



REVIEW PAPER

Plant growth promoting rhizobacteria in promoting sustainable agriculture

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ABSTRACT

Rapid human population growth and its consequences of food shortage become a significant concern in recent decades across the world. The untold reasons behind this food shortage were industrialization, urbanization, modern civilization, etc., where the agricultural land has been deployed. With the decreasing farmland and its cultivation, food productivity declined drastically and failed to serve the world's vast human population. The present challenge is to increase productivity with the least agricultural land. Thus, excessive chemical fertilizer has been used to quickly turn out more outstanding food production, leading to more significant damages to soil ecosystem and human health. Henceforth, bio-fertilizers find the best alternatives to chemical fertilizers. This study focuses on complete nature of plant growth Promoting rhizobacteria, which is used in bio fertilizers for sustainable agricultural productivity and everlasting soil fertility. The characteristics of plant growth promoting rhizobacteria and its role in plant growth and formulation of plant growth promoting rhizobacteria biofertilizers have been revealed through intensive literature. The consortium information collected from various literatures brings the unique findings that plant growth promoting rhizobacteria is the natural boon to the global agriculturist. This study discusses plant growth promoting rhizobacteria bacterial strains' role in protecting the soil from various biotic and abiotic stresses, regulating plant growth and its role in producing biofertilizers. Besides, it is transformed into commercial products. Eventually, the future trends and research in plant growth promoting rhizobacteria bio inoculants that promote sustainable agriculture have been elucidated. The microorganism is the bio fertilizer's main ingredients, promoting the soil nutrients for efficient plant growth and increasing food productivity. Although many microorganisms efficiently contribute to the soil nutrients, this review narrows down to the plant growth promoting rhizobacteria study. Beneficial bacterium plays a vital role in nutrient mineralization and productivity among the various microorganisms. Bio fertilizers containing beneficial bacteria were economically viable and readily available in nature. This review reveals the complete essence of plant growth promoting rhizobacteria and its part in bio fertilizers.

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INTRODUCTION

One of the foremost goals of human life is the consistent and adequate food supply. Due to the increasing rate in population across the world, consistent food supply becomes a challenging phenomenon in current scenario. There are many factors in offering food supply for the rapid population growth, such as production rate, cost, climate, land utilization, adequate water supply, technology, consistency in crop productions and etc. Besides, soil fertility is the crucial element which determines the crop production quantitatively and qualitatively. Soil fertility is in the great need of continuous and consistent monitoring because of its intangible activities like nutrient cycling, structural arrangements, biotic regulation, transformation of harmful elements, holding capacity of nutrients, transferring water and nutrients to plants and etc., Shortage of soil fertility is one of the indispensable limitations in achieving expansive crop production (Franzluebbers *et al.*, 2013). In order to fulfill the world food security, excessive usage of inorganic fertilizers were practiced that in turn became one of the vital reasons for declining in soil fertility (Kumar *et al.*, 2019). The utilization of inorganic fertilizers increases the crop production; however it causes long term degradation of soil fertility over the years (Shambhavi *et al.*, 2017). Massive utilization of organic fertilizers is very essential to regain the soil fertility. The hybrid combo of inorganic with organic fertilizers retains the soil fertility that triggers off crop production rate (Emmerson *et al.*, 2016). Hybridization of fertilizers completely depends on physical, chemical and biological characteristics of soil (Walsh *et al.*, 2012). Utilization of fertilizers greatly concern with biological characteristic changes which in turn indicate the soil fertility rate (Bargaz *et al.*, 2018). Biological components of soil are more pertinent to long term crop productivity and for sustainable agricultural practices (Lima *et al.*, 2015). Improving the soil biological composition evokes amelioration of crop productivity by means of biofertilizers. Biofertilizers is eco-friendly, which aid in sustainable agricultural practices (Santhosh *et al.*, 2018). It holds alive microorganism, which induces the soil nutrients by means of organic matter decomposition (Mazid *et al.*, 2011). Intake of mineral nutrients by plants with the help of biofertilizers brings a better outcome in terms of long term crop productivity (Malusa *et al.*, 2012). All bacterial biofertilizers has significant part in

Nitrogen (N) fixing, Phosphorus (P), Potassium (K), zinc and silica solubilization (Narendra *et al.*, 2017) which helps in fixing all kinds of micro and macro nutrients to the soil. In addition biofertilizers enhance the plant growth through enriching the soil fertility by release of plant growth hormones, antibiotic production and organic matter biodegradations (Sinha *et al.*, 2014). Biofertilizers involves and accumulates the nutrients in the soil and prevents the nutrient loss during intake by plants, thus helping in enhanced plant growth (Singh *et al.*, 2011). PGPR, the main ingredients of bacterial biofertilizers has hefty relationship with different species relevant to host plants. Rhizospheric and Endophytic, the two prime classes of relationship which are found in the intercellular (Imran *et al.*, 2019) and apoplasmic space of the host plant respectively (Qiu *et al.*, 2016). Some of the notable Rhizospheric bacteria are Bacillus, Azospirillum, Azotobacter, Burkholderia, Enterobacter, Klebsiella, Variovorax, Comamonadaceae, Pseudomonas, Gemmatimonadetes, Streptomyces filamentosus and Bacillales. Markable endophytic bacteria are Azoarcus spp, Herbaspirillum, seropedicae and Gluconacetobacter diazotrophicus (Carvalho *et al.*, 2014). Aforementioned PGPR produces Indoleacetic acid (IAA), Cytokinins (CK), Gibberellins (GA) and inhibitors of ethylene which takes up the great responsibilities of nutrients and water uptake required for plant growth (Tsukanova *et al.*, 2017). In this study, PGPR's role in agriculture, various species and its corresponding plants, its mechanism, advantages and disadvantages, future trends were reviewed. The aim of study is to provide adequate knowledge about the characteristics and functionality of PGPR through consortium literature reviews so as to practice the same to attain sustainability in agriculture. The overall literature study and compilation were made at SRM Institute of Science and Technology, Chennai in the year of 2021.

