10 Soil Microbiota: A Key Bioagent for Revitalization of Soil Health in Hilly Regions

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Abstract

Soils of hill regions encompass diverse organic and inorganic substances, where nutrient cycling of these matters and associated factors maintain soil fertility. However, due to rigorous anthropogenic activities and constant exposure of cold temperature the biological behavior of hilly soil get transformed which makes soil more acidic with low nutrient availability. These are the key factors for diminution of plant growth performance and productivity in the hilly regions. In the present era, various strategies such as agricultural interventions, use of chemical fertilizers, etc. are being practiced to improve the soil health. Such strategies are labor demanding, expensive, and affect the ecosystem negatively. Such practices in long term can change the physical, biological, and chemical properties of soil, and may also degrade the quality of soil by lowering down its fertility. On the contrary, microorganism based practices have the potential to restore soil health quite efficiently without disturbing the soil ecosystem. Soil-dwelling microorganisms can promote organic matter management, nutrient cycling, soil aggregation, and soil fertility by means of various mechanisms for sustainable agriculture. These mechanisms include nitrogen fixation, mobilization of phosphorus, potassium, zinc, and iron by the frequent secretion of assorted organic acids and low molecular weight metal chelators, i.e., siderophore. Moreover, soil microorganisms improve soil stability by producing organo-polysaccharides, which act as a gluing agent for soil aggregation. Therefore, microbial inoculation in the soil is considered a striking strategy for maintaining soil health without deteriorating soil physicochemical properties. This manuscript focuses on the splendid role of soil microorganisms in nutrient cycling and their implication as a

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sustainable management strategy for reinstating the fertility of hill regions soil for less reliance on chemical or artificial fertilizers.

Keywords
Psychrophiles · PGPR · Soil health · High hills · Integrated nutrient management

10.1 Introduction

Since prehistoric times, agriculture is the main center for supply of food and employment for major population residing in the hilly regions. The geographical regions of Jammu and Kashmir are mountainous, where agriculture contributes to about 65% of the state revenue. Hilly region encompasses extensive altitudinal variation that attributed to the variability in the ecosystem including variation in altitude, temperature, soil texture and composition, nutrient accessibility, and microflora composition. Generally, the rotational farming is the major practice at hilly regions, but regions with very high altitude where the extremely cold environment prevails provoke employment of monocultural farming which can only be doable in summer. Maize, rice, pulses, millets, wheat, fruit crops, and oilseeds are the major food crops grown in the higher region of hills. Besides, farmers also cultivate some underutilized crops like buckwheat, grain amaranth, black cumin, and saffron. Sustainability and high yield agricultural cropping system chiefly depend upon the native climatic conditions, soil fertility, soil texture, and available nutrients. However, soils of higher altitude are typically characterized as acidic in nature and possess low nitrogen and phosphorus accessibility considered as the principal cause for elevation in disease incidence and reduction in crop growth and productivity. Shrestha et al. (2004) stated that every year about 32 t/ha of topsoil is degrading and leads to a reduction in maize productivity. World's population primarily depends on crop-based nutrients diet, but crops with low nutrients value cause malnutrition and health-related risk (Forouhi and Unwin 2019). Therefore, several plant breeding techniques and anthropogenic activities such as intensive use of pesticides, herbicides, chemical fertilizers, and growth hormones are practiced to reinforce the soil health and crop production in all over the world. The main drawback of nutrient fertilizers application in the soil is their large proportion rapidly convert into fixed form in soil and hence become unavailable for plants (Upadhayay et al. 2018). Moreover, chemical-based fertilizers also show negative impacts on soil health as the rampant application of such fertilizers leads to the descent in soil fertility and native soil microbial ecology.

A number of efforts are taken by the governments of many countries to address the problem and for getting an effective and long-lasting solution to augment the nutrient availability, fertility, stability in soil, crop yield, and ecosystem sustainability. Therefore, the application of potential microflora such as bacteria, fungi, and actinomycetes can endorse plant growth by the revitalization of unavailable nutrients of the soil (Yadav et al. 2016). Such microflora restore nutrients availability and fertility in soil by means of various types of mechanisms such as atmospheric nitrogen fixation, solubilization of phosphorous, potassium, silicon, and zinc by acid production, chelation of metals (iron, zinc, magnesium, etc.) by secreting ionophores such as siderophores (Parveen et al. 2018). Soil microorganisms also secrete various extracellular enzymes essentially required for degradation of polymers and also for the transformation of inorganic nutrients by oxidation or reduction. Moreover, soil associated microbiota secrete exopolysaccharides (EPS) and some gluing agents that promote the aggregation of soil. Production of phytohormone and various metabolites by the soil-dwelling microorganisms assists in plant growth and also reported to confer resistance to the plant from the pathogen attack and also improves the soil health (Bargaz et al. 2018). Indigenous microbial strains of hill region are well adaptive for the native climatic and soil conditions as they can acclimatize easily and therefore they can participate in nutrient management for efficient plant growth promotion. Hence, the application of indigenous microflora is advantageous for nutrient recovery and sustainable agriculture.

