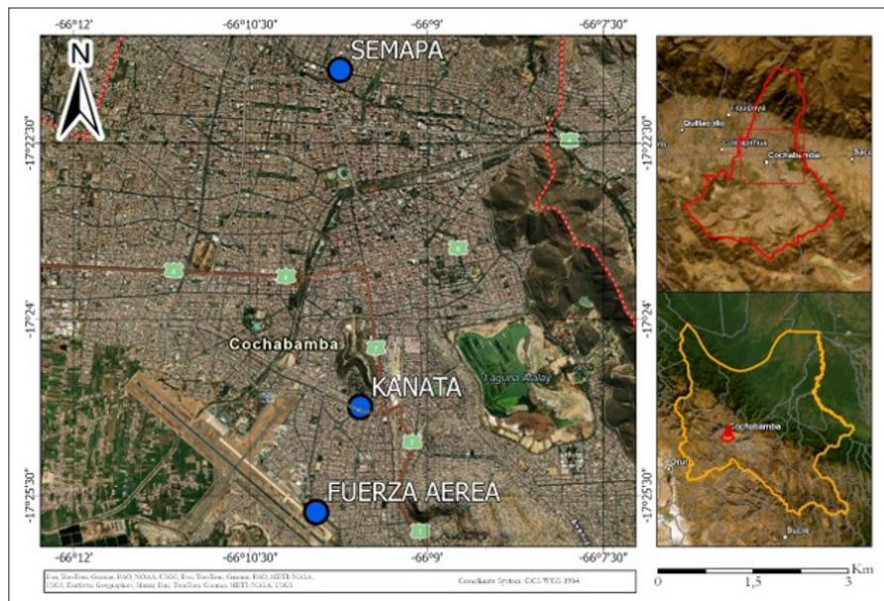
2. MATERIALS AND METHODS

The data analyzed comes from the MoniCA Network of Cochabamba and corresponds to the PM₁₀ pollutant measured in three active automatic stations: Fuerza Aérea (E1), Parque Kanata (E2) and SEMAPA (E3).

The study period spanned five years (2019–2023) and included hourly records and, for some periods, 30-minute resolution series that were subsequently standardized to hourly resolution. Measurements were taken using continuous automatic monitoring with Thermo equipment based on beta particle attenuation (Bascopé, 2001).

PM₁₀ was selected because this variable showed the greatest relative continuity within the available data set, allowing for a consistent temporal analysis. The locations of the three active automatic monitoring stations are shown below.

Figure 1. Visualization of the location of the monitoring stations



Source: Cortez, (2025)

2.1. Time series processing with Tableau® tools

All negative values were filtered out because negative concentrations of air pollutants have no physical meaning. The removal was applied automatically at the data source to prevent erroneous records from affecting descriptive metrics and subsequent analysis routines.

Outlier removal was performed using 4 methodologies:

- i) Interquartile range (IQR, Index Quart),
- ii) Z-score method,
- iii) clustering method using k-means and
- iv) method by calculating percentiles using window functions, the latter being the one that best maintains the behavior of the series (Aggarwal, 2016)

The handling of missing values was performed using Python scripts integrated into Tableau® via TabPy. At this stage, an explicit criterion for data sufficiency was incorporated: for comparative purposes, a series was considered to have at least 75% valid data to support robust interpretations. Furthermore, the interpretation of results took into account the inherent uncertainty of the measurement system and data processing, which depends on instrumental performance, calibration, preventive and corrective maintenance, and the magnitude of the gaps present in each series.

Three methods for imputing missing data were evaluated: linear interpolation, polynomial interpolation, and moving average, implemented using the NumPy and Pandas packages. The comparison between methods considered the length of the gaps, the risk of series distortion, and the preservation of the observed temporal structure.

2.2. Preliminary analysis

The analysis of measures of central tendency and stationarity of the time series was performed using box plots by season and year. This graphical representation allowed for the evaluation of the median as a robust measure of central tendency, the dispersion (interquartile range), and the relative variability between seasons and periods. Additionally, by comparing the monthly averages grouped by season and year, it was possible to identify seasonal patterns and evaluate stationarity in the mean, considering as stationary those series whose monthly averages remained relatively constant over time.

To analyze the relationship between dispersion and the central level of the series, the difference between the 80th and 20th percentiles was plotted against the natural logarithm of the median daily concentrations. This scatter plot allows the determination of whether the components of the series combine additively or multiplicatively, depending on the relationship between the level (median) and variability.

2.3. Statistical analysis and decomposition of time series

To statistically compare PM10 concentrations, a summary table was created in Tableau applying various statistical measures to the [concentration] variable, including minimum, maximum, mean, median, standard deviation, 10th percentile, and 90th percentile. Additionally, the 25th (Q1), 50th (Q2), and 75th (Q3) quartiles were calculated using custom calculated fields (ADS, 2024). All calculations were performed disaggregated by monitoring station over a five-year period, allowing for a detailed characterization of the data distribution.

To analyze the behavior of hourly PM10 concentrations, an additive time series decomposition was applied (Esparza, 2004) using the `seasonal_decompose` function from the `statsmodels` package, integrating Python code into Tableau via TabPy. This allowed for the decomposition of the series into its three fundamental components: trend, seasonality, and noise. A DataFrame was structured with date, time, concentration, season, and year, transforming the date column to datetime format and establishing it as the time index. Concentrations were converted to numerical values, handling conversion errors, and a period of 24 was defined to represent the daily cycle. Each component was extracted separately and aligned with the original series, facilitating a detailed analysis of long-term variations, recurring hourly patterns, and random fluctuations.

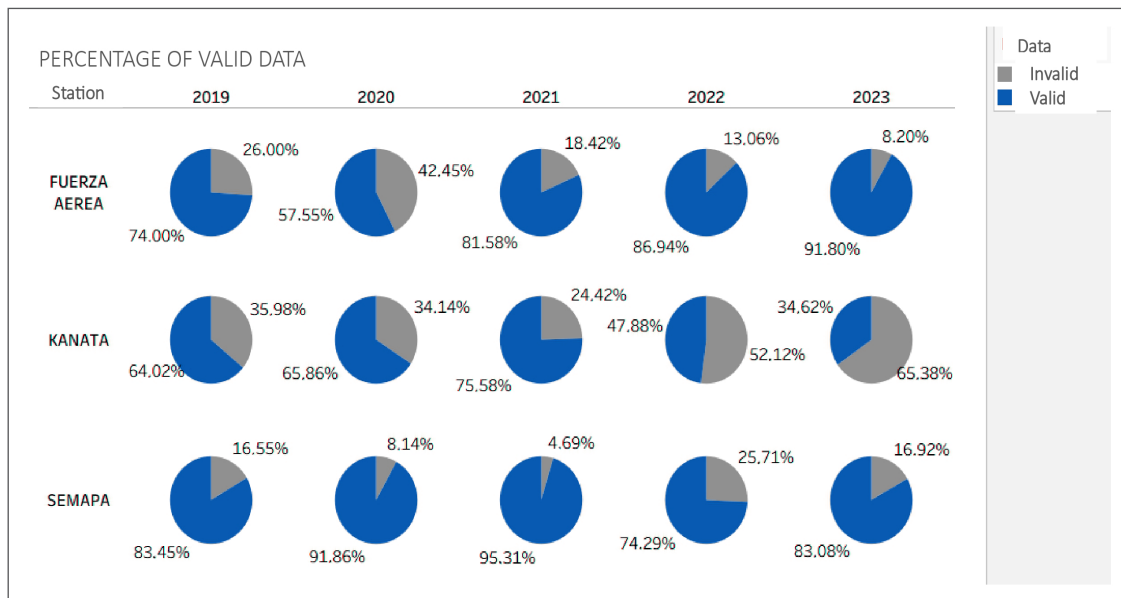
2.4. Development of visualization dashboards

For the exploratory analysis of PM₁₀ concentrations, line graphs, histograms, box plots, and heat maps were used in Tableau®. These representations allowed for the identification of trends, seasonality, dispersion, and periods of high concentrations. In this study, 'critical moments' are defined as hourly or seasonal intervals in which the series shows relatively high concentrations and/or exceedances with respect to reference lines established based on the RMCA (Bolivia, 1995), NB 62011:2018 (IBNORCA, 2018), and WHO guideline values (2021).

3. RESULTS AND DISCUSSION

Once the time series was structured, data cleaning was performed using the percentile method with window functions, selected for its ability to remove outliers without significantly altering the overall behavior of the series. Subsequently, linear interpolation, polynomial interpolation, and moving average methods were compared. The moving average was considered the most suitable procedure for descriptive analysis because it best preserved the visual continuity of the series in short gaps, while linear interpolation was reserved for time decomposition, since this analysis required a complete sequence of observations.

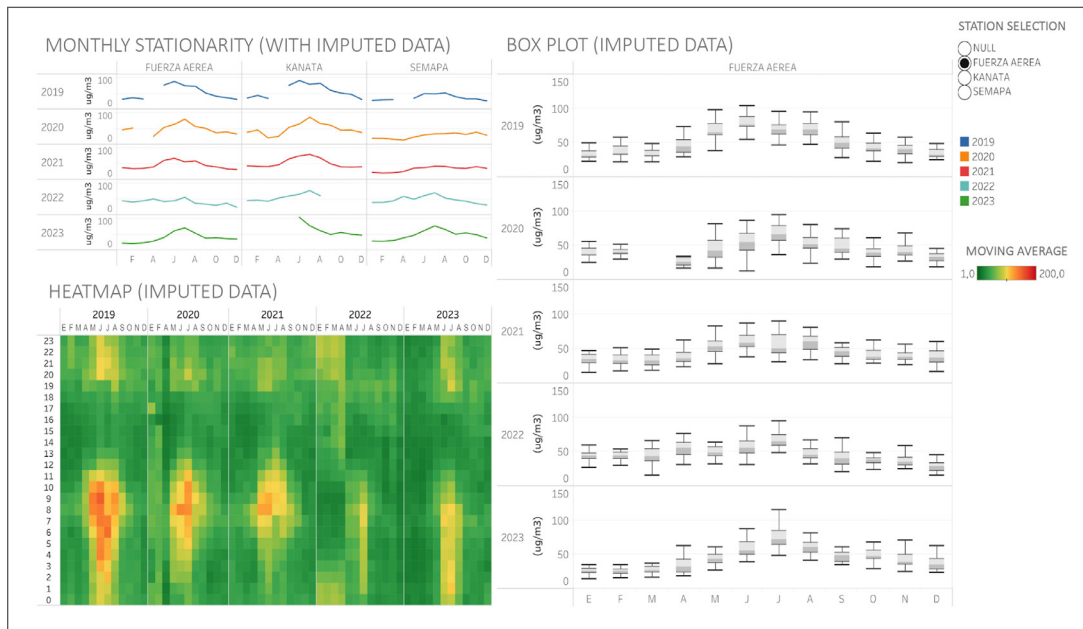
Figure 2. Percentage of valid data after imputation by moving average



Source: Cortez, (2025)

During the period 2019–2023, the three stations showed a marked seasonal pattern: PM₁₀ concentrations tended to be higher between June and September and lower between December and March. This behavior is consistent with the reduced atmospheric dispersion characteristic of the dry winter season in the Cochabamba Valley. Station E1 exhibited the greatest variability in 2019–2020 before stabilizing; Station E2 maintained intermediate dispersion with occasional episodes of high concentration; and Station E3 generally registered the lowest relative variability.

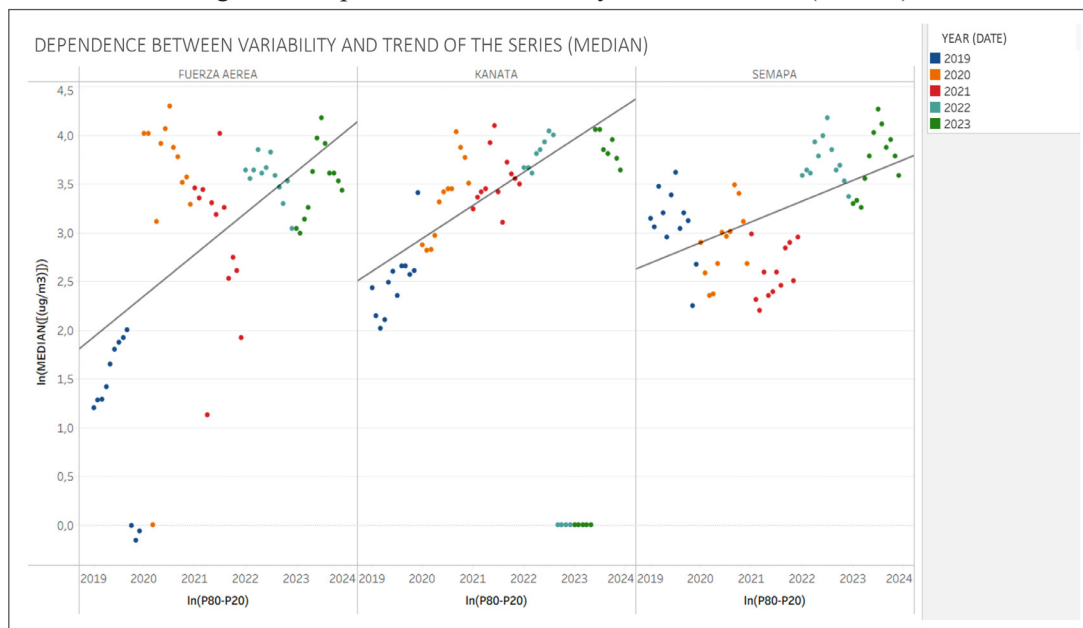
Figure 3. Visualization dashboard seasonal behavior



Source: Cortez, (2025)

When exploring the monthly relationship between the median and its dispersion, it was observed that some isolated years exhibited behaviors consistent with a multiplicative scheme; however, the 2019-2023 period was better suited to an additive model (Alam et al., 2015). Consequently, the classical additive decomposition was considered more appropriate to summarize the overall dynamics of the series.

