CHAPTER: 1

INTRODUCTION

1.1 Introduction

Sustainable food production is a critical challenge in today’s world. Approximately 70–75% of India’s population depends directly or indirectly on agriculture, making it the backbone of the Indian economy. According to the 2013 UN report (Searchinger et al., 2014), the global population is projected to reach approximately 9.6 billion by 2050. The need for high-yield food production while reducing harmful effects on soil presents a significant challenge for sustainable agriculture.

The oilseed sector plays a vital role in India’s agricultural economy. Groundnut, known as the "king" of oilseeds, is a crucial food and cash crop in India and globally. Gujarat contributes nearly 40% of India’s groundnut production, with the Saurashtra region accounting for about 80% of the total area under cultivation and production in the state. This highlights the importance of studying the technical efficiency of groundnut farmers in Saurashtra (Varasani et al., 2016).

India faces the dual challenge of feeding a growing population and addressing food insecurity. According to the State of Food Security and Nutrition in the World (SOFI) report, India has the largest population of food-insecure people. Crop yields are threatened by changes in rainfall patterns, declining soil fertility, severe weather events, and competition from weeds and pests (Ganpule et al., 2023). Additionally, rapid population growth, rural-to-urban migration, unequal land distribution, shrinking landholdings, deepening rural poverty, and widespread land degradation exacerbate food production challenges.

India is the largest producer of major oilseeds, including groundnut, rapeseed-mustard, sunflower, safflower, sesame, soybean, castor, and linseed. The oilseed sector is pivotal to the national economy. However, challenges such as water scarcity have led to a decline in groundnut sowing areas, with farmers shifting to other crops like pulses and sugarcane. The

Indian Oilseeds and Produce Export Promotion Council (IOPEPC) reported a 45% decline in summer groundnut production in Gujarat, from 2,20,000 tons to 1,21,000 tons in recent years, largely due to water scarcity (Radhakrishnan et al., 2022).

The excessive use of chemical fertilizers to boost crop yields has resulted in several adverse effects, including soil degradation, nitrogen leaching, compaction, and loss of organic matter. These issues underline the need for alternative, sustainable agricultural practices.

PGPR offer a promising solution to improve crop yields and soil health sustainably. PGPR can function directly or indirectly as biofertilizers, root growth promoters, disease resistance enhancers, and agents of rhizoremediation. These microorganisms enhance plant health and growth rates without harming the environment (Bhattacharyya and Jha, 2012).

Despite its benefits, the use of PGPR faces environmental, economic, and technical challenges. Modern approaches, including nanotechnology, agricultural biotechnology, and chemical engineering, offer ways to overcome these limitations. Nanomaterials such as copper, gold, zinc, iron, silica, and titanium have been integrated into PGPR applications to enhance plant growth and crop longevity. However, the effects of nanomaterials on rhizobacteria can be either beneficial or detrimental, necessitating careful application and further research.

Combining PGPR with integrated nutrient management (INM) can effectively improve crop growth, yield, and soil fertility under sustainable agriculture. Nanotechnology further enhances agricultural productivity by increasing the efficiency of inputs and minimizing losses. The large specific surface area of nanomaterials allows fertilizers and pesticides to be more effective while reducing their environmental impact.

1.1.1 Research region

Groundnut production in Gujarat has witnessed a concerning decline, attributed partly to the excessive and imbalanced use of chemical fertilizers, which have degraded soil health by depleting essential nutrients and disrupting soil structure, microbial activity, and water retention capacity (Patel et al., 2013). This over-reliance on chemical inputs has significantly reduced soil fertility, leading to lower yields and diminished productivity. Compounding the issue, erratic rainfall patterns and persistent water scarcity have further strained groundnut cultivation, prompting some farmers to shift to alternative crops or adopt organic practices to restore soil vitality. Addressing these challenges requires a transition to balanced fertilization, integration of organic inputs, and sustainable farming techniques to rejuvenate soil health and enhance groundnut yields in the region.