10.2 Importance of Soil Nutrients

The top few inches of earth's crust composed of innumerable organic and inorganic elements providing a favorable platform not only for plants growth but also suitable for flourishing growth of microbes. Among the animal-plant-soil continuum, still the soil is the most neglected one. Moreover, various anthropogenic activities are also resulting in degeneration of soil quality in hill regions. Soil nutrients directly regulate the hormonal status of plants, which in turn regulates the physiological properties of plants. Moreover, the standing nutrient condition of the soil dictates the distribution of vegetation in geological regions of hills. Besides, it also affects physicochemical assets of soil, viz. friability, water holding capacity, bulk density, etc. Plants require nutrients for their metabolic activities and growth. Deficiency of any nutrient triggers diseases development and negatively affects the plant growth. Similarly, soil microbiota also require nutrients (micro and macronutrients) for their growth. There are 18 elements which are reported essential for plant growth, classified broadly into macronutrients (C, H, N, O, S, P, K, Ca, and Mg) and micronutrients (Fe, B, Zn, Cu, Mn, Mo, Cl, Co, and Ni) according to their required quantity of nutrient. Each element has its specific function and their physiological role has been well characterized (Table 10.1). To start with, carbon is the major element of plant skeleton and essentially required for their metabolism. Availability of nitrogen is a crucial factor for plant metabolic activities and essential part of the protein, DNA, hormone, and chlorophyll. Phosphorous is important for energy generation, while potassium, boron, and silicon regulate the disease resistance (Singh et al. 2011; El-Ramady et al. 2014). Micronutrients are accountable to maintain the osmotic pressure and relative continuum inside the plant cell. In addition to nutrition, the higher concentration of micronutrients than their threshold level also affects plant growth through toxicity leading to disease development.

10.3 Factors Affecting Nutrient Status of Soil

The dynamics of soils in hilly terrain is very complex in many ways. A huge hill region is endlessly experiencing degradation of soil, accountable for diminution of soil inherent capacity to support the metabolic activities for plant growth due to the deficiency in the nutrient reservoir of soil. The nutrient status of soil holds the most prominent role in this regard. Therefore, it is an important issue for serious debate and research. There are several factors such as temperature, altitudinal gradient and precipitation, agricultural practices, and microbiological processes, which influence the carbon pool, nutrients cycling, fertility, growth pattern, subtle moisture adherence, seedbed hold, and several other prominent effects in hilly agriculture. Numerous studies are done by various researchers so far but there is still uncertainty on the master factor regulating nutrient management and plant distribution. Diverse abiotic and biotic environmental features are responsible for determining the nutrient composition of the soil and can be categorized into broad areas (Zu et al. 2018).

10.3.1 Temperature and Altitude Gradient

Increase in the elevation temperature decreases accordingly. Therefore, a variation in climatic conditions can be seen at different altitude range that directly affects the soil properties. Continuous exposure of low temperature declines the biological transformation rate of soil nutrients, which results in reduced accessibility for nutrients. However, altitude gradient is also blessed with variation in landscape, i.e., broad or steeper landscape. Thick and nutrients rich soil horizons are generally found in broad hill landscape due to the high filtration rate occurring through the rapid flow rate of water, whereas steeper landscapes form thin and nutrient deficient soil horizons due to the low flow rate and higher leaching.

10.3.2 Agricultural Practices

The soil nutrients pool is critically based on cropping system in the agricultural regions. Repeated and monoculturing cropping pattern reduces the magnitude of some nutrients in the soil, making imbalance in the nutrient reservoir of soils. Whereas, an unscientific practice, i.e., jhum or shifting cultivation also drastically degrades land and reduces its quality. It involves cutting of forest, bushes on steeply slope, and then cultivating on such land for 2 or 3 years and after that, they burn the land and depart from there for the selection of a new site to repeat the same process. It results in the reduction of forest cover that leads to soil erosion and reduces water holding capacity. Moreover, it also reduces carbon (C), nitrogen (N), and other nutrient content of soil (Sati and Rinawma 2014). Sharma (1998) estimated that in Northeastern Himalayan region experiencing loss of 88,346 tons topsoil, 10,669 tons of N, 0.372 tons of P, and 6051 tons of K is due to the shifting cultivation.

10.3.3 Soil Microbiota

Besides the above factors, soil microbiota (bacteria, fungi, actinomycetes, etc.) also regulate the soil properties and considered as the functional backbone of the ecosystem, resides in soil and performs essential functions for the management of soil health and ecosystem sustainability. But their composition varies through different climatic conditions. A healthier soil retains its C:N ratio to 10:1. But due to low-temperature the decline in availability of nitrogen leads to high C:N ratio in soil, which slows down the microbial decomposition rate (He et al. 2016). Generally, only cold-adaptive and cold tolerant microorganisms can prevail in hill region due to the low-temperature persistence (Kumar et al. 2019). They acquire their nutrition from the soil and lead to the transformation of various insoluble macro and micronutrients, along with the balance organic matter of soil by their unique cold-active enzymes and make soil fertile to support the development of the plants.

