Cold-Tolerant Microbes

Subjects: Microbiology
Contributor: Anita Pandey

Cold adapted microorganisms represent a large fraction of biomass on earth due to the dominance of low temperature environments. Himalaya is one of the most important low temperature environments on Earth because it possess environmental similarities to Polar Regions. The extreme cold environments of Himalaya are mainly dependent on the tiny life forms because of climatic restrictions to higher plants and animals. These cold loving microbes are known to possess several structural and functional adaptations in order to perform various life processes under the stressful low temperature environments. Their biological activities maintain the nutrient flux in environment and contribute in the global biogeochemical cycles. The culture dependent and culture independent studies revealed their diversity in community structure and functional potential. Apart from the ecological importance, these microorganisms have been recognized as a source of cold active enzymes and novel bioactive compounds. These products have several applications in biotechnological industries.

Keywords: Cold-adapted microorganisms ; Himalaya ; Bioprospection ; Extremophiles

1. Introduction

The cold-adaptive microorganisms are recognized as potential source of cold-active enzymes and bioactive compounds[1]. In the present scenario, the industries are diverting towards green chemistry to use enzyme-based reactions rather than involve chemicals such as in the textile industries[2]. Working with enzymes has several advantages, such as less interference on byproducts, reduced energy consumption with negligible pollution, and no compromise of product quality. The cold-active enzymes have shown low activation enthalpy and flexibility in structures. Such thermodynamic parameters help these cold-active enzymes to perform catalytic actions under the low kinetic energy of cold environments[3]. Lipase, cellulase, amylase, invertase, protease, and lignin-degrading enzymes, produced by cold-adaptive microorganisms, have various applications in detergent, food, the pharmaceutical industry, and so forth[4]. Antifreeze proteins from cold-adaptive organisms have also been recognized for their important physiological and biotechnological contributions. They are the group of proteins that control the shape and size of ice crystals and allow the biochemical activities below freezing temperatures. The production of AFPs from different organisms is the result of convergent evolution through the pressure of extreme cold temperature. The AFPs are reported for other industrial applications too[5][6].

2. Bioprospection

The microorganisms colonizing the extreme colder regions are adapted to cope with various stress conditions (limited nutrient availability, radiations, desiccation, etc.) and produce novel metabolites that are absent in the mesophiles. These metabolites have significant importance in various industries such as food, textiles, therapeutics, and so forth[7][8]. Bioactive compounds related to antimicrobial and immunosuppressive activities, for example, have also been isolated from the cold environment microorganisms[9].

The low-temperature environments of Himalaya are seen as a promising source for novel products, bioactive compounds, and other industrially relevant substances/compounds[10][11][12]. Metagenomic investigations reveal the functional potential of the inhabiting soil microbial communities and allow to study the metabolic pathways and interactions associated with the uncultured biological components also[13]. For example, cold-active enzymes (amylases, endocellulases) were obtained from the clone library and are highly active at low temperatures[14][15]. These low-temperature active products can be used in industries to reduce energy consumption. Apart from this, the multicopper enzymes, well known as versatile and efficient tools against a range of complex compounds, are highly distributed in the region. Potential to produce laccase enzyme from the cold-adapted microorganisms of glacial sites and the hot springs of Himalaya have been reported through culture-dependent and culture-independent methods[16][17]. The cold-adapted microorganisms of Himalayan soils have also been reported as an abundant source of diverse cold-active lipases[18][19] that have importance in bioremediation, food industries, and cleaning industries[20]. The Himalayan soils are found to possess high diversity of bacteria that produce carbonic anhydrase, which is an important candidate for investigations related to carbon sequestration[21]. Among the microorganisms, cold-adapted yeasts are recognized as an important group for their survival strategies and biotechnological benefits[22]. There are some records available on these single-cell eukaryotes from Himalaya; however, more investigations are awaited for their ecological contributions[23].

Not only the biotechnological benefits but also the inhabiting cold loving microorganisms contribute to several ecological processes in different ecosystems located in Himalaya (Figure 1). In the environmental importance, biodegradation and agriculture (such as plant growth promoting activities and biocontrol) under the colder regions are well supported by the inhabiting microbes[24][25]. These microorganisms have the capability to degrade a range of compounds that have been identified as strong agents in bioremediation. They are also involved in the carbon cycle and contribute in the energy flux in the environment. *Pseudomonas*, *Acinetobacter*, *Rhodococcus*, *Bacillus*, and *Sphingobium* have been found to contribute significantly to the degradation of complex hydrocarbons (such as petroleum products) under low-temperature environments[26][27][28][29]. The presence of a particular hydrocarbon compound also affects the environment on the ecological ground. For example, a colder area (China–Russia) contaminated with petroleum revealed the microbial shifts and the abundance of efficient degraders (endemic communities)[30].