1.1.2 Background Significance

Agricultural production is critical for any form of sustainable future, focusing on the agricultural sector alone without regard for other important factors which influence food production is certainly not the way to tackle the problems. In recent decades there has been impressive growth in food production, which has been attributed to the development of improved, disease-resistant varieties of staple crops; the increased use of bio/nano fertilizers, nanodevices, and biopesticides; and the expansion of irrigated cropland. PGPR along with integrated nutrient management may be more effective for growth, yield, and fertility status under sustainable agriculture. Nanotechnology helps to improve agricultural production by increasing the efficiency of inputs and minimizing relevant losses. Nanomaterials offer a wider specific surface area to fertilizers and pesticides.

A major challenge for the sustainable agriculture system is producing food at a high yield while having less detrimental effects on the soil. Additionally, the crops must be raised to withstand both biotic and abiotic stresses, such as heavy metals, drought, salt, and organisms that cause disease. The application of rhizospheres organisms in soil can provide the aforementioned beneficial features. PGPR are powerful soil organisms that enhance plant health and promote plant growth rate without damaging the environment (Bhattacharyya and Jha, 2012).

1.2 Plant growth promoting rhizobacteria (PGPR)

Plant growth-promoting actions are provided by the beneficial bacteria that colonize the rhizoplane, microhabitats, and root endospheric (Hartman and Tringe, 2019; Morgan et al., 2005). High microbial populations, or around 100–1,000 times more in the rhizospheres soil compared to the bulk soil, are caused by the carbon compounds produced in the soil by the plants (Goswami et al., 2016; Lynch, 1987; Morgan et al., 2005). The plant releases a variety of signaling molecules that draw particular species and control their genetic and metabolic processes (Backer et al., 2018; Massalha et al., 2017; Nelson and Sadowsky, 2015). Because of the various root exudates, the microbial community in the rhizosphere differs from that in bulk soil (Burdman et al., 2000). According to Antoun and Prévost (2005) and Barriuso et al. (2008), the PGPR constitutes up to 5% of all rhizospheres bacteria. They have an indirect as well as direct impact on plant growth. According to George et al. (2008), Wang and Irving (2011), the direct mechanisms involve increasing the concentration and absorption of nutrients in soil by plants through the release of phytohormones (cytokinin, abscisic acid, gibberellins, auxins, and ethylene), biological nitrogen fixation, solubilizing nutrients (K, P, and Zn) to plant-available form, and siderophore production (Glick et al., 1998; Goswami et al., 2016; Grover et al., 2020). Abiotic and biotic stress tolerance (Grover et al., 2011; Van Oosten et al., 2017), plant pathogen suppression (Backer et al., 2018; Beneduzi et al., 2012; Grover et al., 2020), and secretion of various biocontrol specialists, such as Volatile Organic.

The group of PGPR is a diverse collection of beneficial bacteria that play a significant role in promoting plant growth and enhancing soil health. These bacteria are found across various genera, each exhibiting unique traits that contribute to their plant-growth-promoting capabilities. Some of the well-known genera within the PGPR group include *Acinetobacter*, *Agrobacterium*, *Arthrobacter*, *Azoarcus*, *Azospirillum*, *Azotobacter*, *Bacillus*, *Bradyrhizobium*, *Burkholderia*, *Caulobacter*, *Chromobacterium*, *Delftia*, *Enterobacter*, *Flavobacterium*, *Gluconacetobacter*, *Klebsiella*, *Mesorhizobium*, *Micrococcus*, *Pseudomonas*, *Rhizobium*, *Serratia*, *Streptomyces*, and *Thiobacillus* (Goswami et al., 2016; Grover et al., 2011; Vessey, 2003). These bacteria are known to exert a variety of mechanisms that promote plant growth, such as nitrogen fixation, phosphate solubilization, production of phytohormones like IAA (Indole-3-acetic acid), siderophore production, and the suppression of plant pathogens through antibiosis or competition for nutrients and space. The diversity of PGPR reflects the wide range of plant species and soil environments they can inhabit, from rhizospheres to root nodules and beyond. PGPR work together with plants to make them stronger against pests, diseases, and tough growing conditions like drought or poor soil. These bacteria are a great option for sustainable farming because they help plants grow better and improve soil health, leading to higher crop production.