10.4 Properties of Soil at Higher Altitude

Properties of soil are an important aspect because it demonstrates the class and health of soil. Healthy soil is a fundamental component for crop production. Temperature, moisture, and precipitation rate are variable at an altitudinal gradient of mountains. Generally, soil nutrients, texture, and horizon depth are governed by these factors. Generally, hills with a broad and gentle lands experience high vertical water movement, thereby forming a thick layer of soil horizon, whereas steeper hill forms thin soil horizon due to reduced water movement. Majority of Himalayan regions, hill regions of Africa, Bangladesh, and Ethiopia are characterized as a stressful climate with low temperature and soil with acidic in nature, and hence restricted the microbial conversion of N and P, leading to dearth of nitrogen and phosphorous content. Moreover, the soils of such regions also possess the toxicity of manganese and aluminum that is the major cause of poor soil fertility and reduced production. The soils of cold desert areas such as Leh-Ladakh hills are suffering through high salinity stress and are sandy and clay type, coarse-textured, poor in water retaining capacity and mineral nutrients, and have low biological activity. Diverse altitudinal ranges of Himalaya are characterized by unique climatic conditions that govern the different rainfall level, snowfall, organic matter decomposition, soil texture, mineralogy, and fertility. Himalayan soil is generally sandy loam and clay type and acidic in nature (pH below 5.5) and about 65% of soil of Northeastern region experiencing high acidity along with deficiency of nitrogen and phosphorous (Suyal et al. 2017). Similarly, soils of African hills are also suffering by acidity with a pH of less than 5.2 (45–50% soil) and about 65–80% of soil is deficient for phosphorous and 60% soil for nitrogen along with low fertility. Among all factors, biological entities residing in the soil play a very crucial role in determining the soil quality. Nutrient cycling, aggregate stability, size, water preserving capacity, and soil organic matter instigate by microbial actions. Microbial composition in the soil also depends on the temperature, pH, and soil constituents.

Low-temperature environment is an excellent factor for the growth and multiplication of psychrophilic microorganism. They possess the cold-active enzymes which carry out the biological conversion in soil and are also important for industrial purposes. Van Horn et al. (2013) investigated the impact of some abiotic features such as organic matter, pH, sulfates in controlling the biodiversity of microbes in Antarctica soils and found that members of *Actinobacteria* and *Acidobacteria* phyla were majorly prevailing under low elevation site rich in organic carbon, whereas at a higher elevation with high humidity *Firmicutes* and *Proteobacteria* were dominant. Similarly, Himalayan soils hold the substantial diversity of psychrophiles and psychrotolerant microorganisms which are able to manage soil health and crop production.

10.5 Why Require Nutrient Management?

Nutrient management can be defined as the practices that maintain the nutrient balance in the soil and keep remains it healthy in terms of nutrient content, moisture content, and soil organic matter for the support of the production of economic goods. Good management practices ensure the availability of soil nutrients and enhance plant productivity. But in hilly region, soil is drastically degrading due to its steeply sloping landscape, soil erosion by heavy rainfall, continuous exposure of cold temperature as well as it is becoming acidified because at high altitude cation removal becomes high via water runoff, and leaching process makes hill soil gradually acidified, leading to the accumulation of increased soluble Al^{3+} concentrations in clay particles. Increased soluble Al^{3+} concentrations boost its uptake by the plant that disturbs the plant nutrient balance and also reduces regular plant nutrient uptake along with the occurrence of major diseases (Awasthi et al. 2017). Moreover, various anthropogenic activities are also causing a nutrient imbalance in soil and also leading to degradation and erosion of soil at a higher rate. Therefore, in present scenario of the world, management of soil nutrient in hill region is a primary issue of research.

It is expected that the world's population will achieve up to 9.8 billion by 2050; hence, crop production should be enhanced for the feed of such population in a very sustainable manner. Therefore, the soil nutrient management is an issue of great concern because it directly or indirectly depends upon the crop production, human health, soil constancy, and environmental sustainability. Besides, soils of Northeastern Himalayan region are nitrogen and phosphorous deficient, because nitrogen and phosphorous are converted into their unavailable forms, which are inaccessible for the plants. Moreover, soil genesis in hilly area generally depends upon water runoff, deposition, and erosion, which gives different soil properties at the region of hills. Such processes are different due to its topographical variation of hills. Some hills have broad landscape with a gentle slope; it allows boosted water infiltration through the quick flow of water vertically via soil particles causes high deposition of nutrients and such landscape generates thick and well-developed soil horizons. Whereas some other hills have steeply sloping landscapes that do not permit that much vertical water flow through soil particles, hence less deposition is there which leads to the development of a thin and exhausted soil horizon. It also triggers the high soil erosion rate which is the main cause of land degradation and nutrient imbalance due to the removal of the top soil layer, rich in nutrient and soil organic matter. It negatively affects the environment and introduces instability in agricultural productivity. In addition, continuous cultivation practices, without or uneven amendments of nutrients in soil, lead to dearth of nutrients reserves and organic matter in the soil. It also triggers acceleration in degradation and erosion of soil, and hence ultimately reduces crop productivity and causes a discrepancy in environmental sustainability. According to the Karki et al. (2004) hill region of Nepal was facing the deficiency of zinc, molybdenum, and boron at several ecological belts; such zinc was deficient in Terai region; therefore, farmers applied zinc phosphate fertilizer without appropriate advice or proper guidance which resulted in the soil nutrient imbalance and reduced soil fertility. Therefore, identification and development of proficient and multifaceted conservation practices for soil nutrient management, crop productivity enhancement, sufficient and nutritious food diets, and conservation of remaining natural resources are the key future challenges. The current situation not only requires the nutrient management or enhanced crop productivity but it requires more, that is all together with sustainability in the environment.

