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REVIEW

Plant growth promoting soil microbiomes and their potential implications for agricultural and environmental sustainability

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Abstract
Soil microbial diversity is very important part of ecosystem as it plays a significant role in biogeochemical cycles. Currently, health of environment has been depleted due to growing population of the world and human activities like industrialization, overexploitation of chemical based products in agriculture and urbanization. These problems are now being of major concern of the environmentalist and to fix these problems has become an emergence. Soil microbiomes have been recognized as a potent tool for the sustainable agriculture and environment. Such microbes exhibit hidden talent to overcome the environmental related problem like pollution and soil degradation. In agriculture, soil microbiomes can be used as a biofertilizers over the chemical based products. Soil microbes help in reclamation of soil fertility, alleviation of diverse abiotic stresses, and nutrients stress that help in plant growth and development. Soil microbes help plant for growth via direct mechanisms for enhancing plant growth directly in a sustainable way like solubilization of nutrients (P, K, and Zn), fixation of nitrogen and chelation of iron as well as via indirectly by controlling pathogen growth and alleviating abiotic stress. In environment, beneficial soil microbiomes help in the degradation of environment pollutants like chemical pesticides and industrial waste by enzymatic actions and biosorption techniques. Present review deals with the diversity of soil microbiomes and their role in plant growth promotion and remediation of diverse environmental pollutants for agro-environmental sustainability.

Keywords Agricultural sustainability · Biofertilizers · Bioremediation · Environmental sustainability · Soil microbiomes

Introduction

The fashionable buzzword 'sustainable' is an idea, which was introduced in 1980 by the United Nation Environmental Programme for vibrant field of research and innovation. Now a days, sustainability has becomes a core research agenda worldwide as environmental health is adversely depleted (Clark 2007). Land degradation, depletion of nutrients and ozone, increase concentration of carbon dioxide and sulfur dioxide in air and toxic heavy metals and other pollutants in soil and water are the major problems that have been raised by several human activities (Mishra et al. 2016; Pandey et al. 2012b). Afforestation, industrialization, and over exploitation of chemical based products like fertilizers pesticides and dyes are some humans activities which are responsible for such condition of the environment (Araújo et al. 2013). Sustainable strategies are the solution to such problems as these develop new and safe human's practices by integrating biological, chemical, physical, ecological, economical and social sciences in a comprehensive way. It also focus on solving

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problems to meet the urgent needs of humans like adequate quality and quantity of water supply, mitigation of environment related problems like pollution that have harmful impact on the health of humans and enhancement of agricultural production to feed the growing population (Clark 2007).

Agricultural and environmental sustainability are the two different major fields on which world's researchers are focusing from last few decades (Kour et al. 2021a; Yadav et al. 2017a, 2019). World's researches are seeking the support of tiny living organisms known as microorganisms or microbes to fix the tribulations related to environmental and agricultural related issues. Microbes are present in the various environmental conditions like water (hot springs, oceans, and rivers), air and soil (deserts, saline and heavy metal soil). Soil, the natural physical covering of the Earth's surface is the home for many different microbes like bacteria, fungi, archaea that are involved in the functioning of the ecosystems (Mishra et al. 2016). In ecosystem, soil microbial diversity plays key roles for the sustainability of environment by maintaining the essential functions of soil health, through nutrient and carbon turnover through microbiological buffering (Singh and Gupta 2018).

The microbes present in soil can also be used for the betterment of agriculture and environment as they are used as biofertilizers and biopesticides for plant growth promotion and crop protection respectively. Currently, microbial-based products are considered to be a key component of agriculture and environment as it helps in the improvement of crop productivity as well as environment condition that contributes to sustainable agro-ecosystems (Fierer 2017). Microbes can improve crop productivity directly by providing soluble forms of macro (N, P, and K) and micronutrients (Fe, and Zn), growth hormones (auxin, cytokinin and gibberellic acids) and maintaining fertility of soil (Yadav et al. 2017b, c). Crop production is also improved indirectly through protection from pathogens and alleviation of abiotic stresses such as drought, salinity, heavy metals, and temperature extremes (low and high temperature) (Hayat et al. 2010).

Microbes adopted numerous mechanisms for improving plant growth such as fixation of nitrogen, solubilization of nutrients like phosphorus, potassium, zinc, and selenium by producing compounds (organic acids, exopolysaccharides and extracellular enzymes) that lowers pH of soil, chelation of iron by producing siderophores (Gupta et al. 2015; Yadav 2021a). On the other hand, mechanisms like production of antibiotics, hydrogen cyanide, and 1-aminocyclopropane-1-carboxylate (ACC) directly enhance plant growth by controlling growth of pathogens and alleviating abiotic stress (Hayat et al. 2010). In environment, soil microbial diversity mainly helps in bioremediation of various pollutants like heavy metals, xenobiotics present in soil through production and biosorption of extracellular hydrolytic enzymes (Karigar and Rao 2011). Soil microbiomes in both agriculture and environment are used as different bioformulations such as liquid, and solid. The present review deals with the diversity of soil microbes and their potential role in plant growth promotion, bioremediation of environmental as well as mitigation of diverse biotic and abiotic stresses and diverse technologies for developing all bioformulations for agro-environmental sustainability.

Role of soil microbes for agricultural sustainability

Agricultural practices are one of the top most priority of the humans because their foods are crops dependent. On earth humans use to cultivate variety of crops that falls in the category of cereal crops and horticulture crops, in which several types of inputs have been added. The agricultural practices mostly uses chemical based inputs which have harmful impact on the earth. Utilization of soil microbes are believed to work for the enhancement of plant growth and development by increasing the nutrient availability, photosynthesis and along with this it also helps in restoring the soil fertility in sustainable way (Umesha et al. 2018) (Table 1; Fig. 1).

Plant growth promotion

Plant growth and development is one such thing on which the productivity of agriculture products is based on. In order to achieve proper development, plants externally absorb several nutrients in the organic form from the soil like macronutrients (N, P, K, Ca, Mg, S, C, O, H) and micronutrients (Fe, B, Cl, Mn, Zn, Cu, Mo, Ni). These nutrients are used to create and maintain the cells and the necessary life processes such as growth, reproduction, respiration and photosynthesis. Now a day, in soil organic form of nutrients has been depleted and only inorganic form is present. So, to meet the need of the plant nutrients, range of chemical based fertilizer are being applied in the agricultural fields for quite a long time. The use of such harsh chemicals in the fields has raised several problems such as loss of biodiversity, organic form of nutrients and fertility. The utilization of biofertilizers is one of the best alternatives that help in plant growth promotion along with regaining the fertility, biodiversity and organic form of nutrients (Umesha et al. 2018; Yadav et al. 2021) (Table 2).

Biological nitrogen fixation

Nitrogen is the most abundant element on the earth and the main reservoir of this element is biosphere where it is present in form of stable nitrogen gas N_2. This element is important for every living organism as it is a structural component of biomolecules like nucleic acids, proteins and some other biological molecules. In plants also nitrogen is the most important factor that forms nearly 4 % of its dry weight (Gonzalez-Dugo et al. 2010) and its deficiency decreases the protein level, yield and

Table 1 Soil microbiomes and their multifarious plant growth promoting attributes for agricultural sustainability

