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# Patagonian Andean Ecosystems: Conserving and Harnessing Their Microbiota

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**Abstract**: Andean Patagonia is a globally significant yet understudied mountain biodiversity hotspot where microorganisms remain largely overlooked despite their key ecological roles and biotechnological potentials. Here, microbial communities inhabit extreme niches shaped by strong climatic and altitudinal gradients, glacial dynamics, and environmental heterogeneity, harboring unique stress adapted microorganisms with valuable metabolic capabilities and ecosystem functions. Emerging studies from northern and central Andes in Chile, and southern Patagonian systems, reveal highly diverse, spatially structured microbiomes in diverse habitats, closely coupled to local abiotic and biotic conditions, and sensitive to warming induced glacier retreat. Andean Patagonia likely contains many endemic, functionally critical microbial lineages, underscoring the compelling need to integrate microbes into regional conservation strategies and long-term bioprospecting agendas.

**Key words:** Andean Patagonia microbiomes, extremophiles, biotechnological potential, microbial conservation.



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Stretching 7,000 km across South America, the Andes represent the world's longest and most biodiverse mountain range, exceeded in elevation only by the Himalayas. This region supports approximately 40,000 plant species and thousands of vertebrates, with high levels of endemism driven by marked altitudinal and climatic gradients that sustain a mosaic of ecosystems ranging from tropical rainforests to high-altitude deserts (Pennington *et al*., 2010; Pérez-Escobar *et al*., 2022; Tovar *et al*., 2022). Patagonia is a vast natural region at the southern end of South America, spanning diverse aquatic environments from the glaciers and deep lakes of the Andean sector to the shallow lakes and rivers of the Patagonian Plateau and its extensive fjorded coastline. At the southern terminus of the cordillera, the Southern Patagonian Andes define a region spanning both Chilean and Argentinian territories shaped by active plate convergence, extensive temperate icefields, and pronounced west–east climatic gradients (Mazzoni *et al*., 2010). In Southern Patagonia, particularly in remote Andean and fjord landscapes, the region has largely preserved its natural conditions due to its relative inaccessibility and harsh environmental conditions, experiencing minimal human disturbance (Rosas *et al*., 2020; Friedlander *et al*., 2021). It is an area of high conservation value and a biodiversity-rich yet understudied region, with documented hotspots of species richness, endemism, and threatened taxa that are only partially covered by existing protected areas (Cofre and Marquet, 1999; Quiroga and Souto, 2022; Rosas *et al*., 2022).

Most biodiversity assessments in the Andes have focused on plants and vertebrates, yet these groups represent only the visible fraction of Andean life. Microbial life constitutes the majority of Earth's biodiversity and regulates key biogeochemical cycles, plant productivity, and ecosystem services and resilience (Averill *et al*., 2022), but it remains underrepresented in current conservation agendas (Redford, 2023; Gilbert *et al*., 2025). Given that mountain microbial life is emerging as a critical indicator of how communities respond to climate and land-use change (Donhauser and Frey, 2018; Ezzat *et al*., 2025), conserving and harnessing microbial diversity in Andean Patagonia offers a key complement to mainstream flora- and fauna-based conservation approaches.

Recognizing Andean Patagonian microbiomes as part of the region's natural heritage is therefore essential not only for protecting their ecological roles, but also for maintaining the genetic and functional diversity that underpins potential future uses. In this context, the following section examines the distinctive diversity and biotechnological attributes of these microbiomes, showing how they further strengthen the case for their long-term conservation.

**Andean Patagonian microbiomes as natural heritage (Biodiversity, ecosystem function and biotechnological promise):** Microorganisms across the Andes occupy multiple extreme niches (high altitude, intense UV, salinity, temperature and metal stress) and include thermophiles, halophiles, acidophiles, alkaliphiles, xerotolerant and radiation-resistant microbes (Valdebenito-Rolack *et al*., 2017; Orellana *et al*., 2018). Studies carried out in the northern Andes of Chile indicate that these extremophile microorganisms are both scientifically and biotechnologically invaluable. Research on soils from the Altiplano highlands' microbiome suggests a significant reservoir of endemic, yet undescribed microbial diversity, representing previously uncharacterised genetic potential (Maza *et al*., 2019). High-altitude lakes there harbour salt- and UV-tolerant communities dominated by Proteobacteria and Bacteroidetes, with a large fraction of unclassified taxa and clear biotechnological and bioremediation potential (Escudero *et al*., 2007; Demergasso *et al*. 2010; Mandakovic *et al*., 2018). Hyper-arid, high-altitude Andean soils contain extraordinarily diverse and largely uncharacterized actinobacterial assemblages, including many candidate higher taxa and an extensive rare biosphere, making them prime targets for taxonomy and bioprospecting (Idris *et al*., 2017; Bull *et al*., 2018). Consequently, hyper arid, high altitude environments of the northern Chilean Andes and Atacama Desert are now seen as priority reservoirs of novel antimicrobial producing bacteria, especially rare actinobacteria (Goodfellow *et al*., 2018), and recent work on high altitude Atacama thermophiles further reveals a vast diversity of mostly unknown antimicrobial and antioxidant metabolites with strong biotechnological promise (Sequeiros *et al*., 2016).

