



Microbial adaptations at higher altitude for sustainable development: A review

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ABSTRACT

The phyllospheric microbiome and rhizosphere, as well as microbial diversity inhabiting harsh environmental conditions, are studied extensively in the hilly regions. Difficult topography, poor infrastructure, and fragile ecosystems characterize hill agroecosystems. Thus, determining the precise process that determines biodiversity becomes extremely challenging. Plant-microbial interactions may explain why plants evolve to survive. Plant-microbial interactions may be a factor for plants' adaptation approach to survive. Thus, plant-microbe interactions are extremely valuable since they are responsible for practically all biological transformations and the generation of consistent and balanced sources of nitrogen, carbon, and other nutrients that aid in the subsequent growth of plant communities. As a result, it aids in nutrient acquisition and accumulation. These plant-microbial interactions also aid in bioremediation and land restoration. As a result, the first processes of soil formation and nutrient input are dependent on the activity of plant-microbe interactions. Those bacteria that can endure the extremely cold climate at higher altitudes are critical for plant development. To survive in harsh environmental circumstances, microorganisms evolved in a variety of environments. As a result, it is critical to discover the powerful microorganisms and the mechanisms that allow them to live under extreme temperature circumstances. Later, similar ideas can be applied by farmers in field experiments for long-term agricultural production in the world's coldest and harshest regions. This paper includes a brief examination of potential plant-microbe interactions as well as adaptive methods employed by plants and microbial biodiversity living in hilly locations.

INTRODUCTION

Significant research notice has been dedicated to cold-adapted microorganisms during the last two decades, considering the approach that such microbes and their enzymes include an enormous possibility for utilization in biotechnology (Kotmier and Sullivan, 1990). There are wide ranges of natural microbial diversity that create a marked influence on universal high-

impact processes such as the carbon, nitrogen, and other sulfur biogeochemical cycles (Golubiewsk and McGinley, 2010; Singh *et al.*, 2020). A considerable portion of the Earth's stratosphere is represented by frigid environments that are colonized by cold-tolerant bacteria known as "psychrophiles." Adverse temperature conditions can have direct or indirect effects on microorganisms. Direct impacts include decreased enzyme activity, slowed development rate, changes in cell composition, and nutritional deficiencies (Singh *et al.*, 2017, 2018, 2019).

The present review focuses on the study of adaptation strategies of microbes to thrive in the extreme conditions of hilly regions. The plant-microbial interactions also help in bioremediation and reclamation of user land. Therefore, it is obvious that the initial processes of soil formation and input of nutrients rely on

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the activity of plant–microbe interactions. Those microorganisms which can withstand the harsh cold environmental condition at higher altitude are very essential for the plants’ development. To sustain in the adverse conditions of the environment microbes evolved in different environmental conditions. Thus, it is very important to identify the potent microbes and the mechanism involved to thrive in extreme temperature conditions, and later these approaches can be adopted by farmers in field trials for the sustainable agricultural production in the cold and harsh areas of the globe. This review provides a brief study of the possible plant–microbe interaction and the adaptation strategies by the plants and microbial biodiversity thriving in the hilly regions.

ADAPTATION STRATEGIES OF BACTERIA TO LOW TEMPERATURES

To withstand a harsh and cold conditions, due to the drop in temperature bacteria tend to adapt various modes of adaptation in the cell at their structural and physiological state to prevent a decrease in the rate of reaction of various enzymes (Tables 1 and 2; Figs. 1 and 2) (D’Amico *et al.*, 2002).

Regulation of membrane fluidity

The membrane is the first line of defense that can sense environmental adjustments and it acts as a barrier between external and inner environments (Chintalapati *et al.*, 2004). The tension is increased within the membranes at cold temperatures, which resulted in the formation of a membrane-associated stimulation and activation of numerous genes concerned with membrane fluidity inflection for change of metabolites from and to the mobile (Shivaji and Prakash, 2010).

Cold-active enzymes

Comparatively to their mesophilic homologues cold-energetic or “cold-tolerant” enzymes are acknowledged to show off a greater catalytic efficacy at lesser temperatures (Samie *et al.*, 2012). In numerous adaptive capabilities developed by way of confined psychrophiles is that to supply enzymes which are extraordinarily bendy in structure and having an up to 10-fold multiplied unique hobby (K_{cat}) than their mesophilic opposite numbers, consequently ensuing in greater touch to the lively site of substrates at decrease temperatures (Gerday *et al.*, 2000). The

Table 1. Taxonomic and functional relationships of microbes associated with various microbial communities present in Himalaya regions.