Soil microbes	N	P	K	Zn	Sid	IAA	GA	References
Bacillus amyloliquefaciens	✓	✓	✓	✓	✓	✓	✓	Verma et al. (2015a)
Pseudomonas azotoformans	✓	✓			✓	✓	✓	Verma et al. (2015a)
Arthrobacter nicotinovorans	✓	✓		✓	✓	✓		Verma et al. (2015a)
Arthrobacter methylotrophus	✓	✓		✓	✓	✓		Verma et al. (2015a)
Bacillus bronchiseptica	✓	✓		✓	✓	✓		Verma et al. (2015a)
Pseudomonas peli	✓	✓		✓	✓	✓		Verma et al. (2015a)
Pseudomonas geniculata	✓	✓			✓	✓		Verma et al. (2015a)
Achromobacter spanius	✓	✓			✓	✓		Farah Ahmad et al. (2006)
Pseudomonas fluorescens	✓	✓			✓	✓		Verma et al. (2015a)
Stenotrophomonas maltophilia		✓	✓		✓	✓		Verma et al. (2015a)
Bacillus arsenicus		✓		✓	✓	✓		Upadhyay et al. (2009)
Bacillus megaterium		✓			✓	✓		Kumar et al. (2011)
Staphylococcus sciur		✓			✓	✓		Kumar et al. (2011)
Streptomyces carpinensis		✓			✓	✓		Upadhyay et al. (2009)
Streptomyces laurentii		✓			✓	✓		Kour et al. (2020a)
Streptomyces rochei		✓			✓	✓		Upadhyay et al. (2009)
Streptomyces thermolilacinus		✓			✓	✓		Upadhyay et al. (2009)
Bacillus cereus		✓				✓	✓	Upadhyay et al. (2009)
Enterobacter ludwigii		✓				✓	✓	Lee et al. (2019)
Azospirillum lipoferum	✓	✓				✓		Navarro-Noya et al. (2012)
Klebsiella variicola	✓	✓				✓		Navarro-Noya et al. (2012)
Paenibacillus borealis	✓	✓				✓		Navarro-Noya et al. (2012)
Paenibacillus durus	✓	✓				✓		Navarro-Noya et al. (2012)
Paenibacillus odorifer	✓	✓				✓		Navarro-Noya et al. (2012)
Bacillus licheniformis			✓			✓		Saha et al. (2016)
Barnettozyma californica				✓		✓		Fu et al. (2016)
Cryptococcus laurentii				✓		✓		Fu et al. (2016)
Dothideomycetes sp.				✓		✓		Fu et al. (2016)
Enterobacter cloacae				✓		✓		Kamran et al. (2017)
Galactomyces candidum				✓		✓		Fu et al. (2016)
Pantoea agglomerans			✓			✓		Khanghahi et al. (2018a)
Pantoea agglomerans				✓		✓		Kamran et al. (2017)
Pantoea dispersa				✓		✓		Kamran et al. (2017)
Pseudomonas aeroginosa				✓		✓		Jerlin et al. (2017)
Pseudomonas azotoformans			✓			✓		Saha et al. (2016)
Pseudomonas geniculata					✓	✓		Gopalakrishnan et al. (2015)
Pseudomonas orientalis			✓			✓		Khanghahi et al. (2018a)
Rahnella aquatilis			✓			✓		Khanghahi et al. (2018a)
Stenotrophomonas				✓	✓			Costerousse et al. (2018)
Bradyrhizobium japonicum	✓					✓		Navarro-Noya et al. (2012)
Alcaligenes faecalis		✓				✓		Kumar et al. (2011)
Bacillus licheniformis		✓			✓			Kumar et al. (2011)
Bacillus pumilus		✓				✓		Upadhyay et al. (2009)
Enterobacter cloacae		✓				✓		Kumar et al. (2011)
Paenibacillus graminis	✓	✓						Navarro-Noya et al. (2012)
Paenibacillus illinoisensis	✓	✓						Navarro-Noya et al. (2012)
Paenibacillus kribbensis	✓	✓						Marra et al. (2012)
Rhizobiales bacterium	✓	✓						Marra et al. (2012)

N-Nitrogen, P-Phosphorus, K-Potassium Zn-Zinc, Sid-Siderophores, IAA-Indole acetic acid, GA- Gibberellic acid

water use which ultimately stunts the plant growth (Hassen et al. 2016; Hayat et al. 2010; Mikkelsen and Hartz 2008). Plant absorbs nitrogen in the inorganic form i.e. ammonia, which is further used for manufacturing all necessary nitrogen-containing components (Franche et al. 2009). Maximally, nitrogen in atmosphere and soil is present in organic form and, inorganic form of nitrogen is quite low. Therefore, to fulfill the nitrogen requirements of plants, chemically

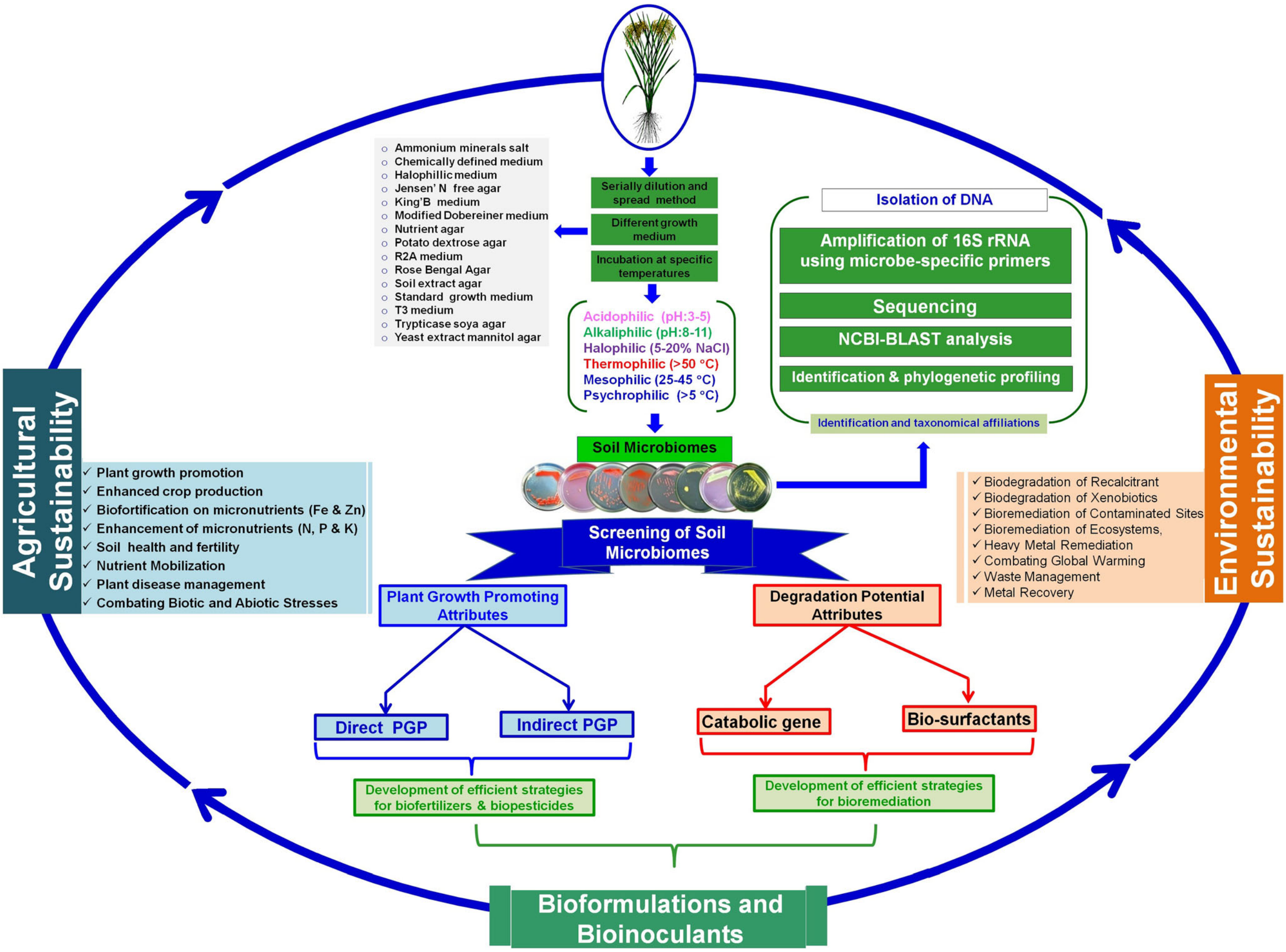

Fig. 1 A systemic representation for the isolation of beneficial soil microbiomes, their characterization and possible potential applications for agricultural and environmental sustainability

synthesized (prepared through Harbors-Bosh process) nitrogen fertilizer (urea) had been used for past many years, that have deleterious effects on environment (Rawat et al. 2018).

Naturally, atmospheric nitrogen is being fixed by bacteria i.e. free-living and symbiotic and associative symbiotic residing inside the plant and soil. All the three categories of bacteria fix nitrogen by undergoing various processes like ammonification, nitrification, assimilation and denitrification in order to obtain the energy for themselves (Bjelić 2014). Ammonification, also known as mineralization, is the first step of nitrogen fixation, in which decomposing soil microbes plays a significant role. They break down the organic matter and nitrogenous wastes into inorganic ammonia (NH_3), by the enzymatic complex, nitrogenase action, generated by the dead plants, animals and their waste. The enzyme nitrogenase is released by microbes because they have a special enzyme coding gene known as *nif* gene which is present in few microbial genera (de Bruijn 2015). The production of ammonia through ammonification is excreted into the environment and becomes available for further processes like assimilation and nitrification and this form of nitrogen can also be absorbed by plants as ammonium ions (Rawat et al. 2018).