Figure 4. Dependence of variability and series level (median)

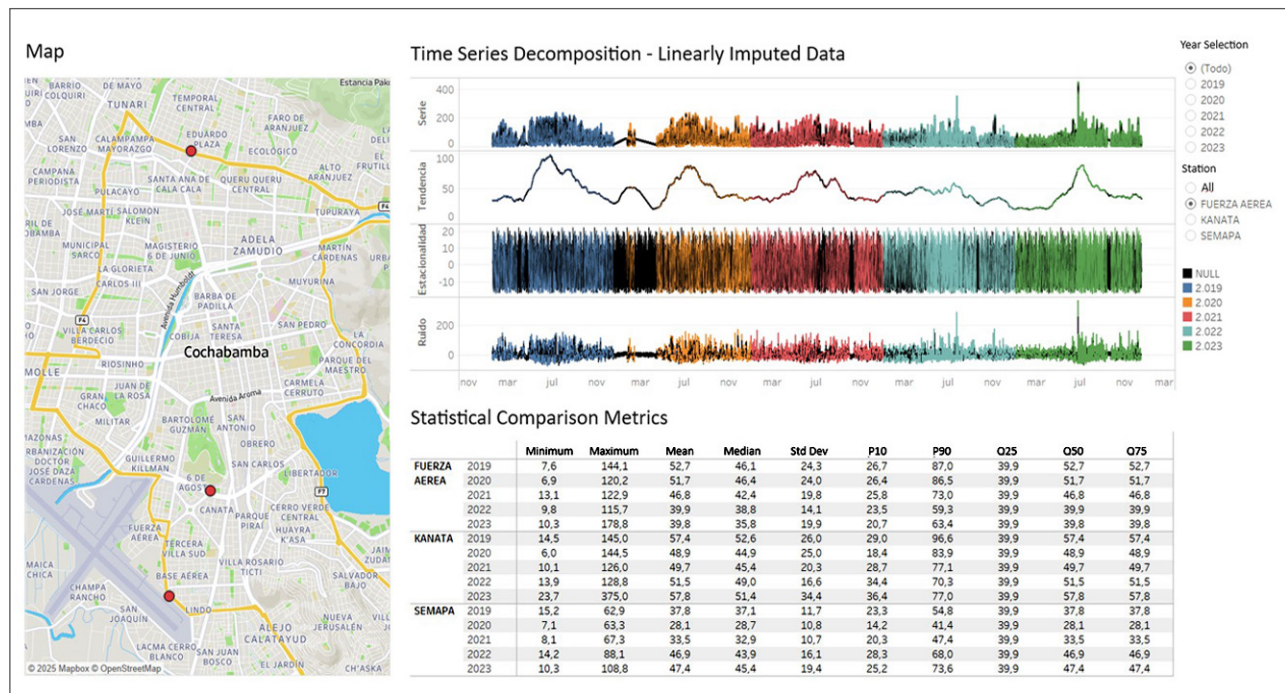


Source: Cortez, (2025)

Using additive decomposition with linear interpolation and a 720-hour smoothing, three main components were isolated:

- Trend, with a decline after 2020 in E1, seasonal fluctuations in E2 and a moderate increase in E3 from 2022;
- Seasonality, with recurring daily and monthly cycles in all three seasons;
- Noise or irregular component, predominantly random, with a greater presence of outliers in some periods of 2022 and 2023.

Figure 5. Time series decomposition and statistical comparison metrics

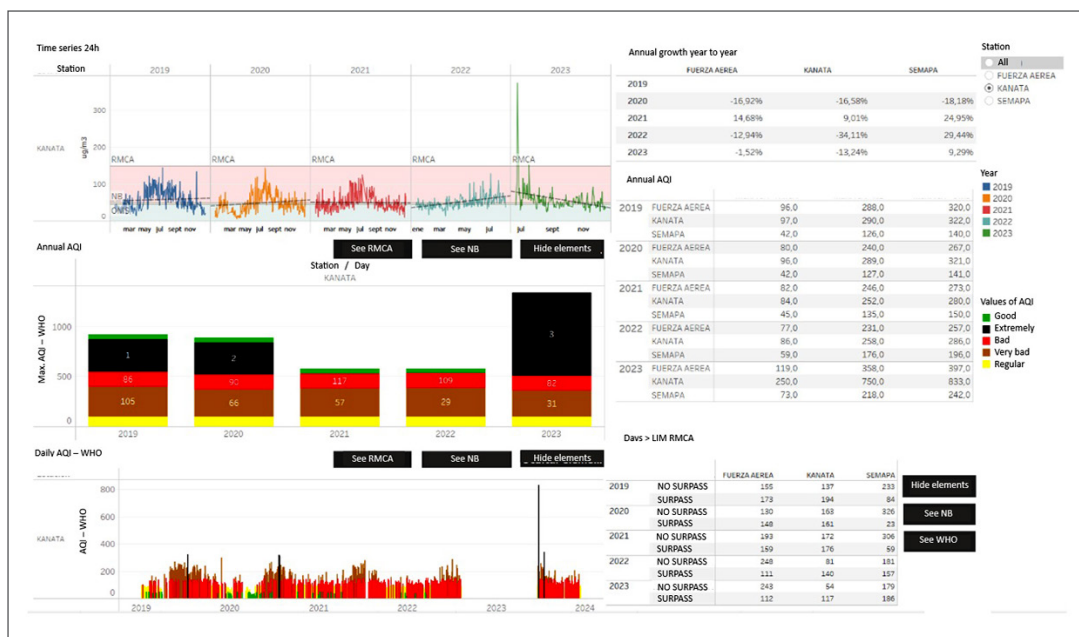


Source: Cortez, (2025)

The heat maps showed that, without imputation, the temporal interpretation was fragmented by gaps in the data series. Using a moving average, time periods with relatively high concentrations during the winter were more clearly observed, especially between 03:00 and 10:00 in E2. The inconsistencies detected in E1 during 2022 suggest possible recording or operational problems with the monitoring system, rather than a conclusive change in the pollutant's dynamics.

In addition, histograms and bar graphs were generated to quantify the frequency of days within different Air Quality Index (AQI) ranges and to compare the observed concentrations with the limits of the RMCA, NB 62011:2018, and the WHO. This comparison allows the results to be contextualized from a regulatory perspective without extrapolating the findings to causal attributions not evaluated in the study.

Figure 6. Trend and permissible limits



Source: Cortez, (2025)

4. CONCLUSIONS

- A PM10 database was compiled for the period 2019–2023, corresponding to three automatic stations of the MoniCA Network in Cochabamba. The existence of discontinuities and differences in the proportion of valid data between stations confirmed that the sufficiency of information is a central condition for the interpretation of air quality time series.
- The debugging and descriptive analysis routines showed that the percentile method with window functions was useful for handling outliers, while the comparison between linear interpolation, polynomial interpolation, and moving average allowed for the selection of different procedures depending on the analytical objective. The moving average proved more convenient for the descriptive exploration of short gaps, and linear interpolation was functional for decomposition when complete continuity was required.
- Additive decomposition allows the separation of trend, seasonality, and noise components, showing a consistent temporal pattern across the three seasons and supporting the use of an additive approach to summarize the overall dynamics of PM10 in the period studied.
- At all three stations, a higher frequency of elevated PM10 concentrations was identified during the dry and winter periods, as well as spatial differences in the variability of these concentrations. The Parque Kanata station showed the highest values and greatest dispersion, while SEMAPA exhibited comparatively more stable behavior.
- The comparison with the limits of the RMCA, NB 62011:2018, and the WHO showed that the interpretation of risk changes depending on the standard applied. In particular, the WHO reference showed a greater number

of exceedances, highlighting the usefulness of including multiple regulatory references in environmental visualization platforms.

5. RECOMMENDATIONS

- It is recommended to strengthen the monitoring Quality Assurance and Quality Control (QA/QC) program through periodic calibrations, preventive and corrective maintenance, systematic data validation, and explicit documentation of measurement uncertainty. Furthermore, integrating meteorological variables and deepening station characterization is advisable to enhance future interpretations of the observed patterns.
- The integration of Tableau® with Python/ TabPy has proven to be a technically useful alternative for visualizing large time series, calculating descriptive metrics, and dynamically presenting comparative results. Its main contribution lies in facilitating the analytical exploration of available information within the limitations of database quality and continuity.

6. ACKNOWLEDGMENTS

We express our sincere gratitude to the MoniCA Network of Cochabamba, which, through the Cochabamba Municipal Government, provided data from its automatic particulate matter (PM10) monitoring system. Likewise, we acknowledge the valuable collaboration of the MoniCA Network's Air Quality Reference Laboratory for its willingness and support in providing supplementary PM10 monitoring data. The information provided by both institutions was fundamental to the development and robustness of this study.

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7. LIST OF SYMBOLS AND ABBREVIATIONS

PM ₁₀	Suspended particles smaller than 10 microns
NO ₂	Nitrogen dioxide
CO	Carbon monoxide
O ₃	Tropospheric ozone
E1	Fuerza Aérea (Air Force)
E2	Parque Kanata (Kanata Park)
E3	SEMAPA
IQR	Interquartile Range
TabPy	Tableau Python Server – An extension that connects Tableau® with a Python environment
DAX	Data Analysis Expressions – Power BI® 's language of formulas and expressions
RMCA	Air Quality Regulations (Bolivia, DS No. 24176)
NB 62011:2018	Bolivian Standard “Air Quality – Outdoor Atmospheric Pollutants – Maximum Permissible Limits”
WHO	World Health Organization
AQI	Air Quality Index
SNIA	National Environmental Information System (Bolivia)
SDC	Swiss Agency for Development and Cooperation

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LECITHIN EXTRACTION VIA DEGUMMING OF TARWI (LUPINUS MUTABILIS) OIL EXTRACTED BY THE SOXHLET METHOD

Nataly Gutierrez Calderón^{1,*}, Jesús Góngora Beltrán²

ABSTRACT

The objective of this research work is to obtain lecithin through the degumming of tarwi oil extracted by the Soxhlet method, the motivation for its realization was to provide an industrialization alternative for the use of the grain and the large cultivation area in our country. The work deals with general aspects of tarwi, methods of: debittering and identification of alkaloids, Soxhlet extraction, definition of: degumming, lecithin, optimization of parameters and analysis techniques to be applied to the lecithin obtained. It begins with the degumming of tarwi by the traditional method, followed by drying at 60 °C in a tray dryer, milling, sieving, oil extraction with the Soxhlet method and ethanol as solvent, obtaining lecithin, optimization of influential parameters with experimental design and lecithin characterization. As results, the best parameters for obtaining lecithin are: temperature= 50°C, percentage in weight of water= 20%, agitation speed= 200 rpm and mixing time= 20 min. Finally, the design of a mixing tank at Bench Scale level was carried out. It is concluded that obtaining lecithin from tarwi is viable, becoming an important alternative for the industrialization of this grain.

Keywords: oil, alkaloids, unmoisturized, degumming, lecithin, tarwi.

1. INTRODUCTION

Tarwi (*Lupinus mutabilis*) is a plant belonging to the legume family that is primarily cultivated in Bolivia, Ecuador, and Peru. In Bolivia, tarwi is known as “chuchus muti”. It is an annual legume species with epigeal germination; it is erect and self-pollinating, with a low rate of cross-pollination (5 to 10%) and a growth period ranging from 6 to 10 months, depending on the planting season and environmental conditions (Meneses, Waarjenberg & Piérrola, 1996). It is well known for its high protein and oil content (Jacobsen & Mujica, 2006), from which lecithin can be obtained through the degumming of crude oil. Currently, in Bolivia, there are no projects dedicated to tarwi industrialization projects, despite the fact that a large area is produced in different regions. Thereby yielding a wide variety of derivative products, such as lecithin, which, as a complex of phospholipids, possesses emulsifying properties (Bueschelberger, Ilona & Schoeppe, 2015) could serve as an alternative for industry (Pino, 2021), thereby promoting the economic growth of the communities engaged in its production (Suca & Suca, 2015).

2. MATERIALS AND METHODS

The first step was the debittering of tarwi using the traditional method, being the most suitable and easy to perform (Aguilar, 2021): hydration (12 hrs) water/tarwi= 4:1; cooking (45 min) water/tarwi= 4:1; washing (5 days)

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water/tarwi= 3:1. Subsequently, drying was carried out at a temperature of 60°C (Mamani, 2009) in a tray dryer, followed by grinding and sieving (Leon & Rosell, 2007). For oil extraction, the Soxhlet extractor and 96° ethanol were used as the solvent (Villa & Benalcazar, 2015) with a solvent/solute ratio = 6/1, for 7 hours.

Once the crude oil was extracted, degumming was carried out in the following order: heating the oil to a range of 40 to 70 °C (Blanco, 2007), adding water at ratios of 5 to 30 % w/w, stirring speed of 100 to 400 rpm, and centrifugation (Stroppiano & Comba, n.d.). The influencing parameters were identified and optimized using experimental design, and verified in the laboratory. The lecithin obtained was characterized by the determination of acidity indices, saponification, HLB (Medina, 2013), toluene insoluble matter, acetone insoluble matter, proteins and alkaloids present in the lecithin.

3. RESULTS

3.1. Tarwi debittering

The following results were obtained for the verification of the absence of alkaloids in the debittered tarwi (Table 1).

Table 1. Percentage of alkaloids in debittered samples

Sample (mg)	Dilution	Absorbance	mg (alkaloids)	Alkaloids %
101.1	1:100	0.01017	0.42108	0.41650
107.2	1:100	0.01121	0.43169	0.40270
104	1:100	0.01234	0.44322	0.42617
		Average	0.43200	0.41512

The value obtained shows the low quantity of alkaloids present in the debittered tarwi.

3.2. Soxhlet extraction of crude oil

To verify the performance of the Soxhlet method in oil extraction, a mass balance was performed, where a yield of 97.07% was obtained (Table 2).