10.6 Strategies of Nutrient Management in Soil

The biological, physical, and chemical properties of hilly soil are imbalanced due to various environmental factors (biotic and abiotic) which reduces its inherent capacity to support the crop production that may lead to shrivel the food quantity for the consumption of continuously increasing world's population. Therefore, for current scenario, practicing of promising strategies for nutrient management, soil conservation, and improved crop production strategies is required to get the more outputs than inputs. In the current era, several techniques are in practice that include agronomical approaches, use of chemical fertilizers, microbial-based approaches, and integrated nutrient management system for nutrient management and soil conservation.

10.6.1 Agronomical Approaches

From the ancient time, natural nutrient cycling has occurred from the soil to the plant and then the animal after that is come back to the soil by the degradation and decomposition of plants and animals. Repeated and intensive cultivation of the same crop declines the content of specific nutrients and increases other nutrients content in the soil which is not utilized by such crop, hence makes imbalance in nutrient composition of hilly soil. Therefore, researchers are making efforts for developing alternate and co-cultivation cropping plans for the reestablishment of soil nutrients. Cropping pattern includes inter-plantation of legumes with cereals which improve the soil fertility by efficient and balanced utilization of nutrients, which reduce production risk and return better to the farmers. Research of 7-year in Northwestern China has been reported around 4–11% high organic matter and nitrogen deposition in the soil during intercropping of faba beans (*Vicia faba* L.), wheat, and corn in comparison to monoculturing of those species in rotations, and triggered the increase in organic matter and nitrogen sequestration rate (approximately 184 and 45 kg ha^{-1} $year^{-1}$ for, respectively) (Cong et al. 2015). Moreover, plant breeding techniques are practicing for the development of novel germplasm that is able to grow in acidic soil and has resistance for cold environmental conditions. Tripathi (2001) selected the novel germplasms of maize, upland rice, wheat, and soybean, which were able to grow under acidic conditions. Similarly, Indian Agriculture Research Institute (IARI) released various varieties of wheat (var. HS 507), rice (var. Pusa Sungandha 5), and lettuce (var. Great lakes) for efficient cultivation in hilly region. In the modern era, researchers are focusing on "conservation agriculture (CA)" which encompasses an efficient farming system that prospers numerous events such as reducing the soil disturbance, maintains permanent soil cover and diversification of plant species. Moreover, "conservation agriculture (CA)" also develops a farming system which increases agricultural practices that preserve natural resource along with high production and also protecting the environment from certain negative aspects such as soil erosion and land degradation. Furthermore, such approaches usually improve the availability of water and its infiltration into the soil, which ultimately encourages the process of carbon sequestration through reduced SOC decomposition.

10.6.2 Use of Chemical Fertilizer

Now it is well-known that the soil of hilly region showed different soil properties as per their topography and observed the deficiency in macro (N and P) and micronutrients (Zn, S, and Fe) and acidic nature of hilly soil. Moreover, repeated monoculture cultivation practices and co-cultivation practices without appropriate nutrients addition in the soil lead to the depiction of the nutrient reservoir of soil. Because plant requires nutrients supplied by soil and it takes a very long time to decompose and return nutrients to the soil. It leads to the reduced fertility of soil declining the productivity of crops. Therefore, there is a need to add only an appropriate quantity of nutrients regularly in the soil to maintain its health. From the several past decades, the exploitation of organic and inorganic synthetic fertilizers is practicing for the replenishment of nutrient reservoir of soil. Synthetic fertilizers are produced through complex industrial processes or mined by earth crust, generally obtained from the nonliving sources. Most synthetic fertilizers are alerted by blending, purification, or mixing for easy handling. Nutrient management through chemical fertilizers application (both organic and inorganic) generally focuses on nitrogen and phosphorus management in soil. Application of different types of chemical fertilizer offers rapid availability of various nutrients for plants. Therefore, its early days were glorious when the application of synthetic fertilizers showed a massive positive change in crop productivity rate. But the long-term intensive, inappropriate, and unplanned utilization of synthetic fertilizers coincided with numerous problems such as a large proportion of chemical fertilizer convert into insoluble form makes soil infertile and become unavailable for the plants. They are toxic and pose environmental and water pollution, and high cost is another disadvantage associated with it.

Different soil type requires different concentration and types of fertilizer such as sandy soil requires high and multiple doses due to high leaching. Corn and green leafy vegetables require a high dose of nitrogen then root crops. Therefore, optimization of the dose of fertilizer application according to the requirement is a great challenge since its keen target is the efficient utilization of fertilizer to augment crop yield and soil nutrient revitalization with environmental safety. For example, in a 9 years phase from 1996 to 2005, application of N and P fertilizers increased about 51% for enhanced crop production but the crop improvement was only 10% in China (Zhang et al. 2012). Besides, appropriate, optimized, and required concentration of chemical fertilizers can replenish the soil nutrient reserve. Under cold temperature, the soil becomes very cold that hinders the fertilizers utilization from the soil. To overcome this problem, liquid chemical fertilizers can be applied by foliar spraying to absorb the nutrients by the plants. Incomplete fertilizers (i.e., fertilizer possesses one or two nutrient separately instead of a combination of many nutrients together) can be used separately as per the soil requirement for the replenishment of soil. A study was conducted in the southern hill region of China from 1998 to 2009 and observed that appropriate fertilizer application was able to sustain the soil pH at 5.89, and extensively improved soil organic matter and total nitrogen (i.e. 22% and 17.8%, respectively) in comparison with control (Dong et al. 2012). Hence the application of suitable fertilizers concentration under optimized conditions is an excellent strategy to augment soil fertility, nutrients pool, and yield of plants.

