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Beneficial microbiomes: Biodiversity and potential biotechnological applications for sustainable agriculture and human health

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ABSTRACT

The beneficial microbes plays an important role in medical, industrial, and agricultural processes. The precious microbes belong to different groups including archaea, bacteria, and fungi which can be sort out from different habitat such as extreme environments (acidic, alkaline, drought, pressure, salinity, and temperatures) and associated with plants (epiphytic, endophytic, and rhizospheric) and human. The beneficial microbes exhibited multifunctional plant growth promoting (PGP) attributes such as N_2-fixation, solubilization of micronutrients (phosphorus, potassium and zinc), and production of siderophores, antagonistic substances, antibiotic, auxin, and gibberellins. These microbes could be applied as biofertilizers for native as well as crops growing at diverse extreme habitat. Microbes with PGP attributes of N_2-fixation, P-, and K-solubilization could be used at a place of NPK chemical fertilizers. Agriculturally, important microbes with Fe- and Zn-solubilizing attributes can be used for biofortification of micronutrients in different cereal crops. The biofertilizers are an eco-friendly technology and bioresources for sustainable agriculture and human health. In general, the concentrations of micronutrient in different crops are not adequate for human nutrition in diets. Hence, consumption of such cereal-based diet may result in micronutrient malnutrition and related severe health complications. The biofortification approach is getting much attention to increase the availability of micronutrients, especially Fe and Zn in the major food crops. The beneficial microbes can be used as probiotic as functional foods for human health. Probiotics microbes such as *Bifidobacterium, Lactobacillus, Methanobrevibacter, Methanosphaera,* and *Saccharomyces* are increasingly being used as dietary supplements in functional food products. The microbes with beneficial properties could be utilized for sustainable agriculture and human health.

1. INTRODUCTION

Extreme environments represent unique ecosystems which harbor novel biodiversity of microbes with the ability to survive at diverse environmental conditions. India is one among 12 mega-biodiversity countries and 25 hotspots of the richest and highly endangered eco-regions of the world. The microbiomes of have been reported in diverse environmental habitat such high/low temperature, hypersalinity, water deficiency, and high/low pH. To survive under such extreme conditions, these organisms referred to as extremophiles have developed adaptive features which permits them to grow optimally under one or more environmental extremes, while polyextremophiles grow optimally under multiple conditions. These extremophiles can grow optimally in some of the earth's most unreceptive environments of temperature (−2°-20°C - psychrophiles; 60°-115°C - thermophiles), salinity (2-5M NaCl - halophiles), and pH (<4 acidophiles and >9 - alkaliphiles). Among diverse extreme habitats, thermal springs represent unique ecological niches and harbor both mesophilic and thermophilic members of archaea and bacteria [1-3]. Phylogenetic characterization of microbiota has been undertaken for geothermal springs worldwide. The different thermal springs such as Bakreshwar, Balarampur, Chumathang, Manikaran, and Vashisht are present in India, which represent an unusual niche for thermophilic microbes (60-100°C), which can be potential sources of novel genes, allele, and microbiota [4-6]. Prospecting low-temperature habitats have led to the isolation of a great diversity of psychrophilic/psychrotrophic microbiomes. The Indian Himalayas represent cold habitat a niche for selection of novel psychrotrophic microbes for different biotechnological, agricultural, and industrial applications. Psychrophilic microorganism*s* are potential bioresources of novel pigments (as food additives), extracellular enzymes (amylase, cellulase, chitinase, laccase, lipase, pectinase, protease, xylanase, β-galactosidase, and β-glucosidase),

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exopolysaccharide production, and antifreeze compounds, which can be valuable in agriculture as inoculants (plant growth promoting [PGP] microbes) or biocontrol agents in extreme cold and high altitude habitats [7-9]. Microbial research in hypersaline environments has also attracted the interest of researchers due to various biotechnological and agricultural applications. Soda lakes and deserts represent the most stable naturally occurring alkaline environments on Earth. The different hypersaline lakes such as Sambhar Lake (Rajasthan), Chilka Lake (Odisha), and the Great Rann of Kutch (Gujarat) are typical saline environments in India, and novel and efficient microbiomes from hypersaline environments have been reported and characterized for its biotechnological applications in agriculture, industry, and medicines [10,11].

Water-deficient/low-moisture conditions coupled with high temperatures in arid deserts lead to enrichment of microbial communities that can survive extreme variations in temperature and drought. Such environments encompass typically poor soils with low organic content and limited amounts of bioavailable inorganic nutrients. The desert microbiomes are not only responsible for the productivity, biogeochemical cycling of elements, and ecosystem balance but also for soil neogenesis and improvement of soil structure. The drought-tolerant microbes from hot deserts have been isolated and characterized for PGP under the rainfed conditions [12,13]. Extremes of high (alkaline) and low (acidic) pH also influence the buildup of microbial population and in turn soil productivity. If the soil is acidic, the availability of essential micronutrients such as P, Ca, Mg, and molybdenum are affected. Very few reports are available on the diversity and distribution of microbiomes in acidic soils [14,15]. Another useful extreme environment is the mangrove ecosystems which is mostly nutrient-deficient, especially in terms of N_2 and P. Inspite of this, mangroves can be highly productive, which can be attributed to microbial activity leading to major nutrient transformations [16].