S. No.	Microorganisms	Report	Location	References
01	Microbial communities	Microbial biomass and associated ecological processes	Annapurna and Sagarmatha region, Nepal	King <i>et al.</i> (2010)
02	Phototrophs	Diversity of Cyanobacteria and	North-Central Nepal	Schmidt <i>et al.</i> (2011)
03	Microbial communities	Comparative study of soil microbial communities by plfa (culture independent)	Uttarakhand, India	Arunkumar <i>et al.</i> (2013)
		Antagonistic Activity		Selvakumar <i>et al.</i> (2009)
		Plant growth promoting activities		Joshi and Bhatt (2010)
		Thermophiles from hot springs	Uttarakhand, India	Sharma <i>et al.</i> (2009)
		Potential of cold-tolerant bacteria in hill agriculture (culture independent)		Kumar <i>et al.</i> (2019)
		Plant growth promoting activities		Joshi and Bhatt (2010)
04	Bacteria	Cold active amylases (culture independent)	Kargil, India	Sharma <i>et al.</i> (2010)
		Bacterial diversity of glaciers (culture independent)	Langtang Valley, Nepal	Liu <i>et al.</i> (2011)
		Bacterial diversity (culture dependent)	Northeast India	Lyngwi <i>et al.</i> (2013)
		Plant growth promoting activities of <i>Pseudomonas</i>	Northwestern Himalayas, India	Bisht <i>et al.</i> (2013)
		Plant growth promoting activities (culture dependent)	Himachal Pradesh, India	Yadav <i>et al.</i> (2015)
		Cyanobacterial communities	Ladakh, India	Capkova <i>et al.</i> (2016)
15	Actinomycetes	Antimicrobial activity	Uttarakhand, India	Tayung <i>et al.</i> (2011)
16	Bacteria and archaea	Taxonomic and functional potential of hyperthermophiles through metagenomics	Himachal Pradesh, India	Mahato <i>et al.</i> (2019)
17	Cyanobacteria	Diversity of Cyanobacteria in hot spring (culture dependent)	Northwestern Himalaya, India	Yadvinder <i>et al.</i> (2018)
18	Bacteria and fungi	Degradation potential of cryoconites inhabiting microbial communities (culture dependent)	Indian Himalaya	Sanyal <i>et al.</i> (2018)
19	Micro-eukaryotes	Planktonic diversity (culture independent)	Khumbu valley, Nepal	Kammerlander <i>et al.</i> (2015)
20	Fungi	Antimicrobial activity	Arunachal Pradesh, India	Shrivastava <i>et al.</i> (2019)
21	Phototrophs	Diversity of Cyanobacteria and Chlorophyceae (culture independent)	North Central, Nepal	Schmidt <i>et al.</i> (2011)

Table 2. List of micro-organisms and the genes and enzymes involved.

