Review Article

"The Rhizosphere Microbiome Revolution: Leveraging Microbial Potential for Climate Resilience in Agriculture Systems and modulating positive plant-soil feedback"

Abstract

The living soil system plays a crucial role in sustainable agricultural production, with soil quality serving as a key indicator of environmental stability, food security, and economic viability. However, in recent years, soil health has been deteriorating due to unsustainable management practices and climatic challenges such as drought, salinity, and unpredictable weather patterns. To restore and maintain soil fertility for future food security, the use of natural soil organisms, particularly microbes, is essential. Soil microorganisms significantly contribute to nutrient mobilization, solubilization, and improved nutrient availability for plants. The rhizosphere, a dynamic zone around plant roots, is the hotspot of intense biological and biochemical interactions among microbes and plants, influencing soil biodiversity, disease suppression, and soil physicochemical properties. Microbes act as sensitive indicators of soil health due to their rapid response to environmental changes and their integral role in soil processes. Beneficial microorganisms like plant growth-promoting rhizobacteria (PGPR) and arbuscular mycorrhizal fungi (AMF) not only enhance crop productivity but also improve plant tolerance to abiotic stresses such as drought and salinity. Additionally, microbial communities contribute to soil structural stability by forming aggregates, enhancing water retention, and facilitating organic matter dynamics. These plant-microbe interactions are vital for promoting crop growth, managing diseases, and achieving sustainable agriculture without harming ecosystem functions. Future research should focus on identifying effective microbial strains and understanding microbial metabolites that influence plant-soil interactions. This review highlights the crucial role of microorganisms in improving soil health and supports their potential application in advancing sustainable agricultural practices.

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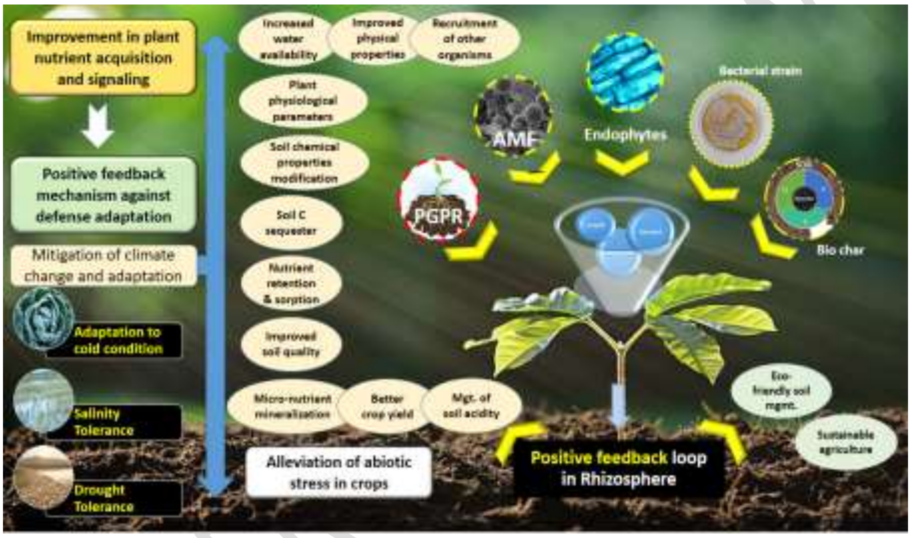
Graphical Abstract



Keywords: soil health; microorganisms; microbial community; rhizosphere.

1. Introduction

Amidst the growing population, including urbanisation as well as industrialisation has now diminishes the growing agricultural land fields. This abrupt change had affected by demand of food and supply ratio, but still the growing population should satisfy the food for their daily needs (Tilman *et al.*, 2011). However, the conventional agriculture is facing reduction in production and increased in cost of input. In addition, loss of agriculture productivity due to natural and anthropogenic activity leads that land degradation and reduced crop yield. Land use pattern shift varies frequently due to modernization and urbanization, hence reduces arable

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land. Farmers are also leaving this practice because of low-cost benefits and introduction of different variety of seed and technology. The current scenario is population getting increased day by day, but the need for agriculture land is important for cultivating crops. For generating every single piece of crop, soil is the wholesome medium thorough which we can able to grow. To make soil alive or fertile, one must shall focus on corresponding way of making it naturally. The other part of organic farming is being not practices every corner which allows farmers to use intensive inorganic fertilizers, pesticide ultimately degrading soil systems (Venkatesan *et al*., 2024).