The plant microbiomes can be grouped as rhizospheric microbes (living in soil near the roots), epiphytic microbes (colonizing on the phyllosphere), and endophytic microbes (residing inside tissue). In general, there are three kinds of plant-microbes interactions are considered, i.e., epiphytic, endophytic, and rhizospheric. The rhizosphere is the zone of soil influenced by roots through the release of substrates that affect microbial activity. The rhizospheric microbes have the ability to attach to the root surfaces allowing these to derive maximum benefit from root exudates. The population and abundances of rhizospheric microbes have been affected by several factors such as soil type, soil pH, and other environmental conditions surrounding any plants. A number of microbial species belonging to different genera such as *Acinetobacter*, *Arthrobacter*, *Aspergillus, Azospirillum*, *Bacillus*, *Burkholderia*, *Enterobacter*, *Flavobacterium*, *Haloarcula, Halococcus, Haloferax, Methylobacterium, Paenibacillus, Penicillium, Piriformospora, Pseudomonas*, *Rhizobium,* and *Serratia* were revealed from the rhizosphere of different crop plants [12,17-22].

The phyllosphere is a common and special niche for synergism between microbes and plant. The plant part, especially, leaves are exposed to dust and air currents, resulting in the establishments of typical flora on their surface aided by the cuticles, waxes, and appendages, which help in the anchorage of microbes. The phyllospheric microbes may survive or proliferate on leaves depending on the extent of influences of material in leaf diffusates or exudates. The phyllospheric microbes may perform an effective function in controlling the airborne pathogens inciting plant disease. Microbes on leaf surface are said to be extremophiles as they can tolerate low/high temperature (5–55°C) and UV radiation. Many microbes such as *Achromobacter, Bacillus, Beijerinckia, Burkholderia, Flexibacterium, Methylobacterium, Micrococcus, Micromomospora, Nocardioides, Pantoea, Penicillium, Planomonospora, Pseudomonas, Streptomyces,* and *Xanthomonas* have been reported in the phyllosphere of different crop plants [15,23-27].

The microbes isolated from inside the plant tissues (endophytes) are referred to those microorganisms, which colonize in the inner of the plant parts, namely, root, stem, or seeds without causing any harmful effect on the host plant. Endophytic microbes enter in host plants mainly through wounds, naturally occurring as a result of plant growth or through root hairs and at epidermal conjunctions. Endophytes may be transmitted either vertically (directly from parent to offspring) or horizontally (among individuals). Microbes reach the rhizosphere by chemotaxis toward root exudates components followed by attachment. The preferred site of attachment and subsequent entry are the apical root zone with a thin-walled surface root layer, such as the cell elongation zone and the root hair zone with small cracks caused by the emergence of lateral roots. Microbial traits putatively involved in endophytic colonization of plant roots. For penetration, the microbes have to produce cellulolytic enzymes required to hydrolyze the exodermal walls, such as endoglucanases and endopolygalacturonidases [22]. Endophytic microbes exist within the living tissues of most plant species in the form of symbiotic to slightly pathogenic. A large number of endophytic microbial species such as *Achromobacter, Burkholderia, Burkholderia, Curtobacterium, Enterobacter, Gluconoacetobacter, Herbaspirillum, Klebsiella, Microbiospora, Nocardioides, Pantoea*, *Planomonospora, Pseudomonas*, *Serratia,* and S*treptomyces* have been identified from different host plants [22,28-33].

Abiotic stresses, such as acidity, alkalinity, drought, extremes of low and high temperature, heavy metals, and soil salinity, cause severe yield loss in agricultural crops. There are many reports on microbial diversity from extreme environments, for example, low temperature [9,34-36], high temperature [3-6,37], saline soil [38], drought [39], acidic soil [39], and alkaline soil [11,39]. Microbe isolated and sort out from extreme environments may have exhibited PGP attributes, and thus, these abiotic stress tolerant microbes can be applied for plant growth under respective abiotic stress conditions.

The microbiomes associated with different crops possess multifunctional PGP attributes, and these microbes promote the growth of plant directly by production of plant growth regulators (indole-3-acetic acid, cytokinins, gibberellins, and abscisic acid); biological nitrogen fixation; solubilization of phosphorous, potassium and zinc; or indirectly by production of ACC deaminase, ammonia, antibiotics (2,4-diacetylphloroglucinol, kanosamine, neomycin A, phenazine-1-carboxylic acid, pyocyanin, pyoluteorin, and pyrrolnitrin), hydrocyanic acid (HCN), lytic enzymes (chitinase, lipase protease, β-1,3-glucanase), and siderophores [16]. Currently, there has been an increased curiosity in the development of new functional foods and their assimilation in a healthy diet. Such products, and especially probiotics, exert a beneficial effect on host-gut microbiota after consumption and may be proficient to prevent several diseases. Probiotics are defined as live microbiomes which when administered in ample amounts confer a health benefit on the host. The present review revealed about microbes reported from different source including extreme microbiomes, plant microbiome, human microbiomes, and its biotechnological application in agriculture, industry, and for human health. Microbiomes having multifunctional PGP attributes can be utilized as bio-inoculants for sustainable agriculture.

2. BIODIVERSITY OF BENEFICIAL MICROBIOMES

The extreme environments possess the potential and novel microbial diversity. Among diverse microbiomes, actinobacteria, firmicutes, and proteobacteria are omnipresent in the environment and play a noteworthy role in agriculture, medicine, and industry. Extreme environments can be a source for novel species of microbes, as they can tolerate extremes of pH, temperature, salinity, and moisture stress. The different groups of microbes have been reported as plant microbiomes (epiphytic, endophytic, and rhizospheric) and from different natural and extreme environments worldwide. The microbiomes belong to all three domains archaea, eubacteria, and fungi, which included different phylum mainly: Archaea (Crenarchaeota and Euryarchaeota), bacteria (Actinobacteria, Bacteroidetes, Chloflexi, Cyanobacteria, Firmicutes, and Proteobacteria), and fungi (Ascomycota and Basidiomycota) (Fig. 1). The proteobacteria were further grouped as α-, β-, γ-, and δ-proteobacteria.