Plant growth promoting rhizobacteria

A cluster of bacteria that colonizes the root of the plant (rhizosphere) is termed as Plant growth promoting rhizobacteria (Egamberdieva *et al.*, 2014). Rhizosphere is considered as the maximum nutrient amalgamate zone, where active microbial activities will be carried out. Though rhizosphere consists of various microbes such as bacteria, fungi, algae, protozoa and actinomycetes, the bacterial colonies were found abundant (Kaymak *et al.*, 2010). The

sustainable plant growth has been made possible through these bacterial colonies and it has been proved under various circumstances (Saharan *et al.*, 2011; Bhattacharyya *et al.*, 2012). Apart from promoting the plant growth through its active mechanism, the bacterial colonies in the rhizosphere has a strong effect on controlling the phytopathogenic microbes (Son *et al.*, 2014). Those bacterial colonies were named as rhizobacteria and are heterogeneous in nature. The unique characteristic of rhizobacteria such as ability to produce plant growth regulators, fixation of nitrogen, siderophore production, nutrients and mineral solubilization shows the superior nature when compared to other microorganism in promoting the plant growth (Souza *et al.*, 2012). Moreover, it acts as the Biocontrol agent to the pathogenic microbes (Beneduzi *et al.*, 2012). These beneficial bacterial colonies were affected by various factors such as temperature, pH, moisture, soil mineralogy and light. Among which the composition and activities of plant associated microbes. Beneficiary microbes enhance the plant growth usually at high temperature (Stephane *et al.*, 2010). pH is the important factor in determining the sustainability of microbes in the soil. pH ranges from 6.0 to 6.5 is found advantageous for the beneficiary microbes sustainability so as to ensure healthy plant growth (Berger *et al.*, 2013). These beneficiary microbes also maintain moisture through active secretion of hormones and enzymes (Dębska *et al.*, 2016).

Role of plant growth promoting rhizobacteria Biotic and abiotic stress tolerance

The various external factors are responsible for the unproductive growth of plants which are referred as stress in plants. These stress disturb the genetic characteristic, metabolic activities, yield of the crops etc. and it can be categorized as biotic and abiotic stresses (Verma *et al.*, 2013). The living organism especially pathogenic bacteria, virus, fungi etc are responsible for causing biotic stress in plants. This affects the host cell of the plant and modifies the genetic code of the plant which leads to mortality of the plant (Suzuki *et al.*, 2014). Abiotic factors such as soil salinity, drought, extreme high temperature, deficient or excessive water supply leads to great reduction in agricultural productivity (Nadeem *et al.*, 2010). Abiotic and biotic stress caused by pathogenic mechanism, brings pre and post-harvest troubles in crops (Nejat

et al., 2017). These stresses are major barriers in sustainable agricultural productivity (Srividya and Sasirekha, 2017). Stresses that cause severe damages to the crop production can be determined by the efficacious process of PGPR. The enzyme called 1-aminocyclopropane-1- carboxylate (ACC) deaminase and Hydroxyacetophenone monooxygenase produced by PGPR and *Pseudomonas fluorescens* respectively breaks the ethylene precursor ACC to a-ketobutyrate and ammonia, that in turn, protects plants from various destructive effects of abiotic stresses (Kumara *et al.*, 2019). The bio-inoculants, developed by *acdS* gene coding for enzyme ACC-deaminase against the abiotic stresses (Shaik *et al.*, 2013). The salinity and drought are the most devastating stresses that lower the agricultural productivity (Hasanuzzaman *et al.*, 2013). In addition, higher levels of ethylene in the plant stimulate premature senescence symptoms such as leaf yellowing, abscission, or desiccation/necrosis (Elisa and Glick, 2015). PGPR plays a major role in lessening the ethylene concentrations in plants, thus reduce the stresses. *Pseudomonas putida* and *Enterobacter cloacae* improve the plant resistance to salt stress (Zhenyu *et al.*, 2012). *Azospirillum brasilense*, *Pseudomonas chlororaphis* (Egamberdieva, 2012), *Streptomyces* sp. strain (Palaniyandi *et al.*, 2014), *Chryseobacterium* (Radzki *et al.*, 2013) on tomato plants, *Pseudomonas putida* in soybean plants (Sang *et al.*, 2014) tends to reduce the ethylene level in plants so as to tolerate the salinity stresses. *Bacillus megaterium* found to be highest phosphate solubilization under salinity stresses in the plants (Chookietwattana and Maneewan, 2012). *Enterobacter* sp in okra plant (Habib *et al.*, 2016), *Phyllobacterium* in strawberries plant (Flores *et al.*, 2015), *Putida*, *Gigaspora rosea* (Gamalero *et al.*, 2010), *Promicromonospora* sp and *Burkholderia cepacia* in cucumber plants (Sang *et al.*, 2014), *Bacillus licheniformis*, *Brevibacterium iodinum*, *Zhihengliuella alba* in red pepper plants (Siddique *et al.*, 2011), *Bacillus* in alfalfa plants (Sokolova *et al.*, 2011), *Pseudomonas* sp in eggplant (Fu *et al.*, 2010) were some of the PGPRs actively diminish the salinity stresses. The functionality of the plants gets affected severely by turgor pressure and water potential during drought conditions. This leads to drought stress, causing severe damages to agricultural productivity (Rahdari and Hoseini, 2012) and flow of nutrients such as sulfates, nitrates, Calcium, Silica, Magnesium (Selvakumar *et al.*, 2012) and photosynthesis process (Anjum *et al.*,

2011; Rahdari *et al.*, 2012) founds to be reducing. The bacterial colonies of rhizosphere and endorhizosphere induce the plant to overcome the drought stress in order to attain sustainable agricultural productivity (Grover *et al.*, 2011). The plant biomass enhanced through the inoculation of *Pseudomonas putida* under the drought stress condition (Sandhya *et al.*, 2010). It is found that *lavandula dentata* with *Bacillus thuringiensis* induces the growth of plant under drought stress by increasing the concentration of proline in the shoot (Armada *et al.*, 2014). *Bacillus polymyxa* in tomato plant (Shintu and Jayaram, 2015), *Pseudomonas jessenii*, *Pseudomonas synxantha*, and *Arthrobacter nitroguajacolicus* strain in rice plants (Gusain *et al.*, 2015), *lipoferum* and *Pseudomonas putida* in maize plants (Sandhya *et al.*, 2010; Bano *et al.*, 2013), *Bacillus* isolates and *Pseudomonas* with mesorhizobium ciceri in green gram plants (Isha *et al.*, 2013), rhizobacterial strain *Bacillus subtilis* in mustard plant (Zhang *et al.*, 2010) were the PGPRs that induce the growth of plants under drought stress. In case of biotic stresses the *Bacillus subtilis* found a better resistance to the cotton pathogen *rhizoctonia solani* (Flavio *et al.*, 2011). Therefore, PGPR actively overcome all the biotic and abiotic stresses and induce the plants growth for sustainable crop productivity as shown in the Fig. 1.

