Extreme Environments of Latin America: Natural Laboratories for Astrobiology

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Abstract

Extreme environments are places where sustaining life is considered challenging by human standards due to harmful environmental conditions. In the last decades, these kinds of environments have awakened the interest of planetary scientists due to their similar conditions to extraplanetary bodies. Most of the research done in extreme environments has been conducted in the North American and Eurasian regions, while in Latin America only the most outstanding places have been explored, even though the region hosts numerous and varied extreme environments. The primary aim of this review is to present an extensive catalogue of around 300 extreme environments in Latin America. We classify them into deserts and semi-arid environments, geothermal and hydrothermal environments, glaciers and high mountain environments, and hypersaline environments. Our review found that a great number of those environments remain unexplored or partially studied; however, many of those environments show multi-extreme features, becoming suitable to conduct astrobiology experiments such as biosignatures detection or planetary analogue missions. This review brings to current and future researchers a summary of the environmental properties of each place and their respective locations, to promote astrobiology and planetary science research in Latin America.

Keywords: Latin America, Extreme Environments, Astrobiology, Microbiology, Extremophiles, Planetary Analogs

1 Introduction

Extreme environments are defined as habitats where the persistence of life is considered difficult from a human perspective. In some cases, it is even considered impossible due to the combination of several hazardous conditions such as high or low temperatures, extreme pH values, high pressure, dry conditions, and high levels of solar radiation. The biological diversity on Earth manifests itself not only in environments usually considered optimal, but also in places that are inhospitable for most living beings Rampelotto (2013), Shu & Huang (2021).

In addition, these locations are the result of complex interactions between geology, climate, geography, and biological activity, and are somehow difficult to find on our planet. Extreme environments are highly sought after by planetary scientists, since they are valuable scenarios to research the behavior of life in possible planetary settings.

These studies usually involve extremophiles, resilient beings that have captured the attention of scientists and explorers since they have developed remarkable adaptations to survive and, in many cases, thrive in environments that challenge the limits of what is considered possible. The study of extreme environments and their extremophiles has proven extremely useful for medical, bioengineering, and food applications, since their adaptations can lead to several practical advantages Irwin (2020), Kochhar et al. (2022). However, probably their major role has been in the study of the limits of life Pikuta et al. (2007), Thombre et al. (2020), which is a key concept for astrobiology, the field of planetary sciences focused on the search for life outside our planet.

Since extremophiles are linked to their extreme environments, planetary scientists are interested in locations on Earth that in some way resemble natural settings that we could find on other planetary bodies. Even if a perfect match is not possible, similar conditions like temperature, pH, radiation, and pluviosity are helpful to understand how life could emerge or behave in another world.

Several researchers have conducted investigations in Earth environments considered extreme not only for human life but also for a great part of living beings, with the aim to test different ways to find extant life or simulate space exploration conditions. However, a good part of this research has been developed in North America, Europe, and Asia; only a lesser proportion has been carried out in Latin America or Africa Preston & Dartnell (2014), Shu & Huang (2021).

The absence of research in this region is not related to a lack of candidates. The vast landmass of South and Central America contains a diverse range of extreme environments and offers a unique setting for the exploration and study of extremophile organisms. Climatic extremes, geology, and unique conditions have shaped singular landscapes that host seemingly unusual forms of life.

From the glaciers of the Andes to the volcanic geysers of the valleys, through arid saline regions and hot springs, Latin America hosts a collection of ecological niches that challenge traditional conventions about where and how life can thrive. Nevertheless, this diversity of environments has been overlooked or poorly studied due to several reasons, such as difficult accessibility, safety conditions, and the lack of investment in basic and applied sciences.

This review highlights the diverse landscape of extreme environments across Latin America and the extremophile organisms that may inhabit them. It explores a wide range of unique and harsh ecosystems, from high-altitude regions and deep ocean trenches to areas of intense radiation, extreme temperatures, and hypersaline conditions, and identifies approximately 300 sites that have been studied to varying extents.

The document aims to serve as a valuable resource for future researchers interested in these environments, not only to advance astrobiology and planetary science, but also to foster bioprospecting efforts in fields such as biotechnology and industry.

In the following sections, we will explain some of the most notable extreme environments in Latin America separated into four principal categories: desert and semi-arid environments, geothermal and hydrothermal environments, high mountain environments and glaciers, and hypersaline environments. We examine the most prominent examples of these environments, the relevant extreme conditions they provide, the microorganisms that inhabit them, and their potential value for research in astrobiology and planetary sciences.

2 The Latin-American extreme environments Atlas

The result of our extensive research is presented in table 1. This compilation resumes the name, country, geographic location, type of environment, and relevant research done in that environment. Given the complexity of defining a location as extreme environment and the wide geodiversity of the continent, our selection contains a wide range of environments, varying in size, conservation, structure, and access. Desert environments can go from semi-arid regions with scarce vegetation to the most arid locations on the planet. Geothermal environments can range from volcanoes to submarine hydrothermal vents, high mountain systems and glaciers contain both isolated mountains and mountain ranges, and hypersaline environments go from brines to salt mines.

This matrix summarizes the physicochemical and environmental stressors present in various extreme environments across Latin America. The columns indicate the presence of specific stress conditions: high temperature (>45°C), low temperature (<15°C), acidity (pH < 6), alkalinity (pH > 8), high salinity, heavy metal presence, aridity, radiation exposure, and pressure anomalies. Each entry marks the presence of these factors in a given site. "N/A" is used where data is not available. The new version includes a final column for bibliographic references supporting the data reported.

Table 1: Summary of extreme environments in Latin America grouped by Kind of Environment.

Kind of Environment	**Local Site / Country**	**Radiation**	**Aridity**	**Temp (+)**	**Salinity (+)**	**Pressure (+)**	**Terrain**	**pH - Physicochemical**	**Temp (-)**
	La Payunia Desert / Argentina		X				X	N	
	El Chaco Desert / Argentina/Paraguay		X						
	Desierto Salvador Dalí / Bolivia		X				X		
	Dunas de Tajzara / Bolivia		X				X		X
	Caatinga Semi arid zone / Brazil		X						
	Desierto de Lençóis Maranhenses, Brasil / Brazil		X						
Arid Environments	Atacama desert / Chile	X	X		X		X	Al	
	semi-arid Coquimbo Region / Chile					X			
	La Candelaria desert / Colombia		X						
	La Guajira desert / Colombia		X			X	X		
	La Tatacoa desert / Colombia		X						
	Sabrinsky Desert / Colombia		X						
	El Oro Desert / Ecuador		X						
	Palmira desert / Ecuador		X			X			
	Santa Elena Desert / Ecuador		X						
	Arizona-Sonora desert / México		X			X	X		
	Dunas del Mogote, Baja California Sur / México		X				X		
	Sonora desert (Reserva de la Biófera Pinacate y Gran Desierto de Altar) / México		X				X	Al	
	Desierto De Ica / Perú		X						

	Desierto de Sechura / Perú		X						
	Nazca desert / Perú		X						
	Dunas de Cabo Polonio / Uruguay		X				X	N	
	Médanos de Coro / Venezuela		X				X		
	Andean Central Glaciers* / Argentina								X
	Andean Desert Glaciers* / Argentina								X
	Castaño Overo Glacier / Argentina								X
	Copahue geothermal field / Argentina			X			X	Ad	
	Llullaillaco volcano / Argentina	X					X	Ad	X
	Ojos de Salado volcano / Argentina	X	X				X	N	X
	Patagonian glaciers (North and south)* / Argentina	X							X
	Perito Moreno glacier / Argentina	X						Al	X
	Rio Manso glacier / Argentina	X							X
	Socompa Volcano / Argentina	X					X	Ad	X
	Termas Concordia / Argentina			X				N	
	Tierra del Fuego and South Atlantic Islands Glaciers* / Argentina								X
	Tocomar geothermal field / Argentina			X			X	Ad	
	Ojos de Salado volcano / Argentina/Chile	X	X	X				Al	X
	Camiri Hot springs / Bolivia			X					
	Charagua Hot springs / Bolivia			X					

	Sol de la mañana Geothermal field / Bolivia	X	X	X			X	Ad	X
	Uturuncu Volcano / Bolivia	X	X				X		X
	Agua Viva Thermas / Brazil			X				Al	
	Caldas Novas Thermal Complex / Brazil			X				Al	
	Chapada dos Veadeiros geothermal reservoir / Brazil			X				N	
	Grandes Lagos Thermas / Brazil			X				Al	
	Hidrothermal vents Campos Basin / Brazil			X		X	X		
	SESC Thermas / Brazil			X				Al	
	Solar das Águas Quentes / Brazil			X				Al	
	Termas São João / Brazil			X				Al	
	geothermal field of the Santos Basin / Brazil			X		X	X		
	Água do Palmito / Brazil			X				Al	
	El Tatio, hot springs and geysers / Chile			X			X	N	
	Tinguiririca Geothermal Area / Chile			X			X		
	Tolhuaca geothermal field / Chile			X			X		
	Cerro Machin volcano / Colombia			X					
	El Azufral volcano / Colombia			X					
	Paipa hot springs / Colombia			X				N	
	Purace volcano / Colombia			X		X	X		
	Margen Continental / Costa Rica								X
	Miravalles volcano / Costa Rica			X				N, HM	
	Poás volcano / Costa Rica			X		X	X	Ad, HM	

	Rincon la vieja volcano / Costa Rica			X		X	X	N, HM	
	Balneario Elguea / Cuba	X		X					
	Boiling Lake and Valley of Desolation / Dominica			X					
	Baños-Cuenca hot springs / Ecuador			X					
	Cachiyacu hot springs / Ecuador			X					
	Chachimbiro volcano / Ecuador			X			X		
	Cotopaxi hot spring / Ecuador			X		X		N, HM	
	Cununyacu hot springs / Ecuador			X				N	
	El Carchi hot springs / Ecuador			X				N, HM	
	El salado hot springs / Ecuador			X					
	El tambo hot springs / Ecuador			X					
	Ilalo hot springs / Ecuador			X					
	Imbabura hotspring / Ecuador			X				N, HM	
	Jamanco hot springs / Ecuador			X					
	La virgen hot springs / Ecuador			X					
	Nangulvi hot springs / Ecuador			X					
	Palictahua hot springs / Ecuador			X					
	Papallacta hot springs / Ecuador			X				N, HM	
	Pitzantzi volcano / Ecuador			X			X		
	Santa Ana hot springs / Ecuador			X		X			
	Tingo hot springs / Ecuador			X					

	Tungurahua volcano / Ecuador			X				N, HM	
	Ahuachapan geothermal field / El Salvador			X				N, HM	
	Berlín geothermal field / El Salvador			X				N, HM	
	Coatepeque geothermal field / El Salvador			X				N, HM	
	Joaquina geothermal field / Guatemala			X				Al, HM	
	Moyuta geothermal field / Guatemala			X				N, HM	
	Tecuamburro Geothermal field / Guatemala			X				N, HM	
	Zunil geothermal field / Guatemala			X				N, HM	
	Eaux Boynes hot springs / Haiti			X					
	Los Pozos hot springs / Haiti			X					
	Azacualpa geothermal field / Honduras			X				HM	
	Pavana geothermal field / Honduras			X				HM	
	Platanares geothermal field / Honduras			X				Al, HM	
	Araró geothermal field / México			X				N, HM	
	Chignahuapan hot springs / México			X				N	
	Crater lake el Chichón / México			X				Ad, HM	
	Golfo de México hydrothermal vents / México			X		X	X		
	Guerrero negro hot springs / México			X					
	Los Azufres, Michoacán / México			X				Ad, HM	

	Los Geiseres geothermal field / México			X				Al, HM	
	Los Hervideros hot springs / México			X		X		N	
	Mapachitos hot springs / México			X		X			
	Paricutin volcano / México			X				N, HM	
	Playa Agua Caliente hot springs / México			X					
	Santispachot springs / México			X					
	cuenca de Guaymas hydrothermal vents, Sonora / México			X			X		
	Momotombo geothermal field / Nicaragua			X				Al, HM	
	Monte Galan geothermal field / Nicaragua			X		X		N, HM	
	Telica's Hervidores de San Jacinto / Nicaragua			X				Ad	
	Pozos de Calobre hot springs / Panamá			X					
	Aguas Calientes La Raya / Perú			X				N	
	Aguas Calientes geothermal spring / Perú			X				Ad	
	Aguas Calientes-Pinaya / Perú			X				N	
	Aguas termales Crucero / Perú			X				Ad	
	Ancocollo geothermal zone / Perú			X				N, HM	
	Aquilina hot springs / Perú			X					
	Aruma hot springs / Perú			X				Ad	
	Barroso hot springs / Perú			X				N	
	Baños Pacchanta / Perú			X				Ad	
	Baños Termales Collpa Apacheta / Perú			X				Ad	