Also agriculture shifts in production and led to insecurity in food production because of climate change, anthropogenic activities, natural resource scavenging and ultimately leads to poor soil health. Continuing traditional practices like heavy application of pesticide and inorganic fertilizers had made soil productivity less and thus making soil organism less motile and active (Bhattacharyya and Jha, 2012). Plants interact with microorganisms in various ways such as positive, negative and neutral. It has been observed that the whole plant, root and shoot system including different organs like buds, flowers, fruits and seeds harbour many kinds of microorganisms inner (endophytes) and outer (epiphytes) surface of the plant and it encompasses various relation like competition, exploitation, neutrality, commensalism, and mutualism (Barea, 2015; Jacoby *et al*., 2017). This review shall focuses on importance of soil micro biome population in soil rhizosphere region and harnessing its critical role in promoting sustainable agriculture and crop resilient systems.

2. Soil bio-engineers

Soil microorganisms were the key players in the soil system. They are often called as **"Bio-engineer"**. The presence of a diverse soil microbial community is crucial to the productivity of any ecosystem, since microorganisms affect all levels within the ecosystem. While potential harmful effects from soil microorganisms include plant diseases, production of plant-suppressive compounds, and loss of plant-available nutrients (Bruehl, 1987), the majority of soil microorganisms are beneficial to plant growth (Lynch, 1983). The general basic function of soil micro biome approach towards crop production, soil health and other ecological feasibility is illustrated in Fig. 1.

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Fig. 1. General aspects of micro biome approaches towards crop production and soil health

Soil micro-biome community were significant contributor of our living eco-system which aid in servicing life on our planet, regulating carbon cycle, and other multifaceted nutrient transformation. But ongoing global climate change crisis, the abundant organisms in soil were prone to detoriate in non-linear manner and thus circumstances paved way for soil degradation and poor land management scenarios (Amundson *et al.*, 2015). Also increased land site prone for industrial deployment, mining site and alloy factories development in recent time causes soil to be getting polluted and prone for heavy-metal contamination (Koushal *et al*., 2025). Hence it subdues the critical utilisation of biological micro-organism rendering in boosting crop growth, development and food security. The effect of micro-biome were elucidated in sections 2.1.

2.1. Effect of microbial community in promoting soil physical, chemical and biological properties

Soil physical properties: Microbial inoculants application increase biodiversity, creating suitable condition for development of beneficial microorganism. They also improve physical properties of soil such as; improve structure and aggregation of soil particles; reduce soil compaction, increase spore spaces and water infiltration (Carvajal-Muñoz and Carmona-Garcia, 2012). The basic buildings blocks of soil are mineral soil particles that are classified based on their sizes into clay (<2 μm), silt (2–63 μm) and sand (63–2,000 μm) (Blott and Pye, 2012). Most soil microorganisms live as interconnected assemblages associated with these particles, so that the soil structure ultimately determines their resources through oxygen diffusion, water flow, organic matter accessibility and nutrient availability (Wilpiszeski *et al*., 2019). Also it is one of the causes for soil genesis and transformation like agents of physical weathering.

Soil chemical properties: Soil chemical properties are strongly associated with soil microorganisms. Soil microorganisms are primarily responsible for many critical processes associated with biogeochemical cycles, as well as the transformation and breakdown of soil components. They also play significant roles in the soil ecosystem (Acunto *et al*., 2018). Although pH of the soil has been reduced when soil with good source of microorganisms. Since, they will excrete organic acids when decomposing organic matter like phenolic, carboxylic acid, they will constantly reduce the state of pH of the soil. Each organism surveillance in soil depends on soil pH, as fungi prefers acidic range (Ali *et al*., 2017), temperature of about 30-50℃ (Zhang *et al*., 2016) and it contributes more to N_2O emissions than bacteria in acidic soil (Yin *et al*., 2023). In the same way, bacterial population opts neutral soil reaction (6.0-7.0) (Wang *et al*., 2019) and actinobacteria rely alkaline condition (Araujo *et al*., 2020).

Soil Biological properties: In general soil biology, enzyme assays have been established to a set of enzymes linked to high-functioning soil microbiota, such as protease, urease, various phosphatases, and sulfatase. Organisms, both animals (fauna / micro-fauna) and plants (flora /

micro-flora) are important in the overall quality, fertility and stability of soil. These microorganisms are responsible for the formation of humus, a product of organic matter degradation and synthesis. Moreover, organisms helps in myriad of biochemical reactions and intricate biological processes that takes place. Fractionation of soil organic matter like humic acid, fulvic acid, hematomelanic acid and humin substances were secreted by microorganisms in the soil system and it aids in other biochemical reaction over soil. Addition of bio char (pyrolysis product) amendment improves soil properties and store long term carbon storage in soil and enhances microbial diversity and function in soil (Muhilan *et al*., 2024).