to fix nitrogen nutrients in the soil (Gothandapani *et al.*, 2017). *Azospirillum* belonging to the spirillaceae family has strong association with the roots of C4 crops and plays a significant role in fixing 20-40kg of nitrogen under aerobic conditions (Trabelsi and Mhamdi, 2013). For leguminous plants rhizobium finds greater potential in fixing the atmospheric nitrogen at major concern (Jehangir *et al.*, 2017). Cyanobacteria (Blue Green Alga, BGA) such as *Nostoc*, *Anabaena*, *Cylindrospermum*, *Gloetrichia Tolypothrix*, *Aulosira* and *Aphanotheca* tremendously increases the rice crop productivity up to 38%, by fixing the nitrogen nutrients (Mishra *et al.*, 2013). *Azolla* proves to be vital nitrogen source for sustainable agricultural productivity and it has the potential of fixing about 50kg of nitrogen (Yao *et al.*, 2018). *Gluconacetobacter diazotrophicus* which colonize enormously in monocotyledon sugarcane plants actively fix the atmospheric nitrogen so as to provide sufficient amount of nitrogen nutrients for the crop growth (Santhosh *et al.*, 2018). Apart from these strains *Bacillus aerius*, *Bacillus amyloliquefaciens*, *Bacillus licheniformis*, *Bacillus mucilaginosus*, *Bacillus subtilis* helps in nitrogen fixation in soil (Singh *et al.*, 2019; Pahari and Mishra, 2017). Addition to nitrogen fixation, phosphorous solubilization is also biologically important. PGPR has strong role in solubilizing phosphorous for the consistent plant growth (Rifat *et al.*, 2010). *Pseudomonas erwinia* and *P. chlororaphis* were has strong tendency to solubilizing the phosphorous and promote the plant growth through proper uptake of phosphorous nutrients (Diriba *et al.*, 2013). From the biochemical characteristics of bacterial isolates of *Pseudomonas putida* and *Bacillus* sp., it has been proven that these colonies have viability to solubilizing the phosphate for consistent supply of nutrients to the

Soil Nutrients accessibility for the plant growth

The overall concentration of soil nutrients in the rhizosphere get increased with the help of PGPR. It helps in fixing the atmospheric nitrogen by preventing the leaching of soil nutrients (Choudhary *et al.*, 2011). The species that comes under *azotobacter* genus such as *armeniacus*, *vinelandii*, *chroococcum*, *paspali*, *beijerinckii*, *nigricans* and *salinestri* has strong potential

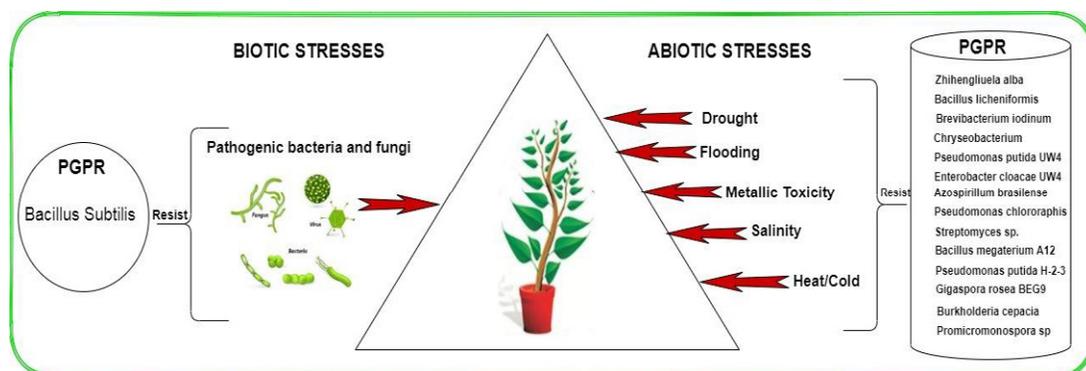


Fig. 1: PGPR in resisting biotic and abiotic stresses

plants (Grobelak *et al.*, 2015). PGPR bacterial strains such as *Achromobacter xylosoxidans*, *Acinetobacter baumannii*, *Acinetobacter calcoaceticus*, *Aeromonas hydrophila*, *Arthroderma cuniculi*, *Aspergillus niger*, *Bacillus aerius*, *Bacillus altitudinis*, *Bacillus amyloliquefaciens*, *Bacillus licheniformis*, *Bacillus megaterium*, *Bacillus mucilaginosus*, *Bacillus subtilis*, *Bacillus thuringiensis*, *Burkholderia cepacia*, *Burkholderia gladioli*, *Enterococcus casseliflavus*, *Enterococcus gallinarum*, *Fusarium proliferatum*, *Lecanicillium psalliotae*, *Paenibacillus favisporus*, *Paenibacillus taichungensis*, *Pseudomonas entomophila*, *Pseudomonas koreensis*, *Pseudomonas luteola*, *Pseudomonas simiae*, *Serratia marcescens*, *Serratia nematodiphila*, *Sphingomonas paucimobilis* actively involves in solubilizing the phosphorous and tends to enhance the plant growth (Leite *et al.*, 2018; Zhang *et al.*, 2017; Martinez *et al.*, 2018; Karmakar *et al.*, 2018; Gore and Navale, 2017; Kumaravel *et al.*, 2018; Vardharajula *et al.*, 2011; Mussa *et al.*, 2018; Kumari *et al.*, 2016; Sandhya *et al.*, 2010; Saikia *et al.*, 2018). Solubilization of soil potassium is biologically an important factor and has equal importance, compared to the nitrogen and phosphorous in contributing sustainable crop production (Tri and Mutmainnah, 2016). Inorganic and organic acids, acidolysis, polysaccharides, complexolysis, chelation, polysaccharides, and exchange reactions produced by the bacteria aid to solubilizing the soil potassium (Archana *et al.*, 2013; Meena *et al.*, 2015). *Bacillus licheniformis* and *Pseudomonas azotoformans* in rice crops finds the best K solubilizing bacteria than others (Saha *et al.*, 2016). Potassium solubilizing capacity is found triggered by *Enterobacter hormoechei* in cucumber crop fields (Prajapati and Modi, 2016). The species such as *Burkholderia*, *Pseudomonas*, *Bacillus mucilaginosus*, *Bacillus edaphicus*, *Bacillus circulans*, *Acidithiobacillus ferrooxidans*, and *Paenibacillus* spp. when inoculated with *frateuria aurantia* strain shows about 39% increase in concentration of potassium in the crops (Subhashini, 2015), the aforementioned information are depicted in the Table 1.