The low-temperature habitat represents hot spots of biodiversity, and several novel cold-adapted microbial species have been sort out from cold environments including *Cellulophaga algicola* [40], *Cryobacterium roopkundense* [41], *Exiguobacterium soli* [42], *Flavobacterium frigidarium* [43], *Flavobacterium psychrolimnae* [44], *Glaciimonas frigoris* [45], *Hymenobacter roseosalivarius* [46], *Lacinutrix jangbogonensis* [47], *Massilia eurypsychrophila* [48], *Octadecabacter arcticus* [49], *Oleispira antarctica* [50], *Pedobacter arcticus* [51], *Pseudomonas extremaustralis* [52], *Psychrobacter pocilloporae* [53], *Psychromonas ingrahamii* [54], *Sphingobacterium psychroaquaticum* [55], and *Sphingomonas glacialis* [56]. Along with novel species of psychrotrophic microbes, some microbial species such as *Arthrobacter nicotianae, Brevundimonas terrae, Paenibacillus tylopili,* and *Pseudomonas cedrina* have been isolated and characterized for multifarious PGP attributes at low temperatures from cold deserts of NW Himalayas [7]. In a study by Yadav *et al*. [8], the microbial species *Alishewanella* sp., *Aurantimonas altamirensis, Bacillus baekryungensis, Bacillus marisflavi, Desemzia incerta, Paenibacillus xylanexedens, Pontibacillus* sp., *Providencia* sp., *Pseudomonas frederiksbergensis, Sinobaca beijingensis,* and *Vibrio metschnikovii* have been isolated and characterized for low-temperature tolerance and PGP attributes first time from high altitude and low-temperature environments of Indian Himalayas. Wheat associated psychrotrophic bacteria such as *Arthrobacter methylotrophus* and *Pseudomonas rhodesiae* have been reported first time from wheat growing in North hills zone of India [28]. In a specific search of economically important *Bacillus* and *Bacillus* derived genera (BBDG) at low temperature, various BBDGs such as *Bacillus psychrosaccharolyticus, Bacillus amyloliquefaciens, Bacillus altitudinis, Bacillus muralis, P. tylopili*, *Paenibacillus pabuli*, *Paenibacillus terrae,* and *Paenibacillus lautus* with efficient PGP attributes have been reported first time by Yadav *et al*. [57].

Thermal springs represent extreme niches of microbiomes as bioresources of biotechnologically important microbes with potential applications in industry and agriculture. In the past few decades, several attempts have been made for isolation and characterization of microbiomes of thermal springs present in worldwide. Novel and efficient thermophilic microbes have been isolated and characterized from thermal extreme environments of world such as *Thermotoga elfii* [58], *Thermotoga hypogeal* [59], *Thermoanaerobacter uzonensis* [60], *Bacillus thermophilus* [61], and *Herbinix luporum* [62]. In the study by Yadav *et al*. [39], 195 isolates from Indian hot water springs (Manikaran, Balarampur, Vashisht, Chumathang, and Bakreshwar) have been isolated and characterized for different beneficial attributes of hydrolytic enzymes production and PGP under normal as well as high-temperature conditions. The many niche-specific *Bacillus* and *Bacillus* and derived genera (BBDG) have been reported from thermal spring, for example, *Bacillus fusiformis* (B-10) from Bakreshwar and *Brevibacillus* from Vashisht and Balrampur [39].

Soil salinity is an important limiting factor for PGP of crops, especially in arid and semi-arid regions worldwide. Haloarchaea thrive in hypersaline environments and have ability to survive with salt concentrations approaching saturation. The microbiomes of saline habitats have been isolated and identified to be present in halobacteriaceae family such as *Haloarcula argentinensis, Halobacterium* sp., *Halococcus hamelinensis, Haloferax alexandrines, Haloferax larsenii, Haloferax volcanii, Halolamina pelagic, Halostagnicola kamekurae, Haloterrigena thermotolerans, Natrinema* sp., and *Nanoarchaeum mannanilyticum*. The haloarchaea have been isolated from many halophilic plants growing in hypersaline region of Rann of Kutch and characterized for different PGP attributes under hypersaline conditions [38,63,64]. In study by Yadav *et al*. [8], a large number of halophilic or halotolerant species such as *Bacillus halodurans* (ABSL-8), *Bacillus methanolicus* (ABSL-11), *Ammoniphilus* sp. (ABSL-2), *Halobacillus trueperi* (ABSL-21), *Bacillus vallismortis* (ABSL-23), and *Halobacillus dabanensis* (ABSL-29) from Sambhar lake, *Marinococcus halophilus* (ABK-3) from Rann of Kutch, and *Pontibacillus* sp. (AB-2) from Chilka lake have been reported and characterized for different potential attributes for agriculture, industry, and human welfare.