2.2. Microbial biomass carbon

Microbial biomass carbon is a measure of the carbon contained within the living component of soil organic matter (i.e. bacteria and fungi). Microbes decompose soil organic matter which in turn releasing carbon dioxide and plant available nutrients. Farming systems that maximise organic matter return to soil and minimise soil disturbance tend to increase the microbial biomass. Soil properties such as pH, clay, and the availability of organic carbon all influence the size of the microbial biomass. Microbial biomass is also an early indicator of changes in total organic C. Unlike total organic C, microbial biomass C responds quickly to management changes. As the soil depth increases, the rate of microbial N release pattern change and it was illustrated in Fig. 2.

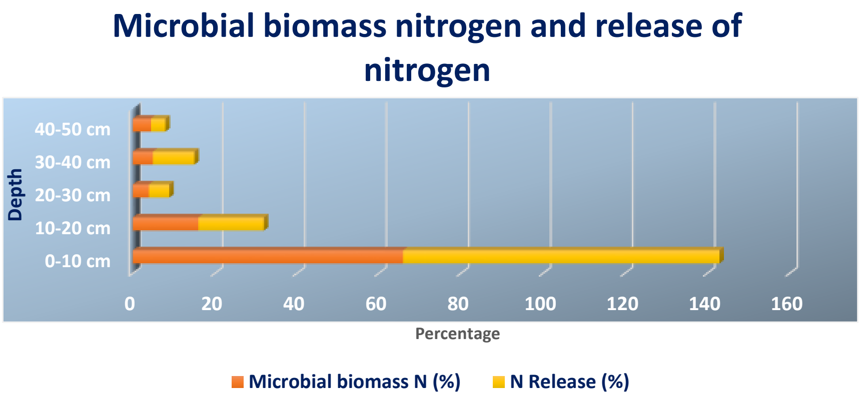

Fig. 2. Relative study of microbial biomass nitrogen and release of nitrogen decreases with depth [Adapted and modified from (Murphy *et al*., 1998)]

2.3. Microbial interaction on plant growth promotion

The interaction between plants and their surroundings is a dynamic process in which plants monitor their environment and react to changes. The root system, which was traditionally thought to only provide anchorage and uptake of nutrients and water, is a key element to a plant interacting with its surroundings (Bais *et al*., 2006). Chemical signals emitted by soil microorganisms are received and recognized by plants and then addressed through the release of chemical compounds in the form of root exudates. Secretion of these compounds varies between different plant species (Rovira, 1969), ecotypes (Micallef *et al*., 2009), and even distinct roots growth within a plant (Uren, 2007).

2.4. Soil health and crop productivity

Earth crust is an important component for earth's biosphere reserves. Every living entity forms an encircled environment through which they fulfil their life style. It was estimated that one gram of soil contains up to ten billion bacterial cells. Decline in soil fertility is major concern for food security. Soil microbes contribute to a wide range of function in controlling soil health and crop productivity (Sahoo *et al*., 2015). Soil microbes helps in maintaining the soil properties in both direct and indirect methods. Plant–microbe interaction is one of the important aspects for agriculture system. This association may help to achieve goal of future sustainable agriculture. Microorganism is fundamental component of soil for all nutrient cycles and plant nutrient. Variation in temperature, low water content, anthropogenic, and grazing causes detrimental impact on microbial diversity and soil process. Soil – root - microbes form a comparatively stable and beneficial association. Some microbes have negative impact also in rhizosphere zone and harmful for plant growth and development (Ahmad *et al*., 2008). Due to intensive cropping and unhealthy effect of fertilizers, this relation declines soil microbial diversity. There are some microbial plant growth promoting substance which was released by the microbes and their role in plant growth and development which was tabulated in Table. 1.

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2.5. Plant Growth Promoting Rhizobacteria and EPS production