Despite recent studies on cryoconite communities, glacier fed streams and deep proglacial lakes in the southern Patagonian Andes (Table 1), Andean Patagonia's microbiomes remain only patchily documented across its vast environmental gradients. Major biomes-such as most forests, peatlands, agroecosystems, and high mountain wetlands-remain under-represented in the literature, so existing work is concentrated in a few focal systems. Together, these studies indicate that Andean Patagonian mountain habitats support highly diverse, distinct, and spatially structured microbial communities that are tightly coupled to glaciers, vegetation, hydrology, and local climate. They also link glacier retreat driven by climate warming to shifts in local microbial communities and their functioning, and highlight Andean Patagonian yeasts as a valuable, underexplored reservoir of extremophile and industrially relevant strains. These largely pristine habitats host microorganisms adapted to extreme conditions (e.g., low temperatures, intense ultraviolet radiation) with promising and still underexplored biotechnological potential. Moreover, because spatial isolation, strong environmental selection and long-term climatic stability in high-mountain systems promote speciation and endemism (Rahbek

*Table 1. Selected recent microbiological studies from Patagonian Andean mountain habitats*

| Mountain ecosystem type | Main finding | Source |
|---|---|---|
| Glacier cryoconite holes | Bacterial communities resemble global ones but show unusually low cyanobacteria abundance. | Pittino *et al.*, 2023 |
| Glacier-fed streams | Dominant phyla: Proteobacteria, Cyanobacteria, Bacteroidota, Actinobacteriota, Acidobacteriota; composition shifts with glacial influence. | Vega *et al.*, 2023 |
| Deep Andean lakes | Strong glacial influence creates a distinct, environmentally filtered and more modular bacterial community | Modenutti *et al.*, 2023 |
| North Patagonian Andean lakes | Treeline-driven vegetation changes strongly restructure lake bacterial communities and assembly | Bastidas Navarro *et al.*, 2024 |
| Shallow lakes in Northern Patagonian Andes | Distinct bacterial communities in lakes beneath the same *Nothofagus pumilio* forest | Bastidas Navarro, 2022 |
| Acidic lake in northern Patagonia | Microbial communities at the Lake Caviahue water–sediment interface actively drive nutrient cycling. | Cuevas *et al.*, 2024 |
| Soil samples from selected *Nothofagus pumilio* rhizosphere | Soil microbiomes recover after moderate wildfires, supporting *Nothofagus pumilio* post-fire regeneration. | Almonacid-Muñoz *et al.*, 2025 |
| Soil in Northern Patagonian Ice Field | Microbial communities increase and regulate C–N accumulation during 70-year soil development | Alfaro *et al.*, 2020 |
| Glacial ice | Cold-adapted Patagonian glacial yeasts decompose organic matter via diverse cold-active extracellular enzymes. | de Garcia *et al.*, 2012 |
| Bark samples of *Nothofagus pumilio* and *N. dombeyi* | Patagonian wild yeasts show beverage-specific fermentation potential; *Lachancea cidri* outperforms commercial strains | Villarreal *et al.*, 2022 |
| Extra-Andean Patagonia's arid soils | Soils harbor novel antibiotic-producing actinomycetes | Vela Gurovic and Olivera, 2017 |
| Andean–Patagonian peatlands | Andean–Patagonian peatlands as hotspots of testate amoeba diversity | (Fernández *et al.* 2025) |
| Ultraoligotrophic lakes in the North Andean Patagonia | UV radiation stimulates bacterial filamentation in clear Andean lakes, without changing community composition | Corno *et al.*, 2009 |
| Stromata of *Cyttaria* species and the bark of *Nothofagus betuloides* and *N. antarctica* | Novel yeast *Hanseniaspora smithiae* discovered in Patagonian forests, showing distinctive gene-loss-driven metabolic traits. | Čadež *et al.*, 2021 |
| Wild flora of Andes Mountains and Patagonia | Psychrotolerant PGPB bioprospecting reveals novel strains with diverse plant-beneficial activities. | Vega-Celedón *et al.*, 2021 |