The second occurring process in nitrogen fixation is nitrification. In this process, some special nitrifying soil bacteria named *Nitrosomonas* and *Nitrococcus* converts ammonium to nitrite and *Nitrobacter* oxidize nitrite into nitrate. Nitrate formed from nitrification is then easily assimilated by the plants and the animals in process of assimilation (Smith et al. 2013). Soil microbes are also involved in the last step of the nitrogen recycling named denitrification, in this process nitrate is reduced to the nitrogen gas and lost in the atmosphere. In this process, soil facultative anaerobic bacteria play a key role (Rawat et al. 2018). These soil microbes can be the prominent and sustainable alternative for chemical based nitrogen fertilizer known as urea. Many microbes isolated from soil have been reported with ability to fix the nitrogen for plants and can be used as nitrogen biofertilizers like *Achromobacter spanius* (Farah Ahmad et al. 2006), *Azospirillum lipoferum*, *Bradyrhizobium japonicum*,

Table 2 Soil microbiomes and thier potentail role in plant growth promotion for agricultural sustainability

Microbes	Source	Role	References
Hartmannibacter diazotrophicus	Alfalfa	Improved seedling growth	Ansari et al. (2017)
Pseudomonas chlororaphis O6	*Arabidopsis*	Increased survival rate	Cho et al. (2013)
Pseudomonas putida UW4	*Brassica*	Enhanced biomass	Cheng et al. (2012)
Pseudomonas fluorescens	Canola	Enhanced biomass	Banaei-Asl et al. (2015)
Pseudomonas putida MTCC5279	Chickpea	Increased germination	Tiwari et al. (2016)
Pseudomonas putida Rs-198	Cotton	Enhanced biomass	Yao et al. (2010)
Pseudomonas aeruginosa PW09	Cucumber	Enhanced biomass	Pandey et al. (2012a)
Pseudomonas putida UW4	Cucumber	Enhanced biomass, photosynthetic activity	Gamalero et al. (2010)
Azotobacter chroococcum	*Dodonaea*	Improved seedlings growth	Yousefi et al. (2017)
Pseudomonas migulae S10724	Green gram	Increased biomass,	Suyal et al. (2014)
Glomus intraradices	*Litchi chinensis*	Increased biomass, IAA concentrations in the roots.	Yao et al. (2005)
Proteus penneri Pp1	Maize	Increased RW and protein	Naseem and Bano (2014)
Pseudomonas fluorescens 002	Maize	Increased yield	Zerrouk et al. (2016)
Citricoccus zhacaiensis B–4	Onion	Increased percent germination, seedling vigour and germination.	Selvakumar et al. (2015)
Pseudomonas pseudoalcaligenes	*Oryza sativa*	Enhanced biomass, glycine betaine-like quaternary compounds	Jha et al. (2011)
Serratia nematodiphila PEJ1011	Pepper	Improved growth	Kang et al. (2015)
Bacillus licheniformis K11	Pepper	Increased biomass, N	Lim and Kim (2013)
Glomus mosseae	Pepper	Increased shoot height	Ozgonen and Erkilic (2007)
Pseudomonas oryzihabitans Ep4	Potato	Increased yield and biomass	Belimov et al. (2015)
Pseudomonas aeruginosa	*Pteris cretica*	Enhanced biomass, root mass in siderophore-containing culture filtrate amended pots	Jeong et al. (2014)
Pseudomonas pseudoalcaligenes	Rice	Enhanced biomass and membrane stability index	Jha and Subramanian (2014)
Pseudomonas putida H-2-3	Soyabean	Increased shoot length and fresh weigt	Kang et al. (2014)
Bacillus pumilus	Soyabean	Increased growth and seed protein yield	Stefan et al. (2010)
Azospirillum brasilense	*Trifolium*	Enhanced yield	Khalid et al. (2017)
Burkholderia phytofirmans PsJN	*Vitis vinifera*	Increased growth	Barka et al. (2006)
Azospirillum brasilense Sp245	Wheat	Affected dry weight	Turan et al. (2012)
Bacillus amyloliquefaciens IARI-HHS2-30	Wheat	Growth and alleviation	Verma et al. (2015b)
Bacillus cereus AS4	Wheat	Growth and yield	Sezen et al. (2016)
Mycobacterium phlei MbP18	Wheat	Growth, root and shoot	Egamberdiyeva and Höflich (2003)
Pseudomonas fluorescens PsIA12	Wheat	higher N, P, and K contents	Egamberdiyeva and Höflich (2003)
Pseudomonas lurida M_2RH_3	Wheat	Growth and nutrient uptake	Selvakumar et al. (2011)
Pseudomonas lurida NPRs3	Wheat	Alleviating cold stress	Mishra et al. (2011)
Pseudomonas putida AS3	Wheat	Growth and yield	Sezen et al. (2016)
Azospirillum brasilense Sp245	Wheat	Grain yield, mineral quality	Creus et al. (2004)
Bacillus safensis W10	Wheat	Plant growth and yield	Chakraborty et al. (2013)
Burkholderia phytofirmans PsJN	Wheat	Growth and grain yield	Naveed et al. (2014)
Ochrobactrum pseudogregnonense IP8	Wheat	Plant growth and yield	Chakraborty et al. (2013)
Pseudomonas aeruginosa (Pa2)	*Zea mays*	Increased biomass	Naseem and Bano (2014)
Streptomyces laurentii EU-LWT$_3$-69	Maize	Increased biomass and P content	Kour et al. (2020a)
Acinetobacter calcoaceticus EU- LRNA-72	Maize	Increased biomass and P content	Kour et al. (2020c)
Pseudomonas libanensis EU-LWNA-33	Maize	Increased biomass and P content	Kour et al. (2020b)

Paenibacillus durus, *P. graminis*, *P. borealis*, *P. pabuli*, *P. illinoisensis*, *P. odorifer*, and *Klebsiella variicola* (Navarro-Noya et al. 2012). In a report, N_2-fixing, *Azotobacter chroococcum* and K solubilizing bacteria, *Bacillus mucilaginosus* were co-inoculated in forage crop of Sudan grass (*Sorghum vulgare*) grown with waste mica under greenhouse conditions. The report concluded significant increase in biomass of plant and higher nutrient acquisition were obtained (Basak and Biswas 2010). *Paenibacillus graminis* sp. nov. from rhizosphere of *Triticum aestivum* was also reported as prominent nitrogen fixer (Beneduzi et al. 2010).

Co-inoculation of two different combination containing P solubilizing and nitrogen fixing bacteria (NFB) i.e. *Pseudomonas chlororaphis*, *Arthrobacter pascens*, *Bacillus megaterium* and *Burkholderia cepacia* was tested on walnut seedlings. The results showed highest plant height, dry weight of shoot and root, nitrogen uptake and maximum amount of P and N in soil in *P. chlororaphis* and *(A) pascens* amended walnut seedlings, as compared to *(B) megaterium* and *Burkholderia cepacia* (Yu et al. 2012). *Azotobacter vinelandii*, from rhizosphere of rice was reported for fixing nitrogen. The strain was also evaluated on rice for plant growth promotion and results showed improvement in growth and yield of the crop (Sahoo et al. 2014). *Azospirillum soli* sp. nov. and *Azospirillum agricola* sp. nov., from agricultural soil of Taiwan was also reported for fixing nitrogen (Lin et al. 2015, 2016). In another study, two species of *Pseudomonas* i.e. *P. koreensis* and *P. entomophila* from sugarcane rhizosphere were found for fixing nitrogen. These strains were used as inoculum in sugarcane crops and observed the remarkable enhancement of growth and nutrients (Li et al. 2017).

Soil bacteria associated with the rhizosphere of gaint reed and switchgrass was isolated. Three bacteria namely *Sphingomonas trueperi, Psychrobacillus psychrodurans* and *Enterobacter oryzae* exhibited nitrogenase activity. These strains were inoculated on maize and wheat seedlings grown under greenhouse conditions. The results showed that these strains were promoting growth and nutrient uptake such as N, Ca, S, B, Cu, and Zn in maize plant and Ca and Mg in wheat (Xu et al. 2018). *Pseudomonas stutzeri* was also found to fix atmospheric nitrogen and its inoculation on maize remarkably improved nitrogen content (Ke et al. 2019). Similarly, *Azospirillum* sp. was reported for fixing nitrogen and enhancing growth of rice plant by enhancing plant biomass and nitrogen uptake (Asiloglu et al. 2020).

Phosphorus solubilization

The phosphorus (P) is another macronutrient which is recycled by the soil microbes. It is the 11th most abundant element on the earth and lithosphere i.e. soil is the largest reservoir of P (400–1200 mg/kg) (Bhattacharyya and Jha 2012). In soil, phosphorus is found in the two chemical forms namely organic P (Po) and inorganic P (Pi), which differ on the basis of their parent material, pH of soil vegetation cover, time and extent of pedogenesis (Kour et al. 2021b; Walker and Syers 1976). These forms are present as mineral compounds that may contain alkaline earth metals like calcium and transition metals such as aluminum, iron, and manganese nonmetal elements like aluminum, iron and manganese. These elements present along with the phosphorus may vary according to the soil pH and minerals conditions, for example in acidic soil, phosphorus forms complex with Al, Fe and Mn, while Ca strongly reacts in the alkaline soil conditions (Jones and Oburger 2011; Saxena et al. 2020).