	Baños de Upis / Perú			X				N	
	Baños termales Lares / Perú			X				Ad	
	Borateras geothermal zone / Perú			X				N, HM	
	Calientes river geothermal zone / Perú			X			X	N, HM	
	Chancos hot springs / Perú			X					
	El Tragadero (Baños del Inca) hot springs / Perú			X				N, HM	
	Geisers hot springs / Perú			X				Ad	
	Huancarhuaz hot spring / Perú			X				N	
	Kallapuma-Chungara hydrothermal systems / Perú			X				N, HM	
	La Calera hot spring (Colca Canyon) / Perú			X					
	Monterrey hot springs / Perú			X					
	Olleros hot springs / Perú			X					
	Quilcate (San Miguel) hot springs / Perú			X				N, HM	
	Tarapoto hot springs / Perú			X					
	The Boiling River / Perú			X					
	Ticaco hot springs / Perú			X				N	
	Tutupaca geothermal zone / Perú			X				Ad, HM	
	Coamo thermal spring / Puerto Rico			X				Al	
	Puerto Rico Trench / Puerto Rico			X		X	X		
	Soufriere Sulphur Springs / Saint Lucia			X					
	Almirón Hot Springs / Uruguay			X				N	
	Arapey Hot Springs / Uruguay			X				Al	
	Daymán Hot Springs / Uruguay			X				Al	

	Guaviyu Hot Springs / Uruguay			X				Al	
	Termas de Salto Grande / Uruguay			X				Al	
	Las trincheras hot springs / Venezuela			X				N	
	Río Aguas Calientes / Venezuela			X				Al	
	Cerro Chajnantor / Bolivia	X	X				X	N	X
	Chacaltaya Glacier / Bolivia								X
	Condoriri Glacier / Bolivia	X	X				X		X
	Cordillera Quimsa Cruz / Bolivia						X		X
	Eduardo Avaroa National reserve / Bolivia	X	X				X		X
	Nevado Ancohuma / Bolivia						X		X
	Nevado Charquini / Bolivia						X		X
	Nevado Cololo / Bolivia						X		X
	Nevado Illampu / Bolivia						X		X
	Nevado Illimani / Bolivia	X	X				X		X
	Nevado Mururata / Bolivia						X		X
	Sajama national Park / Bolivia	X	X	X	X		X		X
	Zongo Glacier / Bolivia						X		X
	Licancabur Volcano / Bolivia/Chile	X							X
	Cerro sillajhuay / Chile						X		X
	Chajnantor volcano / Chile	X					X	N	X
	Chilean Glaciers Austral Zone* / Chile								X
	Chilean Glaciers Central Zone* / Chile								X
	Chilean Glaciers North Zone* / Chile								X
	Chilean Glaciers South Zone* / Chile								X
	Exploradores glacier / Chile	X						Al	X
	Guallatiri glacier / Chile	X					X		X

Glacier and high mountain environments

	Iver glacier / Chile	X					X	Al	X
	Morado glacier / Chile	X					X	Al	X
	Nevado Parinacota / Chile	X					X		X
	Nevado Queulat / Chile								X
	Nevado de las Tres Cruces / Chile						X		X
	Pomerape Glacier / Chile	X					X		X
	Los Nevados National Park / Colombia			X		X	X	Ad	X
	Nevado del Cocuy National Park / Colombia					X	X		X
	Nevado del Huila Volcano / Colombia			X		X	X		X
	Sierra Nevada de Santa Marta / Colombia					X	X		X
	Chirripó National Park / Costa Rica								X
	Altar Glacier / Ecuador					X	X		
	Antisana glacier / Ecuador						X		X
	Cayambe volcanic complex / Ecuador	X				X		N	X
	Chimborazo volcano / Ecuador			X					
	Chimborazo volcano / Ecuador								
	Cotopaxi Glacier / Ecuador						X		
	Sangay Glacier / Ecuador					X			
	Tunguragua / Ecuador								
	Cuchumatanes mountains / Guatemala								X
	Tajumulco volcano / Guatemala								X
	Cerro La Negra, Sierra negra, Puebla / México						X		X
	Citlaltépetl / México								X
	Iztacíhuatl / México							N	X
	La Malinche / México					X			X
	Popocatépetl / México						X		X

	Volcán Cofre de Perote / México								X
	Cordillera Apolobamba region / Perú						X		X
	Cordillera Blanca region / Perú						X		X
	Cordillera Carabaya region / Perú						X		X
	Cordillera Huaytapallana region / Perú						X		X
	Cordillera Vilcanota region / Perú						X		X
	Huascarán National Park / Perú						X	Ad, HM	X
	Huaytrire Wetland / Perú							N	X
	Nevado Coropuna / Perú						X		X
	Nevado Hualcán / Perú						X		X
	Nevado Tuco / Perú						X		X
	Yanamarey Glacier / Perú						X		X
	Sierra La culata / Venezuela								X
	Sierra Nevada National Park / Venezuela								X
	Sierra de Santo Domingo / Venezuela								X
	Laguna Diamante / Argentina				X			Al, HM	
	Laguna Negra / Argentina				X			Ad, HM	
	Laguna Socompa / Argentina				X			Al, HM	
	Laguna Verde / Argentina				X			N, HM	
	Laguna Vilama / Argentina				X			N, HM	
	Ojo de Mar Tolar Grande / Argentina				X		X	N, HM	
	Ojos de Campo Antofalla / Argentina				X			Al	
	Salar Llullaillaco / Argentina				X			Al	
	Salar Pocitos / Argentina				X		X	Al	

	Salar Santa Maria / Argentina				X		X	Al	
	Salar de Antofalla / Argentina	X			X		X	N	
	Salina Grande / Argentina				X		X	Al	
	The Mar Chiquita Salt Lake / Argentina				X			N	
	Laguna Blanca / Bolivia	X	X		X			N	
	Laguna Cañapa / Bolivia				X				
	Laguna Chiarkota / Bolivia				X				
	Laguna Collpa / Bolivia				X				
	Laguna Crater / Bolivia				X				
	Laguna Hedionda / Bolivia	X	X		X				X
	Laguna Honda / Bolivia				X				
	Laguna Verde / Bolivia	X	X		X			Al	
	Salar de Capina / Bolivia				X		X		
	Salar de Chalviri / Bolivia				X		X		
	Salar de Chiguana / Bolivia				X		X		
	Salar de Coipasa / Bolivia	X	X				X		X
	Salar de Empexa / Bolivia				X		X		
	Salar de Laguani / Bolivia				X		X		
	Salar de Uyuni / Bolivia	X	X		X		X	N	
	Pantanal lake / Brazil				X			Al	
	lagoon system of Araruama / Brazil				X				
	Burro Muerto Lake / Chile				X			N, HM	X
	Cejar Lake / Chile				X			N, HM	
	Cisnes lagoon / Chile				X				
	Laguna Amarga / Chile				X			Al	
	Laguna Lejía / Chile	X			X			Al	
	Laguna Tebenquiche / Chile	X			X			N	
	Laguna de la Piedra / Chile				X			N	
	Laguna de la Sal / Chile				X				
	Salar de Aguas Calientes / Chile	X			X	X	X	N	
	Salar de Atacama / Chile				X	X	X		
	Salar de Huasco / Chile	X			X	X	X		

	Salar de Llamará / Chile				X	X	X		
	Salar de Surire / Chile				X	X	X		
	Manaure Solar Saltern / Colombia				X			N	
	Zipaquirá Salt mine / Colombia				X			N	
	Las salinas de la Puntilla / Ecuador				X				
	Salinas de Bolivar / Ecuador				X				
	Salinas de Mira / Ecuador				X				
	Salinas de Tomabela / Ecuador				X				
	Salinas del Morro / Ecuador				X				
	Salinas el Potrero / El Salvador				X			N	
	Salinas de los Nueve Cerros / Guatemala				X				
	Salinas Bahia de San Lorenzo / Honduras				X				
	Campo La Salina, Sonora / México				X	X	X		
	El Salar, Mexicali / México				X		X		
	Guerrero Negro / México				X			N	
	Laguna Salada, Baja California / México				X				
	Laguna de Chichancanab, Quintana Roo / México				X			Al	
	Salinas de Aguadulce / Panamá				X				
	Laguna Salada, Chaco Lodge / Paraguay				X				
	Laguna de Salinas / Perú				X			Al	
	Salineras de Maras, Perú / Perú				X				
	Cabo Rojo Solar Salterns / Puerto Rico				X				
	Salina de Pampatar / Venezuela					X			

	Salinas de Araya / Venezuela					X			

Table 1 also contains a list of the extreme environmental conditions that these locations host. When information was available, we defined if each environment is under a condition that could serve as a planetary analogue, and considered the following variables: high radiation, extreme temperatures, high salinity, high pressure, extreme pH values, and resemblance to an extraterrestrial terrain. These characteristics are only an approximation to what these locations have to offer, since each one of them has specific physicochemical conditions that can be useful for different objectives.

We want this compilation to be a starting point for researchers interested in analogue studies in Latin America. Given the continent's vast size and the limited amount of research available on the topic, it is highly probable that some potential locations have not yet been identified, and certain classifications may be subject to revision as more accurate data becomes available.

3 Extreme environments in Latin America

3.1 Deserts and semi-arid environments

Desert biomes are arid regions that cover one fifth of the total surface of the Earth, usually located at middle latitudes where the atmospheric pressure is high, and thus the amount of precipitation is low. In desert environments, low rainfall, intense doses of radiation, extreme temperatures, and low humidity are common conditions (Gargaud 2011). They can be categorized in terms of their temperature and aridity, in that way, hot, cold, and polar deserts are differentiated (Peel et al. 2007). Deserts can also be defined as tropical sub-humid, semi-arid, arid, or hyper-arid depending on the level of moisture and precipitation deficit in the system Middleton & Thomas (1992). Given the dry nature of most of the planetary bodies in our Solar System, deserts are excellent analogues for astrobiological purposes.

Latin America hosts a variety of deserts and dunes fields, the best-known ones are probably the Atacama Desert in Chile, the Sonora Desert in Mexico, and the Patagonia Desert in Argentina. Nevertheless, almost every country in Latin America hosts deserts, expanding the possibilities to do research on the continent. Some of them are cold deserts, like the Siloli Desert in Bolivia, which being at 5000 m.a.s.l. has an average temperature of 3°C and an average annual rainfall of 65 mm. Other ones are hot, like the Chihuahua desert in Mexico, which can reach temperatures of 45°C in the summer, and has an average annual precipitation of 430 mm Quiroz-Jiménez et al. (2018). A list with all the deserts and their characteristics can be found in Table 1. In addition to the examples mentioned above, most of these environments have little associated published research, and some of them have not been studied at all.

3.1.1 Microbiology research in arid and semi-arid deserts

Nowadays one of the most studied deserts is Atacama (centered 25.1° S, 68.6° W), the oldest and driest non-polar desert on Earth. Microbiology exploration is relatively recent but both fundamental and applied research activities have grown dramatically in recent years Bull et al. (2018). Researchers are focused on its microbiome, ecology, biogeochemistry, natural product potential and Mars-analogue properties Azua-Bustos et al. (2022), Azua-Bustos & González-Silva (2014), Gómez-Silva & Batista-García (2022), Shen et al. (2021), Vítek et al. (2016), Wierzchos et al. (2012).

For instance, Azua-Bustos & González-Silva (2014) record how the finding of *Dunaliella*, a genus of halophilic organisms, could be used for biotechnological with astrobiological purposes.

Other studies have been performed in Colombian deserts. Tatacoa Desert (Fig. 1, B) (3.3° S, 75° W) is one of the most attractive to conduct future astrobiological and Mars analog experiments due to geological, climatological conditions and easy access (Ojeda et al. 2017). However, the microbiology research in this place is still poor and more related to microorganisms' isolation (Bolívar-Torres et al. 2021). This study showed a high presence of *Actinobacteriota*, a typical group in this kind of environments.

Another notable example is La Guajira desert (Fig. 1, A and E), located in northern Colombia (11° N, 71.5° W), which covers an area of 20,848 km^2. This region experiences a range of climatic conditions. Average temperatures fluctuate between 27°C and 30°C, with maximums reaching up to 45°C. The predominant climates include xerophytic savanna in the south and west, and arid or semi-arid steppe in the north and east Chamorro et al. (2015). Leal et al. (2024) conducted a study of microbial communities in islands of fertility, and found a presence of *Actinobacteriota* and *Proteobacteria* phyla, and relevant genera considered dry bioindicators such as *Massilia*, *Herbaspirillum*, and *Altererythrobacter*.