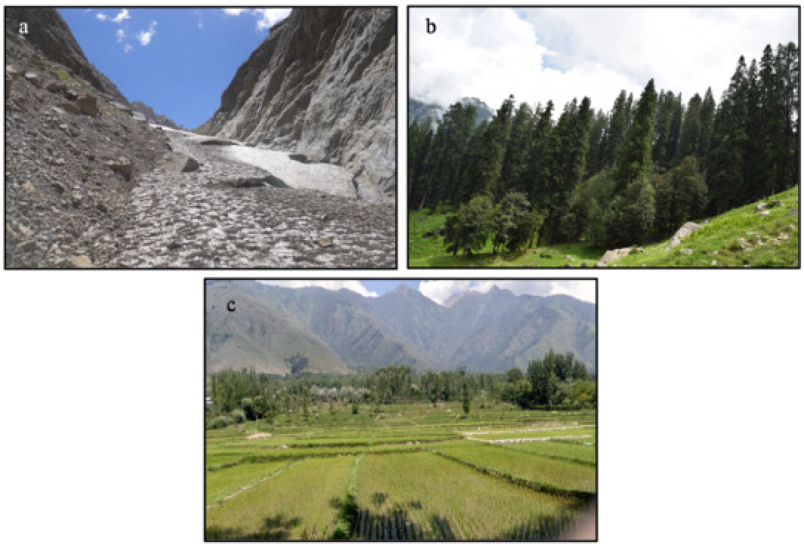

Figure 1. Ecological processes regulated by cold-adapted microorganisms in different ecosystems. (**a**) Biogeochemical cycles in the barren lands of glacial regions (>3500 m asl). (**b**) Nutrient cycles/energy flow in the high-altitude forests. (**c**) Agriculture system under the low-temperature regions of mountains (Photo credit: Khashti Dasila).

The biodegradation process in low-temperature environments is very slow and restricted. Organic carbon is sequestered and accumulates in these environments (in the form of lignocellulosic material). These cold-adapted bacteria were also found to possess different hydrolytic enzymatic activities indicating their contribution in the cycling of nutrients including carbon[31][32][33]. Studies from Indian Himalaya have proved that the associated psychrotolerant spp. (bacteria and fungi) have the potential to produce lignin-degrading enzymes at a wide range of temperature and pH[16][34] (Figure 2).

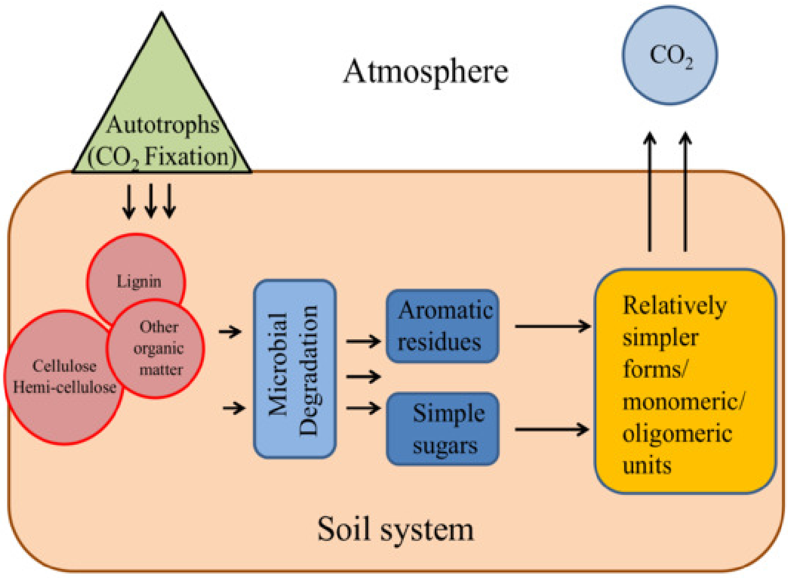

Figure 2. Conversion of different forms of carbon through microbial activities under the biodegradation process.

Apart from degradation, the inhabiting microbial communities have shown their immense contribution to improve the agriculture in low to extreme low temperature environments of Himalaya. These psychrotrophic/psychrophilic microorganisms have been reported for their potential in plant growth promotion activities. They are found to possess activities, such as phosphate solubilization, indole acetic acid production, and siderophore secretion, that are useful in agriculture under low-temperature environments[35][36]. In the recent two decades, several researchers have published the potential utilization of microbial strains from Indian Himalaya. *Rhodococcus*, *Pseudomonas*, *Bacillus*, *Serratia*, and Ascomycetous fungi (*Trichoderma*, *Aspergillus*, *Penicillium*) have been recognized as promising candidates in agriculture and forestry[25][37][38][39][40], but they need further attention for obtaining a form of valuable product. Recently, a strain of *Stenotrophomonas* with multiple plant growth promoting activities and possibilities to utilize as biofertilizer has been reported[41]. In last few years, a range of endophytes have been isolated and screened for their importance in agriculture under the low-temperature environments of Himalaya[42][43]; except for this, they have also been recognized as a good source of antimicrobial compounds[44]. Towards ecological aspects, the specific dark septate endophytes have been also investigated from the high altitude of Himalaya, and they await their recognition for their role as indicators of the changing climate under the mountain ecosystem[45]. By considering the ecological and biotechnological importance of the endophytes, it is important to investigate this group effectively because they are likely to be the important players that help in the nutrient flux between soil and plants (especially in the nutrient-poor soils of high altitudes of Himalaya).