A synergistic group of microorganism which rendered in potential colonisation of plant root and its positive impact on plant growth and development were referred as PGPR (Beneduzi *et al*., 2012; Nosheen *et al*., 2021). It includes member of several genera, e.g., *Agrobacterium,* *Arthrobacter, Alcaligenes, Azotobacter, Acinetobacter, Actinoplanes. Bacillus, Frankia, Pseudomonas, Rhizobium, Micrococcus Streptomyces, Xanthomonas, Enterobacter, Cellulomonas, Serratia, Flavobacterium, Thiobacillus*, etc. (Yadav *et al*., 2017). Their habitual mode of mechanism and role in crop health promotion had been studies and results had better explored in previous studies (Dutta and Podile, 2010; Ahemad and Kibret, 2014; Vejan *et al*., 2016; Parray *et al*., 2016; Swarnalakshmi *et al*., 2020; Gouda *et al*., 2018; Oleńska *et al*., 2020; Glick, 2012). The potential benefits exerted from PGPR improves proper soil nutrient mineralisation and involves overcoming both biotic as well as abiotic stress tolerance in crops. Many studies focused on impact of PGPR as well bio-engineered organism in harnessing rhizospherical exudation patterns and its beneficial role in plant nutrient acquisition. Studies evidenced that inoculation of PGPR had resulted in positive feedback mechanism in crops. It induce tolerant towards drought situation of crops (Timmusk *et al*., 2014; Vurukonda *et al*., 2016; Niu *et al*., 2018; Ilyas *et al*., 2020), saline condition (Mayak *et al*., 2004; Bharti *et al*., 2014) and improvement of biotic stress tolerance (Vasconcellos *et al*., 2009; Verma *et al*., 2016). It also underscores effective breaking on seed dormancy and enhance germination of seed (Almaghrabi *et al*., 2014; Nezarat and Gholami, 2009), boosting soil fertility status (Islam *et al*., 2016; Jang *et al*., 2017) and enhance by producing phyto-hormones like auxin, IAA, gibberellin etc., (Kumari *et al*., 2016; Barnawal *et al*., 2017; Tahir *et al*., 2017). PGPRs not only involved as plant growth factor but also focused on remediation of heavy metals and pollutants in soil (Sayyed *et al*., 2015; Ordookhani *et al*., 2011; Pandey *et al*., 2013; Khan and Bano, 2016; Patel *et al*., 2016).

2.5.1. Micro-biome mediated and augmenting exopolysaccharide production in rhizosphere

PGPRs were capable for producing extracellular polymeric substances which are water soluble polysaccharides that aids in physical properties like promoting soil aggregate stability and soil structural formation. They tend to creation of macro aggregate formation (>0.25mm) and contribute towards soil structure. Soil aggregates are the basic building blocks of soil structure, and their quantity, size range, and stability play a crucial role in influencing soil fertility, water-holding capacity, and erosion resistance (Azizi et al., 2020). Several studies have highlighted the positive version in role of EPS-producing bacteria towards soil and plant health. Study conducted by (Naveen and Balachandar, 2025), revealed that EPS-producing PGPR QS74 enhanced soil aggregation, nutrient cycling, and growth level in maize through biofilm formation and also improved soil carbon, biomass, and dehydrogenase activity upon crop. Also

EPS produced from microbial synthesis in soil were involved in mitigating salt stress especially in arid and semi-arid regions (Yin *et al*., 2024; Rizzo *et al*., 2024) like *Bacillus subtilis* GBW HF-98 an species which facilitates better aggregate formation and structural stability during abiotic stress condition. EPS are key component in soil system as it had to be investigated depth in order to bring about crop resilient tool, eco-friendly and alternative for synthetic polymers. But the resources of EPS strains pertaining towards each bacterial species is limited and further extended studies rely on developing crop specific EPS strain for better crop performance and improvement in soil structure. Though the limited condition of EPS is present, but it was affected by external abiotic stress like temperature, soil reaction level, salinity condition, synergistic effect upon other species, soil organic matter level etc. (Chen *et al*., 2024). Also it was known to occur that developing consortia of EPS as a booster solution at root level feeding improves crop level can be consider as an critical study in future studies. Hence deploying exopolysaccharide as a tool in agriculture especially in plant micro-biome approach will be a promising one and act as a valuable candidate in promoting soil condition and utilizing it into large scale industrial production in future scale.

Table. 1. Plant growth promoting substances (PGPR) released by beneficial microbes and their critical role in plant growth and development

Sl. No.	Plant growth promoting microbes	Sources / plants	Plant growth regulation	References
1.	*Erwinia* species and P. *chlororaphis*	*Coffea rhizosp* L	Efficient uptake of insoluble phosphate from the soil	Muleta *et al*. (2013)
2.	Pseudomonas aeruginosa FP6	Chili	Siderophore produced by biocontrol strain for *Rhizoctonia solani* and *Colletotrichum gloeosporioides*	Sasirekha and Srividya (2016)
3.	*Bacillus amyloliquefaciens* 5113 and *Azospirillum brasilense* NO 40	Wheat	Promote plant growth under drought condition, increase enzyme activity in wheat plant	Kasim *et al*. (2013)