10.6.3 Role of Microorganisms in Reinstatement of Soil Nutrient

Microbial diversity in the soil system is a functional unit that performs numerous activities essentially required for maintaining the fertility of soil. Bacteria, actinomycetes, fungi, and algae are the main components of soil microbial diversity; however, the proper exploration of soil inhabiting microorganisms presented significant roles in sustainable agricultural development, and also in large-scale industrial and commercial applications. The growing concern of soil health, crop production, environmental sustainability, and socioeconomic impacts of climatic variation and chemical dependent conventional agricultural practices developed seek for the identification of alternative tools or techniques in order to develop agriculture practices in more sustainable manner. It is a well-known fact that soil microbiota (bacteria and fungi) play a central role in functioning of the ecosystem. Soil microbiological, microbial eco-physiological, and biogeochemical findings strongly reveal that the soil microorganisms perform biological transformations in soil that ultimately establish the carbon, phosphorous, and nitrogen cycling rates in the ecosystem (Nadeem et al. 2018). Although the composition of soil microbiota affects by various ecological factors but indigenous microbiota, i.e., well adaptive for the native climatic conditions, positively and negatively regulate the processes such as soil genesis, nutrient cycling, plant interactions, and decomposition of dead material in the soil and hence governs the crop production (Siles et al. 2016). In addition, soil microbiota secret gluing agents such as exopolysaccharide that triggers the aggregation of soil, also improves macroporosity to the subsoil surface that stimulates water transmission and declines runoff.

Microbes are the living biological entity, therefore, its application is a sustainable and eco-friendly approach for the improvement of soil fertility, nutrient balance, and crop production. Therefore, eco-friendly approach of present era, i.e., microbes based biofertilizers hold great promises as the key player for sustainable agro-ecosystems. Biofertilizers are the single or group of microorganisms having potential bioactive metabolites to carry out necessary conversion to encourage the complex plant-microbe-soil interactions (Stamenkovic et al. 2018). A group of microorganisms (bacteria and fungi) that display the plant growth promoting (PGP) traits are termed as plant growth promoting microorganisms (PGPMs) and are utilized for the development of biofertilizers (Singh et al. 2013). Biofertilizers are generally classified into four categories such as (1) nitrogen-fixing bacteria (2) phosphate solubilizing bacteria, (3) composting microbes, and (4) biopesticides (Pathak and Kumar 2016). PGPMs govern soil nutrient management and crop production by various mechanisms such as biological nitrogen fixation, solubilization of various nutrients such as phosphorous, zinc, silicon, and chelates metals by siderophores secretion and enhance their availability in the soil. Furthermore, they also produce secondary metabolites extracellularly such as indole acetic acid (IAA), gibberellic acids (GAs), antibiotics and suppress the pathogen attack by Induced systemic resistance (ISR). As discussed above that the soil of various hill regions is acidic in nature, less fertile, and deficient in available macronutrients (C, N, and P) and micronutrients (zinc, iron, and molybdenum) and crops are also suffering from some degree of pathogen attack (Singh et al. 2017). Moreover, the temperature of hill regions generally remains low and inversely decreases with the increase in distance from the ground, hence the PGPMs should be cold-adaptive or cold tolerant for the survival and efficient functioning. Therefore, it is essential to explore indigenous or region-specific plant growth promoting microorganisms to mitigate the problems in a sustainable manner (Hamdan 2018). Previously, various hill regions have been explored by numerous researchers to find the potential PGPMs in order to develop a potent biofertilizer for nutrient management and yield enhancement but unfortunately, the microbiota of a very less number of hill regions has been documented till now. Some of the cold-adaptive plant growths promoting microorganisms are recorded in Table 10.2.

10.6.3.1 Microbial Mechanism for Nutrient Management

Life of most living organisms is sustained by soil. Numerous groups of microorganisms reside in the soil and take part in the biogeochemical cycles to maintain soil fertility and sustainability (Singh and Shah 2013). They carry out multifaceted processes to boost the organic matter content and stimulate nutrients availability in the soil. Exact functional mechanisms of most of the processes are not fully revealed until now. Some of the mechanisms are summarized below in forthcoming sections.