S.No.	Microorganism	Gene	Enzyme/protein	Optimum temperature	Location	References
1.	<i>Pseudomonas fluorescens</i>	SIK W1, PR3	Proteinase and lipase	5°C	Himalyan region	Olson and Nottingham (1980)
2.	<i>Aspergillus oryzae</i> , <i>Aspergillus flavus</i>	AMY1A, bglA, xynA, chi, aprII, ce, lcc1, pecT, lpl, lac Z	Amylase, β -glucosidase, xylanase, chitinase, protease, cellulose, laccase, pectinase, lipase and β -galactosidase	4°C	Himalayan cold desert, glaciers, Antarctica, hilly regions of Uttarakhand, ice-capped rivers, and diverse erosional lakes	Yadav <i>et al.</i> (2018)
3.	<i>Aspergillus niger</i> , <i>Aspergillus sydowii</i> and <i>Aspergillus glaucus</i> <i>Paecilomyces hepiali</i>	SBR5	Phosphate solubilising micro-organism	25°C and 14°C	<i>Svalbard archipelago</i> in the arctic place, Indian Himalaya	Rinu and Pandey (2011)
4.	Mesophilic and psychrophilic micro organism	<i>csp</i> genes	CSPS, (Csp A)	5°C–10°C	Himalyan region	Chattopadhyay (2006)
5.	<i>Moraxella</i> sp	afpA	AFPs	5°C	Antarctica region	Raymond and DeVries (1977)
6.	<i>Pseudomonas</i> , <i>Xanthomonas</i> , <i>Pantoea</i> and some fungi	cry	INPs	4°C	Himalyan region	Kawahara (2002)
7.	<i>Fusarium oxysporum</i> , <i>Rhizoctonia solani</i> , <i>Botrytis cinerea</i> , <i>Sclerotium rolfsii</i> , <i>Pythium ultimum</i> , and <i>Phytophthora</i> Sp.,	<i>ackA</i> , <i>epsB</i> , <i>gltA</i> , <i>mdh</i> . and <i>ppc</i> , SBR5, <i>zsb</i> , <i>hen</i> , PAL5 [†] , <i>asbD</i> , <i>asbG</i> , and <i>asbC</i> , <i>nif</i>	Solubilization of potassium, phosphorus, zinc; production of hydrogen cyanide, indole acetic acids, siderophore, gibberellic acid and function in nitrogen fixation, acc deaminase and biocontrol toward <i>Macrophomina phaseolina</i> and <i>Rhizoctonia solani</i>	4°C	Northwest Indian Himalayas,	Arora (2013)
8.	<i>Arthrobacter</i> , <i>Azospirillum</i> , <i>Burkholderia</i> , <i>Bacillus</i> , <i>Burkholderia</i> , <i>Paenibacillus</i> , <i>Pseudomonas</i> , <i>Enterobacter</i> , <i>Methylobacterium</i> , <i>Serratia</i> , and <i>Rhizobium</i>	Zsb, <i>czc</i> , etc.	PGPRs	40°C–55°C	Crop fields and legumes	Verma <i>et al.</i> (2014)
9.	<i>Rahnella</i> sp R3	R- β -Gal, <i>asbD</i> , <i>asbG</i> , and <i>asbC</i>	Siderophores, phytohormones, natural acids, and enzymes together with phytase and acc deaminase in maize, chick pea, barley and pea combs	5°C–10°C	Himalyan region	Yadav <i>et al.</i> (2017)
10.	<i>Serratia marcescens</i> and <i>P. dispersa</i>	PAL5 [†]	Synthesis of IAA	4°C–15°C	Himalyan region	Selvakumar <i>et al.</i> (2008)
11.	<i>Pseudomonas fluorescens</i>	PVD genes (pyoverdines)	Secretion of siderophores, act as a biocontrol agent and to promote the plant growth ability	15°C–30°C	Himalyan region	Moon <i>et al.</i> (2008)

Continued

S.No.	Microorganism	Gene	Enzyme/protein	Optimum temperature	Location	References
12.	Euryarchaeon, <i>Methanogenium frigidum</i> , <i>Halorubrum lacusprofundi</i> , and <i>Cenarchaeum symbiosum</i> , <i>Methanosarcina SMA-21</i> , <i>Methanolobus psychrophilus</i>	UspA and Rad50	DNA protection and repair strategies	4°C	Deep Lake community in Antarctica	Chen <i>et al.</i> (2015)
13.	Streptomyces and Stenotrophomonas sp	Plt, pfl, phi, hcn, ofa, etc.	Oomycin a, amphisin, phenazine, 2,4-diacetylphloroglucinol, tropolone, pyoluteorin, pyrrolnitrin, tensin, and cyclic lipopeptides produced with the aid of pseudomonads and oligomycin A, kanosamine, zwittermicin A, and xanthobaccin			
14.	Lysinibacillus, Pontibacillus, Sporosarcina, Desemzia, Planococcus, Exiguobacterium, Paenibacillus, Jeotgalicoccus, Sinobaca, Virgibacillus, and Staphylococcus	AMY1A, bglA, xynA, chi, aprII, ce, lccI, pecT, lpl, lac Z	Cellulase, xylanase, β-galactosidase, laccase, chitinase, and lipase activity Amylase, β-glucosidase, pectinase, and protease	4°C—15°C	Sub-glacial lakes of NW Indian Himalayas	Yadav <i>et al.</i> (2016)