In soil, inorganic form of phosphorus is present about 35–75 % of total P pool. Pi is present as a mineral source of Ca, Fe and Al phosphate. Calcium-phosphate mainly exist in the form of apatite like hydroxyapatite ($Ca_5(PO_4)_3OH$), fluoroapatite ($Ca_5(PO_4)_3$ F), and francolites (carbonate-fluorapatite), which are primary source of Pi in the neutral or alkaline soil, whereas in acidic soil Fe and Al exist along with the phosphate as oxy(hydr)oxides such as strengite ($FePO_4.2H_2O$), variscite ($AlPO_4.2H_2O$) and wavellite ($Al_3(OH)_3(PO_4)_2{\cdot}5H_2O$) (Harris 2002). Another phosphorus form i.e. organic form (Po) is averagely, present about 30–65 % in the soil. Inositol, phosphates, phospholipids and nucleic acids are main identified forms of Po in soil, in which inositol is the most abundant and dominant form. Inositol is highly variable and comprise of phosphate monoesters (inositol monophosphate and hexakisphosphate), whereas, phospholipids comprises of phoshoglycerides. There are some other Po forms available in soil namely, organophosphorus (phytin), sugar phosphate, monophosphorylated carboxylic acids and teichoic acids (Jones and Oburger 2011).

Phosphorus is the second most important macronutrients for the plants as it the integral part of its chemical structures (coenzymes, nucleic acids, phosphorproteins and phospholipids) and make up 0.2 % of plant's dry weight (de Oliveira Mendes et al. 2014). In plants, this macronutrient plays a significant role in respiration, photosynthesis, membrane formation, carbon metabolism and energy transfer (Ingle and Padole 2017). Phosphorus helps in root elongation and proliferation for the acquisition of more nutrients and water from the soil (Khan et al. 2014; Singh et al. 2020).

Plants uptake phosphorus from soil through roots in the form of negatively charged primary and secondary orthophosphate ions i.e. $H_2PO_4^-$ and HPO_4^{2-}, but, in soil, majority of phosphorus is mainly present in the complex minerals source and available form is relatively low. So, its solubilization is much important as P deficiency may stunt the plant growth by inhibiting the root system and flowering. Soil microbes have a capability of solubilizing phosphorus named as phosphate-solubilizers (Szilagyi-Zecchin et al. 2016). Soil microbes undergo various mechanisms like production of dissolving mineral compounds such as organic acids (tartaric, succinic, oxalic, malic, malonic, lactic, glycolic and gluconic acids and 2-ketogluconic acids), carbon dioxide, hydroxyl ions, protons and siderophores; and liberation of extracellular enzymes for the release of soluble P (Gyaneshwar et al. 2002). These mechanism ultimately, dissolute the unavailable phosphorus by lowering the pH of the soil (Jones and Oburger 2011).

On the other hand, siderophores, a low molecular weight compound have a high affinity towards iron, chelates Fe from P containing Fe (hydr)oxides and releases P (Jones and Oburger 2011). Release of exopolysaccharides (EPS) by the soil microbes also releases P from the complexes. EPS complex, the metals like Al, Cu, Zn, Fe, Mg, K in the soil, influence the solubility of phosphorus (Ochoa-Loza et al. 2001). Solubilization of P can also be mediated by the microbial enzymes namely, extracellular phosphatases which act as catalyst of the hydrolysis reaction of anhydrides and ester of H_3PO_4 and increase the orthophosphate concentration and it is utilized by plants (Quiquampoix 2005).

The usage of these phosphate-solubilizers as bio-inoculants enhances the assimilation of phosphate and offers numerous advantages to the direct stimulation of plant growth (Hassen et al. 2016). Several reports have concluded that soil microbes solubilize the insoluble form phosphorus to soluble form and enhance the plant growth. In a report, phosphate solubilizing bacteria (PSB) belonging to genera including *Acinetobacter*, *Enterobacter*, *Burkholderia, Exiguobacterium, Pantoea* and *Pseudomanas* were isolated from acidic soil of northeast of Argentina. The isolates were inoculated on common bean and results showed that three bacteria namely *Enterobacter aerogenes*, *Burkholderia* sp. and *Acinetobacter baumannii* were promoting plant growth, P and N content in leaves and photosynthetic rate (Collavino et al. 2010). In another study, thirty four PSB belonging to genera like *Pseudomonas, Stenotrophomonas, Bacillus, Cupriavidus, Agrobacterium*, *Acinetobacter, Arthrobacter, Pantoea*, and *Rhodococcus* were isolated from root associated soil of walnut and all were able to solubilize tricalcium phosphate (TCP) in solid and liquid media. Two species belonging to genera *Pseudomonas* namely, *P. chlororaphis*, and *P. fluorescens* and *Bacillus*, i.e. *B. cereus* were selected for shade house assay on walnut seedlings. The inoculation of *P. chlororaphis*, and *P. fluorescens* resulted in remarkable enhancement of plant biomass, P and N uptake of walnut seedlings (Yu et al. 2011).

Similarly, *Enterobacter* sp. from sunflower rhizosphere was reported for solubilizing tri-calcium phosphate in an *in vitro* plate assay. Moreover, this strain was also reported for producing indole acetic acid (IAA). *Enterobacter* sp. inoculation in sunflower improved host plant height, fresh and dry weight and total P content as compared to un-inoculated plants (Shahid et al. 2012). Thermotolerant bacteria, *Brevibacillus* sp. from rock phosphate mines of Jhamarkotra was reported for solubilizing P sources, hydroxyapatite (H-Ap), aluminium phosphate (Al-P) and ferric phosphate (Fe-P) and rock phosphate (RP) (Yadav et al. 2013). In another study, fungi, *Mortierella* sp. was reported for solubilizing phosphorus and it was inoculated in castor bean growing under saline conditions along with arbuscular mycorrhizal fungi (AMF), *Glomus mosseae*. The study concluded that use of this combination improves the chlorophyll and P content in castor bean. The combination of fungi and AMF also helps in ameliorating salinity stress in plants (Zhang et al. 2014).

In a study archaea was also reported for solubilizing phosphorus. Seventeen distinct species of halo-archaea belonging to eleven genera namely, *Haloarcula, Halobacterium, Halococcus, Haloferax, Halolamina, Halosarcina, Halostagnicola, Haloterrigena, Natrialba*, *Natrinema* and *Natronoarchaeum* were isolated from the soil of Rann of Kutch, Gujarat, India, were found as P-solubilizer. Among all, *Natrinema* sp. has been reported as most efficient P-solubilizer followed by *Halococcus hamelinensis* (Yadav et al. 2015). P-solubilizing bacterial strain *Bacillus circulans* from apple rhizosphere of Himachal Pradesh, India was reported for enhancing tomato germination, shoot and root length and dry weight. Micronutrients such as P, N, and K content in shoot of tomato plant were also reported to be improved by PSB (Mehta et al. 2015). In another study, nine strains namely, *Agrobacterium tumefaciens*, *Azotobacter chroococcum, Bacillus subtilis*, *Bacillus* sp., *B. cereus*, *Burkholderia thailandensis*, *Klebsiella* sp., *Pseudomonas putida*, and *P. fluorescens* were also tested positive for solubilizing tri-calcium phosphate in a plate assay. *B. subtilis*, *P. putida*, and *P. fluorescens* were found to be most efficient P-solubilizer and salinity stress alleviator. When these strains were inoculated in *Curcuma longa* L., these strains significantly enhanced leaves number, stem height and plant biomass (Kumar et al. 2016).

Pantoea ananatis, *Rahnella aquatilis* and *Enterobacter* sp. from paddy soil were reported for solubilizing P and K. These strains improved, P and K in rice seedlings, but *P. ananatis* was most efficient followed by *Enterobacter* sp. and *R. aquatilis* (Bakhshandeh et al. 2017). An entomopathogenic fungus (EPF), *Lecanicillium psalliotae* was also reported for solubilizing phosphorus and zinc and increasing plant growth of cardamom (*Elettaria cardamomum*) (Kumar et al. 2018). *Talaromyces aurantiacus* and *Aspergillus neoniger* from rhizosphere of moso bamboo (*Phyllostachys edulis*), an efficient P solubilizer and both solubilized highest P in media containing $CaHPO_4$, followed by $Ca_3(PO_4)_2$, $FePO_4$, $C_6H_6Ca_6O_{24}P_6$, and $AlPO_4$ (Kumar et al. 2018).