Additional information on the taxonomic and functional aspects of microbial communities of Himalayan regions is provided in Table 1.

Table 1. Taxonomic and functional information associated with the microbial communities of Himalayan region.

Serial. No.	Location	Microorganisms	Report	References
1	Northwestern Himalaya, India	Fungi	Plant growth promoting activities of *Penicillium* spp.	[46]
2	Uttarakhand, India	Bacteria	Antagonistic activity	[47]
3	Uttarakhand, India	Bacteria	Thermophiles from hot springs	[48]
4	Uttarakhand, India	Bacteria	Plant growth promoting activities	[49]
5	Kargil, India	Bacteria	Cold-active amylases (culture independent)	[15]
6	Annapurna and Sagarmatha region, Nepal	Microbial communities	Microbial biomass and associated ecological processes	[50]
7	Langtang Valley, Nepal	Bacteria	Bacterial diversity of glaciers (culture independent)	[51]
8	North-Central Nepal	Phototrophs	Diversity of cyanobacteria and Chlorophyceae (culture independent)	[52]
9	Arunachal Pradesh, India	Fungi	Antimicrobial activity	[53]
10	Northeast India	Bacteria	Bacterial diversity (culture dependent)	[54]

11	Uttarakhand, India	Microbial communities	Comparative study of soil microbial communities by PLFA (culture independent)	[55]
12	Northwestern Himalayas, India	Bacteria	Plant growth promoting activities of *Pseudomonas*	[56]
13	Khumbu Valley, Nepal	Micro-eukaryotes	Planktonic diversity (culture independent)	[57]
14	Uttarakhand, India	Bacteria	Plant growth promoting activities	[58]
15	Himachal Pradesh, India	Bacteria	Plant growth promoting activities (culture dependent)	[35]
16	Ladakh, India	Bacteria	Cyanobacterial communities	[59]
17	Uttarakhand, India	Functional aspect of bacterial communities	Distribution of *nifH* gene through metagenomics	[60]
18	Ladakh, India	Microbial communities	Metagenomics based study of Pangong lake water	[61]
19	Indian Himalaya (Himachal Pradesh and Sikkim)	Bacteria	Potential of hot spring inhabiting bacteria to produce thermostable enzymes (culture dependent)	[62]
20	Khumbu Valley, Nepal	Bacteria	Bacterial diversity associated to snow (culture independent)	[63]
21	Uttarakhand, India	Microbial communities	Microbial biomass associated to the forests and their relation to ecological processes	[64]
22	Ladakh, India	Bacteria	Metagenomics	[65]
23	Himachal Pradesh, India	Bacteria	Bioplastic-producing bacterial communities (culture independent)	[66]
24	Sikkim, India	Bacteria	Contribution of thermophiles in nitrogen and sulfur cycle	[67]
25	Indian Himalaya	Bacteria and fungi	Degradation potential of cryoconites inhabiting microbial communities (culture dependent)	[68]
26	Himachal Pradesh, India	Bacterial and Archaeal viruses	Abundance of viruses in the Manikaran hot spring through metagenomics	[69]
27	Sikkim, India	Bacteria	Culture-dependent diversity	[70]

28	Northwestern Himalaya, India	Cyanobacteria	Diversity of cyanobacteria in hot spring (culture dependent)	[71]
29	Himachal Pradesh, India	Bacteria	Cellulolytic potential	[72]
30	Himachal Pradesh, India	Bacteria	Potential to degrade enzymes from bacteria colonizing hot spring	[73]
31	Himachal Pradesh and Uttarakhand, India	Bacteria	CO_2 mineralization through carbonic anhydrase	[21]
32	Uttarakhand, India	Bacteria	Potential of cold-tolerant bacteria in hill agriculture (culture independent)	[74]
33	Himachal Pradesh, India	Bacteria and Archaea	Taxonomic and functional potential of hyperthermophiles through metagenomics	[75]
34	Sikkim, India	Bacteria	Culture-independent diversity	[76]
35	Uttarakhand, India	Actinomycetes	Antimicrobial activity	[77]