*et al.*, 2019), Andean Patagonia is also likely to harbor valuable, novel endemic microbial lineages, with distinctive genomic and functional traits (Čadež *et al.*, 2019; Čadež *et al.*, 2021)

Patagonian Andean ecosystems are now recognized as global hotspots of cold adapted, biotechnologically promising yeasts. The recovery of biotechnologically relevant yeasts from the Andean Patagonian region clearly illustrates the hidden value of this pristine ecosystem and should motivate more extensive, long-term bioprospecting of its microbial biodiversity. Surveys in Argentine and Chilean Andean Patagonian habitats-including forests, glaciers, and soils-have yielded rich communities of cold-adapted yeasts, as well as novel taxa with biotechnological traits suitable for applications in areas such as brewing and other fermented beverages, psychrophilic extracellular enzymes, agriculture and biocontrol (De Garcia *et al.*, 2012; Garcia and Giraudo, 2016; Libkind *et al.*, 2016; Mestre *et al.*, 2016; Burini *et al.*, 2021; Čadež *et al.*, 2021; Villarreal *et al.*, 2022). Research by Vega-Celedón *et al.* (2021) extends the application of Andean microorganisms, demonstrating that bacteria isolated from the phyllosphere and rhizosphere of Andean wild plants exhibit promising plant growth-promoting traits capable of alleviating cold stress in crops.

Casamayor (2017) argues that high mountain lakes in the Pyrenees, Himalaya, Alps, and the western mountains of North America harbor exceptional microbial phylogenetic richness, and that microbes should therefore be considered as a fundamental component of the natural heritage. In line with this view, exploration and research into the biogeochemistry and microbial diversity of the unique Andean Microbial Ecosystems (AMEs) in the Central Andes of South America have been crucial for designating several high-altitude lakes and salt flats as protected areas (Vignale *et al*., 2022). Similarly, Patagonian Andean ecosystems likewise harbor unique and functionally important phylogenetic diversity of microorganisms and are an essential component of the biological richness of these environments. Safeguarding these unique microbial lineages is therefore central not only to preserving their intrinsic biodiversity and ecological functions, but also to avoiding the irreversible loss of genetic resources and ecosystem services that may be vital for future biotechnological innovation and adaptation to environmental change. In this context, continued exploration and bioprospecting efforts targeting microbial diversity in pristine, poorly explored Andean Patagonian ecosystems will remain important for fulfilling these conservation and biotechnological goals.

## Conclusions

Andean and other mountain ecosystems worldwide are already being transformed by anthropogenic climate change and other human disturbances. Andean Patagonia comprises a mosaic of largely pristine, wild mountain ecosystems shaped by steep climatic and altitudinal gradients and minimal direct human disturbance. Nevertheless, existing evidence shows that this region has not escaped climate change and other human impacts (Veblen *et al*. 2011; Kitzberger *et al*. 2022), and these impacts are likely to intensify in coming decades. The Andean-Patagonian region likely harbors largely unexplored, evolutionarily unique microbial lineages that contribute to key ecosystem processes and may be vulnerable to rapid warming, as shown for other mountain microbiomes worldwide (Broadbent *et al*., 2021; Qi *et al*., 2022). Ensuring the conservation of this endemic microbial diversity will safeguard irreplaceable, largely untapped genetic and metabolic resources, which may prove crucial for future biotechnological applications and for ecosystem responses to ongoing climate change. By revealing the ecological and biotechnological value of these endemic microbiomes, future research can complement existing conservation initiatives and provide further tangible arguments for the public and policymakers to protect the unique ecosystems of Andean Patagonia.

## Competing Interests

The authors declare no competing interests.

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**About the Author**

**Sergio Leiva Poveda** is an Associate Professor at the Institute of Biochemistry and Microbiology at the Universidad Austral de Chile (UACh). He began his academic journey at UACh, where he earned a Bachelor's degree in Marine Biology (1995), followed by a Master's degree in Science with a specialisation in Microbiology (1999). He later pursued doctoral studies at Imperial College London, obtaining his Ph.D in 2007. Upon returning to Chile that same year, he joined the Faculty of Sciences at UACh. His research is driven by the goal of uncovering the little-known culturable, cold-adapted bacterial diversity associated with terrestrial and marine environments in Chile, investigating these organisms as novel sources of biosynthetic potential for biotechnological applications. In recent years, he has focused on the phylogenetic diversity of bacterial communities associated with marine macroalgae and other marine biota in southern Chile and Antarctica, as well as the genome-level exploration of novel or rare bacteria, revealing this region as a hidden treasure of microbial diversity and cold-active biotechnological potential.

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