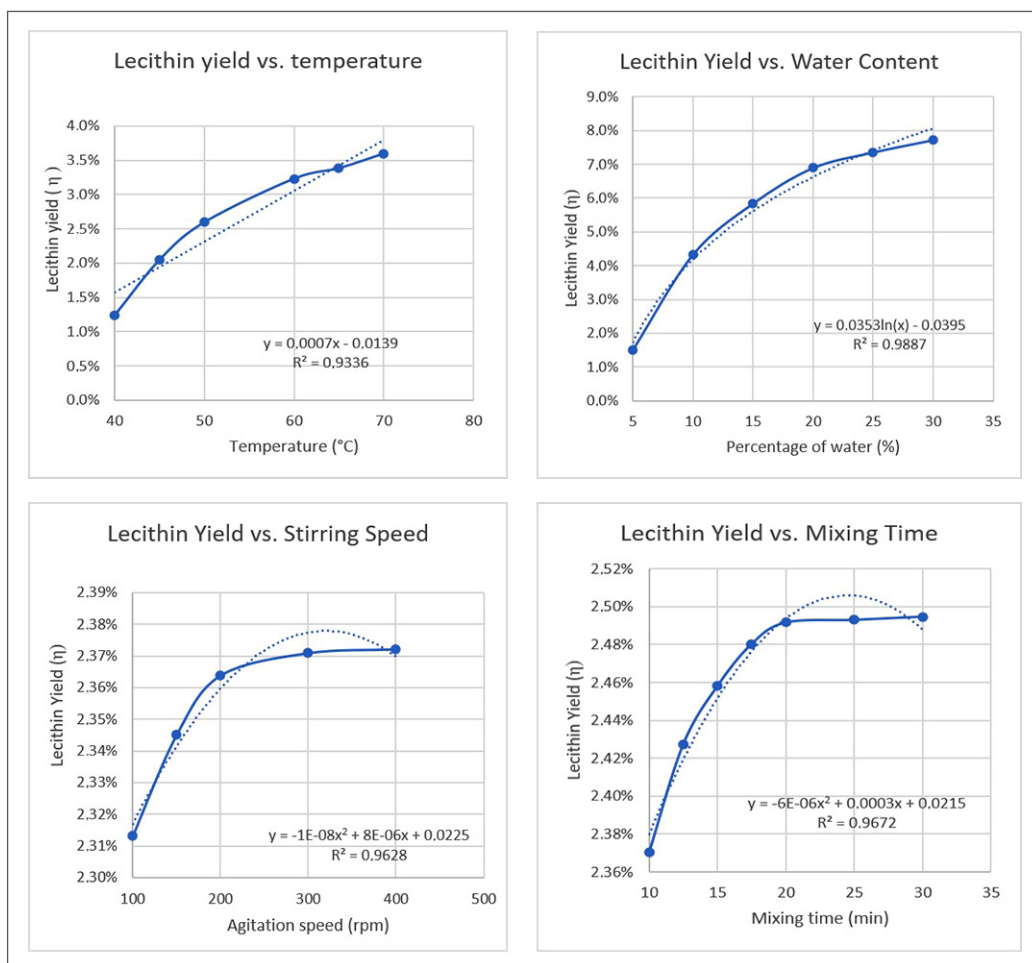
Table 2. Mass balance for oil

Input		Output	
Sample mass	28.029 g	Sample mass	23.2676 g
Oil mass	4.905 g	Oil mass	4.7615 g
Solvent	200 ml	Solvent	200 ml
		Percentage of oil extracted	97.07 %

3.3. Study of factors influencing lecithin production

The lecithin was obtained, in a first stage, by studying the behavior of the influencing factors: temperature, percentage of water, agitation speed and mixing time (Figure 1).

Figure 1. Lecithin yield as a function of influencing parameters



The lecithin yield as a function of temperature has a linear behavior, in relation to the percentage of water it presents a logarithmic behavior, while in relation to the speed of agitation and mixing time it shows a polynomial behavior. It is observed that at speeds larger than 300 rpm and times greater than 20 minutes, the obtaining of lecithin is constant.

3.4. Optimization of influencing parameters

Knowing the factors influencing the production of tarwi lecithin, optimization was carried out with experimental design with the following results (Table 3).

Table 3. Solution predicted by the Design-expert program 12

Number	Percentage of wáter	Temp	Stirring speed	Mixing time	Lecithin	Desirability
1	20 %	50 °C	200 rpm	20 min	7.274 %	0.972

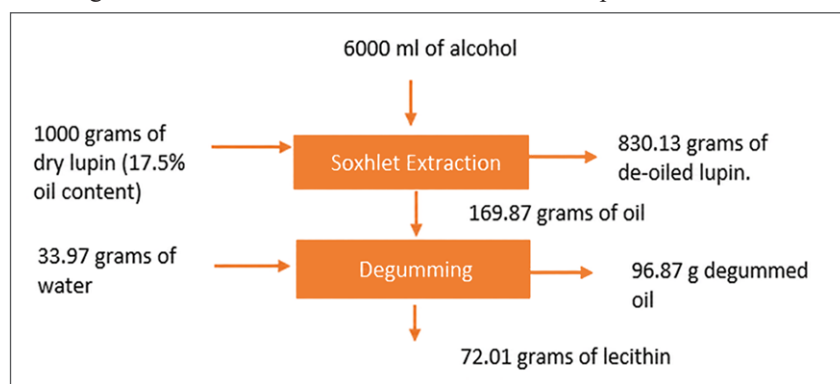
Number: Shows the solution number that the experimental design identified as the best solution.

Desirability: A value between 0.8 and 0.9 indicates a quite good solution.

3.5. Verification of the solution predicted by the experimental design

To verify the solution obtained in the experimental design, 1000 grams of tarwi were handled, performing a mass balance as shown below (Figure 2).

Figure 2. Mass balance for the verification of the predicted solution



After performing the necessary calculations, the following yields were obtained

$$Experimental\ yield = \frac{m_{Lecithin}}{m_{Dry\ tarwi}} * 100 \quad Ec. 1$$

$$Experimental\ yield = 7.201\ \%$$

Where: $m_{Lecithin}$ = Lecithin mass obtained (g)
 $m_{Dry\ tarwi}$ = Dried tarwi mass used (g)

3.6. Characterization of the lecithin obtained

Once the lecithin was obtained, the determination of the indices for its characterization was carried out (Table 4).

Table 4. Characterization indices for Lecithin

Acidity index	10.886 % oleic
Saponification index	130.731 mg KOH/g
HLB index (type of emulsifier)	-220.172 (W/O emulsifying agent)
Amount of phosphorus	0.074 mg P
Matter insoluble in toluene	0.015 %
Matter insoluble in acetone	62.3 %
Proteins	NO
Alkaloids	NO

The values for acetone-insoluble matter and toluene are remarkable, according to the specifications of the NSPA (National Soybean Processors Association, cited by Orthoefer (1995), the minimum percentage of acetone-insoluble matter that lecithin must have is 62%, while the percentage of toluene-insoluble matter must be a maximum of 0.3%, values that are fulfilled by the lecithin produced in this study.

3.7. Design of a mixing tank

Finally, a mixing tank was designed for the degumming process (Villa & Benalcazar, 2015). A calculation basis of 20 liters was used, and the height of the tank was calculated using equation 2 (Corsini, 2020):

$$V = \frac{\pi}{4} * h^3 \quad Ec. 2$$

$$h = 30 \text{ cm}$$

Where: V = Oil volume (cm³)
 h = Tank Height (cm)

With the geometric relationship: $\frac{D_t}{h} = 1 \quad Ec. 3$

Where: D_t = Tank diameter (cm)
 h = Tank Height (cm)

Considering a safety margin for the height of 25%, the following dimensions are obtained (Table 5)

Table 5. Mixing tank dimensions

Tank diameter	30 cm
Tank height	38 cm

For shaking, a flat leaf and 6-leaf disc type agitator was chosen; using the geometric relationships (Table 6), the dimensions of the agitator were calculated (Table 7).

Table 6. Geometric relationships for an inclined blade impeller

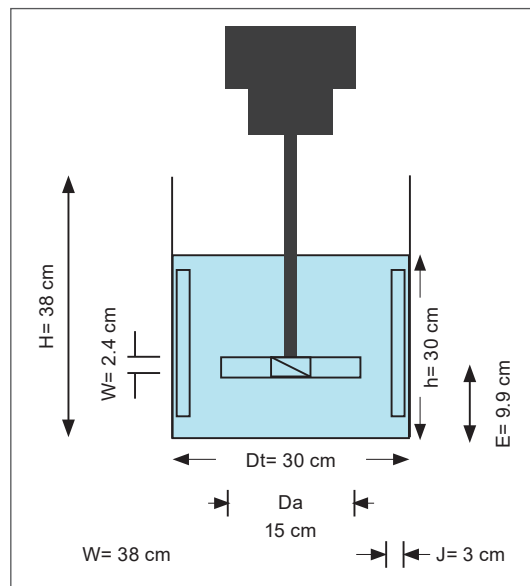
H/Dt	W/Da	Da/Dt	E/Dt	j/Dt	f/Dt	g/Da
1	0.2	0.5	0.33	0.1	0.02	0.25
H/Dt	= Relation Total height of the tank / Tank diameter					
W/Da	= Relation Impeller height / Impeller Diameter					
Da/Dt	= Relation Impeller Diameter / Tank diameter					
E/Dt	= Relation Height between the bottom of the tank and the impeller / Tank diameter					
j/Dt	= Relation Width of the deflector plate / Tank diameter					
f/Dt	= Relation Distance between the tank wall and the deflector / Tank diameter					
g/Da	= Relation Impeller Radius / Impeller Diameter					

Table 7. Stirrer dimensions

Da	15 cm
E	9.9 cm
J	3 cm
W	2.4 cm
F	0.6 cm
G	3 cm

The final dimensions of the mixing tank are presented in Figure 3.

Figure 3. Final dimensions of the stirring tank



The degumming process to obtain lecithin requires heating to an optimum temperature of 50°C; with this value, the heat required for the heating system was calculated:

$$Q = m * C_P * \Delta T \quad Ec. 4$$

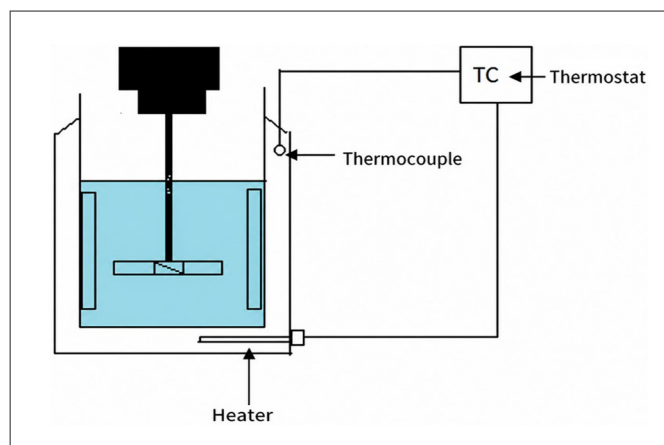
$$V = \frac{(31.41 + 6.28)}{20} \frac{Kg}{min} * 1.8 \frac{KJ}{Kg * ^\circ C} * (50 - 25)^\circ C$$

$$Q = 5089.5 \frac{J}{s}$$

Donde: Q = Heat required for heating (J/s)
 m = Oil-based heating mass ready in 20 minutes (kg)
 C_P = Specific heat of oil (kJ/(kg*°C))
 ΔT = Temperature Change (°C)

Knowing the heat required for degumming, a 6000 W heat sink is selected. To prevent overheating, automatic control with an on/off controller will be used (Figure 4).

Figure 4. Heating system



4. CONCLUSIONS

- Tarwi lecithin was obtained by aqueous degumming of the oil extracted by Soxhlet with a yield of 7.201%.
- The optimized parameters for obtaining lecithin are: Stirring speed = 200 rpm; temperature = 50°C; mixing time = 20 min; water percentage = 20% w/w.
- Oil extraction using the Soxhlet method was successfully carried out, achieving a yield of 97.07%.
- The designed bench-scale tank has as its main characteristic the use of a turbine-type stirrer that will ensure the correct mixing and hydration of the phospholipids.

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POTENTIAL HYDROGEN PRODUCTION FROM URBAN WASTE BIOGAS VIA SORPTION-ENHANCED STEAM METHANE REFORMING: A MODELING STUDY FOR LA PAZ, BOLIVIA

Pedro Aduviri¹, Lizbeth Echenique¹, Soledad Mamani¹, Yecid Nina¹, Wilfredo Parada¹,
Isabel Perez¹, Andres Rojas¹, Cristhian Carrasco^{1,*}

ABSTRACT

Using a reproducible mathematical model, the potential for producing hydrogen from methane associated with urban solid waste biogas in La Paz, Bolivia was evaluated. The study integrated two levels: (i) estimation of potential CH₄ generation using LandGEM 3.02 and municipal data on waste transported between 2010 and 2021, and (ii) simulation of a one-dimensional sorption-enhanced steam methane reforming (SE-MSR) reactor with Ni/Al₂O₃ catalyst and *in situ* CO₂ capture via CaO. For LandGEM, $k = 0.04 \text{ year}^{-1}$ y $L_0 = 100 \text{ m}^3 \text{ CH}_4 \text{ Mg}^{-1}$ were adopted, values previously used for La Paz and consistent with the *Inventory Conventional* dataset of LandGEM 3.02. The cumulative waste mass for 2010–2021 was $2.505 \times 10^6 \text{ Mg}$. The estimated cumulative generation was $1.538 \times 10^8 \text{ m}^3$ of CH₄ by 2039 and $2.068 \times 10^8 \text{ m}^3$ by 2059. In the initial state with fresh sorbent, the reactor model predicted 53.74 % CH₄ conversion and a dry H₂ mole fraction of 0.7967, close to the value of approximately 0.80 reported by Neni et al. (2021). The reduced model qualitatively reproduced the coupling between reforming, carbonation, and thermal propagation, but predicted a faster thermal wave than the reference three-dimensional CFD model. Based on the fresh-state yield of 2.133 mol H₂/mol CH₄ fed, methane generation up to 2039 corresponds to a theoretical indicator of $3.280 \times 10^8 \text{ m}^3$ of H₂; with an illustrative capture efficiency of 80 %, the indicator decreases to $2.624 \times 10^8 \text{ m}^3$. These values represent valorization potential and not industrial production, since they do not include leaks, purification, availability, CaO regeneration, compression, or auxiliary consumption.

Keywords: biogas; hydrogen; LandGEM; steam methane reforming; SE-MSR; CaO; mathematical modeling.

1. INTRODUCTION

Hydrogen is an energy vector and an industrial raw material with high specific energy. However, its environmental performance depends on the production route. Steam methane reforming (SMR) remains a reference technology for producing H₂ from methane, but it generates CO₂ as part of the process chemistry. Integrating a capture stage within the reactor itself, known as sorption-enhanced steam reforming (SE-MSR), shifts the reforming and water-gas shift equilibria by removing CO₂ from the gas phase, with the potential to increase the H₂ fraction in the product (Fernández et al., 2012; Neni et al., 2021; Hu et al., 2023).