References

1. Rosa Margesin; G Feller; Biotechnological applications of psychrophiles. *Environmental Technology* **2010**, *31*, 835-844, 10.1080/09593331003663328.
2. Abdul Razzaq; Sadia Shamsi; Arfan Ali; Qurban Ali; Muhammad Sajjad; Arif Malik; Muhammad Ashraf; Microbial Proteases Applications.. *Frontiers in Bioengineering and Biotechnology* **2019**, *7*, 110, 10.3389/fbioe.2019.00110.
3. Ricardo Cavicchioli; T. Charlton; H. Ertan; S. Mohd Omar; Khawar Siddiqui; T. J. Williams; Biotechnological uses of enzymes from psychrophiles. *Microbial Biotechnology* **2011**, *4*, 449-460, 10.1111/j.1751-7915.2011.00258.x.
4. Gomes, J.; Steiner, W.; Extremophiles and Extremozymes. *Food Technol. Biotechnol.* **2004**, *42*, 223–235, .
5. Hak Jun Kim; Jun Hyuck Lee; Young Baek Hur; Chang Woo Lee; Sun-Ha Park; Bon-Won Koo; Marine Antifreeze Proteins: Structure, Function, and Application to Cryopreservation as a Potential Cryoprotectant. *Marine Drugs* **2017**, *15*, 27, 10.3390/md15020027.
6. S. Venketesh; C. Dayananda; Properties, Potentials, and Prospects of Antifreeze Proteins. *Critical Reviews in Biotechnology* **2008**, *28*, 57-82, 10.1080/07388550801891152.
7. Anna Bratchkova; Veneta Ivanova; Bioactive Metabolites Produced by Microorganisms Collected in Antarctica and the Arctic. *Biotechnology & Biotechnological Equipment* **2011**, *25*, 1-7, 10.5504/bbeq.2011.0116.
8. Giudice, A.L.; Fani, R.. Biotechnology of Extremophiles; Rampelotto, P.H., Eds.; Springer International Publishing: New York, NY, USA, 2016; pp. 83-115.
9. Yuan Tian; Yan-Ling Li; Feng-Chun Zhao; Secondary Metabolites from Polar Organisms. *Marine Drugs* **2017**, *15*, 28, 10.3390/md15030028.
10. Klára Řeháková; Katerina Capkova; Pavel Hrouzek; Michal Koblizek; Jiri Dolezal; Microbial photosynthetic and photoprotective pigments in Himalayan soils originating from different elevations and successional stages. *Soil Biology and Biochemistry* **2019**, *132*, 153-164, 10.1016/j.soilbio.2019.02.008.
11. Anita Pandey; Kusum Dhakar; Rahul Jain; Neha Pandey; Vijai K. Gupta; Rinu Kooliyottil; Ashish Dhyani; Mukesh K. Malviya; Priyanka Adhikari; Cold Adapted Fungi from Indian Himalaya: Untapped Source for Bioprospecting. *Proceedings of the National Academy of Sciences, India Section B: Biological Sciences* **2018**, *89*, 1125-1132, 10.1007/s40011-018-1002-0.

12. A. S. Panwar; D. Molpa; Gopal Krishna Joshi; Biotechnological Potential of Some Cold-Adapted Bacteria Isolated from North-Western Himalaya. *Microbiology* **2019**, *88*, 343-352, 10.1134/s002626171903007x.

13. Jan Vester; Mikkel Andreas Glaring; Peter Stougaard; Improved cultivation and metagenomics as new tools for bioprospecting in cold environments.. *Extremophiles* **2014**, *19*, 17-29, 10.1007/s00792-014-0704-3.

14. Archana Bhat; Syed Riyaz-Ul-Hassan; Nasier Ahmad; Nidhi Srivastava; Sarojini Johri; Isolation of cold-active, acidic endocellulase from Ladakh soil by functional metagenomics. *Extremophiles* **2013**, *17*, 229-239, 10.1007/s00792-012-0510-8.

15. Sarika Sharma; Farrah Gul Khan; Ghulam Nabi Qazi; Molecular cloning and characterization of amylase from soil metagenomic library derived from Northwestern Himalayas. *Applied Microbiology and Biotechnology* **2010**, *86*, 1821-1828, 10.1007/s00253-009-2404-y.

16. Gaurav Singh Kaira; Kusum Dhakar; Anita Pandey; A psychrotolerant strain of Serratia marcescens (MTCC 4822) produces laccase at wide temperature and pH range.. *AMB Express* **2015**, *5*, 92, 10.1186/s13568-014-0092-1.

17. Vijaya Gupta; Naveen Gupta; Neena Capalash; Prince Sharma; Bio-prospecting Bacterial Diversity of Hot Springs in Northern Himalayan Region of India for Laccases. *Indian Journal of Microbiology* **2017**, *57*, 285-291, 10.1007/s12088-017-0656-2.

18. Babu Joseph; Nitisha Shrivastava; Pramod W. Ramteke; Extracellular cold-active lipase of Microbacterium luteolum isolated from Gangotri glacier, western Himalaya: Isolation, partial purification and characterization. *Journal of Genetic Engineering and Biotechnology* **2012**, *10*, 137-144, 10.1016/j.jgeb.2012.02.001.