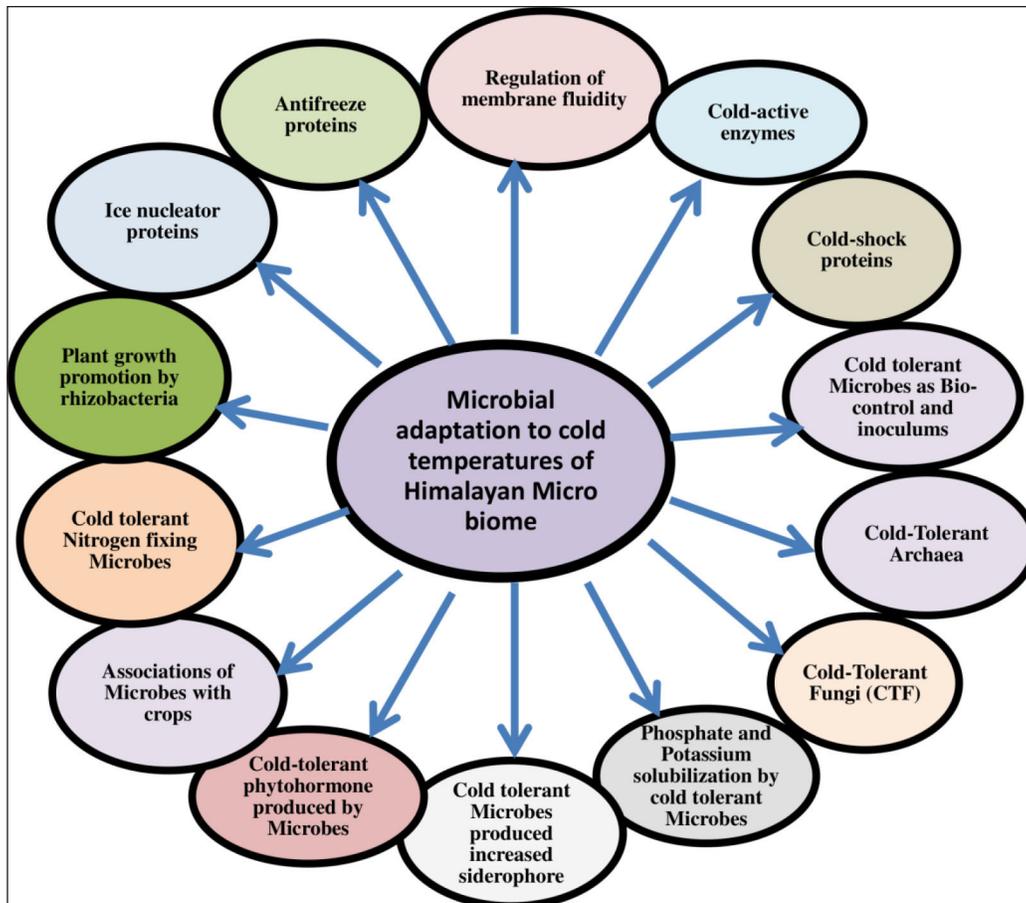


Figure 1. Adaptation strategies of bacteria to low temperatures.