Biogas constitutes an alternative source of methane. Its use as reforming feedstock requires prior conditioning to remove species that could affect the catalyst or equipment, such as sulfur compounds, moisture, and other contaminants. Simulation of biogas-fed reformers has shown that the process can be analyzed using non-isothermal one-dimensional models and that behavior depends strongly on the steam/carbon ratio, temperature, pressure, and heat transfer (Chouhan et al., 2021).

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In Bolivia, the availability and management of urban solid waste varies significantly among municipalities. Available studies show that local characterization and data availability are frequent limitations for evaluating valorization options (Vargas Bautista and Calvimontes, 2017; Ferronato et al., 2021). For La Paz there is a municipal series of waste transported to the Nuevo Jardín de Alpacoma landfill and, subsequently, Sak'a Churu, which allows constant-mass approximations to be replaced with real annual data.

LandGEM 3.02 is an estimation tool based on first-order decomposition kinetics. The model calculates methane generation; it is not directly equivalent to gas captured or available at a plant. Version 3.02 uses a sub-annual integration of 0.1 years, an aspect that is relevant when the degradation constant is high (U.S. EPA, 2005). In this work, the official formulation is used, avoiding the introduction of an external degradable fraction as an independent multiplier of the main equation.

For the SE-MSR reactor, the work of Neni et al. (2021) was taken as a reference; they developed a transient three-dimensional CFD model of a fixed bed with Ni/Al₂O₃ and CaO. Their study reported a maximum dry H₂ mole fraction close to 0.8 while CO₂ capture remained active. The reforming kinetic expressions adopted by Neni et al. derive from the family of equations of Xu and Froment (1989). The reduced model developed here does not aim to reproduce the three-dimensional CFD field, but rather to provide a reproducible, lower-complexity representation for analyzing thermal trends, sorbent consumption, and output performance.

The objective of this work is to evaluate, through reproducible mathematical modeling, the potential for producing hydrogen from methane associated with urban solid waste biogas in La Paz, integrating the estimation of potential CH₄ generation using LandGEM 3.02 with the simulation of a one-dimensional SE-MSR reactor with Ni/Al₂O₃ and CO₂ capture via CaO. The reactor results are contrasted with the behavior reported by Neni et al. (2021), identifying both the trends reproduced by the reduced model and its limitations relative to the reference CFD model.

2. MATERIALS AND METHODS

2.1. General approach

The study was divided into two modules. The first estimated the potential CH₄ generation from urban solid waste using LandGEM 3.02. The second simulated the response of an SE-MSR reactor. The modules were linked solely through a CH₄→H₂ conversion indicator; a complete capture, purification, compression, or sorbent regeneration plant was not modeled.

2.2. Methane estimation with LandGEM 3.02

The LandGEM 3.02 equation is expressed as:

$$Q_{CH_4} = \sum_{i=1} \sum_{j=0.1} k L_0 \left(\frac{M_i}{10} \right) \exp(-kt_{ij})$$

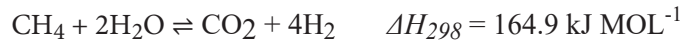
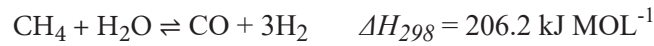
Where: Q_{CH_4} is the methane generation, M is the mass of waste accepted in year i , k is the methane generation rate constant, L_0 is the potential methane generation capacity, and t_{ij} is the age of the j -th fraction of waste in one-tenth of a year (U.S. EPA, 2005).

For the main scenario, $k = 0.04 \text{ year}^{-1}$ y $L_0 = 100 \text{ m}^3 \text{ CH}_4 \text{ Mg}^{-1}$ were used. These values were used for La Paz by Vargas Bautista and Calvimontes (2017) in the absence of kinetic parameters measured specifically at Bolivian landfills and are consistent with the *Inventory Conventional* dataset of LandGEM 3.02. The annual masses published by the Autonomous Municipal Government of La Paz (2022) for 2010–2021 were used.

The calculated generation was interpreted as potential generation. When an 80 % capture scenario was presented, this value was used only as an illustrative sensitivity and not as a measurement of the landfill studied.

2.3. Reactions considered in the reactor

The reduced model included the three main reforming and shift reactions, in addition to CaO carbonation:



The carbon formation and gasification reactions R4–R6 were not included in the main model because the reduced formulation did not incorporate an explicit dynamic state for solid carbon. Their exclusion is treated as a model limitation and not as evidence of the absence of coke.

2.4. Reactor configuration

The geometry and operating conditions were taken from the reference case of Neni et al. (2021). Table 1 summarizes the main parameters.

Table 1. Main reactor and bed parameters

Parameter	Symbol	Value	Unit
Feed temperature	T_{in}	923	K
Pressure	P	35	bar
Steam/carbon ratio	S/C	5	mol/mol
Superficial mass flux	G	3.5	$\text{kg m}^{-2} \text{ s}^{-1}$
Length	L	7.0	m
Internal diameter	D	0.30	m
Bed porosity	ε	0.50	—
Particle diameter	D_p	0.010	m
Maximum CaO conversion	X_{max}	0.40	—
Effectiveness factor	η	0.30	—
Catalyst bulk density	ρ_{cat}	330	kg m^{-3}
CaO bulk density	ρ_{CaO}	1100	kg m^{-3}
Reported solid density	ρ_s	1675	kg m^{-3}

The source of Neni et al. (2021) presents an ambiguity between the mass description of the bed and some reported volumetric bases. Consequently, the main case was kept conservative with respect to the carbon inventory, and alternative interpretations were retained only as sensitivities.

2.5. Reforming kinetics

Rates R1–R3 were formulated with Xu–Froment-type expressions, adopted from the work of Neni et al. (2021). For partial pressures in bar:

$$R_1 = \frac{k_1}{P_{H_2}^{2.5} DEN^2} (P_{CH_4} P_{H_2O} - \frac{P_{H_2}^3 P_{CO}}{K_1})$$

$$R_2 = \frac{k_2}{P_{H_2}^{3.5} DEN^2} (P_{CH_4} P_{H_2O}^2 - \frac{P_{H_2}^4 P_{CO_2}}{K_2})$$

$$R_3 = \frac{k_3}{P_{H_2} DEN^2} (P_{CO} P_{H_2O} - \frac{P_{H_2} P_{CO_2}}{K_3})$$

Where:

$$DEN = 1 + K_{CO} P_{CO} + K_{H_2} P_{H_2} + K_{CH_4} P_{CH_4} + K_{H_2O} \frac{P_{H_2O}}{P_{H_2}}$$

The kinetic constants were represented using Arrhenius relations:

$$k_i = k_{0,i} \exp\left(-\frac{E_{a,i}}{RT}\right)$$

The complete numerical parameters were kept in the editable supplementary file to avoid duplicating extensive tables in the manuscript.

2.6. CaO carbonation

The evolution of the local sorbent conversion was based on the formulation reported by Neni et al. (2021):

$$\frac{dX}{dt} = k_{carb} (X_{max} - X) (y_{CO_2} - y_{CO_2,eq})$$

with $k_{carb} = 0.35 \text{ s}^{-1} \text{ y}$:

$$y_{CO_2,eq} = 4.137 \times 10^7 \exp\left(-\frac{20474}{T}\right)$$

Due to an ambiguity in the placement of the effectiveness factor η between the conversion equation and the published volumetric rate expression, a conservative implementation was adopted in which η is applied only once. In this way, the CO₂ removed from the gas phase remains consistent with the carbon stored as CaCO₃.

2.7. Reduced model and numerical solution

The axial domain was discretized with 141 nodes and $\Delta z = 0.05$ m. The gas phase was solved as pseudo-steady-state for each time state of the solid and temperature. The sorbent state $X(z,t)$ and the thermal field evolved transiently. This approximation significantly reduces the computational cost compared with a three-dimensional CFD model, but does not represent radial gradients or complete gas-phase accumulation.

Species conservation in the gas phase was expressed in general form as:

$$\frac{dF_i}{dz} = A_c \sum_r V_{i,r} R_r$$

while the transient energy balance per cell considered the contribution of the reactions, the sensible enthalpy change of the gas, and axial conduction within an effective volumetric thermal capacity. The numerical implementation was verified through carbon balances, spatial and time step sensitivities, integrator tolerances, and specific audits of the pseudo-steady-state approximation.

The main case, called CURRENT_CONSERVATIVE, was run with a numerical partial pressure floor of 10^{-4} bar. The stored long-time run used $\Delta t = 0.1$ s; the time-step sensitivities were not used to recalibrate physical parameters.

2.8. Comparison strategy with Neni et al. (2021)

The comparison with Neni et al. (2021) was treated as a benchmark and not as experimental validation. The following were contrasted: dry H_2 mole fraction, CH_4 conversion, thermal evolution, and propagation of the carbonation zone. The CFD reference reports a maximum outlet temperature of 968.73 K at 615 s and a maximum dry H_2 mole fraction close to 0.8 while capture is active.

2.9. $CH_4 \rightarrow H_2$ potential indicator

To connect both levels of the study, the fresh-state reactor yield was used:

$$Y_{H_2/CH_4} = \frac{n_{H_2,out}}{n_{CH_4,in}}$$

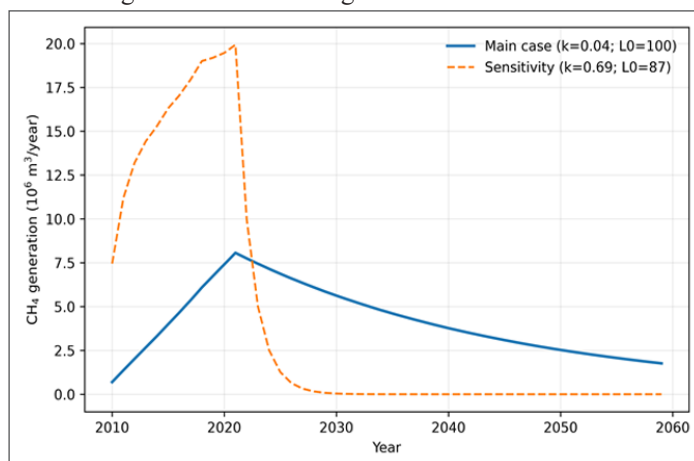
With $n_{H_2,out} = 4.97194 \text{ mol s}^{-1}$ y $n_{CH_4,in} = 2.33134 \text{ mol s}^{-1}$ $Y_{H_2/CH_4} = 2.13265 \text{ mol/mol}$ was obtained. Under the same temperature and pressure reference, the molar ratio was used as a volumetric ratio to construct a potential indicator. The stoichiometric limit of four moles of H_2 per mole of CH_4 fed was used only as a theoretical reference.

3. RESULTS AND DISCUSSION

3.1. Potential CH₄ generation via LandGEM

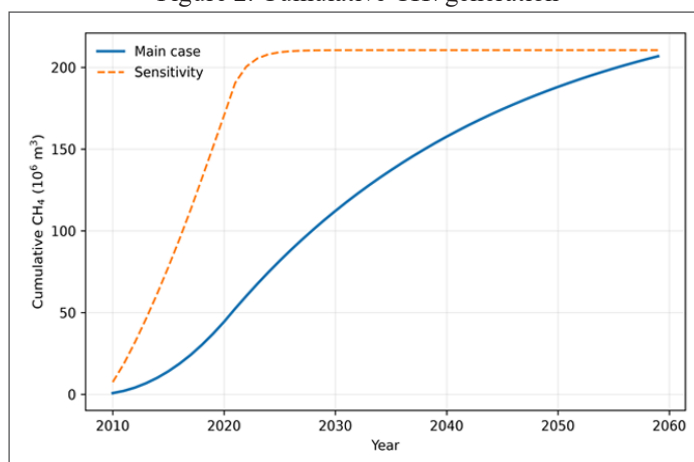
Between 2010 and 2021, 2,504,897 Mg of transported waste were recorded, with an average of 208,741 Mg/year. The series includes Nuevo Jardín de Alpacoma and the subsequent transition to Sak'a Churu, so the geographic scope of the analysis is expressed as the La Paz municipal system and not as the exclusive behavior of a single landfill throughout the entire period.

Figure 1. Annual CH₄ generation via LandGEM



The estimated annual generation reached its maximum in 2021, with 8.064×10^6 m³ CH₄/year, and subsequently decreased according to first-order kinetics. The main scenario produced 153.81 million m³ of cumulative CH₄ by 2039 and 206.77 million m³ by 2059.

Figure 2. Cumulative CH₄ generation



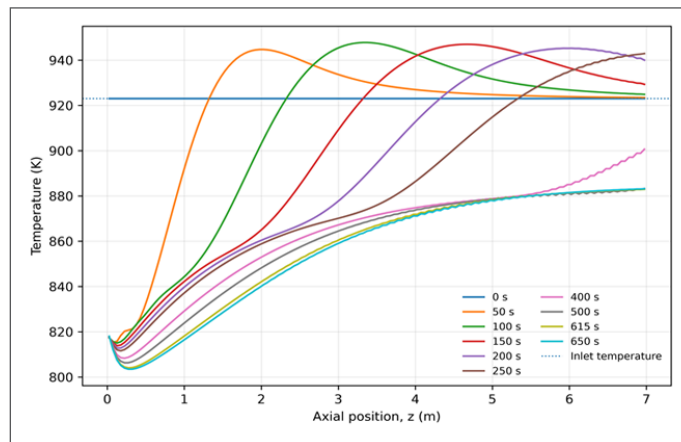
The ultimate capacity associated with the total mass and $L_0 = 100$ m³/Mg is 250.49 million m³ CH₄. Therefore, by 2059 approximately 82.55 % of this capacity had been generated. The sensitivity scenario with $k = 0.69$ year⁻¹ and $L_0 = 87$ m³/Mg concentrated the release of CH₄ over much shorter times and produced 36.85 % more cumulative

CH₄ by 2039 than the main scenario. This difference illustrates the model's sensitivity to the selection of k and justifies not treating literature values as locally measured parameters.