19. Rahul Jain; Anita Pandey; Mukesh Pasupuleti; Veena Pande; Prolonged Production and Aggregation Complexity of Cold-Active Lipase from Pseudomonas proteolytica (GBPI_Hb61) Isolated from Cold Desert Himalaya. *Molecular Biotechnology* **2016**, *59*, 34-45, 10.1007/s12033-016-9989-z.

20. M. Kavitha; Cold active lipases – an update. *Frontiers in Life Science* **2016**, *9*, 226–238, 10.1080/21553769.2016.1209134.

21. Anand Giri; Deepak Pant; CO2 management using carbonic anhydrase producing microbes from western Indian Himalaya. *Bioresource Technology Reports* **2019**, *8*, 100320, 10.1016/j.biteb.2019.100320.

22. Buzzini, P.; Margesin, R. . Cold-adapted Yeasts; Buzzini, P., Margesin, R., Eds.; Springer: Berlin/Heidelberg, Germany,, 2014; pp. 3–22.

23. Manman Wang; Jianqing Tian; Meichun Xiang; Xingzhong Liu; Living strategy of cold-adapted fungi with the reference to several representative species. *Mycology* **2017**, *8*, 178-188, 10.1080/21501203.2017.1370429.

24. Paula M. Tribelli; Nancy I. López; Reporting Key Features in Cold-Adapted Bacteria. *Life* **2018**, *8*, 8, 10.3390/life8010008.

25. Anita Pandey; Luis Andr´´es Yarzábal; Bioprospecting cold-adapted plant growth promoting microorganisms from mountain environments. *Applied Microbiology and Biotechnology* **2018**, *103*, 643-657, 10.1007/s00253-018-9515-2.

26. S. Bisht; P. Pandey; G. Kaur; Himanshu Aggarwal; A. Sood; S. Sharma; V. Kumar; N.S. Bisht; Utilization of endophytic strain Bacillus sp. SBER3 for biodegradation of polyaromatic hydrocarbons (PAH) in soil model system. *European Journal of Soil Biology* **2014**, *60*, 67-76, 10.1016/j.ejsobi.2013.10.009.

27. Rishi Mahajan; Shalini Verma; Madhulika Kushwaha; Dharam Singh; Yusuf Akhter; Subhankar Chatterjee; Biodegradation of di-n-butyl phthalate by psychrotolerant Sphingobium yanoikuyae strain P4 and protein structural analysis of carboxylesterase involved in the pathway. *International Journal of Biological Macromolecules* **2019**, *122*, 806-816, 10.1016/j.ijbiomac.2018.10.225.

28. Rosa Margesin; Alpine microorganisms: useful tools for low-temperature bioremediation.. *Journal of Microbiology* **2007**, *45*, 281–285, .

29. Rosa Margesin; F. Schinner; Biodegradation and bioremediation of hydrocarbons in extreme environments.. *Applied Microbiology and Biotechnology* **2001**, *56*, 650-663, 10.1007/s002530100701.

30. Guang Li Yang; Shu Gui Hou; Ri Le Baoge; Zhi Guo Li; Hao Xu; Ya Ping Liu; Wen Tao Du; Yong Qin Liu; Differences in Bacterial Diversity and Communities Between Glacial Snow and Glacial Soil on the Chongce Ice Cap, West Kunlun Mountains. *Scientific Reports* **2016**, *6*, 36548, 10.1038/srep36548.

31. Siddarthan Venkatachalam; Vasudevan Gowdaman; Solai Ramatchandirane Prabagaran; Culturable and Culture-Independent Bacterial Diversity and the Prevalence of Cold-Adapted Enzymes from the Himalayan Mountain Ranges of India and Nepal. *Microbial Ecology* **2014**, *69*, 472-491, 10.1007/s00248-014-0476-4.

32. Pooja Gangwar; Syed Imteyaz Alam; Sunita Bansod; Lokendra Singh; Bacterial diversity of soil samples from the western Himalayas, India. *Canadian Journal of Microbiology* **2009**, *55*, 564-577, 10.1139/w09-011.

33. Diego Javier Jiménez; José Montaña; Diana Alvarez; Sandra Baena; A novel cold active esterase derived from Colombian high Andean forest soil metagenome. *World Journal of Microbiology and Biotechnology* **2011**, *28*, 361-370, 10.1007/s11274-011-0828-x.

34. Kusum Dhakar; Anita Pandey; Laccase Production from a Temperature and pH Tolerant Fungal Strain ofTrametes hirsuta(MTCC 11397). *Enzyme Research* **2013**, *2013*, 869062, 10.1155/2013/869062.

35. Ajar Nath Yadav; Shashwati Ghosh Sachan; Priyanka Verma; Anil K. Saxena; Prospecting cold deserts of north western Himalayas for microbial diversity and plant growth promoting attributes. *Journal of Bioscience and Bioengineering* **2015**, *119*, 683-693, 10.1016/j.jbiosc.2014.11.006.