10.6.3.1.1 Nitrogen Fixation

Soil is the hub of various nutrients essential for living organisms. Nitrogen (N) is the most vital nutrient necessitating for standard plants growth and metabolism. But often its availability for plants befalls in risk due to the loss through leaching, i.e., a common phenomenon in steeper sloppy landscape and excess denitrification. While, diatomic form (N_2) of nitrogen is abundantly, i.e., 78%, present in the atmosphere, but due to its diatomic structure atmospheric nitrogen is inert. Various physical, chemical, and biological techniques are practicing for the formation of plant-utilizable nitrogen forms from the atmospheric free nitrogen. However, physical and chemical methods require huge energy and these are not economically feasible. Diazotrophic microorganisms reside in the soil mainly includes bacteria and archaea possess unique metabolism to transform atmospheric free nitrogen into ammonia by a unique set of enzymes called as nitrogenase enzyme complex, a process called as biological nitrogen fixation (BNF) (Pérez-Montaño et al. 2014). Nitrogenase enzyme complex comprised of two units, i.e., dinitrogenase reductase and dinitrogenase. Dinitrogenase reductase encompasses high reducing power, therefore donates an electron to the latter enzyme, which actually converts atmospheric nitrogen into ammonia. Later, through nitrification, this ammonia gets converted into nitrite and nitrate by Nitrosomonas and Nitrobacter, respectively. Of note, globally around two-thirds of available ammonia produced by BNF, whereas rest conversion is governing by physical method and Haber–Bosch process**.** On the basis of habitat, diazotrophs are classified into two groups which include free-living diazotrophs (*Herbaspirillum* and *Azospirillum*), reside in bulk or rhizospheric soil whereas, the bacteria fall in the second group, forms symbiotic alliance with leguminous and non-leguminous plants includes *Rhizobia*, *Frankia*, and *Bradyrhizobium*. These symbiotic nitrogen-fixing bacteria establish an association with host plant and form a highly specialized structure called as nodule inside the host, where they colonize and carry out nitrogen fixation. In order to produce one molecule of ammonia, 16 ATP gets consumed.

$$N_2 + 8\,H^+ + 8e - + 16MgATP \rightarrow 2NH_3 + H_2 + 16MgADP + 16Pi$$

Symbiosis and nodule formation is the specific host-microbe interaction. Although it is not only controlled by the host or microbe but also by variety of factors which play a very crucial role and which include soil type, nutrients, temperature, climatic conditions. The maximum rate of biological nitrogen fixation by diazotrophs is generally achieved at mild temperature. Jacot et al. (2000) conducted an experiment for the evaluation of nitrogen fixation at different altitudes and observed that up to certain altitude limit (approx. 2100 amsl), the biological nitrogen fixation is well adaptive for the native climatic conditions. Meta-analysis study revealed that the formation of nodule, their numbers, and activity rate get limited by the scarcity of P, S, and K (Divito and Sadras 2014). Generally, the soil of high altitudes faces phosphorous limitation that also reduces the activity of nitrogenase enzyme complex. Fungi generally do not contribute for fixation of the atmospheric nitrogen but colonization of vesicular-arbuscular mycorrhiza facilitates the high availability of P, S, and K and other necessary nutrients to the nitrogen-fixing microorganisms and stimulates the nitrogen fixation rate. Moreover, vesicular-arbuscular mycorrhiza also provides shelter for free-living diazotrophs. Microbes also participate in the reversion of fixed nitrogen into diatomic atmospheric nitrogen through denitrification to maintain nitrogen cycle occurring in the ecosystem. It is governed by heterotrophic bacteria such as *Paracoccus denitrificance*, *Thiobacillus denitrificance* via anaerobic respiration process, they use nitrate as terminal electron acceptor for the utilization of organic matter and converts nitrate into atmospheric nitrogen as the final product of metabolism.

10.6.3.1.2 Soil Organic Matter Management

Soil organic matter majorly comprised of dead organic material, living plants parts, and soil micro and macro biota (microorganisms and soil animals). Soil organic matter imprints great impact on properties of the soil, governs ecosystem functioning. A small alteration in the amount of organic matter shifts the CO_2 concentration in the soil. It gives structure to the soil and makes it fertile and nutrient rich. Total soil organic carbon content is strictly controlled by two intricate processes, i.e., net primary production and its decomposition rate. Plants, algae, and cyanobacteria are autotrophs, and transfer atmospheric carbon dioxide (CO_2) into the soil as photosynthetic organic material. Most of the soil microorganisms are heterotrophic and they depend upon the primary producers or intermediates for carbon, nutrients, and energy needs. They utilize plant, animal, or microbial carbon for the generation of their biomass and some part of fixed carbon returns in the ecosystem and remaining remains in the soil by a process called decomposition. The decomposition process is majorly driven by the soil bacteria and fungi, whereas only 10–15% of carbon decomposition contributed by other entities. Saprophytic bacteria (*Acetobacter, Bacillus stearothermophilus*) and fungi (*Rhizopus*, *Mucor*, *Aspergillus*, *Penicillium*) converts plant, animal organic material into their microbial biomass (cell material), organic acids, and CO_2. Saprophytic organisms utilize simple components of plants and animal such as sugars, amino acids, lipids. Therefore, initial decomposition process occurred very rapidly but it occurs at a slow rate when saprophytic organisms decompose insoluble complex compounds such as chitin, cellulose, lignin, and hemicelluloses. Variety of enzymes released by microorganisms are necessary for the decomposition of such compounds such as cellulase for cellulose decomposition and chitinase for chitin, lignin peroxidase for lignin degradation and hence different microbial communities (autotrophs and heterotrophs) reside in the soil leads to the carbon balance in the ecosystem.