3.2. Thermal behavior of the reduced reactor

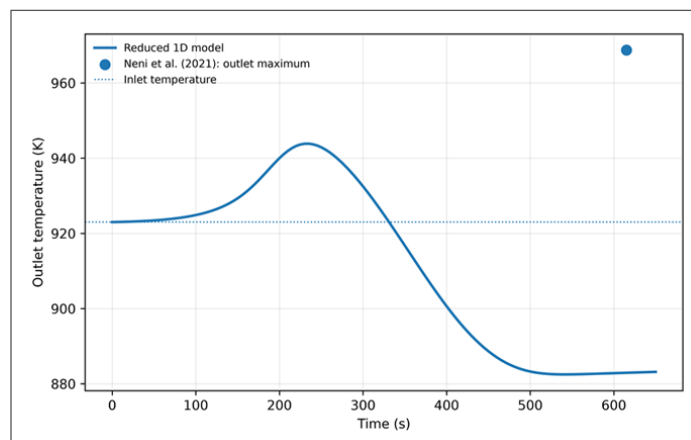
The temperature profiles show the formation and axial propagation of a hot zone associated with the coupling between the endothermic reforming reactions and the exothermic carbonation of CaO.

Figure 3. Axial temperature profiles



In the reduced model, the outlet temperature reached its maximum at approximately 235 s, while Neni et al. (2021) reported 968.73 K at 615 s. At 615 s, the reduced model predicted 882.93 K at the outlet, approximately 85.8 K below the reference CFD maximum.

Figure 4. Outlet temperature of the reduced model and CFD reference point

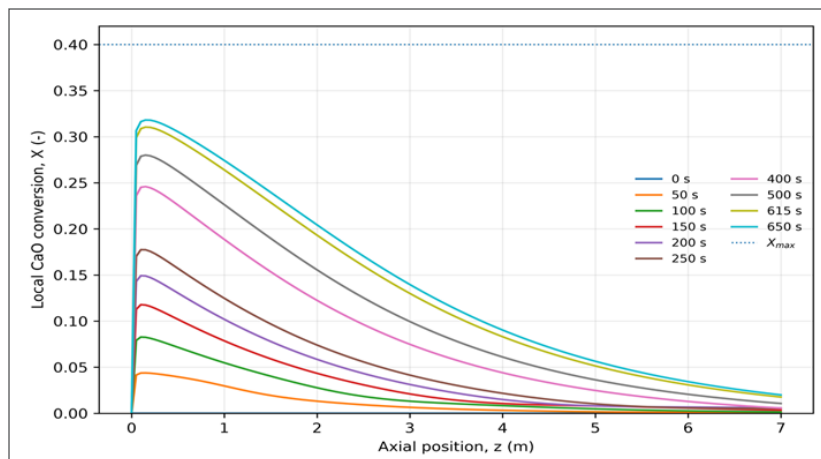


The discrepancy is not interpreted as an isolated numerical error. Sensitivities performed on regularization, spatial step, time step, tolerances, and inventory basis did not eliminate the mismatch. The combination of a faster thermal propagation and a slower sorbent saturation suggests a structural difference between the 1D pseudo-steady-state model and the three-dimensional CFD model, including the representation of transport, the source volumetric bases, and gas-phase accumulation.

3.3. Evolution of CaO carbonation

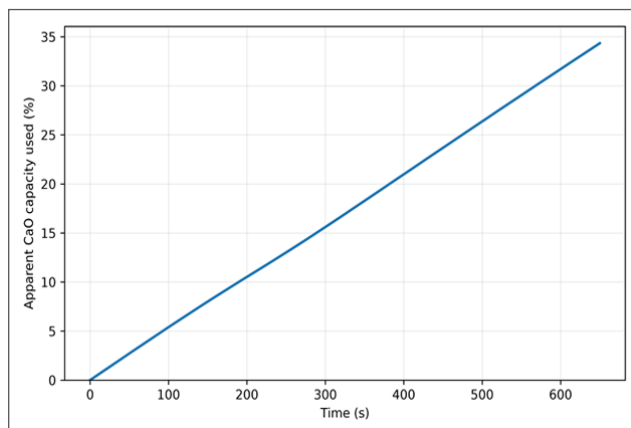
CaO conversion advanced from the inlet toward greater axial positions. Unlike a description based on three time-fixed phases, the results show a continuous evolution that depends on the local availability of CO₂ and on temperature.

Figure 5. Axial profiles of local CaO conversion



The overall indicator of capacity used reached approximately 34.34 % at 650 s. Therefore, the reduced model did not predict complete saturation of the CaO inventory within the simulated horizon.

Figure 6. Use of apparent CaO capacity

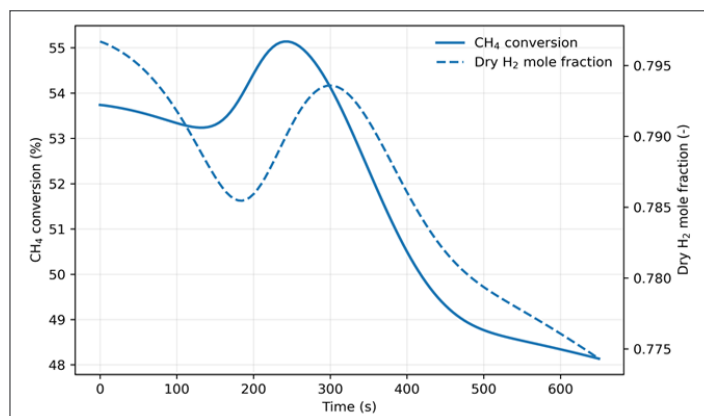


This observation is relevant when comparing with the CFD reference: the reduced model shifts the thermal wave too fast while overall carbonation advances comparatively more slowly. Both differences have opposite signs and cannot be consistently corrected using a single empirical factor without compromising the physical interpretation.

3.4. CH₄ conversion and H₂ production

With fresh sorbent, CH₄ conversion was 53.738 % and the dry H₂ mole fraction was 0.79669. The case without R7 produced approximately 40.84 % CH₄ conversion and 0.6112 dry H₂, which confirms within the model the favorable effect of removing CO₂ from the gas phase.

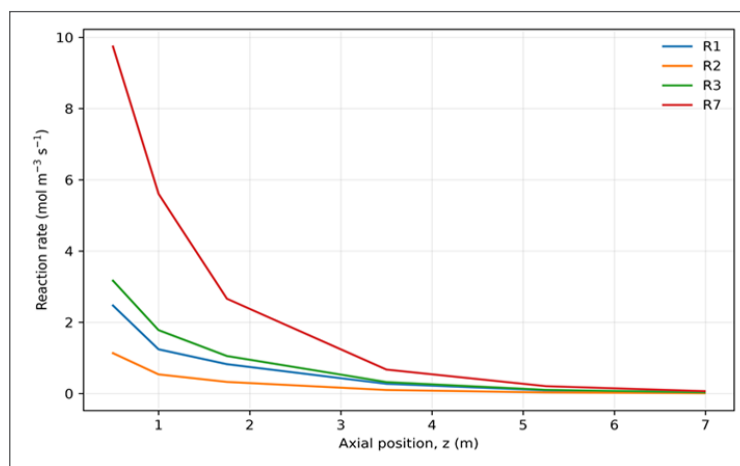
Figure 7. Temporal evolution of CH₄ conversion and dry H₂



The fresh state is very close to the equilibrium calculation at 923 K, 35 bar, and S/C=5, for which 53.93 % CH₄ conversion and 0.79825 dry H₂ were obtained. The dry H₂ fraction of 0.79669 is also close to the maximum value of approximately 0.8 reported by Neni et al. (2021). This closeness constitutes a useful checkpoint, but does not imply validation of the complete transient behavior.

The evolution of local rates shows that the reactions are concentrated mainly in the inlet zone of the reactor in the initial state.

Figure 8. Local rates of R1, R2, R3, and R7 in the initial state



3.5. Synthetic comparison with the CFD benchmark

The results obtained support a moderate conclusion: the 1D model reproduces fundamental qualitative trends of SE-MSR and the increase in H₂ associated with CO₂ capture, but does not quantitatively reproduce the thermal time scale of the CFD of Neni et al. (2021). Therefore, the reference is used as a benchmark to delimit the scope of the reduced model.

Table 2. Comparison of selected indicators

Indicator	Neni et al. (2021)	Reduced model	Interpretation
Dry H ₂ mole fraction with capture	≈0.80	0.79669	Good reproduction of the fresh state
Maximum outlet temperature	968.73 K	≈943 K	Lower magnitude in the reduced model
Time of outlet maximum	615 s	≈235 s	Faster thermal propagation
Outlet temperature at 615 s	968.73 K (maximum reported)	882.93 K	Difference ≈−85.8 K

3.6. Indicative valorization potential of CH₄ as H₂

The fresh yield obtained was:

$$Y_{H_2/CH_4} = 2.13265 \text{ mol H}_2 \text{ mol}^{-1} \text{ CH}_4$$

Applied to the CH₄ generated up to 2039, this yield produces an indicator of 328.02 million m³ of H₂. If a methane capture efficiency of 80 % is adopted solely as a scenario, the potentially captured CH₄ would be 123.05 million m³ and the H₂ indicator would decrease to 262.42 million m³.

Figure 9. Indicative bridge from generated CH₄ to H₂

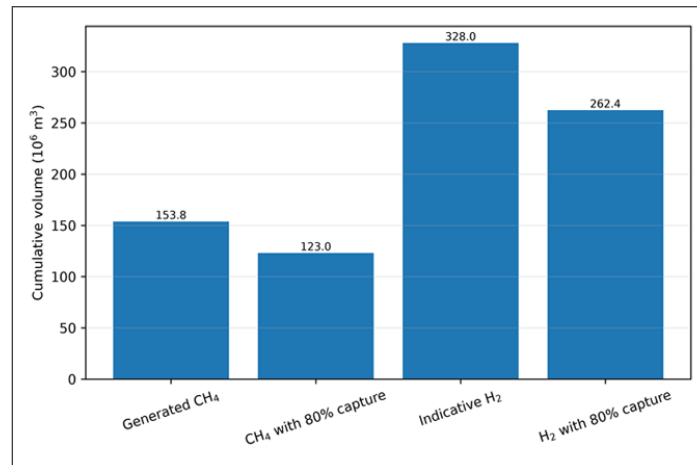


Table 3. Indicative bridge from waste to H₂

Stage	Result
Waste recorded 2010–2021	2.505×10 ⁶ Mg
CH ₄ generated up to 2039	153.81×10 ⁶ m ³
CH ₄ with 80 % capture (scenario)	123.05×10 ⁶ m ³
Indicative H ₂ without applying capture	328.02×10 ⁶ m ³
Indicative H ₂ with 80 % capture	262.42×10 ⁶ m ³

The indicator does not represent industrial production. Collection losses other than the illustrative scenario, the actual composition and purification of the biogas, plant availability, catalyst deactivation, cyclic sorbent degradation, regeneration energy, compression, H₂ separation, or auxiliary consumption were not considered.

4. LIMITATIONS

The study presents four main limitations. First, the LandGEM parameters used for La Paz come from the literature and not from kinetic measurements specific to the landfill. Second, the 2010–2021 municipal waste series represents transported waste and spans the transition between disposal sites; it does not constitute a complete reconstruction of the entire history of each landfill. Third, the SE-MSR model is a reduced 1D model with a pseudo-steady-state gas phase and does not reproduce the radial transport or the three-dimensional hydrodynamic field of the reference CFD. Fourth, the main model does not incorporate a dynamic solid carbon state or CaO regeneration cycles.

These limitations prevent interpreting the results as a final plant design or as a guaranteed production prediction. The value of the model lies in providing a reproducible, auditable, and coherent calculation chain to relate a potential methane source to the behavior of an SE-MSR reactor under literature conditions.

5. CONCLUSIONS

- The official LandGEM 3.02 formulation, combined with real municipal waste data from La Paz, estimated a cumulative generation of 153.81 million m³ of CH₄ by 2039 and 206.77 million m³ by 2059 for the main scenario with $k = 0.04 \text{ year}^{-1}$ and $L_0 = 100 \text{ m}^3/\text{Mg}^{-1}$.
- The reduced SE-MSR model predicted 53.74 % CH₄ conversion with fresh sorbent, and a dry H₂ mole fraction of 0.7967. The comparison with Neni et al. (2021) showed a close reproduction of the initial H₂ level, but a considerably faster thermal propagation: the maximum outlet temperature occurred at around 235 s versus 615 s in the reference CFD.
- The evolution of CaO was continuous and did not reach overall saturation within the 650 s simulated; the capacity used was approximately 34.34 % at the end of the horizon. The combination of an excessively fast thermal wave and a slower saturation indicates that the discrepancy with the CFD is structural and cannot be convincingly attributed to a single numerical parameter.
- The link between LandGEM and the fresh reactor yield produces a theoretical indicator of 328.02 million m³ of H₂ for the methane generated up to 2039, or 262.42 million m³ under an illustrative 80 % capture scenario. These values should be interpreted as valorization potential and not as industrial production.
- Overall, the study shows that urban waste in La Paz represents a potential source of methane suitable for valorization via SE-MSR and provides a reproducible framework for comparing future scenarios with more complete local data and higher-fidelity reactor models.

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TRENDS IN LIMITING CLIMATE FACTORS IN THE SUPPLY OF FORAGE INPUTS FOR THE DAIRY INDUSTRY IN THE BOLIVIAN CENTRAL ALTIPLANO

Edwin Yucra^{1,*}, Omar Pozo²

ABSTRACT

Bolivia's Central Altiplano has transformed much of its subsistence agriculture into a market-oriented dairy farming system, underpinned by the cultivation of forage crops such as alfalfa and oats. This transformation coincides with a stage of locally complex climatic changes: although mean maximum and minimum temperatures show significant positive trends between March and September, extreme minimum temperatures (the ones that produce destructive frosts) do not show a comparable reduction, so the risk of frost persists throughout much of the forage growth cycle. Added to this is a documented delay in the onset of the rainy season and a greater concentration of precipitation, which intensify the atmospheric water deficit. This article integrates recent field studies on the Northern and Central Altiplano with scientific literature on the climatic sensitivity of forage crops and on the effect of heat and water stress on milk production, to argue that these climatic variations (persistent frosts, delayed and intensified rainfall, and greater evapotranspirative demand) constitute a concrete threat to forage availability and, through that pathway, to milk production in the Central Altiplano. Tables and figures are presented with climatic, productive, and Bolivian dairy-sector data, along with a synthesis of the climate–forage–dairy impact chain and its implications for the food and economic security of producer families.