3. BENEFICIAL MICROBES FOR SUSTAINABLE AGRICULTURE

Plant microbiomes are agriculturally important bioresources for agriculture as beneficial microbes may enhance plant growth and improve plant nutrition uptake through solubilization of P, K, and Zn, nitrogen fixation, and other mechanisms including siderophore production (microbes-mediated biofortification of Fe in different crops). Beneficial microbes may increase crop yields, remove contaminants, inhibit pathogens, and produce fixed nitrogen or novel substances. The growth stimulation by plant microbiomes can be a consequence of biological nitrogen fixation, production of plant growth regulators such as IAA, gibberellic acids, and cytokines, and biocontrol of phytopathogens through the production of antibiotic, antifungal, or antibacterial agents, Fe-chelating compounds production, nutrient competition and induction of acquired host resistance, or enhancing the bioavailability of minerals. Sustainable agriculture requires the use of strategies to increase or maintain the current rate of food production while reducing damage to the environment and human health. The use of plant microbiomes as PGP agents/biofertilizers is an eco-friendly alternative to conventional agricultural technology. There are several ways in which different PGP microbes have been reported to directly facilitate the proliferation of their plant hosts. The PGP microbes can fix atmospheric nitrogen and supply it to plants. The plant microbiomes with multifarious PGP ability synthesize several plant growth regulators that can act to enhance various stages of plant growth; they may have mechanisms for the P, K, and Zn that will become more available for plant growth and development; and they may synthesize some less well-characterized, low-molecular-mass compounds or enzymes that can modulate plant growth and development. The indirect plant growth mechanism occurs when microbes prevent the growth of other plant pathogenic microbes

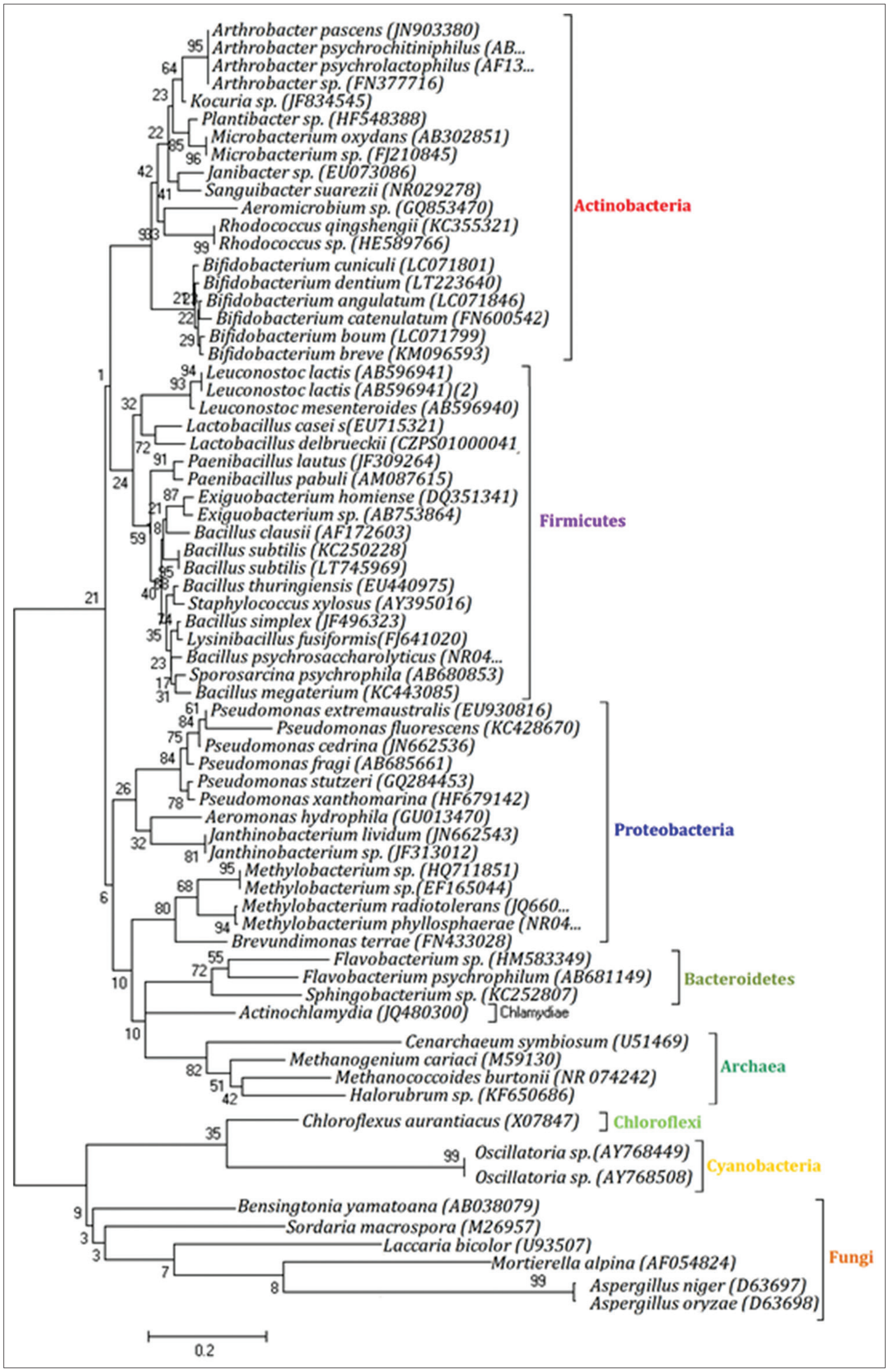

Fig. 1: Phylogenetic tree showed the relationship among beneficial microbiomes for agriculture, industry, and human health. 16S/5.8S rRNA gene sequences obtained from NCBI database, sequence alignment was performed using the CLUSTAL W program, and trees are constructed using maximum likelihood method with an algorithm using MEGA4 software. One thousand bootstrap replicates were performed. Bootstrap values are indicated on the branches.

by mechanisms of production of ammonia, hydrogen cyanide, Fe-chelating compounds (siderophores), β-1, 3-glucanase, chitinases, cellulase, lipase, antibiotics, and different fluorescent pigment. World agriculture faces a great loss every year incurred from infection by pathogenic organisms. The most promising way to increase crops productivity is the application of microbe for control of disease (Table 1).