Other potential location in Colombia is the Villa de Leyva region (Fig. 1, C) (5.7° N, 73.5° W). Corzo-Acosta & Corzo (2022) studied endolithic microorganisms from quartz, K-feldspar, and calcite, testing their growth in mineral-enriched media under varying physicochemical conditions. Using Multiple Factorial Analysis, they found that microbial pigmentation may be linked to tolerance to alkaline conditions, and that Gram-negative rod-shape bacteria shows greater adaptability to enriched minimal media. Additionally, ongoing research is focused on detecting endolithic pigments in gypsum using Raman spectroscopy, SEM, and optical microscopy to characterize the phototrophic endolithic communities.

In Mexico, the Sonoran Desert (Fig. 1D) (29.4° N, 115° W) is one of the driest and hottest environments, and it harbors an active dune field, the largest in North America. Information from regional weather stations indicates that summer temperatures can reach 48° C. In 2021, a study published by the *Bulletin of the American Meteorological Society* revealed that the land surface temperature detected at the Sonoran Desert was 80.8° C, which was 10° C higher than the previous world record observed in 2005 Zhao et al. (2021). In addition, there is El Campo La Salina, an extensive salt flat. Recent exploration studies have been carried out in this reserve showing a high biodiversity of microorganisms such as fungi Esqueda et al. (2013), bacteria, and archaea Guo-Chun & Piceno (2013), Rainey et al. (2005), Ramos-Madrigal et al. (2024).

In Brazil, there exist a couple of environments with microbial research; the most relevant is the Caatinga semi-arid zone ($7° \text{ S}, 40° \text{ W}$), where several studies have been conducted related to the isolation and prospection of Cyanobacteria species. Moreover, several studies have been carried out to isolate Plant Growth Promoting Bacteria Bonatelli et al. (2021), Genuário et al. (2018). Another example is the Lençóis Maranhenses National Park, in northeast Brazil ($2.1° \text{ S}, 43.1° \text{ W}$). This desert is characterized by white sand dunes and freshwater lagoons. It has a dry subhumid climate. Due to the aridity, temperature, and radiation conditions of this site, coupled with the presence of freshwater lagoons that form between the sand dunes, it would be an excellent site to study the changes in microbial communities associated with the rainy and dry seasons in this desert. Despite its potential, there are no studies about the biological properties in this region, which could be rich in microorganisms, microalgae, or cyanobacteria, and that could have value in astrobiology.

In summary, the previously mentioned places in this section represent only a small portion of the possibilities for microbial research in Latin America. The information gathered in Table 1 shows the wide number of arid places that exist from the north of Mexico to the south of the American continent. There are several places in Ecuador, Peru, Venezuela, and Bolivia that remain unexplored and could be ideal for encouraging microbiological studies of arid environments and promoting astrobiological research.

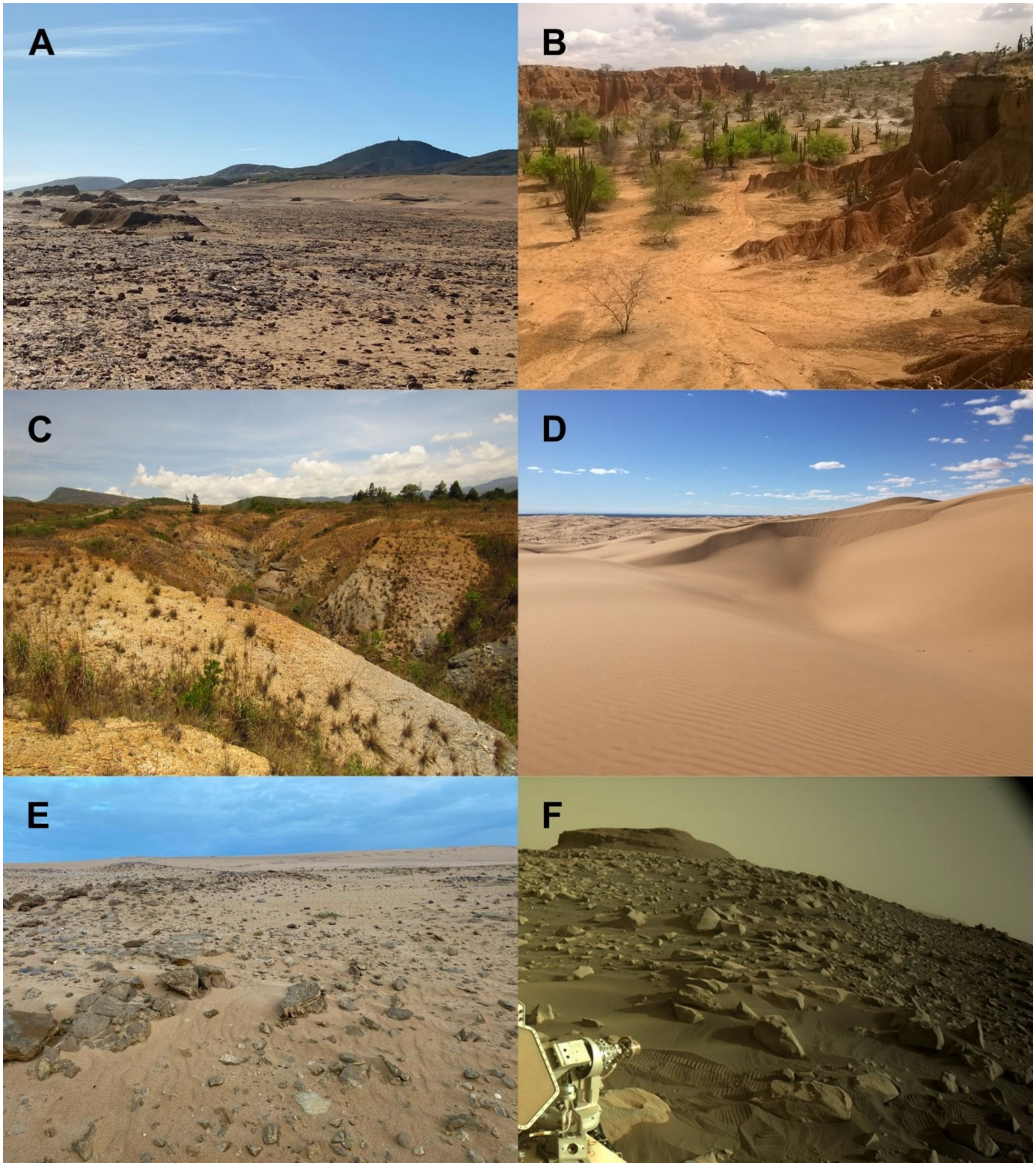

Figure 1: Some deserts and semi-arid environments in Latin America. (A) La Guajira Desert, Colombia. (B) La Tatacoa Desert, Colombia. (C) Gypsum Outcrop in Villa de Leyva. (D) The Pinacate and Gran Desierto de Altar Biosphere Reserve, Mexico. (E) Landscape view from La Guajira, Colombia. (F) Ancient Jezero crater of Mars.

3.2 Geothermal and hydrothermal environments

Geothermal and hydrothermal environments are typically characterized by high temperatures and extreme pH conditions (either acidic or alkaline). Many of these environments also present additional stress factors, such as high concentrations of heavy metals and toxic compounds. These kind of environments are strongly related to the early stages of Earth, and according to several authors, it is possible that life emerged in both hydrothermal vents and geothermal environments (Damer & Deamer 2020, Deamer et al. 2019, Longo & Damer 2020, Matsuno & Imai 2023).

These environments are found in various regions across the globe, particularly in areas with intense geological activity. This activity plays a key role in shaping features such as steam vents, geysers, hot springs, and solfataras on land, as well as hydrothermal vents and submarine volcanoes in the deep ocean. In Latin America, the formation of the Andes Cordillera and the presence of numerous volcanoes greatly influence the occurrence of geothermal manifestations. For this reason, we found a great amount of different geothermal parks along the Andes mountains from Colombia to Chile, existence of volcanoes in central America and geothermal manifestations into the Trans Mexican Volcanic Belt (TMVB) bringing the essential conditions to hot springs, geysers, steam vents and solfataras formation in this Latin American region.

Geothermal environments are arguably the most extensively studied type of extreme environment in Latin America. This trend is driven by several factors. Primarily, the increasing interest in geothermal energy exploration and exploitation has spurred research across numerous geothermal systems in the region. Additionally, we identified a significant number of studies on microbial communities inhabiting geothermal areas in nearly every Latin American country where such environments occur. This topic will be explored further in the following section. While our main focus is microbial research, it is important to note that many of the reviewed studies also highlight interest in geothermal energy development and tourism (see Table 1).

3.2.1 Microbiology research in geothermal and hydrothermal environments

The most extensively studied geothermal environments in Latin America, in terms of microbiological research, include the Los Azufres geothermal field in Mexico, the Copahue geothermal field in Argentina, the Miravalles and Poás volcanoes in Costa Rica, the Paipa hot springs and Los Nevados National Park in Colombia, El Tatio in Chile, the hot springs of the Cordillera Blanca, and the Aguas Calientes plateau in Peru (see Table 1). Research activities at these sites span a wide range of objectives, from descriptive microbial ecology to bioprospecting, with a smaller number of studies focused on astrobiology and planetary sciences.

Los Azufres geothermal field in Mexico (Fig 2A) (19.8° N, 100.6° W) has wide research in microbial exploration of Bacteria, Archaea and viral communities. The findings from these studies have contributed to the reclassification of the order Sulfolobales, driven by the discovery of new *Parvarchaeota* and *Thermoproteota* (formerly *Crenarchaeota*) lineages. In addition, the findings of archaeal viruses from Fusellovirus genus show complex interactions inside the microbial communities in thermal conditions. Regarding Bacteria communities, the research in Los Azufres shows the presence of typical genera from geothermal zones such as *Leptospirillum*, *Ferrimicrobium*, *Acidithiobacillus*, and novelty genus such as *Acidibrevibacterium* . (Bolivar-Torres et al. 2022, Chen et al. 2018, Marín-Paredes et al. 2021, 2023, Marín-Paredes & Servín-Garcidueñas 2020, Servín-Garcidueñas et al. 2013*a*,*b*, Servín-Garcidueñas & Martínez-Romero 2014, Brito et al. 2014).

The combination of multiple extreme conditions and diverse microbial communities makes Los Azufres and nearby geothermal sites, such as the Araró hot springs, well-suited for future astrobiology studies. In addition, Mexico hosts several geothermal sites that should be considered as promising prospects for astrobiology research. For example, the Chichón and Paricutín volcanoes (17.4° N, 93.2° W; and 19.4° N, 102.2° W) exhibit multiple extreme conditions similar to those found in Los Azufres. Studies at these sites have revealed a diverse range of microorganisms adapted to various stress factors, particularly the *Actinobacteria*, *Proteobacteria*, and *Firmicutes phyla*. (Medrano-Santillana et al. 2017, Peña-Ocaña et al. 2022, Velázquez-Ríos et al. 2022)

In Colombia, Los Nevados National Park (4.9° N, 75.3° W) is a major site for research on thermophiles and geothermal environments. Located in the Central Cordillera, this place shares glacier places and volcanic activity, and there are a wide number of hot springs, where several kinds of thermophiles have been isolated. For example, *Acididicaldus sp. Strain* isolated by (López et al. 2014). The same research group studied the thermophiles in this place and their possible biotechnological applications (Bohorquez et al. 2012, Delgado-Serrano et al. 2014). Also, in the eastern cordillera exist several geothermal places where the most studied are Paipa hot springs (See Fig 2A) (5.8° N, 73.1° W). The literature reported a variety of thermophiles from *Thermoanaerobacter*, *Desulfomicrobium*, *Anoxybacillus*, and *Caloranaerobacter* genera in this place (Posada et al. 2004, Rubiano-Labrador et al. 2019). In Peru, the Calientes river receives attention because of the flows of hot water (17.2° S, 70.1° W). This place has been studied as a possible source of geothermal energy (Barragán et al. 1999, Taillefer et al. 2024). Moreover, there are a couple of studies that report on the study of microbial communities and the insolation and characterization of thermophiles (Castellanos et al. 2024, Valdez et al. 2023).

Another interesting place is El Tatio geysers located in Andes altiplano in Chile (22.3° S, 68° W), several studies have been conducted and show the presence of a complex microbial community composed principally by *Proteobacteria*, *Cyanobacteria*, and *Chlroflexi phylum* (Megevand et al. 2022). Additionally, (Sanchez-Garcia et al. 2019) found a high abundance of *Actinobacteria*, *Acidobacteria*, and *Archaea*. The presence of Archaea was reported by (Plenge et al. 2017, Santos et al. 2021) as well. Some of the microorganisims that inhabit this place have been isolated successfully by (Valenzuela et al. 2023, 2024). Due to the combination of several extreme conditions and logistic access, El Tatio has been considered a good place to simulate Martian life detection experiments (Barbieri et al. 2014).