4.	*Bacillus amyloliquefaciens* HK34	Panax	Induction of systemic resistance against *Phytophthora cactorum*	Lee *et al.* (2015)
5.	*Bacillus thuringiensis* AZP2	Wheat	Decrease volatile emissions and increase photosynthesis	Timmusk *et al.* (2014)
6.	*Bacillus thuringiensis* GDB-1	Lavandula dentate	Enhanced phytoremediation of heavy metals (Pb, Zn, As, Cd, etc.)	Babu *et al.* (2013)
7.	*Pseudomonas putida* H-2-3	Soybean	Improve plant growth under saline and drought condition. Increase leaf length and chlorophyll content	Kang *et al.* (2014)
8.	*Aeromonas hydrophila* QS74 and *A. hydrophila* QSRB5	Maize	Enhanced soil aggregation and nutrient cycling	Naveen and Balachandar (2025)
9.	*Bacillus subtilis, and Bacillus amyloliquefaciens*	Tomato	Increased thickness of the upper epidermis, lower epidermis, palisade tissue, spongy tissue, and vascular bundles and improved photosynthetic efficiency	Gashash *et al.* (2022)
10.	*FJS-3(Burkholderia pyromania), FJS-7(Pseudomonas rhodesiae), and FJS-16(Pseudomonas baetica)*	Tea plant, Tobacco, and Chili pepper	Increased plant biomass, enhanced chlorophyll content and carotenoid content	Zhang *et al.* (2024)

3. Use of microbial strains in producing bio fertilizers

Bio-fertilizer are an important component of integrated nutrients management. Microorganisms that are used as bio-fertilizer components include; nitrogen fixers (N-fixer), potassium and phosphorus solubilizers, growth promoting rhizobacteria (PGPRs), endo and ecto mycorrhizal fungi, cyanobacteria and other useful microscopic organisms. The use of bio-fertilizers leads to improved nutrients, water uptake, plant growth and plant tolerance to abiotic and biotic factors. The different mechanisms of action of biofertilizers, including nutrient uptake facilitation, phytohormone regulation, and phytoprotection, must be understood to effectively utilize their potential for increasing the ecological services of forest biomes and promoting production in agriculture sectors (Liu and Boopathy, 2021). By supplying vital nutrients such as nitrogen, phosphorous, and potassium, biofertilizers preserve the soil's natural qualities (Aloo *et al*., 2021) in Fig. 3.

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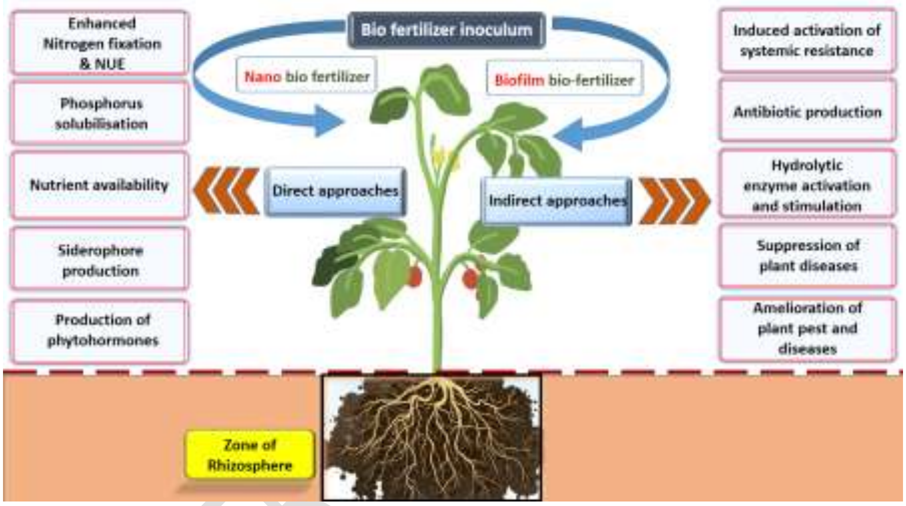

Fig. 3. The beneficial mechanisms of microbial strains as a bio fertilizer and their role in maintaining soil fertility and enhancing crop productivity.

Bio-fertilizer is a substance which contains living microorganisms which when applied to the soil; a seed or plant surface colonizes the rhizosphere (Muhilan *et al*., 2024) and promotes growth by increasing the supply or availability of nutrients to the host plant and containing living cells of different of micro-organisms which have ability to convert nutritionally important elements from unavailable to available form through biological processes (Vessey JK, 2003).This biological fertilizers would play a key role in productivity and sustainability of soil and also in protecting the environment as eco-friendly and cost effective inputs for the small holder farmers. Adding of the nutrients through the natural processes of nitrogen fixation, solubilizing phosphorus, and stimulating plant growth through the synthesis of growth-promoting substances are a good way to sustain our agricultural systems. Soil management strategies today are mainly dependent on inorganic chemical-based fertilizers, which cause a serious threat to human health and the environment Ritika and Uptal (2014). The different types of microorganisms used in biofertilizers are tabulated below in table. 2.