10.6.3.1.3 Phosphate Mobilization

Phosphorus is required for both plant and animal for energy generation and metabolisms; therefore, it is considered as the second crucial macronutrient after nitrogen. Neutrally a huge reservoir of organic and inorganic phosphorous (i.e., inorganic (apatite), organic (inositol phosphate or phytate, phosphomonoesters, and phosphotriesters) is mixed in the soil. Besides, the soil of hill regions illustrated a very minute amount of available phosphorous for the plants, because major portion of phosphorus has converted into their salt or insoluble form. Of note, the reason is the highly reactive nature of inorganic phosphorous, it reacts easily with metal such as Fe, Al, and Ca and approximately 75–90% of P get converted into insoluble salt forms making it inaccessible for the plants. Although plants can only metabolize two forms of phosphorous, i.e., monobasic ($H_2PO_4^-$) and dibasic (HPO_4^{2-}) ions, hence called as soluble forms of phosphorous. Therefore, to cope up with such problem farmers are applying chemical phosphatic fertilizer in fields, but here also a small quantity is utilizing by the plants and bulk of P is becoming insoluble and creating soil infertility and environmental pollution (Singh et al. 2010; Singh et al. 2018). Therefore, exploration of psychrophilic phosphate solubilizing bacteria, able to solubilize and mineralize insoluble form of phosphorous under low-temperature environment, can be an effective and sustainable approach. Mohammadi (2012) stated that phosphate solubilizing microbes based biofertilizers are the most promising strategy to solubilize insoluble phosphorous. Bacterial genera like *Pseudomonas, Bacillus, Massilia, Paenibacillus* are the common genera having psychrophilic phosphate solubilizing bacteria (Dutta and Thakur (2017); Zheng et al. (2017); Rajwar et al. (2018). Microbes generally mobilize soluble phosphorous through direct and indirect mechanisms. Under indirect mechanisms, microbes utilize organic matter for their growth and secrete low molecular weight anions such as citric acid, gluconic acid, oxalic acid, succinic acid, acetic acid for the solubilization of phosphorous by exchanging phosphorous anion with metals on absorption site of soil by a process called ion exchange. Moreover, these hydroxyl and carboxyl anions sequester the cations and thereby enhance phosphorous solubilization in the soil. Psychrophilic phosphate solubilizing bacteria (PSB) also secretes various phosphate solubilizing enzymes like phytases and phosphatases to cleave the C-P bond of insoluble organic phosphorous. Whereas indirect mechanisms exert releasing of numerous proton (H^+) during NH_4^+ assimilation that declines the pH and solubilizes phosphorous. Secondly, heterotrophic bacteria residing in the soil secretes CO_2 during respiration, which reacts with soil water and leads to the formation of carbonic acid, which declines the pH and resulted as solubilize phosphorous (Fig. 10.1). Besides, soil microbes assimilate the phosphate for their energy generation; hence they can govern the phosphorous management in the soil.

10.6.4 Integrated Nutrient Management (INM)

In the past centuries, population and their food demands were low; therefore, farmers relied solely on compost, farmyard manure, litter, and crop residues to maintain the

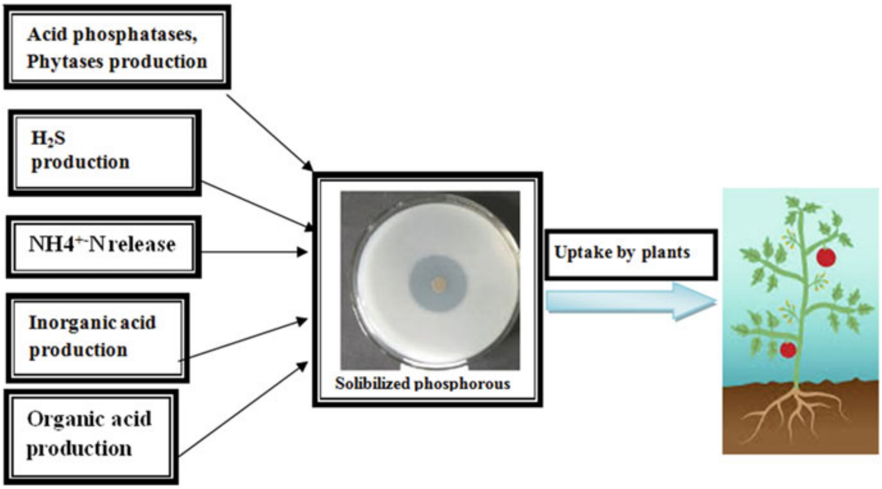

Fig. 10.1 Mechanisms adopted by microbes for phosphorous solubilization (Khan et al. 2019)

soil composition and better crop production. However, in recent decades the population density became very high, consequently, the demand for food supply has been also extremely raised. For the fulfillment of such demand, farmers intensively applying chemical fertilizers for doubling the production, which is causing serious environmental threat. Therefore, the ambition of present day research is the maintenance of sustainability in the ecosystem by efficient use and conservation of natural resources to assure the future human needs and shelter, and along with the improved quality of soil and environment. To achieve such goals a combined application of traditional and modern-day techniques has to be suggested. INM is a kind of united approach, refers to the use of limited and optimized quantity of chemically synthesized fertilizers together with the crop residues, microorganism based biofertilizers, farmyard manure (FYM), compost, and other living nutrient rich degradable materials in equilibrium for efficient use of fertilizer to augment the soil fitness and crop production in a sustainable manner (Shah and Wu 2019).