Even though we show some examples of studied geothermal places in Latin America, there are several geothermal places that remains unexplored or poorly studied in Ecuador, Brazil, Bolivia, Peru, El Salvador, Cuba, Guatemala, Haiti, Nicaragua, Paraguay, and Uruguay. The research is focused on potential geothermal energy exploration, tourism or medical treatments. However, we consider that those places show great potential to expand the research of microbial communities that probably inhabit those places.

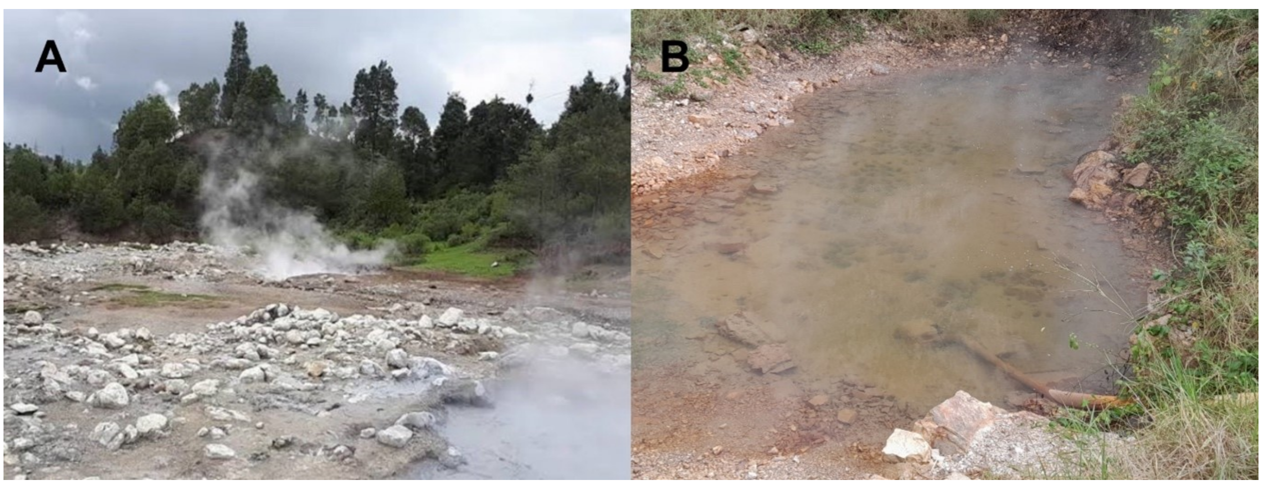

Figure 2: Some thermal environments in Latin America. A. Los Azufres geothermal field, Mexico. B. Paipa Hot Springs, Colombia. Source: Photos taken by Hermes H. Bolivar-Torres.

The existence of submarine hydrothermal vents in Latin America has been less explored. It is probable that their existence is being underestimated, since the extensional geological activity in the Galapagos rift, and the subduction of the Caribbean plate below the Atlantic plate likely results in the formation of hydrothermal vents. We only found articles that reported the existence of this kind of environment in Costa Rica (Wang et al. 2022), western Mexico, the Gulf of Mexico, Brazil, and the Caribbean Sea (See Table 1). Perhaps the most relevant hydrothermal vent studied in Latin America is Cuenca de Guaymas hydrothermal vent located in the Gulf of California (27° N, 111° W). Microbial research shows a great abundance of *Proteobacteria* and *Chloroflexi phylum* and the presence of *Bathyarcheota* and *Thermoplasmata* close to the core of the hydrothermal vents (Ramírez et al. 2021). In the Gulf of Mexico hydrothermal vents, (Merlino et al. 2018) report a microbial community composed by *Deltaproteobacteria*, sulfate-reducing bacteria, and methanogens. But in general, the research in those environments remains restricted to specific places. The lack of research in those areas could be due to the high cost to finance this kind of exploration, as well as the disinterest from the local scientific community to explore deep ocean environments.

3.2.2 Astrobiology research possibilities

The geothermal and hydrothermal environments described in this article represent promising new sites for the development of astrobiology and space exploration research. Particularly for planification and testing of biosignature detection, not only for currently existing life forms but also for ancient life. Places like Los Azufres, Central American volcanoes and hot springs and Calientes river could contribute to the research of primitive earth and the origin of life (Wang et al. 2022). On the other hand, sites with multiple extremophile conditions such as Los Nevados National Park and high-altitude geothermal areas in the Andes can serve as analogues for Mars, as has been proposed for the El Tatio Geysers (Barbieri et al. 2014, Megevand et al. 2022, Ruff & Farmer 2016). In addition, hydrothermal environments also serve as natural laboratories for the exploration of ancient life on Mars (Hays et al. 2017, Ruff et al. 2020), and for the study of the geological activity of outer solar system moons, such as Europa, Enceladus, and Io. This is a key aspect in the encouragement of astrobiology and space research in Latin America that could be extended for biotechnology, environmental, and industry applications. Finally, advancing geothermal and hydrothermal studies will prepare highly qualified professionals in the region through increased investments in scientific research.

3.3 High Mountain environments and glaciers

Low temperatures and high radiation levels are common features among solar system bodies. In Latin America, two types of environments exhibit cold conditions: high altitude mountains, which have freezing temperatures, and year-round glaciers located in the southernmost regions of the continent. High mountain systems also provide the advantage of being more exposed to UV radiation, as well as having a reduced amount of plant and animal life. Some of these locations are among the best planetary analogues, since they recreate both the landscapes and the environmental properties of extraterrestrial locations.

Latin America is home to several mountain ranges, mainly thanks to the subduction of the Cocos and Nazca plates below the South American and Caribbean plates (Flament et al. 2015). These subduction zones have been active for hundreds of millions of years, at least since the Jurassic period (Seton et al. 2012), resulting in large and elevated mountain ranges. The major structure among these is the Andean Mountain range, which spans almost 9000 km from Venezuela to Chile, and hosts many high mountains, like the Sajama or the Tolima volcanoes (Figure 3). From this main structure emerge smaller mountain ranges and massifs, like the Cordillera Madre in Peru or the Cordillera Central in Colombia. Many of these landforms surpass 4000 m in altitude, which makes them potential planetary analogues for cold locations. Others high mountains exist outside of the Andes, like the Sierra Madre in Mexico and volcanoes in Central America. Low temperatures can be also found south of the continent, in Tierra del Fuego and Patagonia; these locations have large glacier masses like the Perito Moreno glacier in Argentina.

3.3.1 Microbiology research in high mountain environments and glaciers

The temperatures of high mountain systems vary across the continent. In tropical latitudes like Colombia and Ecuador, mountains higher than 5000 m have average temperatures between –2 and 15 °C (Castaño et al. 2020), while places closer to the poles reach average temperatures between –25 and 2 °C (Kereszturi et al. 2022). Organisms that can grow within these temperature ranges are known as *psychrophiles*, and they include bacteria, lichens, fungi, and even some insects (Dasauni & Nailwal 2020). They usually have a stronger metabolic activity above 10 °C, but they can multiply at lower rates at temperatures as low as –20 °C (Feller 2017). *Psychrophiles* have special adaptations for these extreme environments, such as thicker cell walls, slower rates of oxidative metabolism, and the production of solutes that protect the cell against freezing and generate energy more efficiently (Irwin 2020). These organisms can grow in the substrate, inside rocks, or in the fluid phases inside ice.

Another important environmental constraint present in high mountain systems is an elevated amount of solar radiation. There is a direct correlation between altitude and the amount of high energy radiation that reaches the surface (Blumthaler & Ellinger 1997). This effect occurs because the atmosphere becomes thinner at higher altitudes, reducing the amount of UV rays that are absorbed by ozone and other atmospheric molecules. Many mountains in the Andes surpass 4500 m.a.s.l., which make them suitable analogs for high UV environments. UV radiation is especially damaging for microbial life by affecting RNA and DNA due to dimer formation, which interferes with cellular transcription and replication (Cutler

& Zimmerman 2011). Organisms that have adaptations to survive high levels of radiation are known as radiophiles; they can synthesize resistant proteins, but more importantly, they have the capacity to repair their DNA quickly and accurately (Basu & Apte 2011), reducing the potential lethal damage of high radiation.

The extreme temperatures and radiation levels of high mountain systems are often accompanied by other interesting characteristics such as low rainfall, absence of vegetation, and plenty of volcanic rocks and volcanic landforms. The combination of these features results in scenarios that are similar to planetary environments, especially Martian ones. The best example is the Atacama Desert in Chile, which is the driest non-polar place on Earth, while being 3500 m.a.s.l. (Pfeiffer et al. 2021). Nevertheless, several less known locations in Latin America also share these properties; places like the Eduardo Abaroa National Reserve in Bolivia or the national parks in the Argentinian Andes are excellent locations for analogue studies.

A good example of a high mountain environment is the Ojos del Salado Volcano (27º S, 68.2º W), located in the Dry Andes Mountain range, in Argentina. It is an inactive stratovolcano with a summit at 6893 m.a.s.l., which makes it the highest volcano on Earth. This site brings together conditions such as strong UV radiation, the presence of permafrost, ephemeral snow, hot springs, volcanic alluviums, and dissected lacustrine floors eroded by strong icy winds Ákos Kereszturi et al. (2020). The combination of these features creates a setting that is close to what we observe in the Tharsis region on Mars Aszalós et al. (2020*a*). The analysis of sediments around the summit and inside fumarolic streams revealed the existence of several genera of extremophilic and even *polyextremophilic bacteria*. Aszalós et al. (2020*a*) found *psychrophilic*, *acidophilic*, and *thermophilic bacteria* adapted to low temperatures, acidic pH values, and a low nutrient medium. Also, eleven genera of *psychrophilic* and *oligocarbophilic bacteria* were identified both in the permafrost and in a pond located at 5900 m.a.s.l. (Aszalós et al. 2020*b*).

In the tropical Andes (Colombia, Peru, Ecuador, and Venezuela), most of the mountain ranges and their associated environments are also volcanic in origin. An example of a high-altitude environment that is not associated with volcanism is the Cordillera Blanca in Perú (centered 9° S, 77.1° W). This sedimentary mountain range extends for more than 200 km, and it contains 70% of the glaciers located in tropical areas of the planet Vuille et al. (2008). The Nevado Pastoruri glacier, located within this mountain range, has a maximum height of 5250 m.a.s.l. González-Toril et al. (2015) investigated the sediments of lakes near the summit, where they found psychrotolerant members of *Cyanobacteria*, *Bacteroidetes* and *Polaromonas*. Additionally, microorganisms associated with soils, permafrost, and deglaciation zones were found around the glacier, including members of *Sphingomonadales*, *Caulobacter* and *Comamonadaceae*. Certain zones are subjected to acid drainage due to the exposure of sulfide-rich lithologies as the glacier retreats, resulting in ponds with low pH and elevated concentration of heavy metals, where sulfur and iron-oxidizing acidophilic species were identified. Although these acidic environments are partially a product of microbial metabolism, they are also of interest for astrobiology research. Metal sulfides are commonly found in ancient Martian rocks Miltra et al. (2013), and they have also been detected on the icy and rocky moons of Jupiter and Saturn Lodders & Fegley (2024).

Mexico contains some relevant glacier environments where microbial research has been conducted. The best example is the Iztaccihuatl volcano (19.2° N, 98.6° W), located at the border of the states of Mexico and Puebla. This place shares multiple extreme conditions like low and high temperatures and heavy metal concentrations. In this place, microbial diversity from prokaryotes and fungi has been studied. 16S rRNA amplicon analysis showed the presence of *Proteobacteria*, *Actinobacteria*, and *Bacteroidetes* from glacier samples Calvillo-Medina et al. (2019). On the other hand, fungi isolations recovered from glacier samples were composed principally of *Cladosporium* and *Alternaria* genera that show adaptations to low temperatures and heavy metals Calvillo-Medina et al. (2020).

Research of extremophiles on the glaciers located in the southernmost part of the continent is also restricted. One of the few examples is a study done by Pittino et al. (2023) in cracks, snow, and cryoconites over glaciers in the Central and Southern Andes. They found bacterial orders such as *Betaproteobacteriales*, *Cytophagales*, *Chitinophagales*, *Frankiales*, and *Micrococcales*, the latter two being highly resistant to UV radiation. These same organisms were found in major numbers in low-elevation glaciers, meaning that even if they thrive in less extreme conditions, they can still survive high UV radiation levels and oxidative stress, as well as lower partial pressures of oxygen and low availability of nutrients.