P-solubilizer, *Bacillus* sp. from the soil associated with rapeseed roots, was inoculated back on the plant under greenhouse and field conditions. The results showed that phosphate solubilizer, promoted plant growth and yield of rapeseed under greenhouse and field trail, respectively (Valetti et al. 2018). In another report, *Pseudomonas libanensis*, a drought tolerant strain was found for solubilizing P. Inoculation of the PSB in wheat seedlings under greenhouse condition improved plant growth and alleviated drought tolerance (Kour et al. 2020b). Similary *Acinetobacter calcoaceticus*, a drought tolerant P solubilizer was reported to enhance the plant growth of foxtail millet under greenhouse conditions (Kour et al. 2020c). In another report, *Bacillus* sp. was reported for solubilizing and mineralizing P. The inoculation of this strain on rice plant amended with rice straw, grown under greenhouse conditions showed remarkable increase in P uptake, biomass and length of plant as compared to un-inoculated plant (Gomez-Ramirez and Uribe-Velez 2021).

Potassium solubilization

The third essential macronutrient solubilized by the soil microbes for plants growth and development is potassium (K). Earthly, potassium is the seventh abundant element, which exists in three different forms i.e. unavailable potassium, slowly available or fixed potassium, and readily available or exchangeable potassium. About 90–98 % of the soil K is found in the unavailable form of silicate minerals i.e. feldspars, muscovite, orthoclase, biotite, illite, vermiculite, micas and smectite (Sparks and Huang 1985). Second form of potassium available in soil is fixed potassium (slowly available) and it makes up 1–10 % of soil potassium. This form is found between the layers of the clay minerals and act as a reserve of the potassium (Sharpley 1989). Exchangeable potassium is the third form of potassium in soil which is soluble form (K^+). This form is K is mixed with the soil water and it is present around 1–2 % on the surface of the clay particles (Sparks 2000). All these forms of K present in the soil are the source of K mineral. Among these forms exchangeable form is the readily used by plants (Srinivasarao et al. 2011).

Plant uptake K from the soil through the root systems and this mineral is transported to every inner cells of the plant tissue through xylem and phloem for several plant functioning. This mineral itself is not a part of the plant chemical structures like nitrogen and phosphorus, but still it is a crucial macronutrient (Zhang and Kong 2014). It particularly helps in the activation of plant enzymes, maintenance of osmotic tension and turgor, proteins synthesis, movement of water, necessary nutrients and carbohydrates. Moreover, K also helps in stomatal cell activity regulation to prevent water loss by transpiration, photosynthesis, and it imparts the plant resistance against pathogens like bacteria and fungi (Ahmad et al. 2016; Teotia et al. 2016). Potassium deficiency in plant can cause various problems such as lowering the yield of the crops and stunting of growth with shortening of internodes, photosynthesis reduction, blackening of some tubers like potato, and scorching of all small grains (Li et al. 2006; Meena et al. 2016).

Potassium is the second most absorbed element after nitrogen (Mora et al. 2012), but worldwide, this element's soluble form level in soil has declined due to long practice of rigorous and exhaustive agriculture which has resulted in reduced availability of K for the plant uptake. To fulfill the plant potassium requirement agriculturists use chemical fertilizer known as potash. Potash utility and its cost have drastically increased thereby leading to several environmental effects. K-solubilizing microbes play a vital role in the solubilization of K from soil by following the processes like organic acid production, acidolysis, capsule absorption, complication through extracellular polysaccharides, lowering of pH and enzymolysis (Avakyan et al. 1985; Friedrich et al. 1991; Verma et al. 2017; Welch et al. 1999). All these processes of K solubilization help in the dissolution of insoluble form of potassium like illite, feldspar, and bolite (Rajawat et al. 2020). In these processes, organic acid production and complication through exopolysaccharides are the most well understood mechanisms and information regarding other mechanisms is very scarce.

The most predominant process for the solubilization of K by the soil microbes is production of organic acids (Sheng and He 2006). In this process organic acids such as tartaric, oxalic and citric acids are produced that are meant for the acidification (lowering of pH) of the surrounding niche and dissolution of K, Si and Al from the potassium bearing minerals like micas, illite and orthoclass (Aleksandrov et al. 1967; Friedrich et al. 1991). The released organic acids from the soil microbes dissolute the K minerals directly by proton or ligand mediated mechanism to bring K into the solution or indirectly by the formation of complexes in solution with the reaction product (Ullman 2002).

Another method of solubilization of potassium is complicated through extracellular polysaccharides (exopolysaccharides). In this mechanism, soil microbes releases slime or acidic polysaccharides externally that combines with the minerals and leads to the formation of bacterial-mineral complexes which releases K mineral from silicates. When bacteria releases such exopolysaccharides, the excreted compound absorb SiO_2, after which the equilibrium between the mineral and fluid phase get affected and lead to the reaction towards the solubilization of K^+ and SiO_2.

Various studies have been conducted for the investigation of potassium solubilizing microbes that further can be used as potassium biofertilizers to reduce the use of chemically synthesized K-fertilizer. *Paenibacillus glucanolyticus* (Sangeeth et al. 2012), *Agrobacterium tumefaciens*, *Burkholderia cepacia*, *Enterobacter aerogenes*, *E. asburiae*, *E. cloacae*, *Microbacterium foliorum*, *Myroides odoratimimus*, *Pantoea agglomerans* (Zhang and Kong 2014), *Rhizobium pusense*, *Agrobacterium tumefaciens* (Meena et al. 2015), *Bacillus licheniformis*, *Pseudomonas azotoformans* (Saha et al. 2016), *Bacillus subtilis*, *Burkholderia cepacia* (Bagyalakshmi et al. 2017), *Pantoea agglomerans*, *Pseudomonas orientalis*, *Rahnella aquatilis* (Khanghahi et al. 2018a) are the few reported potassium solubilizing microbes.

Zinc solubilization

Solubilization of zinc is another vital role of soil microbes that nourish plants with zinc mineral. Zinc is vital nutrient for plant life but required in low concentration. This nutrient has been categorized as micronutrient and plays a pivotal role in plant metabolism as it is cofactor and metal activator of many plant enzymes like tryptophan synthetase. Tryptophan synthetase is responsible for the synthesis of tryptophan in IAA biosynthesis, isomerases, hydrolases, lyases, ligases, transferases and oxidoreductases (Imran et al. 2014). Zinc helps in the development of plant roots, crop yield and in the water uptake (Kaur et al. 2020; Tavallali et al. 2010). Plants absorb zinc like other nutrients, i.e. from soil in form of zinc ions (Zn^{2+}) which is available in a very low concentration. Most of the zinc in soil is present in the insoluble form, which cannot be absorbed by the plants. So, its solubilization and mineralization is much needed, as zinc deficiency results in the plant developmental abnormalities that adversely affect the plant yields (Hafeez et al. 2013; Sahu et al. 2018).

Soil microbes help in zinc solubilization either by using single mechanism or by multiple mechanisms. One of the many mechanisms of solubilization exhibited by the microbes is lowering of pH, which improves the zinc availability (Hussain et al. 2018). Another mechanism of solubilization is mineral chelation. Chelation can be possibly completed by secretion of Zn-chelating compounds, which are metabolites (Obrador et al. 2003). These metabolites are released by soil microflora, that reduces the zinc reaction with soil and chelates, that forms a complex with the metal cation Zn^{2+} (Tarkalson et al. 1998). This chelation also increases the availability of zinc ions in soil that can be absorbed by the plants through their roots. This mechanism is the most dominant methods of microbes for solubilization of zinc (Hussain et al. 2018).

Soil microbes solubilized the zinc by producing various organic acids like gluconate (Saravanan et al. 2011) or the derivatives of gluconic acids, e.g., 2- ketogluconic acid (Fasim et al. 2002), 5-ketogluconic acid (Saravanan et al. 2007) which lower the pH and make zinc available to the plants. Mainly, zinc ions are released by the production of 2-ketogluconic acid (Fasim et al. 2002). As other nutrients, the soluble form of zinc (Zn^{2+}) is also not available in the soil as numerous bacteria have been reported to possess capability of solubilizing zinc. Plant growth promoting microbes (PGPMs) like *Acinetobacter* sp. (Gandhi and Muralidharan 2016), *Bacillus aryabhattai*, *B. subtilis* (Mumtaz et al. 2017), *B. cereus*, *B. tequilensis* (Khande et al. 2017), *Pseudomonas aeroginosa* (Jerlin et al. 2017), *P. fragi*, *Pantoea dispersa*, *P. agglomerans* (Kamran et al. 2017), *Agrobacterium tumefaciens*, *Rhizobium* sp. (Khanghahi et al. 2018b), *Curtobacterium*, *Plantibacter*, *Pseudomonas*, *Stenotrophomonas* (Costerousse et al. 2018), *Pseudomonas* sp., *Bacillus* sp. (Zaheer et al. 2019), and *Bacillus megaterium* (Bhatt and Maheshwari 2020) are the few reported zinc solubilizing microbes which can be used for the zinc solubilization and mobilization.