The study of Smaling et al. (1992) enlightened the need of INM for agricultural sustenance, mostly for those areas that are suffering from reduced soil fertility. INM comprises both traditional approaches such as application of natural living entities along with modern techniques, i.e., judicious and optimized quantity of fertilizer that makes it economically feasible and environment-friendly cropping systems (Fig. 10.2). According to Wu and MA (2015), the main aim of INM is the optimization of chemical fertilizer input along with natural fertilizer according to the nutrient demand of soil and execution of fertilizer application at appropriate timing for improved soil fertility and efficient output. Recently Warjri et al. (2019) conducted field trial on rice in the hill region of Meghalaya to investigate the impact of collective application of chemical fertilizers along with farmyard manure on the nutrient accumulation in soil and observed that the integrated application

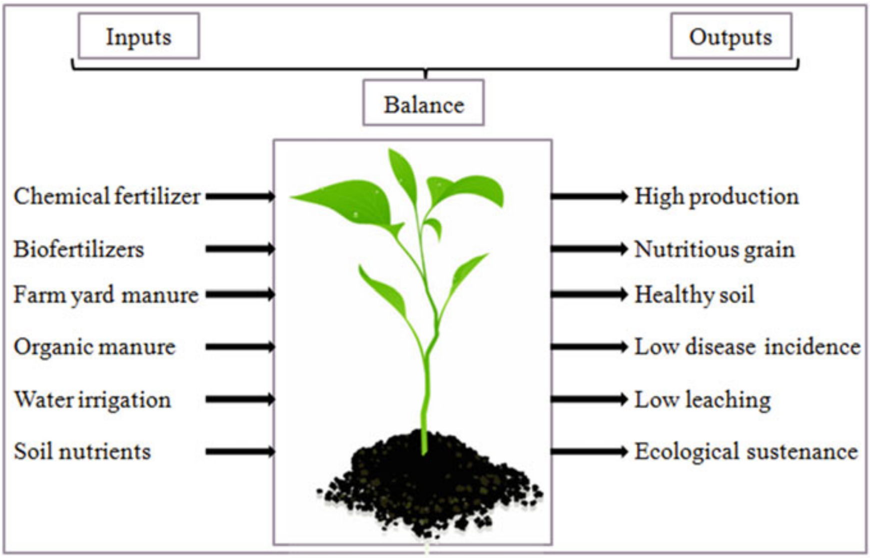

Fig. 10.2 Integrated nutrient management system for sustainable plant growth

significantly improved the soil organic matter, NH_4^+ exchange, soluble NO_3 phosphorous, and potassium availability. Similarly, Kumar et al. (2012) conducted an experiment in Northeast hill region of Meghalaya in acidic soils and reported the liming in combination with integrated nutrient management practice augmented soil nutrients concentration as well as showed three folds increase in maize productivity. Hence, inputs and outputs of all macro and micronutrients, soil organic matter get managed through integrated nutrient management (INM). Moreover, it improves soil water retaining ability and reduces the nutrient losses occur through leaching, immobilization, runoff, and volatilization. INM is economically, ecologically, and socially feasible practice that is practiced by farmers very easily to augment the productivity along with maintaining soil health. Therefore, it is becoming the most popular and acceptable by farmers.

10.7 Conclusion

Soils of hill regions are generally illustrated as degraded, acidic in nature along with the deficiency of nitrogen and phosphorous. In addition, altitudinal variation causes decline in the temperature with increase in elevation accordingly. Therefore, multifarious approaches in “soil nutrients management” are necessitated for improving the soil health to maintain sustainable agriculture in hilly regions, where soil experiences degradation due to environmental factors. Application of chemical fertilizers within the limit assisted in nutrient management but rampant exploitation of such agricultural practices is supposed to be dreadful which disturbs soil nutrient, fertility, and ecosystem sustainability. Therefore, an alternative of chemical fertilizers in form of soil beneficial microorganisms is an escalating approach to improve the soil fertility via various microbiological transformations of nutrients in soil along with the minimum cost and less laborious, and does not show the negative impact on soil characteristics. Soil microorganisms are the “soil engineers” which directly or indirectly participate in nutrient management, and as a “living catalyst” expresses a positive impact on soil health. The roles of soil microbiota in nutrient cycling such as mobilization of nutrients (N, P, K, Zn, Fe, etc.) and organic matter disintegration are admirable where the microbial activities sustain the nutrients level in the soil. Improvement in soil stability through commencing the process of soil aggregation is another important aspect of soil microorganisms. However, indigenous microorganisms adapt existing environmental conditions, i.e., psychrophiles in the hill region of soils, and as key inhabitants of soil, exhibit functional traits regarding nutrient management and also help in plant growth promotion. Soil microorganisms possess various unique characters that are most important in the revitalization of soil in sustainable agriculture with avoiding huge reliance on the application of chemical fertilizers.

10.8 Future Prospects

Application of microorganisms in soil nutrient management and soil vitalization are wider, but existing challenges are still to be addressed in future research. The further research is required for employing microorganisms as “natural fertilizer” for providing a natural way of maintaining the soil fertility/vitality with extra efficiency and circumventing the approaches advocated for using chemical fertilizers. The intense study based on molecular approaches is also required to generate high throughput information about soil microbiome, and to draw metabolic functions of microorganisms in nutrient cycling. The modern research is also directing the future for promotion of using microbial based fertilizers at large scale for solving the purpose of soil revitalization and soil nutrient management.

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