Plant growth regulator

Plant producing organic substances in the name of hormones (also called as phytohormones) such as auxins, gibberellins (GA), abscisic acid (ABA), cytokinins (CK), salicylic acid (SA), ethylene (ET), jasmonates (JA), brassinosteroids (BR), and

peptides were the key factors in developing the immune system against the pathogenic microbes and brings out tremendous agricultural outcomes (Dong *et al.*, 2013). These hormones act as the plant growth regulator for boosting up the crop productivity. Rhizobacterial traits make a major impact on the status of plant hormones by inducing the hormone secretion activities and increase the concentration of the hormones (Dodd *et al.*, 2010). *Bacillus* spp. producing auxin is proven as the deciding molecules which regulates the primary plant growth process (Ahmed and Hasnain, 2010). The most eminent auxin in the plant is indole-3-acetic acid. Lower the amount of IAA causes stimulation of elongation in primary roots, whereas higher concentration of IAA stimulates lateral root formation and root hair production. PGPR plays a vital role in synthesis of IAA which increases the both elongation of primary roots and lateral root formation (Vacheron *et al.*, 2013). Next to auxin, gibberellin is considered as most viable hormone responsible for seed germination, floral induction, flower, fruit, leaf and stem maturation. *Sphingomonas* produces gibberellins (GA) when inoculate with tomato plant, induces all the characteristics discussed above (Khan *et al.*, 2014). The plant organ size and stomata closure functionality is purely regulated by the plant hormone, namely abscisic acid (ABA) which is abundantly synthesized by the strains of *Bacillus amyloliquefaciens* (Raheem *et al.*, 2017). *Bacillus subtilis* strains synthesize the plant hormone called cytokinins which are responsible for plant cell division, inhibiting roots, stems, vascular differentiation and cambium sensitivity (Liu *et al.*, 2013). Reduction in antioxidant enzymes activity carried out by the salicylic acid (SA) were regulated majorly by the PGPR strains such as *Mycobacterium* spp., *Pseudomonas* spp., *Azospirillum*, *lipoferum* and *Pseudomonas cepacia* (Khan *et al.*, 2020). Abscission of leaves and ripening of fruits were primarily regulated by ethylene plant hormones. 1-aminocyclopropane-1-carboxylate (ACC) is a plant, synthesized predecessor of ethylene hormone, which helps in exposing to environmental stress, pathogenic microbes and heavy metal presence (Glick *et al.*, 2012). Hence, PGPR plays a viable activity in decaying cycle of roots through degrading the ACC thus achieving the healthy root system (Glick *et al.*, 2014). Jasmonates (JA) takes part in responding to the wounds in plant tissues and redirects the metabolism to repair the damages, which are mediated by PGPR. *Bacillus subtilis* in wheat

Table 1: Plant nutrients and its corresponding PGPR bacterial strains

Nutrients	PGPR	References
Nitrogen (N)	A. chroococcum	Gothandapani <i>et al.</i> , 2017
	A. vinelandii	Gothandapani <i>et al.</i> , 2017
	A. beijerinckii	Gothandapani <i>et al.</i> , 2017
	A. paspali	Gothandapani <i>et al.</i> , 2017
	A. armeniacus	Gothandapani <i>et al.</i> , 2017
	A. nigricans	Gothandapani <i>et al.</i> , 2017
	A. salinestri	Gothandapani <i>et al.</i> , 2017
	Azospirillum	Trabelsi and Mhamdi, 2013
	Cyanobacteria	Mishra <i>et al.</i> , 2013
	Azolla	Yao <i>et al.</i> , 2018
	Gluconacetobacter diazotrophicus	Santhosh <i>et al.</i> , 2018
	Bacillus aerius	Singh <i>et al.</i> , 2019
	Bacillus amyloliquefaciens	Singh <i>et al.</i> , 2019
	Bacillus mucilaginosus	Pahari and Mishra, 2017
Bacillus subtilis	Pahari and Mishra, 2017	
Phosphorous (P)	Pseudomonas erwinia	Diriba <i>et al.</i> , 2013
	P. chlororaphiswera	Diriba <i>et al.</i> , 2013
	P. putida	Gobelak <i>et al.</i> , 2015
	Bacillus sp	Gobelak <i>et al.</i> , 2015
	Achromobacter xylosoxidans	Leite <i>et al.</i> , 2018
	Acinetobacter baumannii	Zhang <i>et al.</i> , 2017
	Aeromonas hydrophila	Martinez <i>et al.</i> , 2018
	Arthroderma cuniculi	Karmakar <i>et al.</i> , 2018
	Aspergillus niger	Gore and Navale, 2017
	Bacillus aerius	Singh <i>et al.</i> , 2019
	Bacillus altitudinis	Kumaravel <i>et al.</i> , 2018
	Bacillus thuringensis	Vardharajula <i>et al.</i> , 2011
	Enterococcus casseliflavus	Mussa <i>et al.</i> , 2018
	Enterococcus gallinarum	Mussa <i>et al.</i> , 2018
	Lecanicillium psalliotae	Bilal <i>et al.</i> , 2018
	Paenibacillus taichungensis	Zhang <i>et al.</i> , 2017
	Pseudomonas entomophila	Sandhya <i>et al.</i> , 2010
	Pseudomonas koreensis	Kumari <i>et al.</i> , 2016
	Pseudomonas luteola	Martinez <i>et al.</i> , 2018
Pseudomonas simiae	Kumari <i>et al.</i> , 2016	
Pseudomonas stutzeri	Sandhya <i>et al.</i> , 2010	
Serratia nematodiphila	Saikia <i>et al.</i> , 2018	
Sphingomonas paucimobilis	Martinez <i>et al.</i> , 2018	
Potassium (K)	Bacillus licheniformis	Saha <i>et al.</i> , 2016
	Pseudomonas azotoformans	Saha <i>et al.</i> , 2016
	Burkholderia	Subhashini, 2015
	Bacillus mucilaginosus	Subhashini, 2015
	B. edaphicus	Subhashini, 2015
	B. circulans	Subhashini, 2015
	Pseudomonas	Subhashini, 2015
	Acidithiobacillus ferrooxidans	Subhashini, 2015
	Paenibacillus sp	Subhashini, 2015
Enterobacter hormoecheii	Prajapati and Modi, 2016	

seedling finds great response of synthesis of jasmonates hormones (Veselova *et al.*, 2014). PGPR has viable part in synthesizing hormones namely brassinosteroids (BR), and peptides which are responsible for various