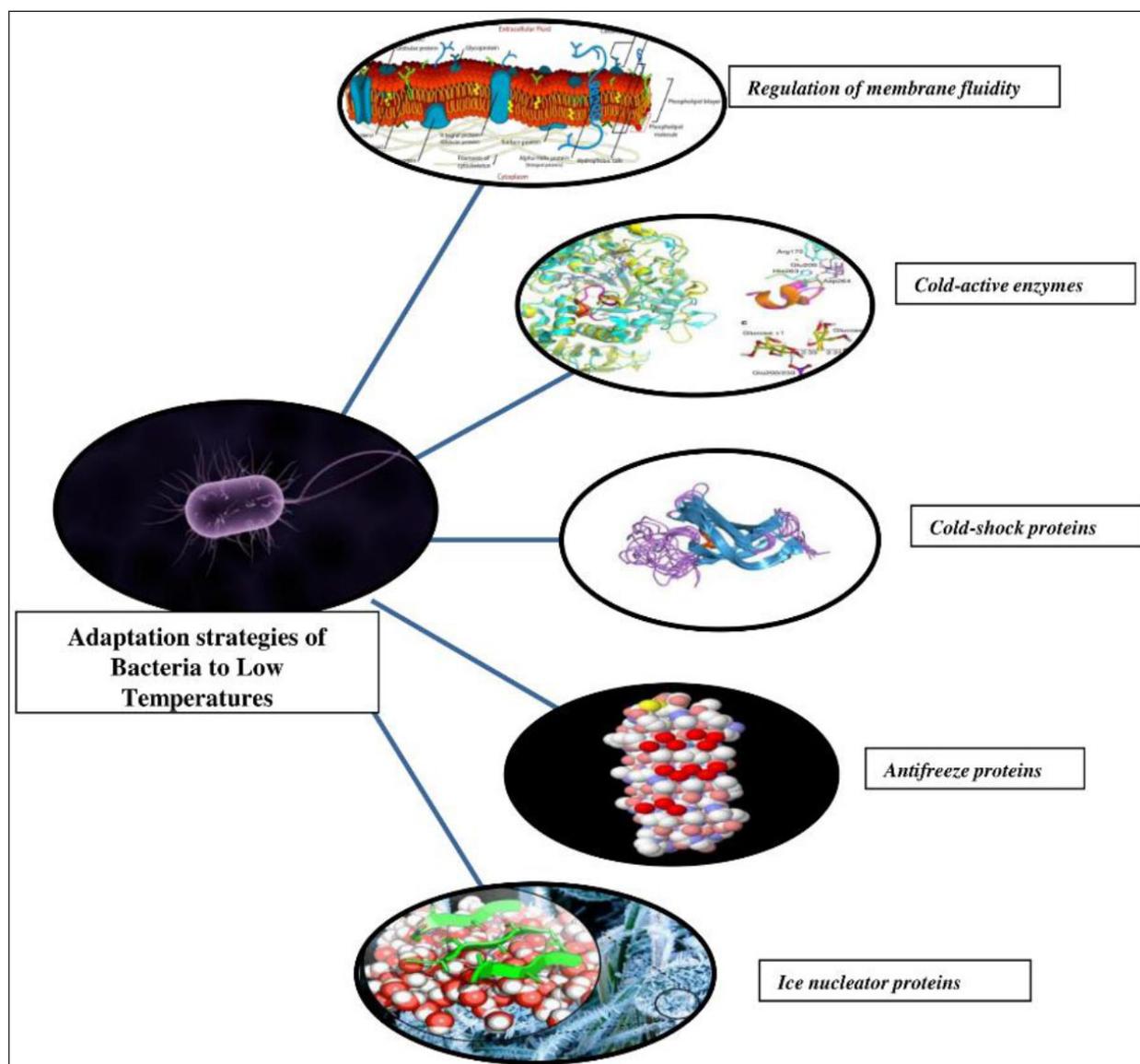


Figure 2. Biochemical changes to low temperatures in bacteria.

viscosity of aqueous surroundings gets expanded below cold conditions so to cope with this circumstance, the plain maximal pastime of cold-tolerant enzymes is displaced at cold temperatures (Hamdan, 2018).

Cold-shock proteins

Cold shock is a situation that is useful in converting the environmental temperature of bacteria from mesophilic situations to a miles lower temperature in a completely quick time of period (Mishra *et al.*, 2011). A protein named cold surprise proteins (CSPS) is determined in every mesophilic and psychrophilic microorganism, which had been swiftly synthesized by way of bacteria to counter cold shock circumstance (Chattopadhyay, 2006). Cold shock response incorporated stimulation of *csp* genes, which sequentially will control the synthesis of cell proteins and mRNA (Mishra *et al.*, 2011)

Antifreeze proteins (AFPs)

AFPs are a bulky cluster of particles that prevent them from freezing the body fluids of plants and animals inhabiting low-temperature environments and affecting the external ice crystals structures (Raymond and DeVries, 1977). At freezing temperatures, these proteins are helpful in preventing of ice crystals from recrystallize, which are harmful to the cell at a lower temperature (Chattopadhyay, 2006).

Ice nucleator proteins (INPs)

INPs are particles that are established onto the outer cell wall of bacteria and resist the processes of diverse nucleation of ice formation which is usual in cold environments, by emulating the ice crystal structure surface. Ices nucleating proteins structure is composed of three distinct domains and was found to make of a repeated contiguously octapeptide chain (Kawahara, 2002). Bacteria consist of ice nucleation active protein on their exterior

cell wall, which are known to work as the nucleating centers which are further known as “ice plus” bacteria (Lee *et al.*, 1995). INPs have been examined in a variety of species of *Pseudomonas*, *Xanthomonas*, *Pantoea*, and some fungi (Kawahara, 2002).