Keywords: climate change, Central Altiplano, dairy farming, forage, frosts, food security.

1. INTRODUCTION

The Bolivian Altiplano has undergone, over the last four decades, a profound transformation of its agricultural production systems. Taboada et al. (2017) report that, from subsistence agriculture oriented toward family food security until the 1980s, communities have evolved toward systems more connected to the market, with intensive onion and commercial potato production in communities of the Northern Altiplano, and (of particular interest to this article) dairy farming in the Central Altiplano.

This productive specialization is no accident: it coincided with the arrival of the PIL-La Paz dairy industry in the 1990s, the establishment of the first communal dairy modules, the availability of extensive land and soils suited to forage, and a secure and steady market for dairy products. However, the dependence of dairy farming on forage availability (mainly alfalfa, oats, and forage barley) makes this production system particularly sensitive to the climate variability that characterizes the Central Altiplano, with low nighttime temperatures, high daily thermal

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amplitude, a short and concentrated rainfall regime, and a strong dependence on water availability to sustain forage growth throughout the year.

Recent climate studies in the region reveal a paradox that is critical for dairy farming: while mean and maximum temperatures tend to rise significantly, extreme minimum temperatures (responsible for the frosts that damage crops and forage regrowth) do not show the same trend, so the risk of forage loss to frost remains present even in a context of general warming. Added to this is the documented delay in the onset of the rainy season and the concentration of precipitation into fewer days, which intensifies dry spells and the atmospheric water deficit faced by cultivated forage.

The aim of this article is to integrate the climatic, productive, and social evidence generated (Garcia et al., 2025; Yucra et al., 2025) on the Bolivian Altiplano, focused, respectively, on local climate trends, on the transformation of production systems, and on an initial summary of the impacts of climate change on Altiplano agriculture, with additional scientific literature on the sensitivity of forage crops to frost and drought, and on the effects of heat and water stress on dairy cattle, in order to argue and document that these climatic variations could cause severe losses to the Central Altiplano's dairy production sector due to a lack of sufficient, quality forage.

2. METHODOLOGY

This article integrates and synthesizes evidence from field studies conducted in the same communities of the Bolivian Northern and Central Altiplano between 2006 and 2024 (Taboada et al., 2017; Garcia et al., 2025; Yucra et al., 2025), complemented with additional scientific literature and official statistics from the Bolivian dairy sector, following three methodological lines:

First, the climate trend analysis was based on data from local weather stations, the ERA5 (temperature) and CHIRPS (precipitation) reanalysis series for a 40-year reference period, contrasted with records from the National Meteorology and Hydrology Service (SENAMHI) in Patacamaya and Ancoraimes. The significance of monthly trends was assessed using the Mann-Kendall test (MAKESENS software), applied to climate indices standardized by the World Meteorological Organization (mean and extreme maximum and minimum temperature, days with frost, accumulated precipitation, days with rain, seasonality index, and aridity index) (Garcia et al., 2025).

Second, the analysis of production systems was based on participatory assessments (workshops, in-depth interviews, case histories, and surveys of 80 households in 2023) carried out in the study communities to reconstruct changes in productive orientation since the 1980s, identifying the institutional, social, technological, market, and climatic factors that drove specialization toward dairy farming in the Central Altiplano (Taboada et al., 2017; Yucra et al., 2025).

Third, to relate these climatic and productive trends to the vulnerability of the dairy sector, additional scientific literature was reviewed on the sensitivity of forage crops grown in the Bolivian high-Andean dairy zone (alfalfa, oats, barley) to frost and drought, and on the effect of water deficit and heat stress on milk production; official statistics were also compiled from the Ministry of Productive Development and Plural Economy, the National Institute of Statistics (INE), and university studies (UMSA) on the Bolivian dairy sector and the production performance of dairy farming in the Altiplano. From this integration, a conceptual synthesis, (not a new, direct

measurement) was constructed of the impact chain linking climate variability, forage availability, and milk production in the Central Altiplano.

Study area

The analysis initially focuses on the municipality of Umala (Aroma province, La Paz department), which includes the communities of Ñacamaya, Sabilani, and Incamaya, commercially linked to the urban center of Patacamaya in Bolivia's Central Altiplano. This area lies at an average altitude of 3,780 to 3,860 m in an arid setting where the larger difference between daily maximum and minimum temperatures reflects lower atmospheric humidity and a poorly buffered nighttime loss of infrared radiation, which intensifies the occurrence and severity of frosts compared with communities near Lake Titicaca. The region is part of the Central Altiplano dairy basin (the Desaguadero zone and the eastern zone, comprising the provinces of Ingavi, Murillo, and Aroma in La Paz, and Cercado and Abaroa in Oruro), one of the country's main dairy basins along with the Northern Altiplano.

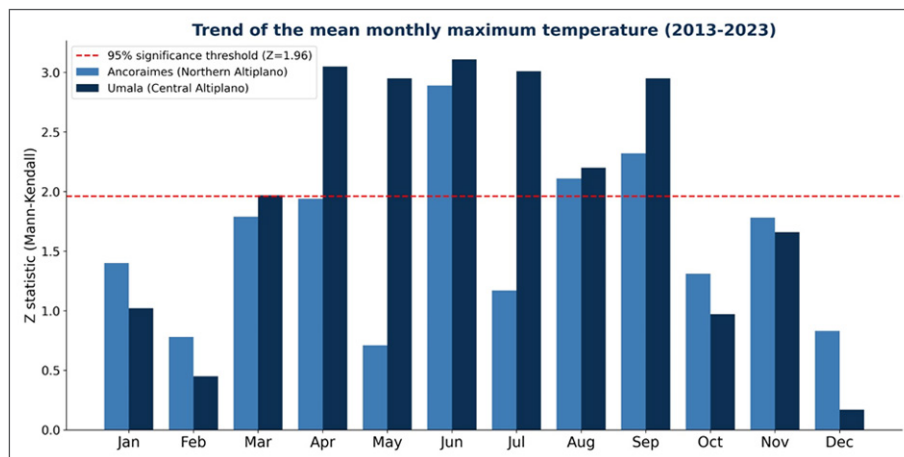
As a comparative reference, the municipality of Ancoraimes is used (Northern Altiplano, communities of Chojñapata, Calahuacani, and Chinchaya), which shares the same regional climate system but has milder thermal and water conditions due to its proximity to Lake Titicaca.

3. RESULTS

3.1. Climate trends observed in the Central Altiplano

The analysis of historical trends (Mann-Kendall, reference period available through 2020) confirms that the mean monthly maximum temperature shows statistically significant increases in Umala (Central Altiplano) for much of the year, with the most pronounced values between March and September, a period that includes the end of the forage growing season and much of the subsequent regrowth. In Ancoraimes (Northern Altiplano), trends are also positive, but less widespread. Figure 1 compares the Mann-Kendall Z statistic for both zones, month by month.

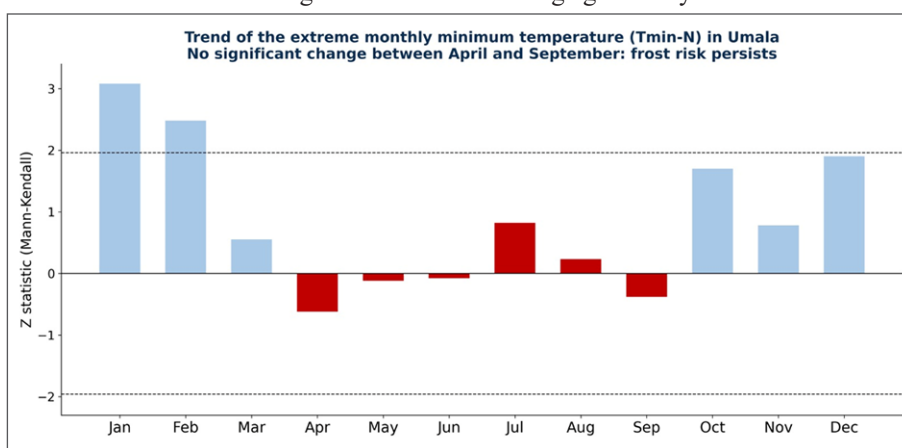
Figure 1. Trend of the mean monthly maximum temperature (Mann-Kendall Z statistic) in Ancoraimes and Umala. Values above the red line ($Z = 1.96$) indicate a statistically significant positive trend at 95%.



Source: Own elaboration based on García et al. (2025)

However, the critical variable for forage is not the mean temperature but the extreme monthly minimum temperature (Tmin-N), which determines the occurrence of destructive frosts. As Figure 2 shows, in Umala this variable shows no significant trend of change between April and September (the period in which the greatest frost risk for forage crops is concentrated), while it does increase in the summer months (January, February) and in the transition months toward the rainy season (October, December). This means that, although the climate is perceived and measured as warmer on average, the extreme frost capable of destroying an alfalfa cutting or an oat regrowth continues to occur with a frequency similar to that of past decades during winter.

Figure 2. Trend of the extreme monthly minimum temperature (Tmin-N) in Umala. The red bars mark the months (April–September) with no significant trend toward reduced frost risk, coinciding with much of the forage growth cycle



Source: Own elaboration based on García et al. (2025)

Added to this persistent frost risk is a documented delay in the onset of the rainy season. In the Central Altiplano, the small September precipitation peak that historically moistened the soil for October planting has virtually disappeared since the year 2000, and planting can now only take place in the second half of November (García et al., 2025). Since the end of the rainy season has not shifted to the same degree, the growth window with low probability of frost and sufficient water has narrowed, affecting both food crops and rainfed and supplementary-irrigation forage. Table 1 summarizes the main climate indices used in this analysis and their relevance to forage production.

Table 1. Climate variables and indices relevant to forage availability in the Central Altiplano.

Variable	Index	Relevance to forage
Maximum temperature (Tmax)	Mean, extreme maximum, extreme minimum monthly.	Determines evapotranspirative demand (ETo) and crop water stress.
Minimum temperature (Tmin)	Mean, extreme maximum, extreme minimum (Tmin-N), days with frost.	Tmin-N defines the risk of frost damage to forage shoots and regrowth.
Precipitation	Monthly accumulated, days with rain, seasonality index.	Determines water availability for rainfed forage growth.
Aridity Index	PP / ETo (FAO Penman-Monteith)	The lower the value, the greater the atmospheric water deficit for forage.

Source: Adapted from García et al. (2025)

3.2. Transformation toward dairy systems in the Central Altiplano

The participatory evidence gathered in Iñacamaya, Sabilani, and Incamaya shows that, since the 1980s, the Central Altiplano's production system shifted from subsistence agriculture (potato, quinoa, cañahua, sheep farming) toward a system specialized in forage and dairy, driven by road improvements, the arrival of the PIL industry, the availability of extensive land, and, according to the producers themselves, the persistence of frost risk, which limited rainfed commercial potato farming (Yucra et al., 2025). Table 2 summarizes this shift, as described by the farmers themselves.

Table 2. Change in productive activity in communities of the Central Altiplano

Period	Productive activity	Factors of change
1980s	Rainfed commercial potato, sheep for meat, quinoa and cañahua for self-consumption.	Subsistence; smaller-scale, low-risk agriculture and livestock.
Present day (2023-2024)	Dairy farming and forage (alfalfa), diverse potatoes and commercial quinoa.	Secure, stable biweekly market; extensive plots; forage more frost-resistant than rainfed commercial potato.

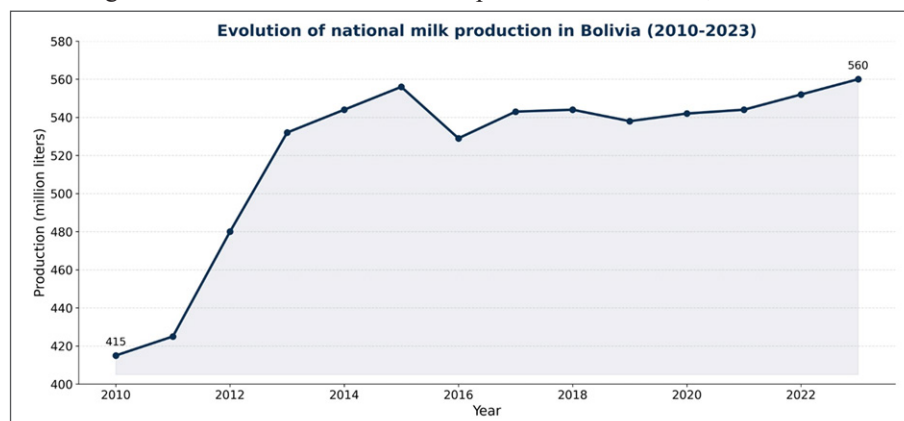
Source: Prepared by the authors based on Yucra et al. (2025) and Taboada et al. (2025).

Unlike communities in the Northern Altiplano such as Chinchaya, where available irrigation allowed production to specialize in high-value vegetables (onion), in dairy communities of the Central Altiplano winter frost risk has not decreased significantly and irrigation remains a costly and difficult option, so farmers chose to integrate annual-cycle forage (mainly alfalfa) alongside various rainfed potato varieties, taking advantage of the greater land area available compared with northern communities (Yucra et al., 2025). This decision, however, concentrates the family's productive risk on forage as virtually the sole critical input, whose availability depends directly on the same climatic variables that affect the other crops: persistent frosts and delayed rains.

3.3. Overview of the Bolivian dairy sector and the role of the Central Altiplano

At the national level, Bolivia produced close to 560 million liters of milk in 2023, with a declining growth rate over the last three decades: 75.6% between 1990 and 2000, 34.2% between 2001 and 2011, and only 15.2% between 2012 and 2022 (Ministry of Productive Development and Plural Economy [MDPyEP], 2025). Figure 3 shows this trend.