Table. 2 Microorganisms inoculum used in Bio-fertilizer Production

Group	Example	References
1. Nitrogen fixing bio-fertilizers		(Choudhury and Kennedy, 2004)
<u>Mechanism</u>: Increase soil nitrogen content by fixing atmospheric N and make it available to the plants		
Free living	*Azotobacter, Bejerinkia, Clostridium, Klebsiella, Anabaena, Nostoc*	
Symbiotic	*Rhizobium, Frankia, Anabaena, Azollae*	
Associative symbiotic	*Azospirillum*	
2. Phosphate solubilizing bio-fertilizer		(Board, 2004)
Mechanism: Solubilize the insoluble forms of P in the soil into soluble forms by secreting organic acids and lowering soil pH to dissolve bound phosphates		
Bacteria	*Bacillus megaterium var, Phosphaticum, Bacillus subtilis, Bacillus circulans*	
Fungi	*Penicillum Spp. Aspergillus awamori*	
3. Phosphate mobilizing bio-fertilizers		(Chang and Yang, 2009)
Mechanism: Transfer phosphorus from the soil to the root cortex. These are broad spectrum bio-fertilizers.		
Arbuscular Mycorrhiza	*Glomus Spp., Gigaspora Spp., Acaulospora Spp. Scutellospora Spp. and Sclerocystis Spp.*	
Ectomycorrhiza	*Laccaria Spp. Pisolithus Spp, Boletus Spp. and Amanita Spp.*	
Ericoid Mycorrhiza	*Pezizella ericae*	
Orchid Mycorrhiza	*Rhizoctonia solani*	

4. Potassium (K) solubilizing bio-fertilizer		(Etesami *et al*., 2017)
Mechanism: Solubilize potassium (silicates) by producing organic acids that decompose silicates and help in the removal of metal ions and make it available to plants.		
Bacteria	*Bacillus. mucilaginosus, B. circulanscan, B. edaphicus, and Arthrobacter spp.*	
Fungi	*Aspergillus niger.*	
5. K mobilizing bio-fertilizers		(Jha, 2017)
Mechanism: mobilize the inaccessible forms of potassium in the soil and confronts near root zone for proper uptake into plant system		
Bacteria	*Bacillus spp.*	
Fungi	*Aspergillus niger.*	
6. Bio-fertilizers for micronutrients		(Itelima *et al*., 2018; Kamran *et al*., 2017)
• Oxidizing sulphur to sulphates which are usable by plants - sulphur oxidizing		
• Solubilize the zinc by proton, chelated ligands, acidification, and by oxidoreductive systems - zinc solubilizing		
Bacillus Spp	Silicate and zinc solubilizer	
7. Plant growth promoting Rhizobacteria		(Backer *et al*., 2018)
Mechanism: Produce hormones that promote root growth, improve nutrient availability, and improve crop yield		
Pseudomonas	Pseudomonas fluorescens	
8. Algae as bio-fertilizer compound		(Chatterjee *et al*., 2017; Ammar *et al*., 2022)
Mechanism: Certain algae, particularly blue-green algae (cyanobacteria), can convert atmospheric nitrogen into forms usable by plants, reducing the need for synthetic nitrogen fertilizers.		
Brown macro algae	*Laminaria digitata* (Oarweed), *Saccharina latissima* (Sugar Kelp), *Fucus vesiculosus* (Bladder wrack), *Ascophyllum nodosum* (Knotted wrack), *Ecklonia maxima, Stoechospermum marginatum*	
Red macro algae and blue green algae	*Phymatolithon calcareum, Lithothamnion corallioides Nostoc, Anabaena, Aulosira, Tolypothrix, Nodularia, Cylindrospermum, Scytonema, Aphanothece,*	

	Calothrix, Anabaenopsis, Mastigocladus, Fischerella, Stigonema, Haplosiphon, Chlorogloeopsis, Camptylonema, Gloeotrichia, Nostochopsis, Rivularia, Schytonematopsis,Westiella, Westiellopsis, Wollea, Plectonema and Chlorogloea	
Anabaena Azolla association	*Anabaena azollae*	

Various kinds of soil indicators are used for assessing the effects of fertilizers. Some of them utilize soil physical and chemical properties whereas others focus on biochemical properties that directly reflect the size and activity of soil microbial biomass (Sparling, 1992). This section encompasses effects of algal biofertilizers on soil physico-chemical, biochemical properties, and indigenous soil microbial community as depicted in Fig. 4.