PLANT GROWTH DEVELOPMENT BY RHIZOBACTERIA

The soil which surrounds the roots region is connected bodily, chemically, and botanically through the foundation of the plant and is normally known as rhizobium. This is an extraordinarily encouraging habitat for the improvement of microbes that creates impression on plant strength and soil richness. Frequently plant boom promoting microorganism (plant growth promoting bacteria) is recognized to be the inhabitants of rhizosphere subsequently additionally called plant growth-promoting rhizobacteria (PGPR).

COLD TOLERANT NITROGEN FIXING MICROBES

There are various free-dwelling, symbiotic and associative bacteria that have the potential to supply ammonia by changing atmospheric nitrogen to ammonia, and this practice is acknowledged as biological nitrogen fixation and which is being measured as noteworthy to the world agriculture and environment (Dixon and Kahn, 2004).

RELATIONSHIP OF MICROBES WITH CROPS

A microbe may be very beneficial for a plant with admire to boom, yield, and adaptation. Microbes integrated with plants can be characterized into three agencies, e.g., rhizospheric, phyllospheric, and endophytic. The microbial pastime is significantly relied on soil zones referred to as rhizosphere which is governed with the aid of roots and by the discharge of substrates which influences the microbial interest (Verma *et al.*, 2017).

COLD-TOLERANT PHYTOHORMONE PRODUCED BY MICROBES

An important phytohormone, the auxin, indole-three-acetic acid (IAA) is shaped by way of PGPR, and alertness of auxin-generating rhizobacteria is led to more suitable plant increase (Patten and Glick, 2002). Auxin, IAA act as a large signaling molecule that regulates the plant development at the extent of tropicresponses, organogenesis, mobile responses inclusive of division, mobile expansion and differentiation, and gene regulation (Yadav *et al.*, 2017). Selvakumar *et al.* (2008) examined the isolates from cold-tolerant plant boom promoting bacterial strains *Serratia marcescens* and *Pantoea dispersa* from the north-western Indian Himalayas.

COLD TOLERANT MICROBES PRODUCED INCREASED SIDEROPHORE

Iron is the fourth maximum plentiful element within the earth’s crust and is vital for existence. (Howard,1999). However, its accessibility to each one is very narrow because it gets fast oxidized from ferrous (Fe⁺⁺) to ferric (Fe⁺⁺⁺) kingdom. Ferric ion is extremely nondissolvable beneath positive physiological conditions and makes its attainment through microorganisms an extensive assignment (Neilands, 1995).

PHOSPHATE AND POTASSIUM SOLUBILIZATION BY COLD TOLERANT MICROBES

Rhizospheric microflora is involved in a giant system of phosphate solubilization that is beneficial in promoting plant increase. Phosphate-solubilizing bacteria (PSB), and their utilization as inoculants, enable plant life to uptake and increase the provision of phosphate (Zaidi *et al.*, 2009). *Rhizobium*, *Pseudomonas*, and *Bacillus* are number one PSB used for worthwhile motive (Figs. 3 and 4) (Bossis *et al.*, 2000).

COLD-TOLERANT FUNGI

Arbuscular mycorrhiza (AM) is one of the prevalent symbiotic dating among plant life and fungus. AM fungi discover normally in the natural habitat and they are concerned in several widespread ecological roles, as they are concerned specific in offering plant nutrients, soil corporation, strain resistance, tolerance, and productivity.

COLD-TOLERANT ARCHAEA

Archaea are distinctive microorganisms which are life in ecological areas of negative environment situations like high/low temperature, Ph, and excessive salinity. Archaea are said to undergo loose or connected actions with plant rhizosphere. Archaea belongs to the microorganism this is said as anywhere and live in a vast array of environments, from low temperature (Dong and Chen, 2012) and thermal springs (De león *et al.*, 2013) and those related to diverse plant life (Gaba *et al.*, 2017).