Siderophores production

Siderophores are the ferric specific ligands having a molecular weight < 10,000 Da (Korat et al. 2001). These small molecules are specially produced by the microbes in order to combat iron from the soil because the preferred form of iron utilized by the microbes is available though it is the fourth most abundant element on this planet. The scavenging agent of iron chelate iron from the soil which exists in the two different oxidation states oxidation states, Fe (III) and Fe (II). The protein named, iron regulates outer membrane proteins (IROMPs), present on the microbial cell surface, transport the complex of ferric iron to cognate membranes that regulates the iron into soluble form and thus the soluble form of iron is available for various metabolic processes (Johri et al. 2003). Microbes produce three different types of siderophores which are categorized on the bases of their oxygen ligands for Fe (III) coordination and named as hydroxamates, catecholates, and carboxylates (Saha et al. 2013). The production of siderophores is one the important mechanism of microbes for iron acquisition because iron is an essential mineral and required for several metabolic processes like electron transport chain, oxidative phosphorylation, photosynthesis and tricarboxylic acid cycle. Iron is also required for the biosynthesis of nucleic acids, vitamins, antibiotics, toxins, pigments, cytochrome and porphyrins (Fardeau et al. 2011). Plants are also not able to utilize the available iron form so, microbes can be used for the biofortification of iron.

Many evidences are available that have reported iron uptake by plants through microbial siderophores and various microbial strains have been found to produce siderophores (Sayyed et al. 2013). Microbes like *Achromobacter spanius* (Farah Ahmad et al. 2006), *Arthrobacter* sp., *Bacillus arsenicus*, *B. sporothermodurances*, *Streptomyces rochei, S. carpinensis, S. thermolilacinus*, (Upadhyay et al. 2009), *B. megaterium*, *B. subtilis*, *B. licheniformis*, *Pseudomonas tolaasii*, *P. synxantha*, *Staphylococcus sciur* (Kumar et al. 2011), *P. geniculata* (Gopalakrishnan et al. 2015), *P. fragi* (Kamran et al. 2017) *Bacillus aryabhattai* (Mumtaz et al. 2017), *Curtobacterium, Plantibacter, Pseudomonas, Stenotrophomonas* (Costerousse et al. 2018), *Streptomyces laurentii* and *Penicillium* sp. (Kour et al. 2020a) are the known to produce siderophores and can be used for the biofortification of iron.

Phytohormones production

Phytohormones are the organic substances which are recognized by plant physiologists as important compounds along with other macro and micro-nutrients. Plant endogenously produces several types of phytohormones like auxin, cytokinin, gibberellic acids, abscisic acid and ethylene that play various well-known functions in the plants. There are some other hormones that have been discovered recently i.e. brassinosteroids, jasmonate, lactones, nitric oxide, polyamines and salicylic acids. The effect of these hormones on the plants is unraveled. These organic compounds are required in very much low concentration, but still they can regulate the plant physiological processes in positive and negative way (Davies 2004 1457). Although plant endogenously produces phytohormones but in several harsh climatic conditions, plants are not able to produce the required amount of phytohormones that affects the growth and development of plants (Frankenberger Jr and Arshad 2020). Plants require exogenous hormones known as plant growth regulators (PGRs), which can be provided to plant by using soil microbes exhibited phytohormones producing attributes as bioinoculants. Microbes been have mainly reported to produce plant hormones like auxin, cytokinin, and gibberellic acids through various biosynthesis pathways (Spaepen 2015). The other phytohormones produced and required by plants for their particular functions are abscisic acid and ethylene. Abscisic acid plays an important role in seed germination, the closing of stomata and environmental stress tolerance (Vijayabharathi et al. 2016). Soil microbes like *Bacillus licheniformis, Pseudomonas fluorescens* (Salomon et al. 2014), *Rhodococcus* sp., and *Novosphingobium* sp. (Belimov et al. 2014) have been reported for producing abscisic acid. Whereas ethylene has a wide range of role in plants like elongation of roots, fruit ripening, lower wilting, seed germination, leaf abscission and activation of plant hormones synthesis (Gupta et al. 2015).

Auxin Auxin plays an essential role in plants, as it has a positive effect on the root development that enhances the uptake of nutrient and minerals from the soil. Along with roots development this phytohormone also helps in cell division, stem development, adventitious root initiation, and differentiation of vascular tissue. This phytohormone also plays role in the division, extension, and differentiation of the cell, vegetative growth biosynthesis of various metabolites, apical dominance, gravitropism and phototropism (Mrkovački et al. 2012) (Davies 2004 1457). Apart from these functions auxin also helps in the regulating the synthesis of other hormones like strigolactones (Al-Babili and Bouwmeester 2015). Naturally, auxin occurs in the form of indole-3-acetic acid (IAA), indole-3-butryric acid and phenylacetic acid, among which IAA is the most important auxin and being extensively studied (Spaepen 2015).

Auxin is biosynthesized by both plants and microbes. In microbes six different biosynthesis pathways are known till now, but besides two pathways, other doesn't have genetic evidence. The two known pathways includes pathway via indole-3-acetamide (IAM) and via indole-3-pyruvate (IPyA). In IAM pathway, firstly tryptophan is converted into tryptophan monooxygenase and to IAM. This IAM is catalyzed by the IAM hydrolase and converted it into IAA. Another pathway of IAA biosynthesis via IPyA includes the transmission of IPyA by an aromatictranferase in the first step and then its conversion into indole-3-acetaldehyde (IAAld) through decarboxylation reaction catalyzed by an enzyme known as IPyA decarboxylase (IPDC, encoded by a *ipdC* gene). Most of these pathways use aromatic amino acid tryptophan as precursor. These two pathways i.e. IAM and IpyA exist in the pathogenic microbes and beneficial plant-associated microbes respectively (Spaepen 2015).

Numerous soil microbes like *Achromobacter spanius* (Farah Ahmad et al. 2006), *Arthrobacter* sp., *Bacillus arsenicus*, *B. sporothermodurances*, *Streptomyces rochei, Streptomyces carpinensis, Pseudomonas medicona, Streptomyces thermolilacinus*, (Upadhyay et al. 2009), *Alcaligenes faecalis, B. megaterium*, *B. subtilis, Enterobacter cloacae* (Kumar et al. 2011), *Azospirillum lipoferum, Bradyrhizobium japonicum, Paenibacillus durus, P. borealis* (Navarro-Noya et al. 2012) *P. geniculata* (Gopalakrishnan et al. 2015), *Aureobasidium pullulans, Barnettozyma californica, Cryptococcus laurentii, Dothideomycetes* sp., *Galactomyces candidum, Hanseniaspora uvarum, Kazachstania jiainicus, Meyerozyma caribbica, Torulaspora* sp., *Pseudozyma aphidis, P. rugulosa, Rhodosporidium paludigenum, Sporidiobolus ruineniae, Ustilago esculenta* (Fu et al. 2016), *Acinetobacter* sp. (Gandhi and Muralidharan 2016), *Rhizobium* sp., *Pantoea agglomerans*,-and *P. dispersa* (Kamran et al. 2017), *Pseudomonas aeroginosa* (Jerlin et al. 2017), and *Enterobacter ludwigii* (Lee et al. 2019), *Penicillium* sp. (Kour et al. 2020a) have been reported for producing auxin which is utilized by the plants.

Cytokinins Cytokinin is another hormone produced by the plants and microbes. In plants this phytohormone helps in the differentiation of shoot and part in the growth of plant callus. This hormone also help plant in increasing the stress tolerance specially water flooding stress (grain filling stage). Exogenously, this hormone is produced by microbes. *Bacillus subtilis* (Kudoyarova et al. 2014; Liu et al. 2013), *Pseudomonas syringae* (Großkinsky et al. 2016), *Citrococcus zhacaiensis*, and *Bacillus amyloliquefaciens* (Selvakumar et al. 2018) are cytokinin producing soil bacteria reported so far.

Gibberellic acids Another phytohormone endogenously produced by the plants is Gibberellic acids (GAs). GAs is a broad group of 100 compounds, which is classified as tetracyclic diterpenoid acids, with ent-gibberellane as backbone. This phytohormone in plants helps in their cellular elongation and division, as well as the internodium elongation (Davies 2004 1457). Exogenously, this hormone is produced by the soil microbes. The biosynthesis pathway is still under the black box which is unraveled. Besides the unknown biosynthesis pathway of GAs, a lot of research is have been conducted to find the microbes producing this plant growth regulator. *Arthrobacter* sp., *Bacillus aquimaris*, *B. cereus* (Upadhyay et al. 2009), *B. subtilis*, *Burkholderia cepacia* (Bagyalakshmi et al. 2017), and *Enterobacter ludwigii* (Lee et al. 2019) have been known to produce gibberellic acid.