36. Rahul Jain; Anita Pandey; A phenazine-1-carboxylic acid producing polyextremophilic Pseudomonas chlororaphis (MCC2693) strain, isolated from mountain ecosystem, possesses biocontrol and plant growth promotion abilities. *Microbiological Research* **2016**, *190*, 63-71, 10.1016/j.micres.2016.04.017.

37. Trivedi, P.; Pandey, P.; Sa, T. Chromate reducing and plant growth promoting activities of psychrotrophic Rhodococcus erythropolis MTCC 7905. J. Basic Microbiol. 2007, 47, 513–517.

38. Selvakumar, G.; Mohan, M.; Kundu, S.; Gupta, A.D.; Joshi, P.; Nazim, S.; Gupta, H.S. Cold tolerance and plant growth promotion potential of Serratia marcescens strain SRM (MTCC 8708) isolated from flowers of summer squash (Cucurbita pepo). Lett. Appl. Microbiol. 2008, 46, 171–175.

39. Suyal, D.C.; Shukla, A.; Goel, R. Growth promotory potential of the cold adapted diazotroph Pseudomonas migulae S10724 against native green gram (Vigna radiata (L.) Wilczek). 3 Biotech 2014, 4, 665–668.

40. K. Rinu; Mukesh Kumar Malviya; Priyanka Sati; S. C. Tiwari; Anita Pandey; Response of Cold-Tolerant Aspergillus spp. to Solubilization of Fe and Al Phosphate in Presence of Different Nutritional Sources. *ISRN Soil Science* **2013**, *2013*, 1-10, 10.1155/2013/598541.

41. Kumar, A.; Soni, R.; Kanwar, S.S.; Pabbi, S; Stenotrophomonas: A versatile diazotrophic bacteria from the rhizospheric soils of Western Himalayas and development of its liquid biofertilizer formulation. *Vegetos* **2019**, *32*, 103–109, .

42. Dina Barman; Mamtaj S. Dkhar; Plant Growth-Promoting Potential of Endophytic Bacteria Isolated from Costus speciosus in Tropical Deciduous Forest of Eastern Himalaya. *Proceedings of the National Academy of Sciences, India Section B: Biological Sciences* **2019**, *89*, 841-852, 10.1007/s40011-018-0998-5.

43. Priyanka Adhikari; Neha Pandey; Phosphate solubilization potential of endophytic fungi isolated from Taxus wallichiana Zucc. roots. *Rhizosphere* **2019**, *9*, 2-9, 10.1016/j.rhisph.2018.11.002.

44. Palak Arora; Zahoor A. Wani; Tanveer Ahmad; Phalisteen Sultan; Suphla Gupta; Syed Riyaz-Ul-Hassan; Community structure, spatial distribution, diversity and functional characterization of culturable endophytic fungi associated with Glycyrrhiza glabra L.. *Fungal Biology* **2019**, *123*, 373-383, 10.1016/j.funbio.2019.02.003.

45. Anita Pandey; Are dark septate endophytes bioindicators of climate in mountain ecosystems?. *Rhizosphere* **2019**, *9*, 110-111, 10.1016/j.rhisph.2019.01.001.

46. Anita Pandey; Namrata Das; Bhavesh Kumar; K. Rinu; Pankaj Trivedi; Phosphate solubilization by Penicillium spp. isolated from soil samples of Indian Himalayan region. *World Journal of Microbiology and Biotechnology* **2007**, *24*, 97-102, 10.1007/s11274-007-9444-1.

47. Govindan Selvakumar; Piyush Joshi; Sehar Nazim; Pankaj K. Mishra; Samaresh Kundu; Hari S. Gupta; Exiguobacterium acetylicum strain 1P (MTCC 8707) a novel bacterial antagonist from the North Western Indian Himalayas. *World Journal of Microbiology and Biotechnology* **2008**, *25*, 131-137, 10.1007/s11274-008-9874-4.

48. Avinash Sharma; Anita Pandey; Yogesh Shouche; Bhavesh Kumar; Girish Kulkarni; Characterization and identification ofGeobacillusspp. isolated from Soldhar hot spring site of Garhwal Himalaya, India. *Journal of Basic Microbiology* **2009**, *49*, 187-194, 10.1002/jobm.200800194.

49. Joshi, P.; Bhatt, A.B.; Diversity and function of plant growth promoting rhizobacteria associated with wheat rhizosphere in North Himalayan Region. *Int. J. Environ. Sci.* **2010**, *1*, 1135–1143, .

50. Andrew J. King; Debendra Karki; Laszlo Nagy; Adina Racoviteanu; Steve K Schmidt; Microbial biomass and activity in high elevation (>5100 meters) soils from the Annapurna and Sagarmatha regions of the Nepalese Himalayas. *Himalayan Journal of Sciences* **2011**, *6*, 11-18, 10.3126/hjs.v6i8.2303.