Nitrogen is the one of the major limiting factors for plant growth, and the application of N_2-fixing microbes as biofertilizers has emerged as one of the most efficient and eco-friendly sustainable methods for increasing the growth and yield of crop plants. The chemical nitrogen fertilizers may be replaced by microbes having nitrogen-fixing ability which could lead to more productive and sustainable agriculture without harming the environment. The plant microbiomes and microbes from different habitat in normal as well as extreme

Table 1: Microbes with PGP attributes for agricultural application for the amelioration of diverse abiotic stresses.

Plant growth promoting microbes	Abiotic stress	Response	Reference
Achromobacter xylosoxidans 249	Salinity stress	Growth and SOD activity	[73]
Aeromonas hydrophila MAS-765	Salinity stress	Alleviate salinity, growth	[74]
Aeromonas vaga BAM-77	Alkalinity stress	Growth and yield	[75]
Aeromonas vaga BAM-77	Salinity stress	Growth and yield	[75]
Arthrobacter sulfonivorans IARI-L-16	Cold stress	Growth and alleviation	[8]
Azospirillum brasilense NO_{40}	Drought and heat stress	Improved homeostatic	[76]
Azospirillum brasilense Sp245	Drought and heat stress	Coleoptiles growth	[77]
Azospirillum brasilense Sp245	Drought and heat stress	Grain yield, mineral quality	[78]
Azospirillum brasilense Sp245	Cold stress	Affected dry weight	[79]
Azospirillumlipoferum AZ1, AZ9, AZ45	Drought and heat stress	Alleviate the drought stress	[80]
Bacillus aerophilus BSH15	Acidic stress	Growth and alleviate acidity	[81]
Bacillus alcalophilus BCZ14	Drought and heat stress	Growth, yield, stress	[81]
Bacillus altitudinis IARI-HHS2-2	Cold stress	Growth and yield	[28]
Bacillus altitudinis BNW15	Alkalinity stress	Growth and alleviate alkalinity	[81]
Bacillus amyloliquefaciens BNE12	Salinity stress	Growth and alleviate salinity	[81]
Bacillus amyloliquefaciens IARI-HHS2-30	Cold stress	Growth and alleviation	[82]
Bacillus aryabhattai BCZ17	Drought and heat stress	Growth, yield, stress	[81]
Bacillus endophyticus BNW9	Alkalinity stress	Growth and alleviate alkalinity	[81]
Bacillus licheniformis HSW-16	Salinity stress	Growth and productivity	[83]
Bacillus nanhaiensis IARI-THD-20	Alkalinity stress	Growth and alleviation	[15]
Bacillus safensis W10	Drought and heat stress	Plant growth and yield	[84]
Burkholderia phytofirmans PsJN	Drought and heat stress	Growth and grain yield	[85]
Cellulomonas turbata AS1	Cold stress	Growth and yield	[86]
Flavobacterium psychrophilum HHS2-37	Cold stress	Growth and yield	[28]
Klebsiella sp. SBP-8	Salinity stress	Plant growth and yield	[87]
Lysinibacillus fusiformis IARI-THD-4	Acidic stress	Growth and yield	[15]
Micrococcus roseus SW1	Acidic stress	Growth and yield	[88]
Paenibacillus polymyxa BNH18	Cold stress	Growth, alleviate cold	[81]
Paenibacillus xylanexedens BNW24	Alkalinity stress	Growth and alleviate alkalinity	[81]
Pantoea intestinalis DSM 28113^T	Drought and heat stress	Alleviate drought stress	[89]
Piriformospora indica (Pi)	Drought and heat stress	Drought resistance, growth	[90]
Planococcus salinarum BSH13	Acidic stress	Growth and alleviate acidity	[81]
Pseudomonas fluorescens 153	Salinity stress	Salinity stress, growth	[91]
Pseudomonas lurida M_2RH_3	Cold stress	Growth and nutrient uptake	[92]
Pseudomonas poae IARI-NIAW2-1	Drought and heat stress	Growth, yield	[13]
Pseudomonas putida AKMP7	Drought and heat stress	Growth, alleviate heat stress	[93]
Pseudomonas putida 108	Salinity stress	Salinity stress, growth	[91]
Pseudomonas rhizosphaerae IARI-DV-26	Alkalinity stress	Growth and alleviation	[81]
Pseudomonas sp. $NARs_9$	Cold stress	Germination, shoot, root lengths	[94]
Rhodobacter sphaeroides IARI-NIAW1-7	Drought and heat stress	Growth, yield	[13]
Serratia marcescens 73	Salinity stress	Growth and SOD activity	[73]
Sporosarcina sp. BNH20	Cold stress	Growth, alleviate cold	[81]
Staphylococcus arlettae BNW27	Alkalinity stress	Growth and alleviate alkalinity	[81]
Staphylococcus epidermidis IARI-THW-28	Acidic stress	Growth and yield	[15]

conditions are known to fix atmospheric nitrogen. There are many groups of microbes reported as nitrogen fixation with associative or free livings such as *Arthrobacter*, *Azospirillum*, *Azotobacter*, *Bacillus*, *Enterobacter*, *Gluconoacetobacter,* *Herbaspirillum*, *Klebsiella*, *Pseudomonas,* and *Serratia* (Table 1) [65-69].