Photosynthesis

Assimilation of carbon dioxide from the air by the means of photosynthesis process is a important mechanism because 90 % of the plant biomass and better growth depends on it (Long et al. 2006). This important process of plants can be enhanced by the addition of microbial based biofertilizers. Various studies have reported different soil microbes that help in the enhancement of photosynthetic pigments. *Rhizobium* sp., *R. leguminosarum*, *Bradyrhizobium* sp. (Peng et al. 2002), *Bacillus subtilis* (Wu et al. 2016; Zhang et al. 2008) are the reported bacteria that have been found to increase the photosynthesis in plants. Plant growth promoting rhizobacteria (PGPR), *Arthrobacter protophormiae* and *Dietzia natronolimnaea* were reported to increase photosynthetic efficiency of wheat grown under salt and drought stress (Barnawal et al. 2017).

Moreover, *Pseudomonas fluorescens* was reported for enhancing the photosynthetic pigments in plant, black gram (*Phaseolus mungo*) grown under saline conditions (Yasin et al. 2018). In another report, co-inoculation of AMF, *Rhizophagus irregularis* and a bacterium, *Bacillus amyloliquefaciens* on *Trifolium repens* and *Fragaria vesca* was reported for increasing photosynthetic efficiency of host plants (Xie et al. 2018). Inoculation of *Planomicrobium chinense*, *Bacillus cereus* and *Pseudomonas fluorescens* on wheat was also reported for increasing photosynthesis efficiency (Khan et al. 2019). ACC-deaminase producing rhizobacteria, *Achromobacter xylosoxidans* were reported for higher photosynthetic rate in maize plant as compare to control (Danish et al. 2020).

Reclamation of soil fertility

Soil is a combination of texture, air, water, biomass, organic matter and microbes which is a complex system. Plants main nutrient source comes from the soil and its fertility is the major component by which the functioning of agricultural ecosystem is governing. Due to over exploitation of chemical based products, agriculture soil fertility has been declined which leads to the poor quality of soil. To reclaim the fertility of soil, soil microbes are fundamental for the maintenance of soil fertility in agro ecosystem. Soil microbes are important for reclamation of fertility of soil because they are deeply involved in the various nutrients cycle like nitrogen, phosphorus, potassium and many more (Bastida et al. 2018; Fierer 2017). The use soil microbes as biofertilizers is one of the appropriate methods for retaining the fertility of soil. Bacteria, actinomycetes, fungi, algae, protozoa, viruses are the various soil microorganism which can be used to improve the soil quality and fertility (Bharti et al. 2017). In a study, three non-rhizospheric plant growth promoting bacteria namely *Enterobacter aerogenes*, *E. asburiae* and *E. cloacae*, were reported for stimulating the bacterial count in the rhizosphere of cow pea after inoculation which helps in increasing the fertility of the soil (Deepa et al. 2010).

Pantoea agglomerans and *Burkholderia anthina* isolated from non-rhizospheric soil were found be an efficient solubilizer of P. The co-inoculation of these two strains in tomato plant enhances plant growth, P uptake and also reclaims the soil fertility (Walpola and Yoon 2013). *Paenibacillus* sp. from bulk soil was also reported for enhancing the fertility of soil (Liu et al. 2012). In a study, P solubilizer, *Pantoea cypripedii* and *Pseudomonas plecoglossicida* from organic field were also reported for improving the soil fertility (Kaur and Sudhakara Reddy 2014). In another report, *Bacillus cereus*, a plant growth promoting rhizobacteria was reported for enhancing biological fertility along with crop productivity of plant *Vigna radiata* (Islam et al. 2016). In an investigation, *Rhizobium* sp. from chickpea were reported for enhancing the plant growth, N uptake and also this strains potential reinstate the soil fertility (Khaitov et al. 2016).

Role of soil microbes in environmental sustainability

Earth is the home of uncountable creatures and it provides all the necessary need which is important for living. Humans are one of the earth's creature that need synthetically synthesized good's for luxurious living. In order to synthesize good's, industries were established in which different types of harsh chemical is used. Industrialization without a doubt eases the lives of humans but along with it the use of chemical also leads to accumulation of environmental pollutants. The pollutants like pesticides (DDT), toxic heavy metals, xenobiotics, poly aromatic hydrocarbons, oil, effluents of the industries, found in the environment are known to be present on the earth from the very long period of time because they can't be degraded due to their complexity. The presence of such pollutants in the environment is causing problems like degradation of soil quality, extinction of biodiversity and increase of diseases.

To overcome such problems, microbes plays a significant role in the removal of pollutant because they have a capability to undergo special mechanisms like that breakdown of the complex molecules of pollutants that normally can't be degraded (Bhargava et al. 2017; Kumar et al. 2021; Mishra et al. 2017). *Acinetobacter* sp., *Arthrobacter* sp., *Bacillus* sp., *Corynebacterium* sp., *Flavobacterium* sp., *Micrococcus* sp., *Mycobacterium* sp., *Nocardia* sp., and *Pseudomonas* sp., are some bacterial genera that have been used for the bioremediation of pesticides, heavy metals and other toxic metals which successfully improves the environment (Beškoski et al. 2012; Milić et al. 2009) (Table 3). Microbes undergo different mechanism like microbial enzyme action and bio-sorption to remove various pollutants from the environment.

Mechanism of microbial remediation

Bioremediation through enzyme action is one of the common mechanisms of microbes to bio-remediate pollutants. Different types of enzymes are being used for the remediation of pollutants released by the microbes i.e. oxidoreductases, oxygenases, monooxygenases, dioxygenases, laccases, peroxidases, lipases, cellulases, proteases that cleaves the chemical bonds to lower the complexity of the pollutants (Karigar and Rao 2011). Biosorption is mainly involved in alleviating the heavy metals. This mechanism involves the adsorption and absorption phenomenon in which heavy metals are firstly accumulated by the microbes and get attached to the cell surface because of their structure. After adsorption, metals ions are absorbed inside the microbes by the addition of anionic groups i.e. phosphoric acid and carboxyl that interacts with the cationic group (mostly heaby metals carries cationic group) and then metals are allowed to pass through the cell membrane and in this way pollution caused by heavy metals are remediated by the microbial cells (Karigar and Rao 2011).

Soil microbiomes as biofertilizers

Soil microbes are the emerging panacea of both sustainable agriculture and environment as it can be used for plant growth promotion along with the removal of hazardous pollutants; so, they can be used as biofertilizers. Biofertilizers are the living cells of the soil microbes that can be used in different types of bio-formulation. Microbes with multifarious plant growth promoting (PGP) attributers could be used for formulation as single or in a consortium for plant growth promotion, soil health and mitigation of diverse stress conditions (Yadav 2021b, c). These beneficial PGP soil microbes plays significant role in plant growth promotion and soil fertility under the natural normal as well as harsh environmental conditions (Mondal et al. 2020). Biofertilizers are available in two different types of bioformulation namely liquid and dry which are is commercially available in the market.

Development of bioformulations

Microbial formulation development is mainly developed because of its application on the crop or on the environments. So, genetic stability even if the production is on large and its viability in unfavorable conditions is much essential (Moënne-Loccoz et al. 1999). The formulation of bioinoculants is the vital factor because formulation should be stable and microbe's functionality should be retained till they have been inoculated (Jones and Burges 1998). The function of the microbes depends upon the type of formulation. Bioinoculants formulations are of two types' conventional and advance. Conventional types are further of two type's namely solid and liquid formulation. Solid formulation like peat, granules and powder has short shelf life because they have been desiccated. Liquid formulation is another type of conventional formulation which is based on broth cultures. The drawback of this formulation is that they lack carrier protection due to which microbes lose their viability quite fast. Microencapsulation formulation is advance type of formulation, proved to be the beneficial over conventional types because this technique constructs carrier of the microbe. Carrier is the vehicle the transport microbes from industries to the field in good physiological condition (John et al. 2011). Storage and transport completely depends upon the type of formulation and conditions of the surroundings (Malusá et al. 2012). It is reported that microencapsulation formulation can be stored for six long months at the temperature of 4 °C or at room temperature (Rouissi et al. 2010).

Liquid bioformulations

The flowable or aqueous suspension that consists of 10–40 % biomass and 35–65 % a carrier liquid which can be an oil or a water, 1–3 % suspender ingredient, 1–5 % dispersant and 3–8 % of surfactants is known as liquid formulations. Liquid formulation are further of four types namely suspension concentrate (SCs), oil miscible flowable concentrate (OF), Ultralow volume suspension (ULV) and oil dispersion (OD). In suspension concentrates solid active ingredients that have poor solubility in water and satisfactory stability to hydrolysis is added. This type of formulation is diluted in water before they are used (Tadros 2013). On the other hand, OF formulation is oil based which is diluted in the organic liquid before use. The liquid formulation ULV can be used by the using ULV equipment is an aerial or ground spray, which generates extremely fine spray (Singh and Merchant 2012). OD bioformulation is formulation in with active ingredient is mixed into a water-immiscible solvent or oil (Singh and Merchant 2012).