51. Yongqin Liu; Tandong Yao; Nianzhi Jiao; Lide Tian; Anyi Hu; Wusheng Yu; Shenghai Li; Anyi Hu; Microbial diversity in the snow, a moraine lake and a stream in Himalayan glacier. *Extremophiles* **2011**, *15*, 411-421, 10.1007/s00792-011-0372-5.

52. Steven K. Schmidt; R. C. Lynch; A. J. King; D. Karki; Michael Scott Robeson; L. Nagy; M. W. Williams; M. S. Mitter; K. R. Freeman; Phylogeography of microbial phototrophs in the dry valleys of the high Himalayas and Antarctica. *Proceedings of the Royal Society B: Biological Sciences* **2010**, *278*, 702-708, 10.1098/rspb.2010.1254.

53. Tayung, K.; Barik, B.P.; Jha, D.K.; Deka, D.C.; Identification and characterization of antimicrobial metabolite from an endophytic fungus, Fusarium solani isolated from bark of Himalayan yew. *Mycosphere* **2011**, *2*, 203–213, .
54. Nathaniel A. Lyngwi; Khedarani Koijam; D. Sharma; S.R. Joshi; Cultivable bacterial diversity along the altitudinal zonation and vegetation range of tropical Eastern Himalaya.. *Revista de Biología Tropical* **2013**, *61*, 467–490, 10.15517/rbt.v61i1.11141.
55. Arunkumar, K.; Singh, R.D.; Patra, A.K.; Sahu, S.K.; Probing of microbial community structure, dehydrogenase and soil carbon in-relation to different land uses in soils of Ranichauri (Garhwal Himalayas). *Int. J. Curr. Microbiol. App. Sci.* **2013**, *2*, 325–338, .
56. Shekhar Chandra Bisht; Pankaj Kumar Mishra; Gopal Kishna Joshi; Genetic and functional diversity among root-associated psychrotrophic Pseudomonad's isolated from the Himalayan plants. *Archives of Microbiology* **2013**, *195*, 605-615, 10.1007/s00203-013-0908-4.
57. Barbara Kammerlander; Hans-Werner Breiner; Sabine Filker; Ruben Sommaruga; Bettina Sonntag; Thorsten Stoeck; High diversity of protistan plankton communities in remote high mountain lakes in the European Alps and the Himalayan mountains.. *FEMS Microbiology Ecology* **2015**, *91*, fiv010, 10.1093/femsec/fiv010.
58. Deep Chandra Suyal; Anjana Shukla; Reeta Goel; Growth promotory potential of the cold adapted diazotroph Pseudomonas migulae S10724 against native green gram (Vigna radiata (L.) Wilczek).. *3 Biotech* **2014**, *4*, 665-668, 10.1007/s13205-014-0259-0.
59. Kateřina Čapková; Tomáš Hauer; Klára Řeháková; Jiri Dolezal; Some Like it High! Phylogenetic Diversity of High-Elevation Cyanobacterial Community from Biological Soil Crusts of Western Himalaya. *Microbial Ecology* **2016**, *71*, 113-123, 10.1007/s00248-015-0694-4.
60. Ravindra Soni; Deep Chandra Suyal; Santosh Sai; Reeta Goel; Exploration of nifH gene through soil metagenomes of the western Indian Himalayas.. *3 Biotech* **2016**, *6*, 25, 10.1007/s13205-015-0324-3.
61. Rashmi Rathour; Juhi Gupta; Madan Kumar; Moonmoon Hiloidhari; Anil Mehrotra; Indu Shekhar Thakur; Metagenomic Sequencing of Microbial Communities from Brackish Water of Pangong Lake of the Northwest Indian Himalayas. *Genome Announcements* **2017**, *5*, e01029-17, 10.1128/genomeA.01029-17.
62. Harmesh Sahay; Ajar Nath Yadav; Atul Kumar Singh; Surendra Singh; Rajeev Kaushik; Anil K. Saxena; Hot springs of Indian Himalayas: potential sources of microbial diversity and thermostable hydrolytic enzymes. *3 Biotech* **2017**, *7*, 118, 10.1007/s13205-017-0762-1.
63. Roberto Sergio Azzoni; Ilario Tagliaferri; Andrea Franzetti; Christoph Mayer; Astrid Lambrecht; Chiara Compostella; Marco Caccianiga; Umberto Filippo Minora; Carlo Alberto Garzonio; Eraldo Meraldi; et al. Bacterial diversity in snow from mid-latitude mountain areas: Alps, Eastern Anatolia, Karakoram and Himalaya. *Annals of Glaciology* **2018**, *59*, 10-20, 10.1017/aog.2018.18.
64. Kiran Bargali; Vijyeta Manral; Kirtika Padalia; S.S. Bargali; V.P. Upadhyay; Effect of vegetation type and season on microbial biomass carbon in Central Himalayan forest soils, India. *CATENA* **2018**, *171*, 125-135, 10.1016/j.catena.2018.07.001.
65. Garima Bisht; Anuradha Sourirajan; David J. Baumler; Kamal Dev; 16S rRNA Gene Amplicon Data Set-Based Bacterial Diversity in a Water-Soil Sample from Pangong Tso Lake, a High-Altitude Grassland Lake of the Northwest Himalayas. *Microbiology Resource Announcements* **2018**, *7*, e01192-18, 10.1128/MRA.01192-18.
66. Vijay Kumar; Vikas Thakur; Ambika; Sanjay Kumar; Dharam Singh; Bioplastic reservoir of diverse bacterial communities revealed along altitude gradient of Pangi-Chamba trans-Himalayan region. *FEMS Microbiology Letters* **2018**, *365*, null, 10.1093/femsle/fny144.
67. Ishfaq Nabi Najar; Mingma Thundu Sherpa; Sayak Das; Nagendra Thakur; Draft genome sequence of Geobacillus yumthangensis AYN2 sp. nov., a denitrifying and sulfur reducing thermophilic bacterium isolated from the hot springs of Sikkim. *Gene Reports* **2018**, *10*, 162-166, 10.1016/j.genrep.2017.12.007.
68. Aritri Sanyal; Runa Antony; Gautami Samui; Meloth Thamban; Microbial communities and their potential for degradation of dissolved organic carbon in cryoconite hole environments of Himalaya and Antarctica. *Microbiological Research* **2018**, *208*, 32-42, 10.1016/j.micres.2018.01.004.
69. Anukriti Sharma; Matthias Schmidt; Bärbel Kiesel; Nitish K. Mahato; Lauren Cralle; Yogendra Singh; Hans H. Richnow; Jack A. Gilbert; Wyatt Arnold; Rup Lal; et al. Bacterial and Archaeal Viruses of Himalayan Hot Springs at Manikaran Modulate Host Genomes. *Frontiers in Cellular and Infection Microbiology* **2018**, *9*, 3095, 10.3389/fmicb.2018.03095.
70. Mingma Thundu Sherpa; Ishfaq Nabi Najar; Sayak Das; Nagendra Thakur; Bacterial Diversity in an Alpine Debris-Free and Debris-Cover Accumulation Zone Glacier Ice, North Sikkim, India. *Indian Journal of Microbiology* **2018**, *58*, 470-478, 10.1007/s12088-018-0747-8.