Among different major essential macronutrient, phosphorus (P) is one of best sources for biological growth and development of crops. Microorganisms offer a biological rescue system capable of solubilizing the insoluble inorganic P of soil and make it available to the plants. The ability of many microbes to convert insoluble P to an accessible form (orthophosphate) is an important trait in PGP microbes for increasing plant yields for sustainable agriculture. The rhizospheric P-solubilizing microbes could be a promising bioresource for PGP agents in agriculture. Phosphate solubilization is a common trait among microbes associated with different crops. The plant microbiomes from wheat, rice, maize, and legumes and microbiomes of extremes habitat were able to solubilize mineral P in plate assays. There are many reports on microbe having capability to solubilized phosphorus under the normal and different abiotic stresses conditions, which belong to *Arthrobacter*, *Azotobacter*, *Burkholderia*, *Enterobacter*, *Halolamina*, *Pantoea*, *Pseudomonas*, *Citrobacter,* and *Azotobacter* (Table 1) [63,70-72].

Phytase (myo-inositol 1,2,3,4,5,6-hexakisphosphate phosphohydrolase) is a hydrolytic enzyme which hydrolyzes phytate (*myo*-inositol 1,2,3,4,5,6-hexa*kis*phosphate; IP_6) complexes into myoinositol, inorganic phosphate, and divalent cations. This is produced by bacteria [95], fungi [96], and plants [97] with tremendous diversity in various agro-climatic and environmental conditions. Four classes of phytases, namely, (HAPhy), (BPPhy), (PAPhy), and (CPhy), have been reported in the literature based on catalytic and sequence features [98]. These have also been categorized as 3-phytase and 4/6-phytase based on initial site of action and liberation of inorganic phosphate from phytate structure [99]. Several applications of phytases and phytase-producing microbes have been reported leading to tremendous opportunities in using these microbes for beneficial purposes. Bacterial isolates and their consortiums for PGP have been well documented in several reports [95,100]. Although microbes promote the growth of plants by different means, the presence of enough organic phosphorus (as phytate) in soil increases the significance of phytate-hydrolyzing microbes in soil for efficient utilization of this source of phosphorus by plants as it is a major element determining proper health of plant. An application of phytase-producing bacterial isolates (*Advenella* sp., *Cellulosimicrobium* sp., *Acromobacter* sp., *Tetrathiobacter* sp., and *Bacillus* sp.) has been resulted in improved growth of plants. Studies on potential PGP attributes in phytase-positive bacterial isolates have revealed multiple attributes of PGP including the production of plant growth hormones and siderophores, solubilization of phosphorus, and inhibition of plant pathogenic fungal growth [95,100]. These attributes with additional phytase production potential make these microbes more useful as they also reduce the use of phosphorus fertilizers, thereby decreasing environmental phosphorus pollution and contribute toward sustainable agriculture. Reducing environmental phosphorus pollution is of great importance in areas of intensive livestock production of monogastric animals, where unavailable phosphate excreted and deposited in nearby water bodies leading to its eutrophication. Excess phosphorus in such places causes algal blooms and death of aquatic life therein [99]. Phytase-producing microbes or neutral phytases have a potential role to be used as a supplement in meals of aquatic animals [101,102].

The indirect mechanism of plant growth occurs when one type of microbes prevents the detrimental effects of other type of microbes having pathogenic capability. These beneficial PGP microbes have ability to produced siderophores (Fe-chelating compounds), chitinases, antibiotics, different fluorescent pigment, and hydrogen cyanide production [103,104]. Biological controls are eco-friendly and cost-efficient and involved in improving the soil consistency and maintenance of natural soil flora. To act efficiently, the biocontrol agent should remain active under large range of conditions, namely, high/low temperature, pH, and salinity. The production of siderophores by microbe is beneficial to plants because it can inhibit the growth of plant pathogens and also for uptake of Fe to plant and finally to seed which said to be a best way for biofortification of Fe in different cereal crops. Siderophores have been implicated for both direct and indirect enhancement of plant growth by PGP microbes.

Biofertilizers are beneficial microbes which can help plant growth and enrichment of the nutrients of the soil by enhancement of the availability of the nutrients to the crops. The production of the healthy crops so as to meet the demands of the world's expanding population mainly relies on the type of the fertilizers which are basically used to supplement all the nutrients to the plants, but more reliability on the chemical fertilizers is damaging the environmental ecology as well as affecting the human health with great severity. Thus, the use of the microbes as biofertilizers is considered as an alternative to chemical fertilizers so as to improve the fertility of the soil as well as increasing the productivity of the crops. These microbes are considered to be the biopotential and a novel tool for providing substantial benefits to the agriculture. These microbes colonize the roots and stimulate the growth. The PGP microbes possess multifarious PGP attributes, which help in plant growth directly by production of plant growth hormones and N_2-fixation; solubilization of phosphorous, potassium, and zinc; or indirectly by production of ACC deaminase, ammonia, antibiotics, hydrocyanic acid, lytic enzymes, and siderophores. Extensive works on the biofertilizers are available which reveals that these microbes have the capability of providing the required nutrients to the crops in amounts which are sufficient for the enhancement of yield of the crops. Microbes having multifunctional PGP attributes can be utilized as eco-friendly biofertilizers for sustainable agriculture [13,28,70,105,106].