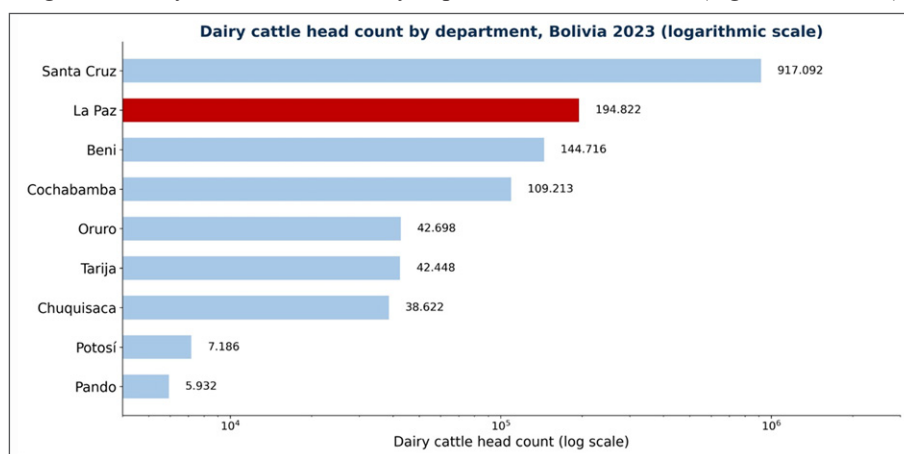
Figure 3. Evolution of national milk production in Bolivia, 2010–2023.



Source: Own elaboration based on data from the National Institute of Statistics, cited in MDPyEP (2025)

The department of La Paz accounts for 9.7% of national milk production, and 32.5% of its cattle herd is dairy cattle, being the second-highest proportion in the country after Oruro (MDPyEP, 2025). Within La Paz, the dairy basin is divided between the Northern Altiplano (the lakeside zone and the Andean plain, comprising the provinces of Omasuyos, Los Andes, and Ingavi) and the Central Altiplano (the Desaguadero zone and the eastern zone, comprising the provinces of Ingavi, Murillo, and Aroma), where Umala and Patacamaya are located (MDPyEP, 2025). Figure 4 situates La Paz within the national context of dairy cattle numbers.

Figure 4. Dairy cattle head count by department, Bolivia 2023 (logarithmic scale).



Source: Own elaboration based on data from the National Institute of Statistics, cited in MDPyEP (2025).

Bolivian dairy yields are low by regional standards: 8.4 liters/cow/day on national average, compared with 15.8 liters/cow/day in South America and 22.9 liters/cow/day in Argentina (MDPyEP, 2025). In the La Paz Altiplano, the reported yield is even lower: a study in the Northern Altiplano reports an average of 6.5 liters/cow/day (Cortez Quispe, 2017), while UMSA's Choquenaira Experimental Station (Central Altiplano) recorded an average production of 9.0 liters/cow/day in Holstein cattle, but with a marked difference between the wet season (11.9 kg/day) and the dry season (6.6 kg/day): a drop of approximately 45% in daily production during the months of lowest forage and water availability (Apthapi magazine, n.d.). Table 3 compares these yields.

Table 3. Comparison of dairy yields at the regional, national, and local (Altiplano) levels.

Geographic reference	Yield (liters/cow/day)	Source
South America average	15.8	MDPyEP (2025)
Argentina	22.9	MDPyEP (2025)
Bolivia national average	8.4	MDPyEP (2025)
Santa Cruz	9-10	MDPyEP (2025)
Cochabamba	15	MDPyEP (2025)
La Paz (departmental average)	10	MDPyEP (2025)
Northern Altiplano (small-scale producer)	6.5	Cortez Quispe (2017)
Central Altiplano, Choquenaira, wet season	11.9	Revista Apthapi (s. f.)
Central Altiplano, Choquenaira, dry season	6.6	Revista Apthapi (s. f.)

This seasonal gap of nearly half the daily production at UMSA's Choquenaira Experimental Station (also in the Central Altiplano) is consistent with what the scientific literature describes as a direct effect of lower forage availability and quality, and not solely of heat stress (which is itself heightened even in a climate of moderate temperatures like that of the Altiplano), since rainfed and supplementary-irrigation forage production depends on the rainy season, and its scarcity or delay reduces both the quantity and protein quality of the feed available to livestock (Ministry of Productive Development and Plural Economy, 2025; Riquezas de Bolivia, 2021).

3.4. Climatic sensitivity of forage crops grown in the Central Altiplano

The main forage crops grown in the Central Altiplano (alfalfa (*Medicago sativa*), forage oats (*Avena sativa*), and forage barley (*Hordeum vulgare*)) were originally introduced to the Altiplano zones, among other reasons, for their greater relative tolerance to frost and drought compared with vegetables or other commercial crops (Forage Research Center, CIFUMSS, n.d.). However, this relative tolerance does not make them immune to climate variability: agronomic research in the region documents that the sharp temperature swing between day and night (worsened by the Central Altiplano's low atmospheric humidity) remains the main threat to forage crop growth between April and September, while water scarcity between August and November limits regrowth before the start of the rains (Jiménez & Mendoza-Pedroza, 2017).

Bolivian forage research explicitly recognizes the need to develop alfalfa and other legume varieties with greater tolerance to pests, disease, drought, and frost, an objective that remains valid because currently available varieties are still vulnerable to these climatic factors (CIFUMSS, n.d.). In this context, the introduction of alternative pastures such as maralfalfa grass (*Pennisetum* sp.) has been evaluated at UMSA's Choquenaira Experimental Station as a possible way to increase forage yield per hectare in tempered environments, precisely in response to the need to ensure forage availability for the Central Altiplano's dairy cattle (Jiménez & Mendoza-Pedroza, 2017).

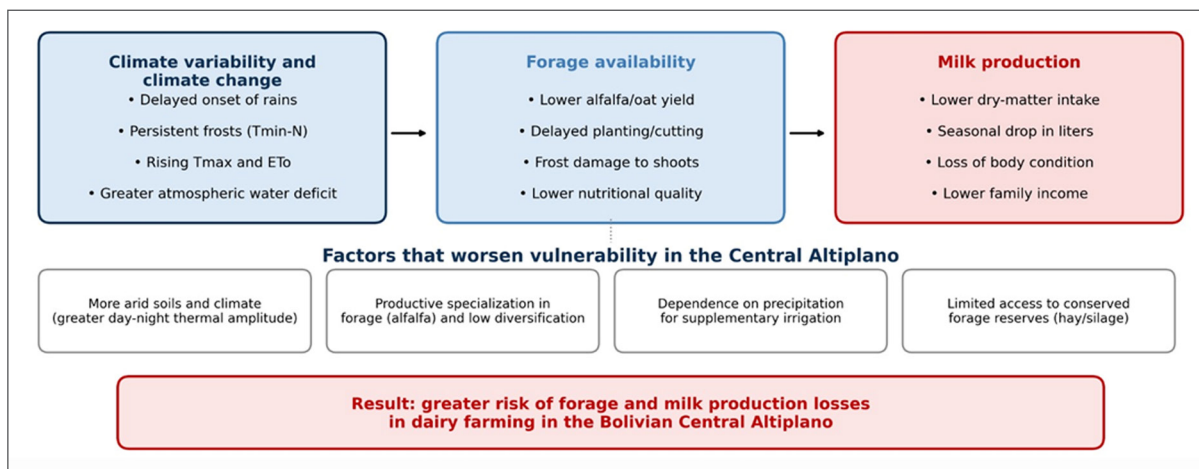
Internationally, scientific evidence on pastures and forage confirms that both water deficit and late frosts reduce the yield and nutritional quality of alfalfa and other forage legumes, effects that intensify when these events occur during the regrowth or first-cutting stages of the crop, precisely the period in which, according to the trend analysis presented in section 3.1, the Central Altiplano's frost risk has not declined significantly.

3.5. Cascade of impacts: from climate variability to milk production

Integrating the climatic, agronomic, and productive evidence presented makes it possible to build a conceptual synthesis of the impact chain that links climate variability to milk production in the Central Altiplano, illustrated in Figure 5.

This synthesis does not replace direct measurements of the economic effect on dairy production, which were not the subject of the baseline studies reviewed, but it organizes the available evidence into a causal sequence verifiable against the cited literature.

Figure 5. Conceptual cascade of impacts: from climate variability to dairy production in the Central Altiplano.



Source: Own elaboration based on a synthesis of the sources cited in this article.

First, the persistence of frost risk (Tmin-N with no significant reduction trend between April and September) and the delay and intensification of rainfall concentration reduce the safe forage growth window and increase the atmospheric water deficit (higher ETo due to the rise in Tmax). **Second**, this translates into lower forage availability and quality: delayed planting and first cutting, damage to tender shoots from late frosts, and lower protein content in forage harvested under water stress. **Third**, lower forage availability reduces dry-matter intake by dairy cattle, which, according to local evidence from Choquenaira, (where production falls from 11.9 to 6.6 liters/cow/day between the wet and dry seasons) translates directly into a seasonal drop in liters produced, with a consequent loss of income for producer families.

This process is worsened in the Central Altiplano by four structural factors: (a) a more arid climate than the Northern Altiplano, with greater day–night thermal amplitude; (b) growing productive specialization in forage and dairy, with less crop diversification than in the Northern Altiplano; (c) dependence on supplementary irrigation (costly and hard to access in Iñacamaya) to sustain forage outside the rainy season; and (d) producer families' limited access to forage conservation methods (hay, silage) that would help buffer seasonal scarcity, a practice that Bolivian technical literature identifies as necessary but not widespread among small-scale producers (Riquezas de Bolivia, 2021).

4. DISCUSSION

The results presented support the argument that the climatic changes documented for the Central Altiplano (particularly the persistence of frost risk during the forage growth cycle, despite the general warming of mean temperatures, together with the delay and intensification of rainfall) constitute a concrete and verifiable threat to forage availability and, through that pathway, to dairy production in the Central Altiplano's dairy-producing zones (analyzed using information from communities in the Municipality of Umala and climate data from Patacamaya). This reading is consistent with the productive transformation described in section 3.2, since farmers in Iñacamaya themselves explain that they shifted toward dairy farming partly because frost risk remained too high to sustain rainfed commercial potato farming, turning instead to forage for its greater relative tolerance.

However, the agronomic evidence reviewed (section 3.4) shows that this relative tolerance does not eliminate forage's vulnerability to late frosts and water deficit, but only reduces it compared with other crops.

The magnitude of the economic risk becomes clearer when looking at the seasonal variability documented at the Choquenaira Experimental Station itself, within the Central Altiplano: a drop of nearly 45% in daily production per cow between the wet and dry seasons. While this figure comes from a controlled experiment and cannot be mechanically generalized to family producers as a whole (whose animals, management, and access to conserved forage differ from experimental conditions) it offers an order of magnitude consistent with the international literature on the effect of forage deficit on milk production, and suggests that prolonged droughts, delayed rains, or late frosts that further reduce forage availability could deepen this seasonal gap, particularly in years with climate conditions more adverse than average, for example, the very strong ENSO event with a high probability of occurring in the 2026–2027 agricultural season (CIIFEN, 2026).

It is important to note that, unlike dairy systems in hot or temperate climates, where heat stress (measured using the temperature-humidity index, THI) is the main mechanism of production loss, in the Central Altiplano the dominant vulnerability mechanism is not heat but the combination of persistent frosts and water deficit that limits forage production. The international literature on THI is useful as a conceptual reference framework, showing that even moderate reductions in dry-matter intake (associated, in hot climates, with lower consumption due to heat stress) consistently translate into lower milk production; however, its direct application to the Bolivian Altiplano requires adapting the analysis to the region's own climatic mechanisms, which favor the impact of frost over high temperatures, and forage deficit over direct heat stress on the animal.

The combination of growing productive specialization toward dairy farming, low diversification of income sources, and limited access to irrigation and conserved forage suggests that producer families in the Central Altiplano could face growing economic vulnerability in the face of extreme climate events, underscoring the need for risk-management strategies specific to the dairy sector: forage diversification, efficient irrigation systems, forage conservation for the dry season, and early-warning mechanisms for late frosts.

5. CONCLUSIONS

- The evidence integrated in this article indicates that the Bolivian Central Altiplano, and particularly communities in the Municipality of Umala and Patacamaya, face a specific climatic combination that threatens forage availability and, through that pathway, milk production in Bolivia's high-Andean zones (rising mean and maximum temperatures that do not translate into a comparable reduction in extreme frost risk during the forage growth cycle, and a delay and intensification of rainfall concentration that shortens the safe growth window). This combination is consistent with the sharp seasonal production drop observed locally (from 11.9 to 6.6 liters/cow/day between the wet and dry seasons in Choquenaira), and with the agronomic literature documenting the sensitivity of alfalfa and other forage crops to late frost and water deficit.
- The productive specialization toward dairy farming, adopted by Central Altiplano families partly as an adaptation strategy in response to the persistence of frost risk in other crops, may be generating a new form of vulnerability, concentrating the family's productive risk on forage availability as a critical input, whose production depends on the same climatic variables (frosts, rains) that originally drove the shift in

activity. In light of this scenario, it is suggested that: (a) research and dissemination of forage varieties with greater frost and drought tolerance be strengthened; (b) access to efficient irrigation and forage conservation technologies (hay, silage) that would help buffer seasonal scarcity be expanded; (c) early-warning systems for late frosts, specifically geared to the forage planting and cutting calendar, be developed; and (d) strategies for productive diversification and climate risk management that reduce dependence on a single production system be promoted, in view of increasingly uncertain future climate scenarios.

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MULTITEMPORAL EVIDENCE OF HYDRO-VEGETATIONAL CHANGE IN HIGH-ANDEAN WETLANDS OF ANTOFAGASTA (1994–2024): IMPLICATIONS FOR CLIMATE CHANGE MANAGEMENT

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ABSTRACT

This study analyzes the hydro-vegetational dynamics of the Miscanti Lagoon and the Pujsa Salt Flat, two strategic high-Andean ecosystems in the Antofagasta Region of Chile, during the period 1994–2024. Landsat time series (5, 7, and 8) were processed through atmospheric correction, cloud masking, and radiometric harmonization, from which NDVI, NDWI, and NDMI indices were derived. These indices were integrated with climatic variables (precipitation, temperature, and evapotranspiration) to evaluate spatiotemporal patterns using descriptive statistics and coefficients of variation. Results reveal a progressive deterioration of vegetation cover and surface water balance, expressed in the decrease of NDVI and NDWI and the increase of NDMI, with a more sustained deterioration in the Miscanti Lagoon, while the Pujsa Salt Flat showed greater interannual variability but comparatively higher stability. The coherence between spectral signals and climatic trends confirms the vulnerability of high-Andean wetlands to climatic and environmental pressures, highlighting the usefulness of spectral indices as monitoring tools and as support for adaptive management and conservation of these socio-ecological systems.

Keywords: High-Andean wetlands, spectral indices, climate change.