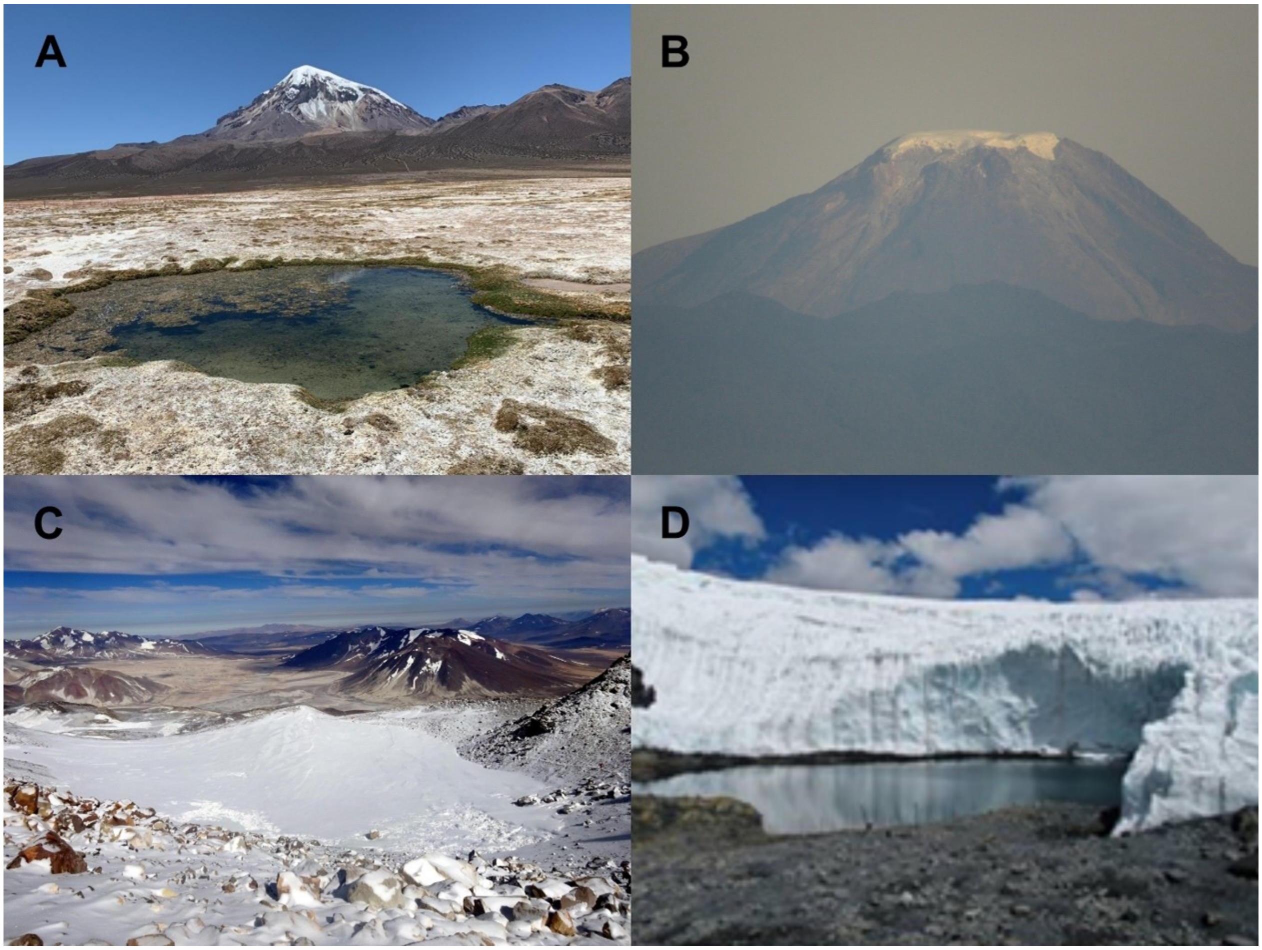

Figure 3: Some high mountain and glacier environments in Latin America. A. Water pond at 4150 m in altitude, in the background is the Sajama Volcano, in the Bolivian Andes. B. Nevado del Tolima, Colombia. C. Nevado Ojos del Salado, Argentina-Chile. D. Pastoruri Glacier. Sources: A and B by project authors, D taken from González-Toril et al. (2015).

3.3.2 Astrobiology research possibilities

High mountain systems host low temperatures, high radiation levels, and sometimes even acidic waters. These conditions are commonly found in extraterrestrial environments. The surface temperature of the bodies in the solar system greatly decreases as they are located further away from the Sun. Martian temperatures range between –100 and 20 °C (Piqueux et al. 2024), while the far away Pluto has surface temperatures ranging between –226 to –200 °C (Earle et al. 2017). The result is that many extraterrestrial environments are exposed to low temperatures, many of which also have an abundance of glaciers of varied compositions. The study of organisms living under cold conditions, as well as the development of techniques and technologies to explore these kinds of environments on Earth are important for future missions to planetary bodies alike.

The elevated level of UV radiation in high mountain systems is another valuable property to be considered in astrobiology research. Many planetary bodies have weak atmospheres, which results in elevated levels of high-energy radiation. As an example, the Martian surface is on average exposed to higher levels of UV radiation than Earth (Cockell et al. 2000). Research on terrestrial radiophiles could give us clues about how living beings evolve and survive under these conditions, and what to expect in similar environments on other planets.

This study presents a great number of glaciers in Latin America that remain unexplored or poorly studied. Places in Mexico like the Citlaltépetl volcano and the Pico de Orizaba offer the opportunity for future astrobiology researchers to propose and develop multiple projects and experiments. In Central America, high mountain environments are a good alternative to promote this kind of research for early career scientists from a local perspective that encourages not only the space sciences research, but also local basic sciences and innovation. Finally, in South America, the Andean cordillera shows great potential as an astrobiology laboratory. As an example, the Sierra Nevada de Santa Marta is a poorly explored location, but its unique geology, weather, and geographic position make it a potential place for research. In summary, glacier environments in Latin America offer great possibilities to conduct astrobiology research and encourage the development of collaborative projects to promote early career scientists to study these places before they disappear because of climate change (Battin et al. 2025).

3.4 Hypersaline environments

Hypersaline environments are characterized by extreme salinity levels, exceeding the one of seawater (∼35 g/L) (Saccò et al. 2021), and support extremophiles adapted to high osmotic stress and fluctuating salinity conditions (Filker et al. 2017). These environments include coastal lagoons, salt and soda lakes, salterns (human-made hypersaline ponds for producing salt) (McGenity & Oren 2012, Oren 2015), deep-sea brine pools (formed from the dissolution of salt during seafloor tectonic activity), and brine channels in sea ice (Rich & Maier 2015). Examples of those systems include the Great Salt Lake (Perl & Baxter 2020), the Dead Sea (Sass & Ben-Yaakov 1977), and the Sambhar Salt Lake (A.P. & Cherekar 2015).

Microorganisms adapted to survive these conditions are known as halophiles. Some of their adaptations include the use of osmotic organic and inorganic solutes, changes in the lipid composition of the cell membrane, modified proteins optimized for high salt concentrations (Gunde-Cimerman et al. 2018), and the use of the hygroscopic properties of salt to obtain water under extremely dry conditions (Ruginescu et al. 2019, Wierzchos et al. 2012). These adaptations could be expected on living beings in dry planetary bodies like Mars.

In Latin America, several conditions contribute to the existence of hypersaline environments, from the coastal regions to the high mountains in the Andes. We identified a variety of them, including hypersaline lakes, salterns, salt pans, and salt mines (Table 1). Many of these locations were known due to the importance of salt as a resource for the human communities that inhabit Central and South America. For this reason, most of the research done in hypersaline environments is related to the extraction of mineral resources such as salt and lithium.

3.4.1 Microbiology research in hypersaline environments

The Salar de Atacama (25.1° S, 68.6° W), located in Chile, is a major salt flat in the Atacama Desert characterized by high salinity, alkalinity, and the presence of lithium-rich brines. These conditions support unique microbial communities, including halophilic and polyextremophilic microorganisms (Osman et al. 2021, Joseph 2023). This site is probably the hypersaline environment that attracts the most attention from microbiologists and astrobiologists. Hypersaline environments in the Atacama Desert and Andean lakes harbor halophilic bacteria such as *Halomonas* and *Salinibacter*, as well as polyextremophiles that tolerate high salinity, UV radiation, and temperature fluctuations. These microorganisms have evolved unique survival strategies, including the production of osmolytes and UV-protective compounds (Albarracín et al. 2015, Osman et al. 2021). The discovery of novel bacterial and archaeal species in these environments has expanded our understanding of microbial diversity. For example, the identification of novel *Streptomyces* species in the Salar de Huasco (20.2° S, 68.9° W), Chile, highlights the potential for discovering new antimicrobial and pharmaceutical compounds (Cortés-Albayay et al. 2019).

The southern Bolivian Altiplano has high potential for astrobiology and planetary geology studies. It is a volcanic area which contains numerous undrained basins occupied by playas and saline lakes, locally named salars. Solutes carried by springs and rivers into the salars originate mostly from the alteration of the volcanic rocks and the re-solution of ancient buried evaporites. The most significant environment in this area is the Uyuni salt flat (20.1° S, 67.5° W), at an elevation of more than 3600 m.a.s.l. in the central Bolivian Altiplano. It is the world's largest salt-filled saline pan (Risacher & Fritz 2000). Archaea from the phyla Euryarchaeota, Nanoarchaeota and Hadesarchaeota have been found in salt crusts from this salar, as well as Bacteria of the phyla Bacteroidetes, Proteobacteria and Patescibacteria (Pecher et al. 2020). Genera such as *Halorubrum*, *Halomonas*, *Salinibacter*, *Natronomonas* and *Halobacterium* were some of the halophiles found in this place.

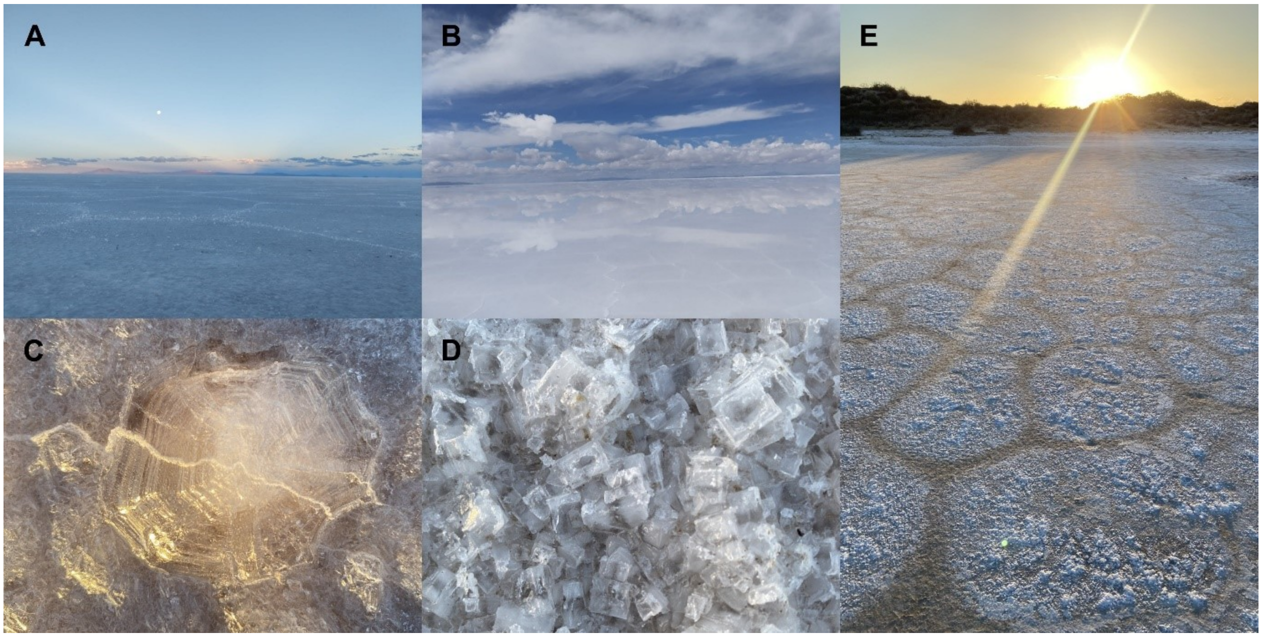

Figure 4: Some hypersaline environments in Latin America. A-B. Salt crust and the famous mirage in the Salar de Uyuni, Bolivia. Source: Photos taken by Nicole Jimeno. C-D. Salt formation in the Campo La Salina, northern Mexico. E. Salt crusts in the Campo La Salina, northern Mexico. Source: Photos taken by Karen Reyes.