COLD TOLERANT MICROBES AS BIO-CONTROL AND INOCULUMS

Diverse microbes play a position because the secondary machine in plant boom merchandising by way of limiting or saving you the harmful results of pathogens on vegetation by releasing

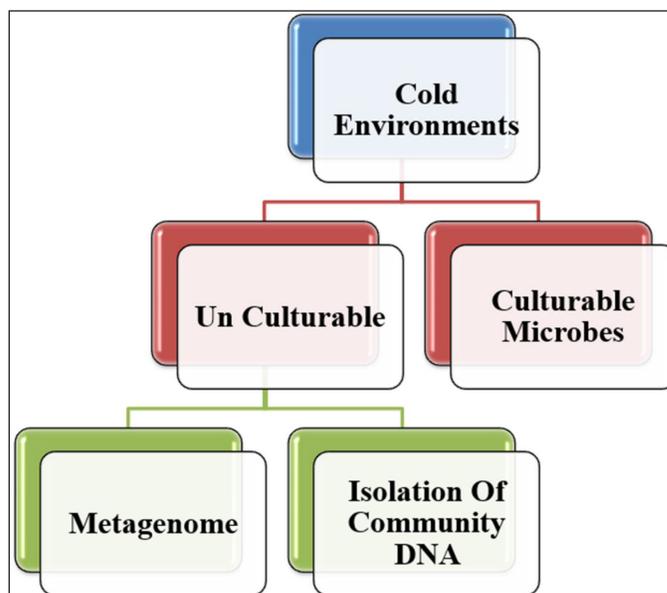


Figure 3. Types of microbes present in cold environments.

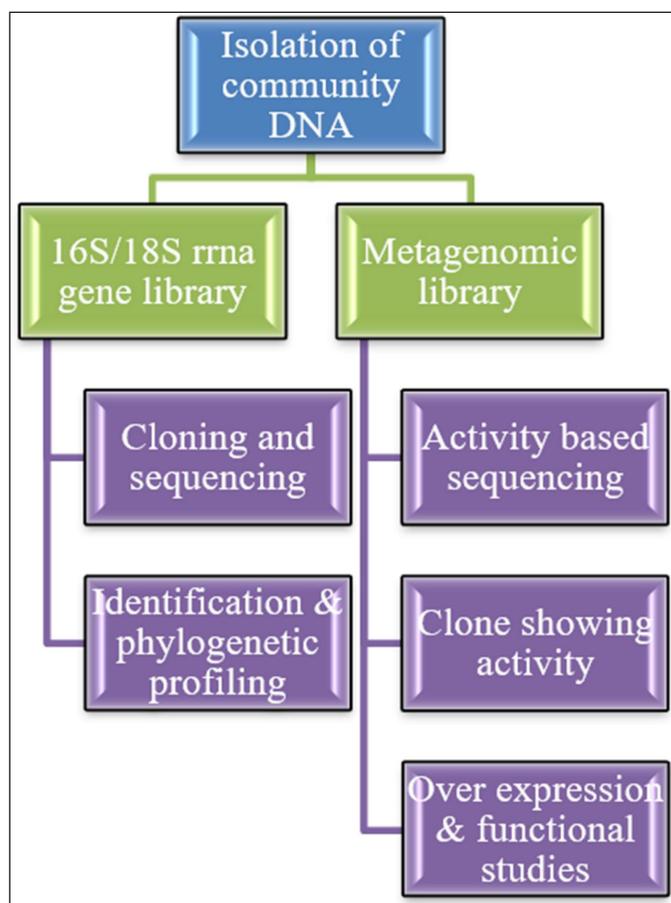


Figure 4. Schematic representation of microbial adaptation to cold temperatures.

inhibitory substances or by raising the immune system of the plants (Vyas *et al.*, 2010).

CONCLUSION

Improvement of agricultural yield in the hilly regions is a chief challenge these days. With this overview, the study of cold-tolerant microbes which are inhabiting the hilly and cold regions offers a way to improve agricultural productivity without using harmful chemicals and insecticides. A number of PGPR species are studied and used to combat cold pressures which can additionally be used to reduce the impact of climate change. The rhizosphere microbiome affords a huge view of understanding plant interactions with bacteria. Because of the excessive variety of microorganisms, it unearths direct touch with a given plant and is consequently able to influence plant resistance and adaptability.

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CONFLICT OF INTEREST

There is no conflict of interest of the authorship.

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DATA AVAILABILITY

All the data generated and analyzed are included within this report.

AUTHOR CONTRIBUTIONS

All authors made substantial contributions to conception and design, acquisition of data, or analysis and interpretation of data; took part in drafting the article or revising it critically for important intellectual content; agreed to submit to the current journal; gave final approval of the version to be published; and agree to be accountable for all aspects of the work. All the authors are eligible to be an author as per the international committee of medical journal editors (ICMJE) requirements/guidelines.

ETHICAL APPROVALS

This study does not involve experiments on animals or human subjects.

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