stress tolerance amelioration (Sharma *et al.*, 2017). Apart from aforementioned hormones PGPR Oozes out small, high-affinity iron-chelating compounds called Siderophores which is responsible for enhancing

the plant growth through iron intensification (Flores *et al.*, 2015). *Bacillus subtilis*, *Bacillus megaterium*, *Azotobacter vinelandii*, *Pantoea allii* and *Rhizobium radiobacter* were some of the PGPR strains that have strong ability to chelate iron in the form of Siderophores compounds (Ferreira *et al.*, 2019). In addition to iron magnification, PGPR produce volatile organic compounds (VOC) in order to manage plant pathogens, disease resistivity abatement and stunted plant growth (Hafiz *et al.*, 2017). Bacterial species such as *Bacillus*, *Pseudomonas*, *Serratia*, *Arthrobacter*, and *Stenotrophomonas* enhance the crop productivity through synthesizing the VOC (Yong *et al.*, 2015). Thus the various hormones and compounds synthesized by PGPR regulate the mechanism of plant growth and crop production as shown in the Fig. 2. Hence, PGPR is referred as plant growth regulator (Porcel *et al.*, 2014).

Need for inhibiting PGPR as biofertilizers

In spite of various beneficial characteristics of PGPR, it has natural inducing quality without any external agents (Klett *et al.*, 2011). However, it is a need of utilizing these PGPR as biofertilizers (Salme *et al.*, 2017) to overcome tangible and intangible soil infertility problems due to excessive utilization of chemical fertilizers.

Increased utilization of chemical fertilizers

In late 1970s the utilization of chemical fertilizers

has been drastically increased, since the labor cost increased day by day, the practice of blending biofertilizers with soil get decreased (Yan *et al.*, 2010). Over the past few decades huge quantity of chemical fertilizers has been applied in the cultivable ground (Sun *et al.*, 2015; Savci, 2012). This leads to serious issues such as degradation and compaction of soil, lowering of soil organic matter and soil carbon. Over the years, due to the continuous usage of chemical fertilizers leads to decline crop productivity (Sun *et al.*, 2015; Nkoa, 2014). In the modern agriculture systems, a chemical fertilizer raises the acidity nature of soil, which forces the nitrogen cycle in the soil to being complete (Guo *et al.*, 2010). It shows the path to heavy metals mobility in the soil which could be taken up by the plants (Yang *et al.*, 2010). Although some of the microbes have strong tendency to absorb the heavy metals, the entire structure and biomass of microbes get affected (Carpio *et al.*, 2014). Soil contaminants bioaccumulation take place which results in overall deflation in crop productivity due to uncontrolled utilization of phosphate and superphosphate fertilizers (Carvalho, 2017). Accumulation of chemical fertilizer such as dithiothreitol (DDT), endosulfan, heptachlor, lindane in the soil leads to perishing soil organic content (Jayaraj *et al.*, 2016). Moreover, the chemical fertilizers block the process of photosynthesis which leads to stunted growth in plants (Pesce *et al.*,

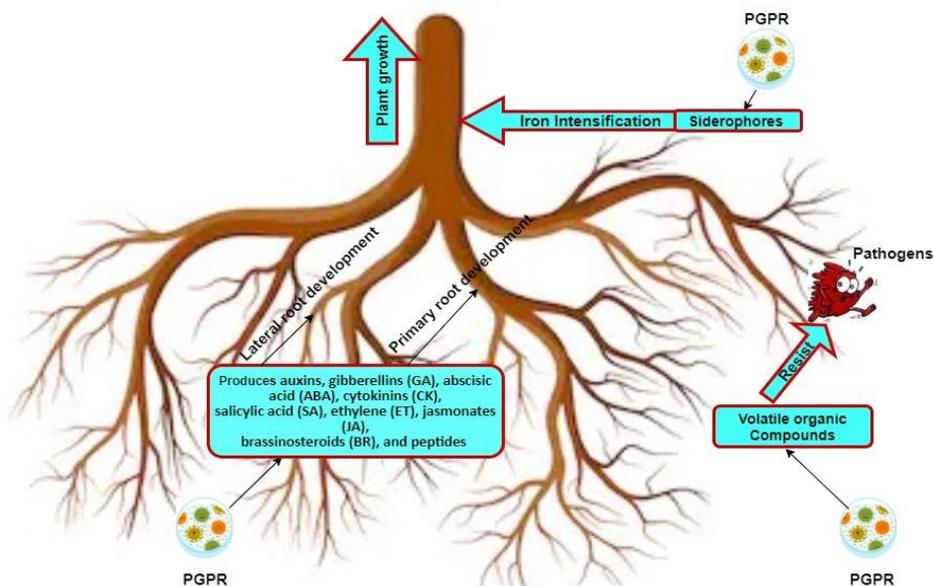


Fig. 2: Mechanism of PGPR in plant growth regulating

2011). Various evidential reports clear that chemical fertilizers volatilize and blend with the atmospheric air causes extreme atmospheric pollution (Chandrima *et al.*, 2020). The agricultural activities based on chemical fertilizers brings huge volume of crop productivity at short duration, however for the long term, it may not be suited for sustainable agricultural activities. It also have negative impacts on flora and fauna (Pimentel and Burgess, 2014; Goulson, 2014). To overcome these sort of problems and to achieve sustainable crop productivity, without any side effects, utilization of the rhizosphere bacterial communities PGPR as a biofertilizers is essential (Wu *et al.*, 2016).

Formulation of PGPR biofertilizers

The biofertilizers that comprises of live microbes needed to be formulated for its existence. Before formulation there is need to identify the beneficiary microbes which have to be cultivated and formulated for the further process. In identification of microbes, genotype and phenotype distinction were usually carried out. In genotype distinction of microbes rRNA functionalities were identified whereas in phenotype distinction microbial colonies, cell morphology, gram staining, metabolic and growth characteristics were identified in order to confirm the specific beneficiary bacteria. Confirmatory test is done usually for the precise identification of microbes (Lehner, 2013). After identifying the beneficiary bacterial culture it is isolated and cultured followed by formulation of biofertilizers (Rassem *et al.*, 2017). Formulation of biofertilizers includes a carrier that supports live microorganism existence, long term storage, and maintenance. It aids to supply the active live microbes to blend with the soil or plant so as to undergo aforementioned PGPR activities to improve the crop yield and soil fertility (Sahu and Brahma Prakash, 2016). These formulations were prepared to strengthen both the crop yield and soil health (Arora *et al.*, 2010). Metabolically viable, adjustments in pH, non-toxic in nature and biodegradable are some of the basic characteristics for good formulation of bio fertilizers (Divjot *et al.*, 2020). Among the different types of commercial bio fertilizers, the liquid formulation found to be more convenient in handling compare to conventional solid base carrier inoculants (Herrmann and Lesueur, 2013; Brar *et al.*, 2012). A formulated bio fertilizer is demanding growth media for any selected bacteria. Although the cost of growth media for the microbes