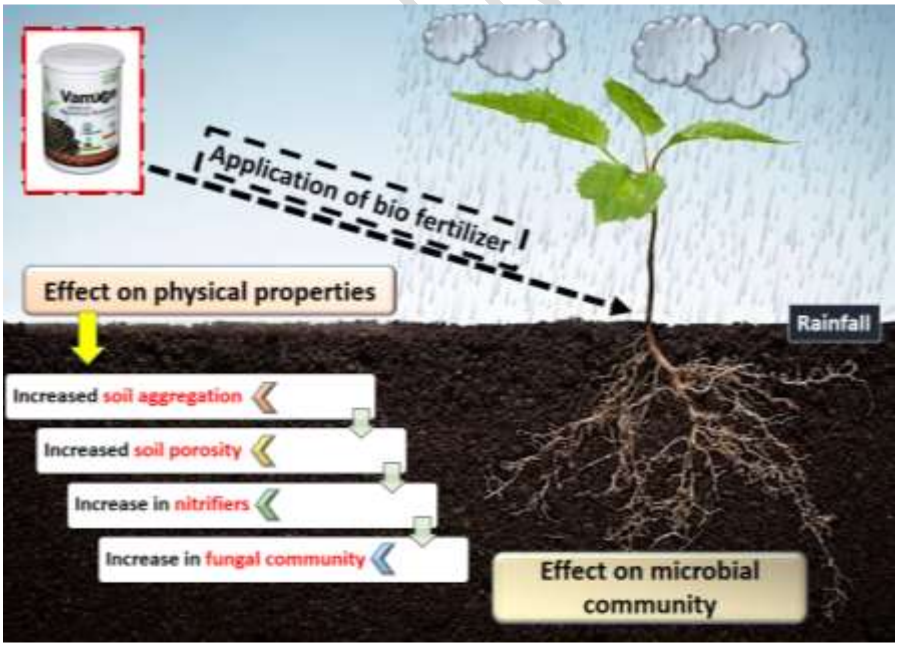

Fig. 4. Effects of biofertilizers on physiological and biochemical properties of soil

4. Recent advancement of micro-biome in soil system by metagenomics study

Soil microorganisms play an important role in the decomposition and circulation of organic matter, nutrients or xenobiotic. They are responsible for plant health and nutrition and have an impact on the structure and fertility of the soil (Wolejko *et al*., 2020). Soil metagenomics is a cultivation-independent molecular approach to explore and exploit the enormous diversity of soil microbial communities. This technology comprises isolation of soil DNA and production and screening of clone libraries. Screening of metagenomic soil libraries, especially by activity-based approaches, has led to the identification of various novel biomolecules, including enzymes and antibiotics of industrial importance (Daniel, 2005).

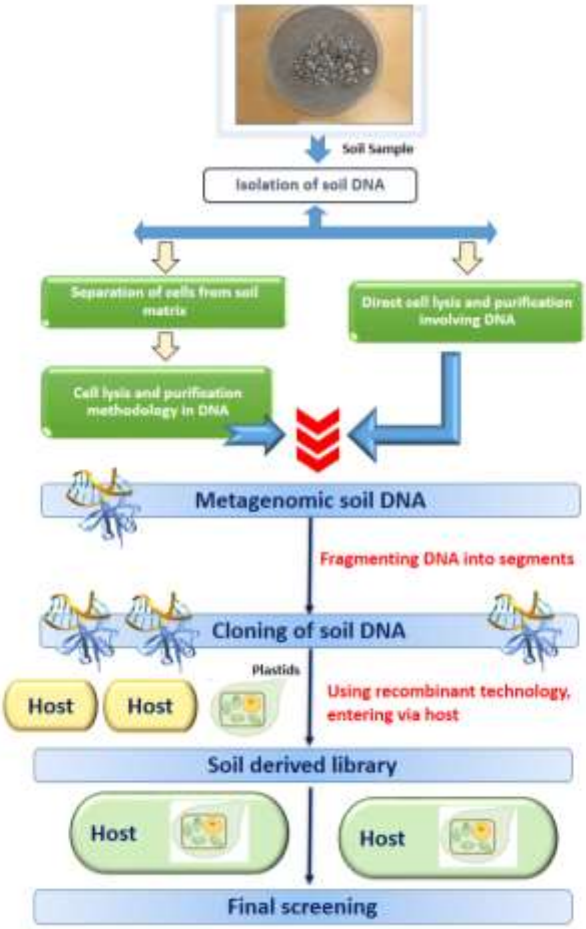

Fig. 5. Essential steps to explore and exploit the genomic diversity of soil microbial communities by metagenomics

Also, other method for quantifying the soil microbiome is profiling. The method of analysing soil microbial community composition and function is known as SM analysis. Since scientists have realised how important microorganisms are to the production and health of soil, this method has grown in popularity. This is a step by-step instruction explaining our methodology for microbiome analysis (Nalage *et al*., 2022; Wydro, 2022). It involves Sample collection, DNA extraction, sequencing and finally data interpretation. Thus, it aids in strain based bio-formulation preparation on crop specific target which facilitates better use of microbial activity in soil. Usually the character of any species or human or animal were determined by their DNA. Thus extraction of DNA will prone for species identification. Fig. 6. Explains different soil DNA extraction procedure.