1. INTRODUCTION

High-Andean wetlands of the Chilean Altiplano are strategic ecohydrological systems that fulfill essential functions in water regulation, carbon storage, and biodiversity conservation. However, they present high vulnerability to climatic and anthropogenic pressures, which makes them particularly sensitive environments to the effects of climate change and to territorial transformations induced by extractive activities (Squeo et al., 2006).

Recent regional-scale research has evidenced heterogeneity in the responses of these ecosystems to such pressures, highlighting the detection of “re-greening” processes in previously degraded bofedales, resulting from complex interactions between climate, hydrological dynamics, and vegetation regeneration (Chavez et al., 2019).

Within this framework, the Miscanti Lagoon and the Pujsa Salt Flat, located in the Antofagasta Chilean Region, constitute cases of particular interest. Both ecosystems have undergone significant hydro-vegetational transformations over the last decades (Chavez et al., 2019; Anderson et al., 2021), which have placed pressure on

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both water availability and the provision of ecosystem services, compromising the community and ecological sustainability of the region.

To address this challenge, multitemporal remote sensing has become established as a robust tool that allows the quantification of variations in vegetation productivity, surface moisture, and water stress through spectral indices such as NDVI, NDWI, and NDMI. The use of these indicators at annual, monthly, and even daily scales generates standardized and reproducible information, making it an indispensable input for the monitoring, strategic management, and conservation of fragile ecosystems (Alemayehu et al., 2023; Espinosa et al., 2011).

In this context, the objective of the present study is to characterize the hydro-vegetational dynamics of the Miscanti Lagoon and the Pujsa Salt Flat located in the Chilean High-Andes (Antofagasta) during the period 1994–2024 through multitemporal remote sensing using the spectral indices NDVI, NDWI, and NDMI, with the purpose of generating solid scientific evidence to support environmental planning and decision-making in the face of climate change scenarios in high-Andean wetlands.

2. METHODOLOGY

The study was carried out in three interrelated phases. The first consisted of the collection and preprocessing of Landsat 5 TM, Landsat 7 ETM+, and Landsat 8 OLI satellite images corresponding to the period 1994–2024 for the Miscanti Lagoon and the Pujsa Salt Flat, processed in Google Earth Engine. The procedure included atmospheric correction, and cloud, snow, and shadow masking using the QA_PIXEL band, radiometric harmonization of Landsat 8 relative to Landsat 5/7, and spatial resampling to 30 m, ensuring consistency across the time series (Roy et al., 2016).

For the harmonization, the coefficients of Roy et al. (2016) were used (Table 1), who propose a correction for each common band of Landsat 8 OLI, (Equation 1).

$$\text{adjusted value} = \frac{(\text{OLI value} - \text{intercept})}{\text{slope}} \quad \text{Equation (1)}$$

Table 1. Intercept and slope for the radiometric harmonization of bands 3, 4, 5, and 6 of Landsat 8

Band (common name)	OLI Band	Intercept	Slope	Observation
GREEN	SR_B3	-0.0016	0.9542	Adjustment applied
RED	SR_B4	-0.0022	0.9825	Adjustment applied
NIR	SR_B5	-0.0021	1.0073	Adjustment applied
SWIR1	SR_B6	—	—	No adjustment required

In the second phase, the NDVI, NDWI, and NDMI spectral indices were calculated (combinations NIR-RED, GREEN-NIR, and NIR-SWIR1, respectively), used jointly to characterize vegetative vigor, surface moisture, and water stress (Chavez et al., 2019; Alemayehu et al., 2023).

Table 2 shows the reclassification of the spectral indices, developed from EOS Data Analytics:

Table 2. Reclassification of spectral indices to assess: vegetative vigor, surface moisture, and water stress

Spectral Index	Original values	Reclassification	Classification
NDVI	≤ 0	0	No vegetation
	> 0 and < 0.2	1	Sparse vegetation
	≥ 0.2 and < 0.6	2	Moderate vegetation
	≥ 0.6	3	Dense vegetation
NDWI	< -0.1	0	No water presence
	≥ -0.1 and < 0.2	1	Low water presence (flooding, moisture)
	≥ 0.2	2	Water surface
NDMI	< -0.2	0	No water content
	≥ -0.2 and < 0.2	1	High water stress
	≥ 0.2 and < 0.4	2	Low water stress
	≥ 0.4	3	No water stress

The indices were aggregated into monthly median composites and multi-year series for each ecosystem, ensuring spatiotemporal comparability between both sites. Statistical measures of central tendency and dispersion (mean, median, standard deviation, and coefficient of variation) were applied to these series, aimed at identifying hydro-vegetational anomalies and critical episodes linked to regional droughts.

The third phase integrated the spectral patterns with monthly climatic records of precipitation, temperature, and evapotranspiration, with the aim of evaluating coherences, divergences, and possible lags between climatic variability and ecosystem response (Anderson et al., 2021). This comparative approach, based on robust metrics (e.g., sign concordance and changes in mean and coefficient of variation), made it possible to consolidate a reference methodological framework for understanding and interpreting the hydro-vegetational dynamics of the Miscanti Lagoon and the Pujsa Salt Flat, as well as their sensitivity to climatic forcings in the Altiplano (Chavez et al., 2019; Anderson et al., 2021; Alemayehu et al., 2023; Espinosa et al., 2011; Roy et al., 2016). The climatic information used in the analysis corresponds to monthly time series of precipitation, temperature, and evapotranspiration for the period 1994–2024. These data were obtained from the Center for Climate and Resilience Science (CR2), through the CAMELS-CL platform, specifically from the Cuenca 2510001 – Río San Pedro, Cuchabrachi meteorological station.

3. RESULTS AND DISCUSSION

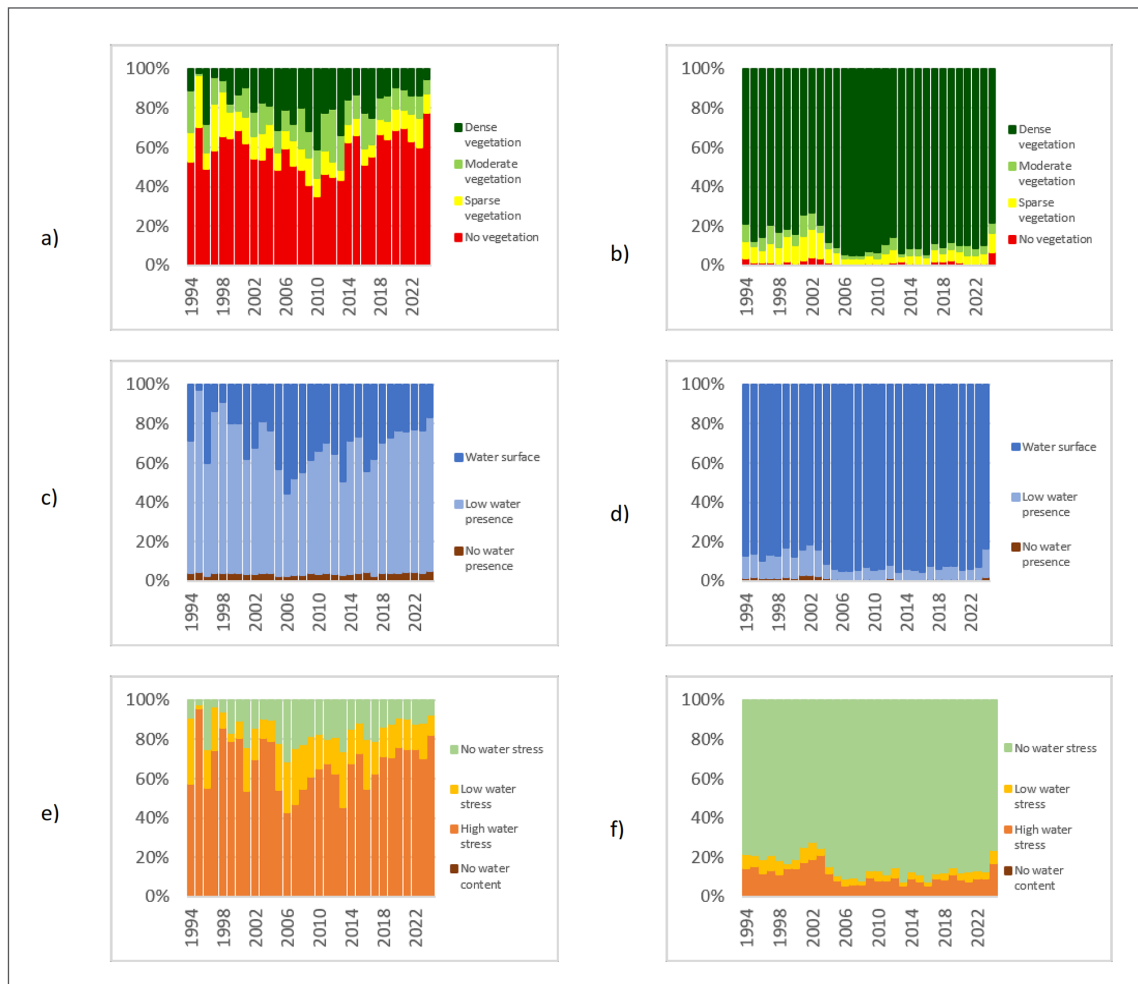
The analysis of the Landsat series (1994–2024), following preprocessing and radiometric harmonization, evidenced contrasting hydro-vegetational transformations between the Miscanti Lagoon and the Pujsa Salt Flat. The spectral indices revealed significant variations in both vegetation cover and surface moisture, reflecting differentiated trajectories of ecosystem vulnerability. NDVI showed a progressive decrease in moderate and dense vegetation sectors, particularly around the Miscanti Lagoon (Figure 1a), where the NDVI annual mean remained close to 0.0 and the maximum value only reached 0.023. The proportion of dense vegetation exhibited marked interannual fluctuations, with comparable values between the beginning and the end of the series; nevertheless, the multi-year statistical treatment (Table 3) showed a reduction in the mean and median NDVI (data not presented) together with an increase in the coefficient of variation, which indicates a net long-term deterioration of vegetative vigor, rather than a year-to-year linear decline as reported by Anderson et al., (2021). In contrast, the Pujsa Salt Flat showed greater interannual variability, with occasional episodes of increase in low-cover areas (Figure 1b), which confirms its high sensitivity to extreme climatic conditions.

Table 3. Coefficient of variation by index and by season

Site	Season	NDVI	NDMI	NDWI
Miscanti Lagoon	Wet	0.285	0.131	0.116
	Dry	0.326	0.510	0.456
Pujsa Salt Flat	Wet	0.284	0.107	0.525
	Dry	0.187	0.255	1.717

Convergently, the NDWI showed a differentiated dynamic between the two wetlands (Figure 1c–d). In Miscanti, the area with water increased until 2007, and then steadily declined until the end of the period. In Pujsa, on the other hand, this proportion remained stable and high, with a decrease only around 2022–2024, when the NDWI reached values below 0.01. In turn, NDMI showed a progressive increase in values associated with water stress (Figure 1e–f), with a more marked trend of ecohydrological degradation in the Miscanti Lagoon, where “high water stress” categories predominated (70% of the surface; see Figure 1e). The joint interpretation of the three indices showed an oscillatory pattern, associated with recurrent drought episodes (2007, 2013, 2019, and 2023), embedded within a net multi-year trend of reduced vegetation productivity and greater exposure to water deficit, which reinforces the hypothesis of increasing vulnerability in these high-Andean ecosystems.

Figure 1. Multitemporal evolution (1994–2024) of the spectral indices: a) NDVI in the Miscanti Lagoon, b) NDVI in the Pujsa Salt Flat, c) NDWI in the Miscanti Lagoon, d) NDWI in the Pujsa Salt Flat, e) NDMI in the Miscanti Lagoon, f) NDMI in the Pujsa Salt Flat



The statistical treatment of the time series corroborated these trends. The mean and median of NDVI, NDMI, and NDWI decreased over the last fifteen years, while the standard deviation and coefficient of variation increased, reflecting growing instability in vegetation response and hydrological dynamics. In Miscanti, NDMI showed intra-seasonal hydrological instability during dry periods ($CV = 0.510$), while in Pujsa, NDWI recorded the greatest variability ($CV = 1.717$), reflecting strong surface water fluctuations. These fluctuations correspond to anomalies detected in critical drought years (2007, 2013, 2019, and 2023), confirming the capacity of spectral indices to capture the incidence of regional climatic events (Squeo et al., 2006).

Integration with climatic records reinforced these interpretations. The decrease in NDVI and NDWI coincided with sustained reductions in precipitation and increases in mean temperature, in parallel with an intensification of potential evapotranspiration. In Miscanti, vegetation dynamics showed greater dependence on thermal factors, evidenced by the positive correlation of NDVI with temperature ($r = 0.69$) and accumulated evapotranspiration ($r = 0.60$), while the relationship with precipitation was weak ($r = 0.16$). In Pujsa, by contrast, vegetation responded mainly to water availability, with NDVI significantly correlated with accumulated precipitation ($r = 0.60$).

This coherence between spectral patterns and climatic forcings suggests that the observed degradation responds mainly to large-scale climatic variability, with a marginal influence of internal ecosystem processes. However, in the Pujsa Salt Flat, exceptions were identified, where occasional NDVI increases in seasonal intervals did not correspond to climatic improvements, suggesting the presence of differentiated resilience mechanisms associated with halophytic vegetation and specific ecohydrological dynamics.

4. CONCLUSIONS

- Satellite processing and the combined application of the NDVI, NDWI, and NDMI indices allowed for the precise characterization of the net decline in vegetative vigor, the decrease in surface moisture, and the increase in water stress in both wetlands, within the context of marked interannual variability. Miscanti Lagoon exhibited the most sustained decline, while the Pujsa Salt Flat showed greater interannual variability along with relative stability.
- The statistical analysis, integrated with climatic variables, evidenced the high sensitivity of these ecosystems to decreased precipitation and increased temperature, corroborating consistent patterns of hydrological and ecological deterioration throughout the study period.
- Taken together, the results obtained highlight the relevance of combining spectral metrics with climatic information to interpret ecosystem responses and anticipate vulnerability scenarios. This approach constitutes a solid scientific basis for strengthening management, conservation, and sustainable planning strategies for high-Andean wetlands in the face of increasing anthropogenic pressure and the impacts of climate change.

5. ACKNOWLEDGMENTS

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