is high, still there are some natural media such as whey, water sludges, composts and etc., are can be used as source for the growth of microbes (Samer *et al.*, 2012). Rock phosphate along with agro based industrial residuals and biofilms can also be used as source for growth media (Allah *et al.*, 2017; Gamini *et al.*, 2010). Proper inoculation in formulation of bio fertilizers has equal importance for the plant growth (Indra *et al.*, 2014). Crop growth rate pattern increases through simultaneous inoculation with different PGPR rather than single inoculation mechanism (Martinez *et al.*, 2010). As per the literature, nitrogen and phosphorous content increases tremendously when *A. brasilense* is inoculated with maize (Shrivastava, 2015) and nodule-inducing rhizobia with AM fungi (Xiu rong *et al.*, 2010). Mycorrhizal fungi were co-inoculated with PGPR to gain increased root colonization (Josef *et al.*, 2010). Thus co-inoculation resultant in formulation of biofertilizers is consistent for different PGPR microorganism consortium (Malusa *et al.*, 2012). Hence, effective commercial usage of biofertilizers, genuine inoculation of PGPR consortium under different species with different field condition is inevitable (Cristian *et al.*, 2017). The inoculants consist of carriers which helps the consortium PGPR microbes to be delivered at satisfactory physiological state (Jambhulkar *et al.*, 2016). Good moisture, absorptions, easy processing, sterilizing, pH buffering capacity, low cost and its availability are some of the most essential properties of carriers (Rawat *et al.*, 2020). The physical form of biofertilizers is solely depends on the carriers used, such as peats, coal, clays, compost, soybean meal, wheat bran, saw dust, vermiculite, perlite and etc., (Herrmann and Lesueur, 2013). Solid type carriers are in different forms such as powders, granules and beads (John *et al.*, 2011). Alternative to carriers, freeze drying mechanism which is commonly known as lyophilization can be used where the bacterial survival rate is high (Fernanda *et al.*, 2014). In order to avoid dehydration, cryoprotectant is added during the process. Henceforth, combination of growth media, inoculation and good carriers are helping to formulate strong PGPR biofertilizers. The above mentioned formulation processes of biofertilizers has been portrayed in Fig. 3.

Role of PGPR Bio fertilizers in plant growth

More than 90% of plant growth is purely depends on photosynthesis, since the plant biomass is derived from carbon dioxide assimilation. A photosynthetic

process rate increases when rice gets inoculated with various rhizobia strains (Mia and Shamsuddin, 2010). *Bacillus lentus*, *Pseudomonas* sp., and *Azospirillum brasilens* increases the antioxidant and photosynthetic pigment that leads to rise in chlorophyll content in the plant (Heidari and Golpayegani, 2012). *Bacillus* sp., when inoculated with potato gives positive growth in photosynthetic performance (Gururani et al., 2013). Thus PGPR biofertilizers induces photosynthesis mechanism for sustained growth of the plant even under various stress conditions. Amino acid plays an important role in plant growth by supporting the roots to intake water and nutrients from the soil (Berg et al., 2014; Hildebrandt et al., 2015). The active synthesis of amino acids is greatly relay on plant species and their associated microbes (Kang et al., 2010). Thus PGPR biofertilizers increases the synthesis of amino acids for active performance of root system that nourishes the plant growth. Though there are certain factors that are responsible for sustainable plant growth, still few agents that causes the adverse hindrance to the plant growth. It can be perished with the help of PGPR biofertilizers. The major barrier to the plant growth is contamination in soil. The various factors contributing to the contamination in soil are accumulation of heavy metals in the soil, dumping of plastics, usage of chemical fertilizers etc. Heavy metal presence is mainly due to the rapid industrialization and population growth (Shinwari et al., 2015). Heavy metals are non-biodegradable in nature and biodegradation is the only effective strategy to minimize the effects of heavy metals in the soil biosphere (Akhtar et al., 2013; Lim et al., 2014). In this connection, PGPR bacterial strains such as *Azotobacter*, *Bacillus*, *Brevibacillus*, *Kluyvera*, *Mesorhizobium*, *Pseudomonas*, *Achromobacter*,

Psycrobacter, *Bradyrhizobium*, *Rhizobium*, *Sinorhizobium*, *Ochrobactrum*, *Ralstonia*, *Variovox*, and *Xanthomonas* were widely used for the purpose of biodegradation of heavy metals (Shinwari et al., 2015). PGPR strains such as *Azospirillum* sp., *Bacillus* sp., *Acinetobacter* sp., *Achromobacter* sp., *Cronobacter sakazakii*, *Agrobacterium* sp., *Alcaligenes* sp., *Mesorhizobium* sp., *Burkholderia* sp., *Klebsiella* sp., *Enterobacter* sp., *Halomonas* sp., *Ralstonia* sp., *Methylobacterium fujisawaense*, *Pseudomonas* sp., *Rhizobium* sp., *Serratia* sp., *Variovorax paradoxus* and *Zhihengliuella alba* (Chen et al., 2013; Gontia et al., 2017; Jha et al., 2012; Siddikee et al., 2011) were capable to synthesis ACC deaminase, that reduces the concentration of ethylene in plants which overcome the heavy metal stress. Thus, with the combination of these bacterial strains biofertilizers can be formulated that tends to degrade the heavy metal and reduce the contamination of the soil so as to enhance the plant growth. As it is discussed, the modern agriculture includes the practice of utilizing chemical pesticides for increasing the crop productivity which leads to adverse soil contamination and sustainability in agricultural practice (Kumar and Puri, 2012). Hence, there is a need of eco-friendly pesticides as alternatives to existing practice. The bacterial strains such as *Azospirillum*, *Azotobacter*, *Bacillus*, *Enterobacter*, *Gordonia*, *Klebsiella*, *Paenibacillus*, *Pseudomonas* and *Serratia* possess greater tendency to fight and degrades the harmful effects of pest, thus leading to reduce the soil contamination and provide pathway for sustained plant growth (Shaheen and Sundari, 2013). Microbial activity induce the plant growth through degradation of pesticides by synthesizing enzymes such as esterases, hydrolases and glutathione (Hernandez