4. BENEFICIAL MICROBES FOR HUMAN HEALTH

The beneficial microbes from different natural and extreme environments as well as associated with plant could be used for different processes. Apart from their application in agricultural sciences, phytase-producing microbes provide great promises for nutritional applications in human food and animal feed. Exogenous phytase addition has been used to enhance the mineral bioavailability [107], and dephytinization by the addition of exogenous phytase in porridges of different cereal crops such as maize, oats rice, and wheat has been shown to improve iron bioavailability in human [108]. It has been demonstrated that phytic acid significantly reduces (about 86%) bioavailability of Fe from infant cereal diets in an *in vitro* digestion study in a Caco-2 cell model [109], and dephytinization markedly improved Fe and Zn bioavailability in these diets [110]. Park *et al*. [111] reported a decrease of 20-40% in phytate content in a reaction time of 30-60 min by addition of alkaline phytase to whole-wheat bread. Phytate degradation enhanced the Fe and Zn availability of bread with a maximum increase of 10 fold in the level of dialyzable Fe. According to Sanz-Penella *et al*. [112], the addition of phytase probiotic *Bifidobacteria* during bread making (direct or indirect) significantly reduced the phytic acid concentration in final bread compared to control samples. Fe-dialyzable content in samples with *Bifidobacteria* was increased to 2.3-5.6-fold. The results demonstrated the usefulness of phytase-producing *Bifidobacteria* to reduce phytate during bread making and increase Fe-accessibility. According to Kumar *et al*. [113], lower myo-inositol phosphate derivatives as hydrolysis products of phytic acid were proved to have potential applications in various health-related aspects such as cell signalling and Ca^{2+} mobilization in intracellular spaces with several proposed applications as antioxidants [114] and painkillers [115]. Inositol hexakisphosphate and inositol application have revealed inhibition of cancer by Vucenik and Shamsuddin [116]. Microbial phytases produced myo-inositol trisphosphate isomer as an end product of phytate hydrolysis and could be used for the synthesis of myo-inositol phosphate derivatives under various conditions [113].

Production of various food crops (wild, traditional, or ancient), which are genetically very diverse and rich in micronutrients, has decreased and even disappeared. Out of 7000 species ever cultivated by humans, currently, only 30 plant species account for >95% of the world's food energy supply. Among different cultivated food and cereal crops, wheat (*Triticum aestivum* L.) plays a predominantly imperative role in daily energy intake. The modern wheat (*T. aestivum* L.) cultivars with a high-yield capacity are poor sources of Fe and Zn, for convention daily desires of humans. Along with different micronutrients such as Fe and Zn, wheat is rich in antinutritional compounds (phytic acid and phenolic compounds) that reduce biological availability of Fe and Zn in the human digestive tract. In general, Fe and Zn concentrations in commercial wheat cultivars are 20-35 mg/kg. The concentrations of micronutrients are not sufficient for human nutrition in diets with wheat constituting the main source of essential minerals. Hence, such wheat-based diets consumed over a period of time can result in micronutrient malnutrition. Farmers chose to grow more profitable, highly productive cereal crops, leading to a decline in the area under protein and micronutrient-rich legumes. This tendency is evident in a proportional decrease in cereal prices and an increase in price for legumes, fruits, vegetables, animal, and fish protein. At present, biofortification approach is getting much attention to increase the availability of micronutrients, especially Fe and Zn in the major food crops. The use of PGP bacteria is becoming an effective approach to substitute synthetic fertilizers, pesticides, and supplements. The selected efficient PGP bacteria mobilize the nutrients by various mechanisms such as acidification, chelation, exchange reactions, and release of organic acids [21,117,118].

Currently, there has been an increased curiosity in the development of new functional foods and their assimilation in a healthy diet. Such products, and especially probiotics, exert a beneficial effect on host gut microbiota after consumption and may be proficient to prevent several diseases [119]. Probiotics are defined as live microbiomes which when administered in adequate amounts confer a health benefit on the host. Bioprocessing has been used to manufacture an ample series of foods and food ingredients ever since the initially verified food preservation by humans. Beneficial microbiomes (archaea, bacteria, and yeast) are widely used to convert raw food materials into many of fermented products. Bioprocessing engineering has developed this further, with the particular production of food. The genus *Lactobacillus* and other species of *Lactobacillus* are beneficial microbes of particular interest because of their long history of use [120]. The fermented beverages are traditional products that act as vehicles of probiotics in human diet. The global diversity of the fermented and probiotic foods is presented in table. Among different probiotic microbes, the species of *Lactobacillus* were the first bacteria used by man for processing foodstuffs [121] and for preserving food by inhibiting invasion by other microbiomes that cause foodborne illness or food spoilage [122]. The term "Probiotic" is used to describe food supplements, specifically designed to improve health, and this concludes the probiotic as a "live microbial feed supplement which beneficially affects the host animal by improving its microbial balance."

The procedures of microorganisms by which they act as probiotics or do their effects are not properly known, but the many studies revealed that they may be involved in modifying the pH value, may neutralize the pathogens through production of compounds that exerts property of antimicrobial, and may occupy the receptor sites of the pathogens as well as chase them for available nutrient [123]. The role of functional food which includes the probiotics microorganisms in human health is well known. The development of probiotic was totally focused on pharmaceutical applications such a intestinal disorders, acute diarrhea, lactose intolerance, and so on. Antibodies were produced by giving *Lactobacillus rhamnosus* in infants, and those were suffering from diarrhea. Antibodies present in infants shorter the duration of the diarrhea [124]. Specific probiotics have beneficial immunomodulatory effects for the *Helicobacter pylori*-associated gastritis [125], and growth of allergies or decrease in allergy symptoms (Table 2) [126].