In Mexico, the most studied of those extreme environments is Cuatro Ciénegas Basin (26.9° N, 102.1° W), described as a "lost world" due to the primitive characteristics preserved in the microbial communities (Souza et al. 2018). Studies show that microbial communities here have adaptations to oxidative stress, temperature shocks, osmotic stress, and nutrient limitation (Medina-Chávez et al. 2025, 2023, Moreno-Letelier et al. 2012, Rodríguez-Cruz et al. 2024, Souza et al. 2012). Archaea such as *Halorubrum*, *Haloferax*, *Haloarcula*, and endemic *Bacillus* relatives show phylogenetic links to ancient marine communities.

Campo La Salina (29.6° N, 112.4° W), located in the coastal zone of the Sonoran Desert, revealed archaeal-dominated microbial communities, with only members of the phylum Halobacterota detected (Ramos-Madrigal et al. 2024). Dominant species include *Natronococcus occultus* and *Halalkalicoccus jeotgali*. Another interesting site, Guerrero Negro Saltern (27.9° N, 114.1° W), hosts microbial mats dominated by methanogenic archaea such as *Methanosarcinales* and *Methanomassiliicoccales* (García-Maldonado et al. 2023, Ramírez-Arenas et al. 2024). Bacterial phyla *Chloroflexi* and *Cyanobacteria* form the bulk of microbial biomass and their interactions shift with environmental conditions (Ley et al. 2006). The carbonate precipitation in microbialites from Laguna Negra (25.2° N, 68.7° W), Argentina, aids understanding of biosignature formation (Gomez et al. 2014).

Although we have highlighted some of the most extensively studied hypersaline environments, many others remain unexplored. These include Laguna Verde and Laguna Blanca (Bolivia), the Zipaquirá salt mine and Manaure saltern (Colombia), Maras salt ponds (Peru), and Salina Grande (Argentina). Their extreme conditions make them strong candidates for future research in astrobiology and biotechnology.

3.4.2 Astrobiology research possibilities

Many satellites and planets in our Solar System, such as Europa or Mars, are believed to harbor salty subsurface water bodies (Carr et al. 1998, Lauro et al. 2020). Earth's halophilic extremophiles offer models of how life could survive there (Dassarma 2006), demonstrated by microbial life in halite deposits and evaporitic systems (Phillips et al. 2023, Vítek et al. 2016).

High-altitude Andean lakes and salt flats (e.g., Argentinean Puna, Atacama, Uyuni) feature hypersalinity, UV radiation, and sometimes low oxygen. They support polyextremophilic microbial ecosystems, such as microbial mats and stromatolites, analogs of early Earth and Mars (Saona et al. 2020, Farías & Acuña 2020).

Some hypersaline environments, like Salinas Grandes (24.3° N, 66.7° W), Argentina, have not been microbiologically explored despite their size and elevation. With multiple stressors (UV, salinity, elevation), these locations are excellent analogues for Mars and should be targeted for collaborative astrobiological projects in Latin America.

4 Concluding remarks

4.1 Distribution of extreme environments

A map of Latin America showing around 300 extreme environments described in this work can be seen in Figure 5. Most of the environments are located along the western margin of the continent. This is concordant with the active geological margins that involve the Nazca and South American tectonic plates to the south (Espurt et al. 2008), the Cocos and Caribbean Plate in Central America (Daisuke et al. 2014), and the Pacific and North American plates to the north (DeMets & Merkouriev 2016).

There is a clear relation between geological activity, geography, climate, and the diversity of extreme environments. Most of the geothermal and hydrothermal environments are located inside mountain ranges and volcanic arcs, the biggest one being the Andean Mountain range that crosses South America. This is expected, given that the energy that feeds these systems usually comes from magmatic activity under the crust (e.g., Gómez Díaz & Mariño Arias 2020), even in the occurrences that are away from the western margin of the continent, like in Brazil and Uruguay, the thermal waters are likely related to local volcanic systems (Zuo et al. 2023).

The glacial and high mountain environments are mainly constrained by geography: most of the locations that surpass 3500 m.a.s.l are in the Andes or in the Sierra Madre, which in turn are the result of the regional geological activity mentioned before. However, glaciers do persist at lower altitudes in the southern latitudes of the continent, since temperatures are low enough to maintain them.

Hypersaline environments are mainly concentrated in the Puna of the central Andes, which is also the location that hosts the environments with the most extreme conditions. This is the result of a combination of geological and climatic factors. The central Andes have the highest peaks, and it is the widest portion of the mountain range (Tassara 2005), which makes the mobilization of wet winds from the east or west difficult, generating a dry environment (Garreaud et al. 2003). Most of the basins in these regions are endorreic, so the water bodies become saline over time due to constant evaporation (Pueyo et al. 2020). Other hypersaline environments are associated with arid environments, these ones are mainly controlled by climatic factors; the deserts in Mexico, Colombia, and Brazil are controlled by high-pressure Hadley cells (Seager et al. 2007), while the ones in Peru and Chile are mainly defined by the dynamic of the Humboldt marine current and rainshadow (Garreaud et al. 2009).

Figure 5: Map of Latin America showing the location of the extreme environments presented in this review.

4.2 Advantages in developing research in Latin America extreme environments and recommendations

This review shows that many extreme environments throughout Latin America offer easy access to researchers for gathering samples, conducting in-place experiments, and obtaining novel results. The limited amount of research that has been done in these locations is also an opportunity for new studies to be carried out in them, broadening our general knowledge of extreme environments and finding conditions that are suitable for analog experiments. In that same line, many of the locations described here host multiple extreme conditions in a single place, thus generating natural environments that are closer to planetary settings (for example martian-like environments). This level of fidelity could give us a better approximation of the expected behavior of life in other planetary bodies. Many activities can take place in these locations, including the testing of protocols, equipment, and experiments that could increase the success of extant life detection in real conditions. Latin American environments are also geologically and climatically diverse, allowing direct comparison with planetary surfaces.

Latin America is home to a remarkable variety of extreme environments, from high-altitude Andean lakes to hypersaline coastal lagoons, many of which remain poorly explored despite their scientific potential. These ecosystems, besides challenging our understanding of the limits of life on Earth, are natural laboratories for astrobiological research. As the search for life beyond Earth becomes increasingly intensive, particularly on Mars and the icy moons of certain planets in the Solar System, the study of these analogous environments becomes increasingly important. This review collects knowledge about the extreme environments in the region and discusses their potential in basic and applied sciences, contributing to the global search for planetary analogs. We hope that this compilation opens opportunities for researchers in Latin America, as well as broadening cooperation with researchers and institutions around the world.

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6 Data availability

The datasets used to create the map and the shapefile with the extreme environments can be reached at a Zenodo repository (Suarez-Valencia 2025).

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Supplementary Material – Reference Matrix of Extreme Environments in Latin America

This supplementary material includes a structured table listing selected extreme environments across Latin America. Each entry provides the name of the site, its country of location, geographic coordinates, and the corresponding bibliographic reference.

Table 2: References associated with extreme environments in Latin America.

Place	**Country**	**Latitude**	**Longitude**	**References**
Desierto de la Patagonia, Argentina	Argentina	-40.0, -55.0	-65.0, -70.0	Temperini et al. (2019)
El Chaco Desert	Argentina/Paraguay	-22.0, -28.0	-57.5, -63.0	Benítez (2020)
El Monte Desert	Argentina	-25.0, -40.0	-63.0, -68.0	García et al. (2021), Ángela D Vega Ávila et al. (2010)
La Payunia Desert	Argentina	-36.1	-69.5	Carmanchahi et al. (2020)
Parque Nacional Sajama	Bolivia	-18.1	-69.0	Darack (2020)
Desierto Salvador Dalí	Bolivia	-22.61	-67.66	Guía Turismo Bolivia (2023)
Dunas de Tajzara	Bolivia	-21.71	-65.07	Convención de Ramsar (1971), Jiménez-Robles & la Riva (2019)
Desierto Siloli	Bolivia	-21.7	-66.9	Mulligan & Eckstein (2010)
Desierto de Lençóis Maranhenses, Brasil	Brazil	-2.0	-42.6	Souza dos Santos & dos Santos (2015)
Caatinga Semi arid zone	Brazil	-5.5, -9.0	-39.0, -41.5	Duarte et al. (2012), Bonatelli et al. (2021), Genuário et al. (2019)
Atacama desert	Chile	-24.5, -26.3	-68.2, -69.0	Shen et al. (2021)
semi-arid Coquimbo Region	Chile	-29.5	-71.1	Montecinos et al. (2016)
Palmira desert	Ecuador	-0.8	-79.4	Vélez-Macías et al. (2024)
Santa Elena Desert	Ecuador	-2.1	-80.3	Nazareno (2022)
El Oro Desert	Ecuador	-3.5	-79	Cerón' et al. (2006)
Desierto de Sechura	Perú	-5.9	-80.4	Gálvez et al. (2006)
Nazca desert	Peru	-14.8	-75.1	EITEL et al. (2005)
Desierto De Ica	Perú	-14.1	-75.7	Salinas et al. (2007)
Dunas de Cabo Polonio	Uruguay	-34.5	-53.7	Mezquida (2016), Delfino & Masciadri (2005)
La Tatacoa desert	Colombia	-3.3	-75.0	Bolívar-Torres et al. (2021), Hermelin (2016)
La Guajira desert	Colombia	11	-71.5	Aponte (2010)
La Candelaria desert	Colombia	5.7	-73.5	Corzo-Acosta & Corzo (2022)
Sabrinsky Desert	Colombia	10	-72.5	Ojeda et al. (2017)
Sonora desert (Reserva de la Biófera Pinacate y Gran Desierto de Altar)	México	33.5, 25.0	-105.5, -116.5	Andrew et al. (2012)

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Table 2 – continued from previous page

Place	**Country**	**Latitude**	**Longitude**	**References**
Samalayuca desert, Chihuahua	México	31.7	-106.8	Guerra-Murcia et al. (2021)
Cuatro Ciénegas Coahuila	México	26.9	-101	Souza et al. (2018, 2012), Moreno-Letelier et al. (2012)
Arizona-Sonora desert	México	33.8, 25.0	-105.5, -117.0	Shen et al. (2021), Nagy et al. (2005), Rainey et al. (2005)
Desierto de Baja California	México	32.7, 23.0	-113.0, -118.0	Puente et al. (2004), Rocha et al. (2019)
Dunas del Mogote, Baja California Sur	México	24.6	-112	Rodríguez-Revelo et al. (2017), López et al. (2006), Chávez-López (2022)
Médanos de Coro	Venezuela	11.8	-69	Morón (2011), Goddard & Picard (1972)
Copahue geothermal field	Argentina	-37.8	-71.1	Urbieta et al. (2015)
Tocomar geothermal field	Argentina	-37.8	-71.1	Aguillar et al. (2024), Filipovich et al. (2022)
Termas Concordia	Argentina	-31.4	-58	Lazzerini & da Silva (2020)
Sol de la mañana Geothermal field	Bolivia	-22.4	-67.8	Quiroga et al. (2023)
Charagua Hot springs	Bolivia			Montaño (2014)
Camiri Hot springs	Bolivia	-18.65	-59.2	Montaño (2014)
Uturuncu Volcano	Bolivia	-22.2	-67.1	Kukarina et al. (2017)
Nevado Sajama	Bolivia	-18.1	-69.0	Panajew & Gałaś (2020)
Chapada dos Veadeiros geothermal reservoir	Brazil	-14.1	-47.6	Junqueira et al. (2022)
Hidrothermal vents Campos Basin	Brazil	-22.5	-40	Alvarenga et al. (2016)
geothermal field of the Santos Basin	Brazil	-25	-45	Zuo et al. (2023)
Caldas Novas Thermal Complex	Brazil	-17.7	-48.6	de Carvalho et al. (2015)
Solar das Águas Quentes	Brazil	-23.4	-51.9	Lazzerini & da Silva (2020)
Água do Palmito	Brazil	-20.7	-51.6	Lazzerini & da Silva (2020)
Agua Viva Thermas	Brazil	-20.2	-50.2	Lazzerini & da Silva (2020)
Grandes Lagos Thermas	Brazil	-20.2	-50.6	Lazzerini & da Silva (2020)
SESC Thermas	Brazil	-22.1	-51.4	Lazzerini & da Silva (2020)
Termas São João	Brazil	-26.9	-48.6	Lazzerini & da Silva (2020)
El Tatio, hot springs and geysers	Chile	-22.3	-68	Ruff & Farmer (2016)
Tinguiririca Geothermal Area	Chile	-34.8	-70.5	Clavero et al. (2011)
Tolhuaca geothermal field	Chile	-38.3	-71.6	Lahsen et al. (2015)
Paipa hot springs	Colombia	5.8	-73.1	Rubiano-Labrador et al. (2019)
El Azufral volcano	Colombia	1.1	-77.7	Valero et al. (2008)
Parque Nacional Los Nevados	Colombia	4.9	-75.3	Delgado-Serrano et al. (2014), López et al. (2014), Bohorquez et al. (2012), Sanín et al. (2024*a*)
Purace volcano	Colombia	2.3	-76.4	Torres et al. (2016)
Cerro Machin volcano	Colombia	4.5	-75.4	Díaz & Arias (2020)
Miravalles volcano	Costa Rica	10.7	-85.2	Brenes-Guillén et al. (2021)
Poás volcano	Costa Rica	10.2	-84.2	Wang et al. (2022)