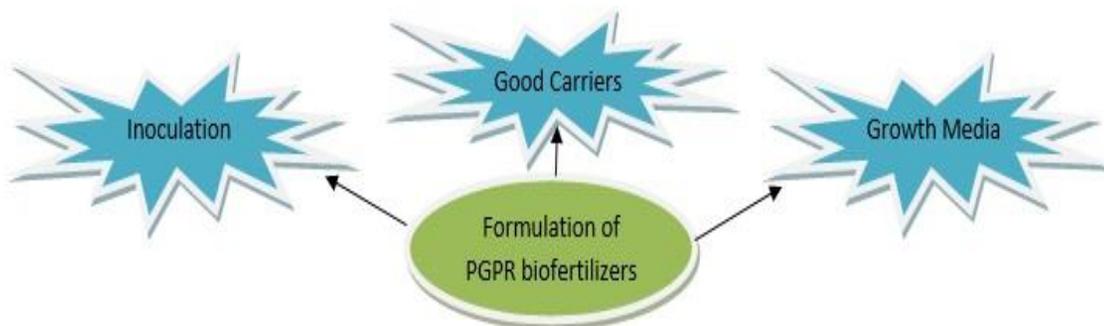


Fig. 3: Formulations of PGPR Bio-fertilizers

et al., 2013). Hence PGPR biofertilizers actively eradicate the harmful nature of pesticides that causes soil contamination so as to boost the plant growth. Moreover PGPR act as biocontrol for plant pathogens in which metabolites productions such as antibiotics and hydrogen cyanide were the primary biocontrol mechanism (Reddy, 2014). This mechanism involves wide variety of compounds having many antimicrobial activities which act as defence layer to pathogenic microbes. Phytopathogenic proliferation can be minimized or eradicated by antagonist mechanism. Antagonist mechanism includes production of siderophores, bacteriocins and antibiotics (Beneduzi *et al.*, 2012). In case of plastic waste, the bacteriological hormones such as IAA, GA and kinetins help to resist the effects causes by the plastic waste. Thus PGPR biofertilizers effectively resist the effects of plastic and reduces the soil contamination (Ikhwan and Nurcholis, 2020). It is reported that lack of micronutrients is basic problem of plant growth, specifically zinc (Zn) deficiency create a major barriers to the plant growth, especially to the cereals crops (Ashish *et al.*, 2012). PGPR bacterial strains increase the zinc and iron nutrients in the soil which is mandatory for the sustainable plant growth (Yadav *et al.*, 2017). Besides, bacterial colonies which includes *Pseudomonas alcaligenes*, *Pseudomonas aurantiaca*, *Pseudomonas aureofaciens* and *Pseudomonas chlororaphis*, *Bacillus subtilis*, *Bacillus pumilus*, *Achromobacter xylosoxidans*, *Serratia marcescens*, *Pseudomonas extremorientalis*, *P. fluorescens*, *Serratia plymuthica*, and *Stenotrophomonas rhizophila*, *Phyllobacterium brassicacearum* fight against biotic and abiotic stresses that are major barriers to the plant growth (Verma *et al.*, 2017; Yadav *et al.*, 2018; Liu *et al.*, 2013; Forchetti *et al.*, 2010; Lavania and Nautiyal, 2013; Egamberdieva, 2011; Timmusk *et al.*, 2014; Bresson *et al.*, 2014). In overview, it is revealed that PGPR bacterial inoculated biofertilizers has multi-disciplinary role in enhancing the sustainable plant growth. The roles of various PGPR strains utilized in biofertilizers are tabulated as shown in Table 2.

Commercialization of PGPR bio fertilizers

Around 24 countries were commercially engaged in producing PGPR biofertilizers both in large and small scales (Bharti *et al.*, 2017). Phosphorous solubilizing bacteria and atmospheric fixing nitrogen bacteria have been used for commercialization (Lesueur *et*

al., 2016). Non-rhizobial PGPR inoculants containing azospirillum were most frequently used commercial biofertilizers in global market (Herrmann *et al.*, 2013). The Non-rhizobial PGPR biofertilizers reached only 5% of global market and remaining were occupied by the chemical fertilizers because of its expensiveness (Wellesley, 2014). Later in developed countries legume and nitrogen fixing inoculants were dominated (GVR, 2020). In global biofertilizers market about 78% were occupied by rhizobial inoculants, whereas 15% and 7% has been occupied by Phosphorous solubilizers and other bioinoculants respectively (Owen *et al.*, 2015). Zinc and potassium based biofertilizers were the emerging commercial products that address the soil nutrient deficiencies (Shaikh *et al.*, 2017; Khatibi, 2011). Among this, potassium based biofertilizers has been increasing tremendously in most of the countries (Teotia *et al.*, 2016). In this regard, India stands in fourth whereas nations like USA, China and Brazil stands first in producing potassium solubilizing biofertilizers (Investing News Network, 2019). In PGPR biofertilizers commercialization, Asia-pacific nations started attaining maximum growth from 2014 and the global biofertilizers market expanded to increase the sustainable food productivity (Verma *et al.*, 2019). This shows the progress of potential nature of PGPR in the commercialization aspects.

Limitations and future trends in PGPR utilization in agriculture

In recent days the utilization of bio fertilizers became an integral part of sustainable agricultural practices and major developed countries achieved the sustainability (Weekley *et al.*, 2012). In developing countries, there is a minimum impact of PGPR bio fertilizers, due to the poor quality in inoculants and stringent regulatory legal frameworks (Berninger *et al.*, 2018). In addition, the bio fertilizer takes time to bring out the productivity in agriculture which makes the investors and scientist difficult to bring the PGPR inoculants to general farmers (Mahanty *et al.*, 2017). Large scale commercialization of PGPR inoculants requires large volume trials in understanding the bacteriological characteristics and their activities which is not an economically feasible for the farmers (Qiu *et al.*, 2019). In this connection, research in biofertilizers should be focused on cost effective, faster benefits, sustainable higher productivity under various environmental conditions (Ijaz *et al.*, 2019). Besides,

Table 2: PGPR bacterial strains utilized in bio-fertilizers and its role in plant growth