Probiotics have the property to enhance the immune system. A better precise immune response to a *Salmonella typhi* oral vaccine has been described in persons consuming a probiotic containing *Lactobacillus johnsonii* and *Bifidobacterium lactis* [145], and *Lactobacillus fermentum* showed positive results for influenza [146]. Probiotics containing *Lactobacillus gasseri*, *Bifidobacterium longum,* and *Bifidobacterium bifidum* concise the duration of common cold and reduced fever [147]. Irritable bowel syndrome, one of the most common disorders seen by primary care physicians, affects 7-10% of the world population. In the absence of an efficient therapy with no side effects, well-selected probiotic strains might provide a valuable alternative such as *Bifidobacterium infantis* [148]. The lactose converted into lactic acid with use of lactic acid bacteria (*Carnobacterium, Enterococcus, Lactobacillus, Lactococcus, Leuconostoc, Oenococcus, Pediococcus, Streptococcus, Tetragenococcus, Vagococcus,* and *Weisella*) ingestion of certain active strains may help lactose intolerance individuals tolerate more lactose than they would have otherwise. Intestinal discomfort and constipation that represents the most ubiquitous problem among the general adult people were also checked by a probiotic fermented milk containing *Bifidobacterium animalis* [149]. *Lactobacillus paracasei* improved recovery of skin immune homeostasis [150]. Probiotics have also impact on anxiety, mood, and behavior; the first human trials suggest that probiotic interventions may modulate mood and stress-induced gastro-intestinal symptoms [151,152].

5. CONCLUSION AND FUTURE PROSPECT

The plant microbiomes and microbiomes from different extreme habitats represent the richest extent of molecular and chemical diversity in nature. The explorations of microbial diversity have been spurred due to beneficial role of microbes for sustainable agriculture (microbes may be used as biofertilizers/bioinoculants), for human welfare (microbes with probiotics properties may be used as foods), and for industry (microbes may be used for the production of different compounds of pharmaceutical importance). The beneficial microbes may play an important role in nutrient cycling and environmental detoxification. The microbiomes abound in all kind of habitats, namely, with extremes of pH, temperature, salinity, and water stress

Table 2: Probiotic microbes in fermented food products its distributions worldwide.

Products	Source	Probiotic microbes	Country	References
Alheira	Pork	*Lactobacillus brevis, Lactobacillus paracasei, Lactobacillus plantarum, Lactobacillus rhamnosus, Lactobacillus sakei*	Portugal	[127]
Bekang	Soybean	*Bacillus coagulans, Bacillus licheniformis, Bacillus pumilus, Bacillus sphaericus, Bacillus subtilis*	India	[128]
Cheese	Animal milk	*Lactobacillus casei, Lactobacillus delbrueckii, Lactobacillus helveticus, Lactobacillus plantarum, Lactobacillus salivarius, Leuconostoc lactis*	Worldwide	[129]
Chhurpi	Yak/cow milk	*Lactobacillus biofermentans, Lactobacillus curvatus, Lactobacillus fermentum, Lactobacillus paracasei, Lactobacillus plantarum, Leuconostoc mesenteroides*	Bhutan, India, Nepal	[130]
Chungkokjang	Soybean	*Bifidobacterium* sp., *Bacillus licheniformis, B. subtilis, Pantoea agglomerans*	Korea	[131]
Datshi	Milk product	*Enterococcus faecalis, Enterococcus. faecium*	Bhutan	[132]
Dha muoi	Mustard, Beet, Eggplant	*Lactobacillus fermentum, Lactobacillus pantheris, Lactobacillus pentosus, Lactobacillus plantarum, Pediococcus pentosaceus*	Vietnam	[133]
Dua gia	Bean	*Lactobacillus plantarum, Lactobacillus fermentum, Lactobacillus helveticus*	Vietnam	[134]
Fufu	Cassava	*Lactobacillus brevis, Lactobacillus cellobiosus, Lactobacillus coprophilus, Lactobacillus lactis, Lactobacillus plantarum, Leuconostoc mesenteroides*	West Africa	[135]
Jiang-gua	Cucumber	*Lactobacillus paraplantarum, Lactobacillus pentosus, Lactobacillus plantarum, Leuconostoc lactis, Leuconostoc mesenteroides*	Taiwan	[136]
Kefir	Goat, Sheep, Cow	*Lactobacillus brevis, Lactobacillus bulgaricus, Lactobacillus casei, Lactobacillus caucasicus, Lactobacillus plantarum, Streptococcus thermophilus*	Russia	[137]
Kimchi	Cabbage	*Lactobacillus delbrueckii, Lactobacillus fermentum, Lactobacillus plantarum, Lactobacillus sakei, Leuconostoc citreum, Leuconostoc gasicomitatum, Leuconostoc mesenteroides*	Korea	[138]
Koumiss	Milk	*Lactobacillus acidophilus, Lactobacillus bulgaricus, Lactobacillus helveticus, Lactobacillus plantarum, Lactobacillus salivarius*	Russia, Mongolia	[139]
Pao cai	Cabbage	*Lactobacillus brevis, Lactobacillus lactis, Lactobacillus pentosus, Lactobacillus plantarum*	China	[140]
Sourdough	Rye, wheat	*Lactobacillus casei, Lactobacillus delbrueckii, Lactobacillus plantarum, Lactobacillus reuteri*	America, Australia	[141]
Takuanzuke	Japanese radish	*Lactobacillus brevis, Lactobacillus plantarum, Leuconostoc mesenteroides*	Japan	[142]
Tungrymbai	Soybean	*Bacillus subtilis, Bacillus licheniformis, Bacillus pumilus*	Meghalaya Mizoram	[143]
Uji	Maize, Cassava	*Lactobacillus plantarum, Leuconostoc mesenteroides*	Kenya, Tanzania	[135]
Yogurt	Animal milk	*Bifidobacterium* sp., *Lactobacillus casei, Lactobacillus acidophilus, Lactobacillus delbrueckii, Streptococcus thermophilus*	Europe, Australia, America	[144]

are said to be beneficial for agriculture, and human health as they could be used as PGP agents (biofertilizers) for sustainable agriculture and biofortification of micronutrients such as Fe and Zn and as probiotics as new functional foods.

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