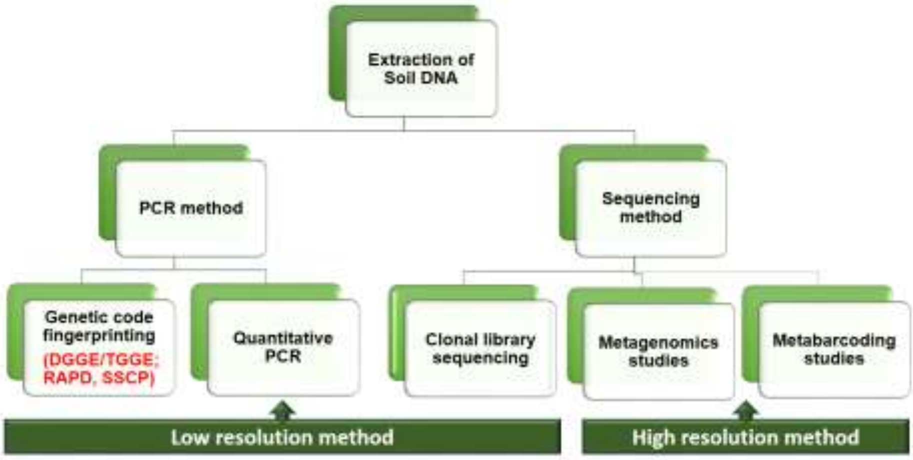

Fig. 6. Procedures for analysing the soil microbiome (SM) through PCR and Sequencing

5. Future Thrust

Plant and soil are inter-connected in biosphere. Plant micro biomes levering in agriculture plays a significant role in promoting rapid diverse and beneficial micro-organisms which contributes to better crop health and productivity. Although interlinking of plant associated microbiome towards cropping system had been utilized and recognized for past centuries, and it was known to be progress for mid 1980s, and harnessed its potential. Several research studies and scientists were focused on preparation of microbial consortia (group of microbial inoculum) and its effectiveness in real world scenario was limited and haven't reach other end circumstances (Kimotho *et al*., 2024). This urgency delineates in preparing crop specific microbial inoculum through its RNA pattern and synergistic effect, different formulation with altering ratios, improved delivery method through ML algorithm practices and predicting soil organic status through DSSAT or RothC models.

Promoting microbial inoculum towards crop specific and environmentally stable without altering its structure and function can show maximum promising effect in overcoming challenges like land degradation, land use changes, soil desertification. Tailoring and interlinking various agronomic practices like crop rotation, intercropping, mulching, soil residue management, legume cropping, rice fallow pulse might increase the state of native microbial population and can effectively recruit other organisms through synergistic effects (Wang and Li, 2019). Also, advancing microbial sequencing can favour and can enumerate their efficiency and tolerance towards biotic as well as abiotic stress in environmental condition offering exciting possibility for boosting crop productivity and sustainability.

Soil microorganisms, regarded as the biological bridge between plant and soil ecosystems, play a pivotal role in the PSF (positive soil feedback) system. Future prediction studies can focuses and fill the existing gap on how introduced inoculum affects native standard microbial diversity, their dynamic changes and what are the factors which promotes and limits the microbial population in agriculture forum. This make a necessary for preparing resilient microbial inoculants and consortia which can sustain at various environmental situations. Developing target and delivery mechanism which suites to specific crop and local climatic condition is essential in inoculating microbiome load. Bridging the gap between lab to field level and possible errors can be minimised in future research shall promote sustainable and precision farming thereby farmers will be benefitted in better ways in future scenarios.

6. Conclusion

Soil is the base for cultivation and nation food security. Hence keeping soil media healthy and more fertile helps us to make diversified cultivation and for sustainable future. This review paper clearly stated the role of soil micro biome under soil system and usage of biofertilizer in agricultural. As its use enhance productivity by biological nitrogen fixation or solubilization of insoluble phosphate or by producing hormones, vitamins and other growth promoters required for plant growth, minimize the use of chemical fertilizers, to stimulate the production of growth promoting substances, mobilize phosphate, antagonists, suppress the occurrence of soil borne pathogens, bio-control of diseases, nitrogen fixing and thereby in the recycling of plant nutrients. Ultimately, the complex interplay of microbes, soil health, and ecosystems production has been made clear by advancements in the study of the soil microbiome. Hence, it is clearly believed that everyone shall add well decomposed organic manure like FYM,

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compost, goat manure can create a wide complex in soil system and pave a way for soil organisms to develop more and give beneficial attributes towards soil ecosystem.

Details of software used in art preparation

The smart art illustration were prepared using **MS PowerPoint v 2013** and **bio render** software (free licensed)

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