Solid bioformulations

Solid bioformulations contains solid carrier mixed with the live cells. These types of formulation are generally preferred

Table 3 Soil microbiomes and their potential applications for biodegradation of different compounds

Soil Microbes	Source	Compounds	References
Bacillus pumilus	Soil from cotton field	Chlorpyrifos	Anwar et al. (2009)
Sphingobium quisquiliarum	HCH dumpsite, India	HCH	Bala et al. (2010)
Alkanindiges illinoisensis	Oil-contaminated soil, Illinois	Squalane	Bogan et al. (2003)
Sphingomonas flava	HCH-contaminated soil, Germany	α-, γ- and δ-HCH	Böltner et al. (2005)
Sphingobium francense	HCH-contaminated soil	δ-HCH	Cérémonie et al. (2006)
Novosphingobium naphthae	Oil-contaminated soil, Nepal	Hydrocarbon	Chaudhary and Kim (2016)
Sphingobium naphthae	Oil-contaminated soil, South Korea	Aliphatic hydrocarbons	Chaudhary et al. (2017)
Paenibacillus naphthalenovorans	Marsh rhizosphere	Phenanthrene	Daane et al. (2002)
Sphingobium chinhatense	HCH dumpsite, India	HCH	Dadhwal et al. (2009)
Mycobacterium pyrenivorans	PAH contaminated soil, Germany	PAH	Derz et al. (2004)
Sphingobium lucknowense	HCH dumpsite, India	HCH	Garg et al. (2012)
Bacillus circulans	HCH-contaminated soil, India	α, β, γ, and δ-HCH	Gupta et al. (2000)
Alcaligenes faecalis	HCH-contaminated soil, India	HCH	Gupta et al. (2001)
Mycobacterium aromaticivorans	Pristine-contaminated soil, Hawaiian	PAH	Hennessee et al. (2009)
Pseudomonas paucimobilis	Paddy Soil	δ-HCH	Imai et al. (1989)
Celeribacter persicus	Mangrove soil	PAH	Jami et al. (2016)
Arthrobacter phenanthrenivorans	Creosote-contaminated soil, Greece	Phenanthrene	Kallimanis et al. (2009)
Sphingomonas paucimobilis	Tar oil-contaminated, soil	PAHs	Kästner et al. (1998)
Mycobacterium hodleri	Fluoranthene-polluted soil	PAH	Kleespies et al. (1996)
Sphingomonas formosensis	Agricultural soil, Taiwan	PAH	Lin et al. (2012)
Pseudomonas aeruginosa	Pesticide contaminated dumpsite	γ-HCH	Lodha et al. (2007)
Sphingobium barthaii	Cattle pasture soil	PAH	Maeda et al. (2015)
Rhodanobacter lindaniclasticus	Wood treatment site	Lindane	Nalin et al. (1999)
Sphingomonas indica	HCH-contaminated soil, Czech republic	HCH	Niharika et al. (2012)
Sphingobium fuliginis	Fly ash dumping site, India	Phenanthrene	Prakash and Lal (2006)
Novosphingobium lindaniclasticum	HCH-contaminated soil, India	HCH	Saxena et al. (2013)
Sphingobium ummariense	HCH-contaminated soil	HCH	Singh and Lal (2009)
Pseudomonas aeruginosa	HCH-contaminated soil	δ-HCH	Singh et al. (2007)
Mycobacterium frederiksbergense	Coal tar-contaminated soil, Denmark	PAH	Willumsen et al. (2001)
Burkholderia cocovenenans	Petroleum-contaminated soils	PAH	Wong et al. (2002)
Bacillus pumilus	*Panicum aquaticum* rhizosphere	Petroleum	Viesser et al. (2020)
Providencia vermicola	Radionuclide containing soil	Radionuclide waste	Shukla et al. (2019)
Bacillus safensis	Soil, India	Chromium	Kalaimurugan et al. (2020)
Bacillus Mojavensis	Oil-Contaminated Soil	PAH	Eskandari et al. (2017)
Pseudomonas stutzeri	Copper mine soil	Copper	Palanivel et al. (2020)
Rhodococcus opacus	Oil-spilled soils	Benzoate, phenol, and chlorophenols	Puntus et al. (2019)
Rhodopseudomonas palustris	Paddy fields	Heavy metals	Sakpirom et al. (2017)
Burkholderia vietnamiensis	Soil, Malaysia	Glyphosate	Manogaran et al. (2017)
Stenotrophomonas maltophilia	*Pistia stratiotes* rhizosphere	Copper and Nickel	Ghosh et al. (2020)
Massilia aromaticivorans	Arctic soil, Norway	BTEX	Son et al. (2021)
Bacillus cereus	Diesel contaminated, soil	Diesel	Oyewole et al. (2020)
Brevibacterium macroides	Agricultural soil	Fluazifop-p-buty	Erguven and Nuhoglu (2020)

PAH: Polycyclic Aromatic Hydrocarbon; HCH: Hexachlorocyclohexane; BTEX: Benzene, toluene, ethylbenzene and xylene over the liquid bioformulations because of longer shelf life and are easier to store and transport. This type of formulation are also of different types like granules (GR), microgranules (MG), wettable powder (WP), dusts, water-dispersible granules (WDG), where granules are the dry particles containing ingredient, binder and carrier (Guijarro et al. 2007). Wettable powder is known as a the oldest type of formulation and it consist of a technical powder, filler, dispersant and surfactants in the concentration of 15–45 %, 1–10 % and 3–5 %, respectively. This type of formulation is added into liquid carrier before the implementation into the fields. Another type of formulation named dust is also an oldest formulation with mixture of active ingredient finely grounded (size ranging from 50 to 100 μm). WDG, another formulation type is known as a dry flowables. They are the non-dusty, free flowing granules ecofriendly and easy to use by just dissolving in water (Mishra and Arora 2016).

Applications of biofertilizers

Biofertilizers introduction into field depends on several factors like type formulation, its concentration, microbe survival in the field (competition of microbes with native niches) (Dey et al. 2012). The inoculation of biofertilizers in the field can be done by four ways including inoculation with seeds, spraying onto furrow of bioinoculants and liquid formulation and powder inoculation (Bashan 1998). Recently, a study was published in which different bioformulations of microbes like cell based, supernatant based and metabolite based formulations of *Bradyrhizobium* sp. strain was tested on pigeon pea crop and results showed that cell based formulation were the best to improved plant growth (Tewari et al. 2020). Presently, different types of microbial formulation are commercially available in the market that are inoculated in the fields such as *Azolla-Anabaena* is marketed as foliar spray and commercially available in the countries like Australia, China, India, and Japan. The other commercial available product of *Trichoderma* sp. and AM fungi is commercially available as soil inoculant in the countries like Germany, France, Spain, Italy and Denmark (Rani and Kumar 2019).

Rule and regulation for release of biofertilizers

Biofertilizers, the best alternative to the chemical based fertilizers are gaining the prime attention in the world of the researchers due to their sustainable nature. The implementation of such formulation in the agriculture fields avail various required nutrients from the soil to the plants without harming the environment and helps in improving the soil quality. These advantageous products are now drastically increasing their growth and the market value. So, various countries have implemented some regulation policies in order to register the biofertilizers Like in India, biofertilizers registration has to follow Essential Commodities Act, 1955 (10 of 1955) under Sec. 3. The rules according to this act details that biofertilizer product should contain carrier, living microbes and should be useful as nitrogen fixer, phosphorus solubilizer and nutrient mobilizer to increase the productivity of the crop and soil. In Europeon countries, European parliament has launched the registration policy of biofertilizers under Regulation (EU) 2019/1009. This regulation includes the rules for both organic and inorganic fertilizers (Barros-Rodríguez et al. 2020).

Conclusion and future prospects

Soil has one of the largest microbial diversity that plays a significant role in plant growth promotion, nutrient uptake and cycling in agro-ecosystem. The roles of microbes and their applications for agricultural and environmental sustainability are under spotlight and now they have been used for quite a long time. The application of soil microbes as single or as in consortium as bio-inoculants are considered as best alternative to reduce the uses of chemicals based fertilizers. These tiny creatures' inhabitants of soil have a capability to maintain the agriculture sustainability by performing various roles like reclamation of lost soil fertility, alleviation of both environmental stresses (biotic and abiotic), with that soil microbes were able to solubilize zinc, potassium, phosphorus, fix nitrogen and produces siderophores, plant growth hormones (auxin, cytokinin, gibberellic acids and abscisic acids), hydrogen cyanide that all helps directly or indirectly in the promotion of plant growth and soil fertility. Soil microbes helps in the degradation of complex pollutants like DDT and make it useful as well as beneficial soil microbes use in bioremediation of diverse environmental pollutants. Soil microbes could be used as the bioinoculants as biofertilizers and biopesticides for agricultural sustainability and in bioremediation and biodegradation for environmental sustainability.

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