71. Yadvinder Singh; Arvind Gulati; D.P. Singh; Jis Khattar; Cyanobacterial community structure in hot water springs of Indian North-Western Himalayas: A morphological, molecular and ecological approach. *Algal Research* **2018**, *29*, 179-192, 10.1016/j.algal.2017.11.023.
72. Vikas Thakur; Vijay Kumar; Sanjay Kumar; Dharam Singh; Diverse culturable bacterial communities with cellulolytic potential revealed from pristine habitat in Indian trans-Himalaya. *Canadian Journal of Microbiology* **2018**, *64*, 798-808, 10.1139/cjm-2017-0754.
73. Ritika Verma; Aditya Bhalla; Sudhir Kumar; Valorization of Lignocellulosic Residues for Cost-Effective Production of Thermo-Alkali-Stable Xylanase by Geobacillus thermodenitrificans X1 of Indian Himalayan Hot Spring. *Waste and Biomass Valorization* **2018**, *11*, 1–11, 10.1007/s12649-018-0402-y.
74. Saurabh Kumar; Deep Chandra Suyal; Amit Yadav; Yogesh Shouche; Reeta Goel; Microbial diversity and soil physiochemical characteristic of higher altitude. *PLOS ONE* **2019**, *14*, e0213844, 10.1371/journal.pone.0213844.
75. Nitish Kumar Mahato; Anukriti Sharma; Yogendra Singh; Rup Lal; Comparative metagenomic analyses of a high-altitude Himalayan geothermal spring revealed temperature-constrained habitat-specific microbial community and metabolic dynamics. *Archives of Microbiology* **2019**, *201*, 377-388, 10.1007/s00203-018-01616-6.
76. Mingma Thundu Sherpa; Ishfaq Nabi Najar; Sayak Das; Nagendra Thakur; Culture independent bacterial diversity of Changme Khang and Changme Khangpu glaciers of North Sikkim, India. *Environmental Sustainability* **2019**, *2*, 241-253, 10.1007/s42398-019-00067-z.
77. Nidhi Srivastava; Ipsita Nandi; Ahongshangbam Ibeyaima; Sanjay Gupta; Indira P. Sarethy; Microbial diversity of a Himalayan forest and characterization of rare actinomycetes for antimicrobial compounds. *3 Biotech* **2019**, *9*, 27, 10.1007/s13205-018-1556-9.