Role of PGPR Bio fertilizers in inducing:	PGPR	References
photosynthesis	Pseudomonas sp	Heidari and Golpayegani, 2012
	Bacillus lentus	
	Azospirillum brasiliense	Gururani et al, 2013
	Bacillus sp	
Amino acid	B. subtilis	Luke et al, 2013
	P. putida	
	Rhizobium sp	
Biodegradation of heavy metal	Achromobacter	Shinwari et al., 2015
	Azotobacter	
	Bacillus	
	Bradyrhizobium	
	Brevibacillus	
	Kluyvera	
	Mesorhizobium	
	Ochrobactrum	
	Pseudomonas	
	Psycrobacter	
	Ralstonia	
	Rhizobium	
	Sinorhizobium	
Variovox		
Xanthomonas		
Controlling pesticides	Azospirillum	Shaheen and Sundari, 2013
	Azotobacter	
	Bacillus	
	Enterobacter	
	Gordonia	
	Klebsiella	
	Paenibacillus	
	Pseudomonas	
Serratia		

these researches promote the usage of bio inoculants and develop the confidence among the local farmers, based on their utilization and performance (Gupta et al., 2015). Future world looking to bring novel biofertilizers which are very affordable, safe and best substitute to agrochemical fertilizers by the usage of consortium multi-tarit PGPR strains. It enhances the communication with the plant through quorum sensing (Ijaz et al., 2019; Vassilev et al., 2015; Khan et al., 2017). Utilization of biofilms protects the bio inoculants from varying environments. It is expected to evolving in future that leads to increase in microbial population (Sahai et al., 2017; El-Ghamry et al., 2018). According to the literatures, future strategies could focus on biofertilizers which involves interactions of microbes with nano particle. It is mainly to improvise the micronutrients to bacteria and plants. It became the revolution in future agricultural practices by introducing nanofertilizers (Tarafdar et al., 2013). The efficiency of nano fertilizers has been proven as

best alternatives to all traditional ones because of its characteristics of reducing nitrogen loss, leeching, toxic effects, long term sustainability of microbes in the soil (Suman et al., 2010). Thus Nanoencapsulation technology will be a versatile tool to protect PGPR from various environmental changes and to extract its complete benefits so as to make sustainable crop productivity with maintained soil fertility.

A summary of present and forthcoming ideas

The present studies on PGPR in sustainable agriculture focus on formulation of biofertilizers. Moreover the PGPR bacterial strains are isolated and cultured for the formulation purpose. Followed with the formulation, the biofertilizers were commercialized so as to use in agricultural field. PGPR due to its unique characteristic such as nutrients intake, stress tolerance, wide hormonal secretion etc. finds wide range of scope in inducing the plant growth. Forthcoming challenges in agriculture can be faced with the help of genetically

modified PGPR bacterial strains. Genetically modified PGPR bacterial strains can be produced without disturbing its beneficiary nature and tends to increase the efficiency. In terms of biofertilizers efficiency can be increased through these modified PGPR bacterial strains. Thus sustainable agricultural practice will tends to grow through continuous research in genome sequence analysis and characteristic of PGPR bacterial strains.

CONCLUSION

In the late 1960s, green revolution tremendously increases the crop productivity by triggering the utilization of chemical fertilizers along with other advances in agricultural practices. Thus more than billions of world population were protected from starvation and ensured the food security. But, due to the excessive population and civilization, the need of individuals were increased which leads to over utilization of chemical fertilizers in order to achieve the rapid crop productivity. Besides, the mono-cultivation strategy was widely followed because of easy handling and management resulting in complete dependency on chemical fertilizers. It leads to complete disturbance in soil ecosystem and challenge to attain sustainable crop production. Hence, it is mandatory to switch over from inorganic to organic agricultural practices for the welfare of future agricultural productivity. Organic agricultural practices needs frequent analysis of soil report for every cropping season which helps them to choosing proper organic manure and suitable crops. Although the manual soil testing gives effective information about the major soil parameters N, P and K, it is essential to identify the major minerals which supports for sustainable productivity. Though, there is a least chance to utilize the traditional agricultural practices in this modern era, the good natures of PGPR can be imported in agricultural practices. As it is discussed in this extensive literature review, PGPR plays major role in handling biotic and abiotic stress by utilizing the aforementioned bacterial strains. PGPR bacterial strains induce the plants for its effective uptake of soil macro, secondary and micro nutrients. PGPR bacterial secretion of different plants hormones such as auxins, gibberellins, abscisic acid, cytokinins, salicylic acid, ethylene, jasmonates, brassinosteroids, and peptides helps in nourishing plant growth. Adapting the PGPR in fields, makes viable impact

in crop productions due to its unique features such as protecting against different environmental stresses, regulating the plant growth, influencing the crop productivity and soil ecosystem so on. In addition, PGPR utilization comes in reality and finds best alternative to various strategies in agricultural sustainability. Biofertilizers were formulated as liquid as well as solid fertilizers through proper usage of PGPR inoculation, carriers and growth medium. This formulated biofertilizers were commercialized and makes perfect alternatives to the chemical fertilizers in all means. Though the usage of these biofertilizers takes more time to show the productivity, the sustainability is rich enough. But the scientists and researchers target to bring back the organic farming and resolve the time consumption problems through major innovations such as consortium multi-trait PGPR strains, biofilms, Nanoencapsulation technology. It leads to practice multiple cropping in agricultural fields. In this modern agricultural era many farmers and policy makers aims to bring sustainable profit in agriculture through multi cropping. This makes to have more focus on PGPR biofertilizers and advanced nanotechnology intrusion in agriculture. Thus the plant growth promoting Rhizobacterial products and its corresponding technologies will be a boon to upcoming world agriculturist in ensuring the sustainable crop productivity and soil ecosystem.

AUTHOR CONTRIBUTIONS

V. Dhayalan performed the literature review, experimental design, analyzed and interpreted the data; K. Sudalaimuthu prepared the manuscript text, and manuscript edition.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues including plagiarism, informed consent, misconduct, data fabrication and, or falsification, double publication and, or submission, and redundancy have been completely witnessed by the authors.

ABBREVIATIONS

ABA	Abscisic Acid
ACC	1-aminocyclopropane-1-carboxylate
acdS	ACC deaminase structural gene
<i>a-ketobutyrate</i>	alpha-ketobutyrate
AM fungi	Arbuscular Mycorrhiza fungi
BGA	Blue Green Alga
BR	Brassinosteroids
CK	Cytokinins
DDT	Dithiothreitol
ET	Ethylene
etc	Et cetera
Fig.	Figure
GA	Gibberellins
IAA	Indole-3-acetic acid
JA	Jasmonates
K	Potassium
Kg	Kilogram
N	Nitrogen
PGPR	Plant growth promoting rhizobacters
P	Phosphorous
pH	Potential of Hydrogen
SA	Salicylic acid
Sp.	Single bacterial type
Spp.	Number of bacteria with different names belong to one genus
USA	United States of America

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