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Table 2 – continued from previous page

Place	Country	Latitude	Longitude	References
Rincon la vieja volcano	Costa Rica	10.8	-85.3	Brenes-Guillén et al. (2021)
Margen continental	Costa Rica	10.18	86.18	Sahling et al. (2008), Ashford et al. (2021)
Balneario Elguea	Cuba	23	-80.6	Zerquera et al. (2011)
Boiling Lake and Valley of Desolation	Dominica	15.3	-61.2	Christian (2018)
Soufriere Sulphur Springs	Saint Lucia	13.8	-61	Christian (2018)
Baños-Cuenca hot springs	Ecuador	-2.9	-79	Beate et al. (2020)
Cachiyacu hot springs	Ecuador	-0.9	-76.4	Beate et al. (2020)
Chachimbiro volcano	Ecuador	0.5	-78.2	Beate et al. (2020)
Cotopaxi hot spring	Ecuador	-0.7	-78.4	López et al. (2012)
Cununyacu hot springs	Ecuador	-0.3	-78.4	Uvidia (2016)
Chimborazo volcano	Ecuador	-1.5	-78.8	Beate et al. (2020)
El salado hot springs	Ecuador	-1.4	-78.4	Beate et al. (2020)
El tambo hot springs	Ecuador	-2.5	-78.6	Beate et al. (2020)
El Carchi hot springs	Ecuador	0.6	-77.8	López et al. (2012)
Imbabura hotspring	Ecuador	0.4	-78.2	López et al. (2012)
Jamanco hot springs	Ecuador	-0.4	-78.4	Beate et al. (2020)
Ilalo hot springs	Ecuador	-0.3	-78.4	Beate et al. (2020)
La virgen hot springs	Ecuador	-1.4	-78.4	Beate et al. (2020)
Nangulvi hot springs	Ecuador	0.3	-78.6	Beate et al. (2020)
Palictahua hot springs	Ecuador	-1.5	-78.4	Beate et al. (2020)
Papallacta hot springs	Ecuador	-0.4	-78.1	Beate et al. (2020), López et al. (2012)
Pichincha hot spring	Ecuador	-0.2	-78.6	López et al. (2012)
Pitzantzi volcano	Ecuador	-0.8	-77.9	Beate et al. (2020)
Santa Ana hot springs	Ecuador	-2.2	-79.2	Arguello & de los Angeles Bravo Mora (2023)
Tingo hot springs	Ecuador	-0.4	-78.5	Beate et al. (2020)
Tungurahua volcano	Ecuador	-1.5	-78.4	Beate et al. (2020), López et al. (2012)
Ahuachapan geothermal field	El Salvador	13.9	-89.9	López et al. (2012)
Coatepeque geothermal field	El Salvador	13.9	-89.6	López et al. (2012)
Berlín geothermal field	El Salvador	13.5	-88.5	López et al. (2012)
Joaquina geothermal field	Guatemala	14.6	-90.9	Libbey et al. (2015)
Moyuta geothermal field	Guatemala	14	-90.1	López et al. (2012)
Tecuamburro Geothermal field	Guatemala	14.1	-90.5	López et al. (2012)
Zunil geothermal field	Guatemala	14.8	-91.5	López et al. (2012)
Eaux Boynes hot springs	Haiti	19.6	-72.9	Brown (1924)
Los Pozos hot springs	Haiti	19.1	-71.7	Brown (1924)
Azacualpa geothermal field	Honduras	14.8	-88.7	López et al. (2012)
Pavana geothermal field	Honduras	13.2	-87.1	López et al. (2012)
Platanares geothermal field	Honduras	14.6	-88.6	López et al. (2012)
Araró geothermal field	México	19.8	-100.8	Prieto-Barajas et al. (2018, 2017)
Chignahuapan hot springs	México	19.8	-97.9	Castelán-Sánchez et al. (2020)
Los Geiseres geothermal field	México	19.7	-100.8	González-Guzmán et al. (2019)

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Place	Country	Latitude	Longitude	References
Los Hervideros hot springs	México	21.8	-102.3	Óscar López-Sandoval et al. (2016)
Los Humeros geothermal field	México	19.7	-97.5	Carrasco-Núñez et al. (2017)
Los Azufres, Michoacán	México	19.8	-100.6	Brito et al. (2020), Bolivar-Torres et al. (2022), Servín-Garcidueñas et al. (2013*a*), Brito et al. (2014), Marín-Paredes et al. (2021)
Crater lake el Chichón	México	17.4	-93.2	Peña-Ocaña et al. (2022), Velázquez-Ríos et al. (2022)
Guerrero negro hot springs	México	27.9	-114	Rodríguez-Valdez et al. (2022)
Cuenca de Guaymas hydrothermal vents, Sonora	México	27	-111.5	Ramírez et al. (2021), Dombrowski et al. (2018), Edgcomb et al. (2002), Keeler et al. (2021)
Golfo de México hydrothermal vents	México	30.2 and 28.76	-113.61 and -88.35	Merlino et al. (2018), Marshall et al. (2021)
Mapachitos hot springs	México	26.67	-111.84	Peña-Pelayo et al. (2022)
Paricutin volcano	México	19.4	-102.2	Souza-Brito et al. (2019)
Santispac hot springs	México			Peña-Pelayo et al. (2022)
Playa Agua Caliente hot springs	México	24.11	109.99	Peña-Pelayo et al. (2022)
Monte Galan geothermal field	Nicaragua	12.5	-86.6	López et al. (2012)
Momotombo geothermal field	Nicaragua	12.4	-86.5	López et al. (2012)
Telica's Hervidores de San Jacinto	Nicaragua	12.5	-78.4	Hynek et al. (2013)
Pozos de Calobre hot springs	Panamá	8.4	-80.8	Fábrega (2020)
The Boiling River	Perú	-8.8	-74.7	Comet (2018), Fortier et al. (2024)
Huancarhuaz hot spring	Perú	-8.9	-77.7	Tamariz-Angeles (2014), Newell et al. (2015)
Baños termales Lares	Perú	-72	-13.1	Upin et al. (2023)
Baños de Upis	Perú	-71.2	-13.7	Upin et al. (2023)
Baños Pacchanta	Perú	-71.2	-13.7	Upin et al. (2023)
Aguas Calientes La Raya	Perú	-71	-14.4	Upin et al. (2023)
Baños Termales Collpa Apacheta	Perú	-70.1	-16.2	Upin et al. (2023)
Aguas Calientes-Pinaya	Perú	-70.8	-15.5	Upin et al. (2023)
Aguas termales Crucero	Perú	-70.1	-16.7	Upin et al. (2023)
Aguas Calientes geothermal springs	Perú	-7.3	-75.0	Paul et al. (2016)
El Tragadero (Baños del Inca) hot springs	Perú	-7.1	-78.4	Valdez-Nuñez & Rivera-Jacinto (2024)
Quilcate (San Miguel) hot springs	Perú	-6.8	-78.7	Valdez-Nuñez & Rivera-Jacinto (2024)
Tarapoto hot springs	Perú	-6.4	-76.3	Borja et al. (2012)
La Calera hot spring (Colca Canyon)	Perú	-15.6	-71.5	de Vijver & Cocquyt (2009)
Ticaco hot springs	Perú	-17.4	-70.0	Taillefer et al. (2024)
Aruma hot springs	Perú	-17.7	-69.8	Taillefer et al. (2024)
Barroso hot springs	Perú	-17.3	-69.7	Taillefer et al. (2024)

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Place	Country	Latitude	Longitude	References
Geisers hot springs	Perú	-17.1	-70.1	Taillefer et al. (2024)
Tutupaca geothermal zone	Perú	-17.0	-70.3	Barragán et al. (1999), Pauccara (2018)
Calientes river geothermal zone	Perú	-17.2	-70.1	Barragán et al. (1999), Pauccara (2018), Valdez et al. (2023), Castellanos et al. (2024), Taillefer et al. (2024)
Ancocollo geothermal zone	Perú	-17.2	-69.7	Pauccara (2018)
Borateras geothermal zone	Perú	-17.2	-69.7	Pauccara (2018)
Kallapuma-Chungara hydrothermal systems	Perú	17.1	-69.6	Pauccara (2018)
Aquilina hot springs	Perú	-16.5	-69.5	Newell et al. (2015)
Chancos hot springs	Perú	-9.3	-77.5	Newell et al. (2015)
Monterrey hot springs	Perú	-9.4	-77.5	Newell et al. (2015)
Olleros hot springs	Perú	-9.6	-77.4	Newell et al. (2015)
Coamo thermal spring	Puerto Rico	18	-66.3	Valle et al. (2017)
Puerto Rico Trench	Puerto Rico	19.7	-66.5	George (2020)
Almirón Hot Springs	Uruguay	-32.3	-57	Porto et al. (2023), Lazzerini & da Silva (2020)
Guaviyu Hot Springs	Uruguay	-31.9	-57.9	Porto et al. (2023), Lazzerini & da Silva (2020)
Daymán Hot Springs	Uruguay	-31.4	-57.9	Porto et al. (2023), Lazzerini & da Silva (2020)
Arapey Hot Springs	Uruguay	-30.9	-57.5	Porto et al. (2023), Lazzerini & da Silva (2020)
Termas de Salto Grande	Uruguay	-31.4	-57.9	Lazzerini & da Silva (2020)
Las trincheras hot springs	Venezuela	10.2	-68	Viviano et al. (2011)
Río Aguas Calientes	Venezuela	9.1	-71.1	Urbani & Galarraga (2016)
Ojos de Salado volcano	Argentina/Chile	-27.1	-68.5	Aszalós, Szabó, Megyes, Anda, Nagy & Borsodi (2020), Ákos Kereszturi et al. (2020)
Perito Moreno glacier	Argentina	-50.5	-73.1	Pittino et al. (2023)
Abra del Gallo	Argentina	-24.3	-66.1	Albarracín et al. (2015)
Socompa Volcano	Argentina	-24.4	-68.2	Schmidt et al. (2018)
Llullaillaco volcano	Argentina	-24.7	-68.5	Schmidt et al. (2018)
Frias galcier	Argentina	-41.1	-71.8	de Garcia & Giraudo (2016)
Rio Manso glacier	Argentina	-41.5	-71.8	de Garcia & Giraudo (2016)
Castaño Overo Glacier	Argentina	41.1	-71.8	de Garcia & Giraudo (2016)
Patagonian glaciers (North and south)*	Argentina	-50.0, -52.5	-70.0, -74.5	de Garcia & Giraudo (2016), Zalazar et al. (2018)
Andean Desert Glaciers*	Argentina	-25.0, -30.0	-68.0, -71.5	Zalazar et al. (2018)

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Place	**Country**	**Latitude**	**Longitude**	**References**
Andean Central Glaciers*	Argentina	-30.0, -45.0	-68.0, -71.5	Zalazar et al. (2018)
Tierra del Fuego and South Atlantic Islands Glaciers*	Argentina	-53.0, -57.0	-65.0, -68.0	Zalazar et al. (2018)
Nevado Huayna Potosi	Bolivia	-16.26	-68.14	Nina Huanca et al. (2015)
Sajama National Park	Bolivia	-18.1	-68.9	Darack (2020)
Eduardo Avaroa National Reserve	Bolivia	-22.3	-67.3	Veettil & Kamp (2017)
Chacaltaya Glacier	Bolivia	-16.3	-68.1	Veettil & Kamp (2017)
Cordillera Quimsa Cruz	Bolivia	-17	-67.33	Nina Huanca et al. (2015)
Nevado Charquini	Bolivia	-16.29	-68.10	Nina Huanca et al. (2015)
Nevado Mururata	Bolivia	-16.53	-67.82	Nina Huanca et al. (2015)
Nevado Ancohuma	Bolivia	-15.85	-68.54	Nina Huanca et al. (2015)
Nevado Illampu	Bolivia	-15.81	-68.54	Nina Huanca et al. (2015)
Condoriri Glacier	Bolivia	-16.2	-68.3	Veettil & Kamp (2017)
Nevado Cololo	Bolivia	-14.5	-68.9	Veettil & Kamp (2017)
Nevado Illimani	Bolivia	-16.6	-67.8	Veettil & Kamp (2017)
Zongo Glacier	Bolivia	-16.2	-68.1	Veettil & Kamp (2017)
Cerro Chajnantor	Bolivia	-23.0	-67.7	Bull et al. (2018)
Licancabur Volcano	Chile/Bolivia	-22.8	-67.9	Fleming & Prufert-Bebout (2010)
Antisana glacier	Ecuador	-0.5	-78.1	Veettil & Kamp (2017)
Cayambe volcanic complex	Ecuador	0.0	-77.9	Díaz et al. (2023)
Chimborazo volcano	Ecuador	-1.5	-78.8	Veettil & Kamp (2017)
Cotopaxi Glacier	Ecuador	-0.7	-78.4	Veettil & Kamp (2017)
Altar Glacier	Ecuador	-1.7	-78.3	Veettil & Kamp (2017)
Sangay Glacier	Ecuador	-2.0	-78.3	Veettil & Kamp (2017)
Tunguragua	Ecuador	-1.5	-78.4	Veettil & Kamp (2017)
Cerro sillajhuay	Chile	-19.8	-68.7	Barcaza et al. (2017)
Nevado de las Tres Cruces	Chile	-27.0	-68.8	Barcaza et al. (2017)
Nevado Queulat	Chile	-44.5	-72.5	Barcaza et al. (2017)
Exploradores glacier	Chile	-46.5	-73.2	Pittino et al. (2023)
Guallatiri glacier	Chile	-18.4	-69.1	Barcaza et al. (2017)
Iver glacier	Chile	-53.8	-71.9	Pittino et al. (2023)
Morado glacier	Chile	-33.7	-70.1	Pittino et al. (2023)
Nevado Parinacota	Chile	-18.1	-69.1	Veettil & Kamp (2017)
Pomerape Glacier	Chile	-18.1	-69.2	Barcaza et al. (2017)
Chajnantor volcano	Chile	-24.5	-67.7	Bull et al. (2018)
Chilean Glaciers North Zone*	Chile	-15.0, -32.0	-68.0, -71.0	Rivera (2011), Rocha & Giering (2017)
Chilean Glaciers Central Zone*	Chile	-32.0, -36.0	-71.0, -72.0	Rivera (2011), Rocha & Giering (2017)
Chilean Glaciers South Zone*	Chile	-36.0, -46.0	-72.0, -74.0	Rivera (2011), Rocha & Giering (2017)
Chilean Glaciers Austral Zone*	Chile	-46.0, -57.0	-70.0, -75.0	Rivera (2011), Rocha & Giering (2017)
Los Nevados National Park	Colombia	4.75	-75.6	Alfaro et al. (2002), López et al. (2017), Borda-Molina et al. (2017), Sanín et al. (2024*b*)
Nevado del Cocuy National Park	Colombia	6.4	-72.3	Molano et al. (2022), Mendivelso (2016)
Nevado del Huila Volcano	Colombia	2.9	-76.0	de Vries et al. (2022)

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Place	Country	Latitude	Longitude	References
Sierra Nevada de Santa Marta	Colombia	10.8	-73.7	Martín & Álvaro Ortiz Dávila (2021)
Chirripó National Park	Costa Rica	9.5	-83.5	Quesada-Román et al. (2020)
Cuchumatanes mountains	Guatemala	15.5	-91.3	Lachniet & Vazquez-Selem (2005)
Tajumulco volcano	Guatemala	15.0	-91.9	Wake (1987)
Huascarán National Park	Peru	-9.3	-77.4	González-Toril et al. (2015)
Huaytrire Wetland	Peru	-14.1	-71.3	Salazar-Torres & Huszar (2012)
Yanamarey Glacier	Peru	-9.8	-77.3	Veettil & Kamp (2017)
Nevado Hualcán	Peru	-9.2	-77.6	Veettil & Kamp (2017)
Nevado Coropuna	Peru	-15.5	-72.6	Veettil & Kamp (2017)
Nevado Tuco	Peru	-9.9	-77.3	Veettil & Kamp (2017)
Cordillera Blanca region	Peru	-8.9, -10.5	-76.7, -77.8	Veettil & Kamp (2017)
Cordillera Vilcanota region	Peru	-12.8, -13.3	-70.3, -71.1	Veettil & Kamp (2017)
Cordillera Carabaya region	Peru	-12.8, -13.3	-68.8, -70.3	Veettil & Kamp (2017)
Cordillera Apolobamba region	Peru	-14.6, -15.3	-67.7, -68.3	Veettil & Kamp (2017)
Cordillera Huaytapallana region	Peru	-11.4, -12.1	-74.8, -75.2	Veettil & Kamp (2017)
Laguna Negra, Argentinian Puna	Argentina	-26.8	-67.5	Gomez et al. (2014)
Pico de Orizaba	México	19.0	-97.3	Angeles et al. (2023)
Iztacíhuatl	México	19.2	-98.6	Palacios et al. (1999), González & García (2019), Calvillo-Medina et al. (2019)
Citlaltépetl	México			Calvillo-Medina et al. (2020)
Xinantécatl ó Nevado de Toluca	México	19.1	-99.8	Tapia-Vázquez et al. (2020)
Popocatépetl	México	19.0	-98.6	Varley & Armienta (2001), Espinasa-Perena & Pozzo (2006)
La Malinche	México	19.3	-98.0	Castillo-Rodríguez et al. (2010), Montoya et al. (2004)
Volcán Cofre de Perote	México	19.5	-97.1	Guzmán & Villareal (1984)
Cerro La Negra, Sierra negra, Puebla	México	18.9	-97.4	Carrasco et al. (2002)
Sierra Nevada National Park	Venezuela	8.5	-71.1	Ball et al. (2014)
Sierra La culata	Venezuela	8.9	-71.2	Couput et al. (2013), Silva (2001)
Sierra de Santo Domingo	Venezuela	8.8	-71.2	Schubert (1977)
Salina Grande	Argentina	-24.3	-66.7	Lara-Reséndiz et al. (2024), Barták et al. (2018)
Salar de Antofalla	Argentina	-25.5	-67.7	Villafañe et al. (2021)
The Mar Chiquita Salt Lake	Argentina	-30.2	-62.8	Bucher (2019)
Laguna Negra	Argentina	-25.2	-68.7	Pittino et al. (2023)
Laguna Verde	Argentina	-24.9	-68.4	Pittino et al. (2023)
Laguna Verde	Argentina	-22.8	-67.8	Pittino et al. (2023)
Laguna Diamante	Argentina	-27.5	-68.5	Pittino et al. (2023)

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Place	**Country**	**Latitude**	**Longitude**	**References**
Ojos de Campo Antofalla	Argentina	-26.4	-68.2	Pittino et al. (2023)
La Lagunita	Argentina	-24.0	-67.5	Pittino et al. (2023)
Laguna Vilama	Argentina	-22.5	-66.9	Pittino et al. (2023)
Laguna Socompa	Argentina	-24.5	-68.3	Pittino et al. (2023)
Ojo de Mar Tolar Grande	Argentina	-24.5	-67.3	Pittino et al. (2023)
Salar Santa Maria	Argentina	-24.1	-67.3	Pittino et al. (2023)
Salar Llullaillaco	Argentina	-24.8	-68.3	Pittino et al. (2023)
Salar Pocitos	Argentina	-24.0	-67.8	Pittino et al. (2023)
Salar de Chiguana	Bolivia	-21.25	-68.13	Ballivián & Risacher (1981)
Laguna Hedionda	Bolivia	-21.56	-68.04	Ballivián & Risacher (1981)
Laguna Cañapa	Bolivia	-21.50	-68.01	Ballivián & Risacher (1981)
Laguna Chiarkota	Bolivia	-18.04	-69.05	Ballivián & Risacher (1981)
Laguna Honda	Bolivia	-21.61	-68.06	Ballivián & Risacher (1981)
Laguna Crater	Bolivia	-19.46	-67.43	Lamb et al. (1992)
Salar de Laguani	Bolivia	-21.02	-68.24	Lázaro (2017)
Salar de Chalviri	Bolivia	-22.53	-67.56	Ballivián & Risacher (1981)
Salar de Capina	Bolivia	-21.92	-67.57	Ballivián & Risacher (1981)
Salar de Empexa	Bolivia	-20.38	-68.52	Ballivián & Risacher (1981)
Laguna Collpa	Bolivia	-22.30	-67.30	Risacher (1985)
Salar de Coipasa	Bolivia	-19.38	-68.16	Ballivián & Risacher (1981)
Laguna Blanca	Bolivia	-22.8	-67.6	Cabrol et al. (2018), Pittino et al. (2023)
Laguna Verde	Bolivia	-22.8	-67.8	Cabrol et al. (2018), Pittino et al. (2023)
Pastos grandes	Bolivia	-22.6	-67.8	Daga-Quisbert et al. (2023)
Salar de Uyuni	Bolivia	-20.1	-67.5	Haferburg et al. (2017), Pecher et al. (2020)
lagoon system of Araruama	Brazil	-22.9	-42.3	Walter et al. (2021), Duarte et al. (2012)
Pantanal lake	Brazil	-16.6	-57.0	Schleder et al. (2022)
Laguna Amarga	Chile	-50.9	-72.8	Gajardo et al. (2019)
Cisnes lagoon	Chile	-44.7	-72.7	Gajardo et al. (2019)
Laguna de la Sal	Chile	-23.7	-68.3	Gajardo et al. (2019)
Laguna Lejía	Chile	-23.5	-67.7	Demergasso et al. (2010)
Laguna Tebenquiche	Chile	-23.0	-68.2	Fernandez et al. (2016), Pittino et al. (2023)
Burro Muerto Lake	Chile	-24.4	-68.1	Albarracín et al. (2015)
Cejar Lake	Chile	-24.2	-68.2	Albarracín et al. (2015)
Laguna de la Piedra	Chile	-24.5	-68.5	Albarracín et al. (2015)
Salar de Aguas Calientes	Chile	-24.2	-67.6	Demergasso et al. (2010), Pittino et al. (2023)

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Place	Country	Latitude	Longitude	References
Salar de Atacama	Chile	-23.3	-68.0	Gajardo et al. (2019)
Salar de Huasco	Chile	-20.2	-68.9	Gajardo et al. (2019)
Salar de Llamará	Chile	-21.5	-69.6	Gajardo et al. (2019), Demergasso et al. (2003)
Salar de Surire	Chile	-18.9	-69.0	Gajardo et al. (2019)
Zipaquirá Salt mine	Colombia	5.02	-74.0	Díaz-Cárdenas et al. (2017), Correa-Cárdenas et al. (2017)
Manaure Solar Saltern	Colombia	11.78	-72.44	Conde-Martínez et al. (2017)
Salinas de Bolivar	Ecuador	-1.0	-79.14	Tigrero (2018)
Salinas de Tomabela	Ecuador	-1.44	-78.55	Tigrero (2018)
Salinas de Mira	Ecuador	0.28	-78.32	Tigrero (2018)
Salinas del Morro	Ecuador	-2.33	-80.83	Tigrero (2018)
Las salinas de la Puntilla	Ecuador	-2.6	-80.42	Tigrero (2018)
Salinas el Potrero	El Salvador	13.2	-88.6	de Granados & Mestanza (2017)
Salinas de los Nueve Cerros	Guatemala	15.55	-90.42	Woodfill & Wolf (2020)
Salinas Bahia de San Lorenzo	Honduras	13.4	-87.43	Rodriguez (2024)
Rio Lagartos, Yucatán	México	21.6	-88.1	Vega-Cendejas & de Santillana (2004)
Cuatro Ciénegas	México	26.99	-102.08	Medina-Chávez et al. (2023)
Campo La Salina, Sonora	México	29.67	-112.45	NA
Guerrero Negro	México	27.97	-114.06	Dillon et al. (2013), Ley et al. (2006), Spear et al. (2003), Ramírez-Arenas et al. (2024)
Laguna Salada, Baja California	México	32.4	-115.9	Alcocer & Hammer (1998)
Laguna de Chichancanab, Quintana Roo	México	19.87	-88.59	Arana-Ravell et al. (2022)
Salinas de Aguadulce	Panamá	8.23	-80.55	Sáez et al. (2020)
Laguna Salada, Chaco Lodge	Paraguay	-22.55	-59.3	Lesterhuis et al. (2007)
Laguna de Salinas	Perú	-16.62	-71.22	Quispe-Choque & y. María Rosario Elsa Valderrama-Valencia (2024)
Salineras de Maras, Perú	Perú	-13.33	-72.16	Calderón-Toledo et al. (2023), Hernández (2004)
Cabo Rojo Solar Salterns	Puerto Rico			Cantrell & Baez-Félix (2010)
Salinas de Araya	Venezuela	10.58	-64.24	Guevara et al. (2016)
Salina de Pampatar	Venezuela	11.0	-63.8	de Chacín & Boadas (2016)