1.2.1 Optimal PGPR

A rhizobacterial strain is viewed as an evident PGPR when it exhibits plant development advancing qualities and can upgrade plant development on inoculation. An optimal PGPR follows the indispensable criteria:

(1) It must be highly sustainable and rhizosphere-capable.
(2) After inoculation, it should establish colonies in the plant in a critical number.
(3) The ability to promote plant development is required to be included.
(4) It should show a variety of activities.
(5) It has to survive in the presence of several tiny rhizosphere organisms.
(6) It should be tolerant of physicochemical factors such as oxidants, radiation, hotness, and parching.

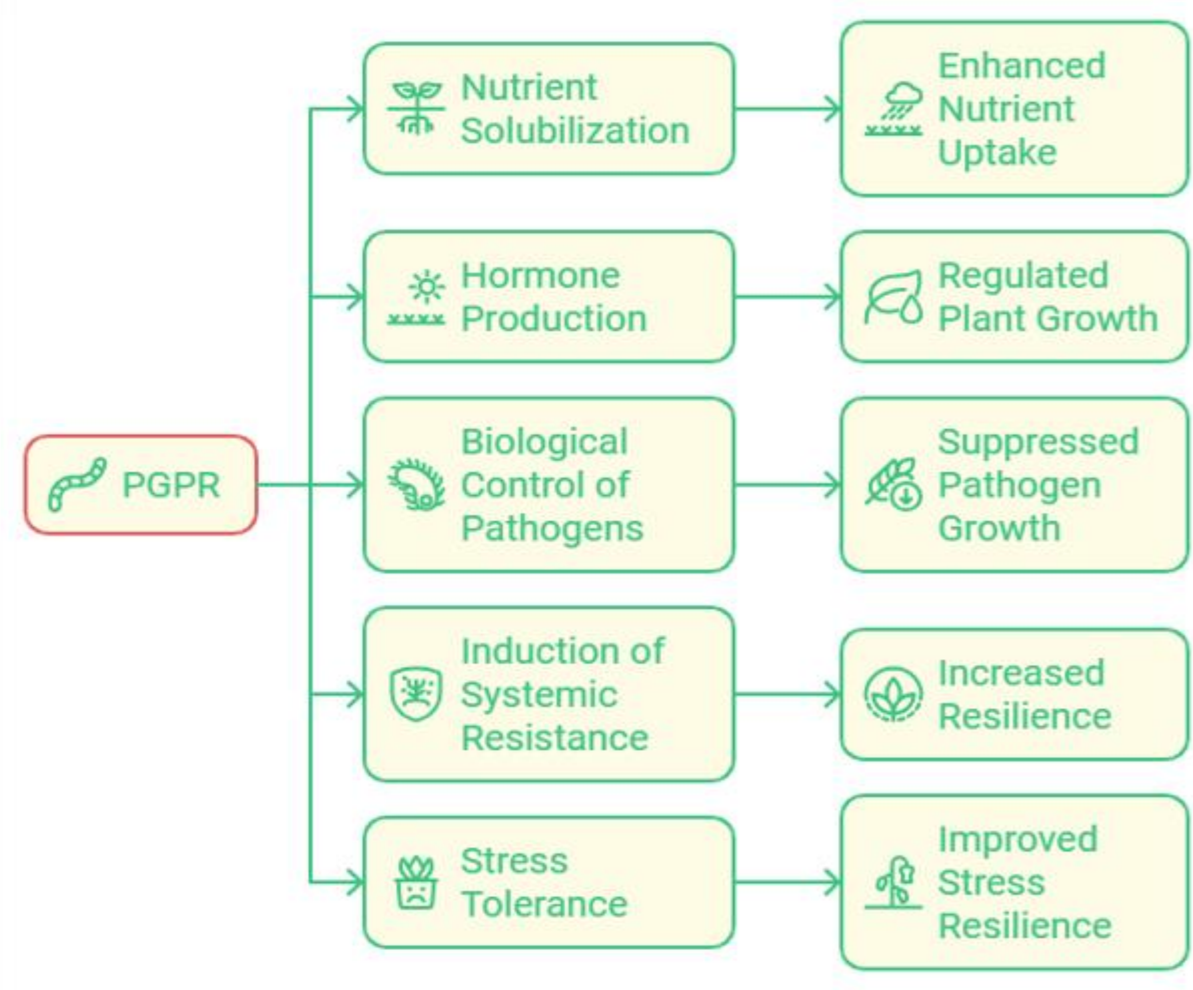

Figure 1.1: Schematic representation of Plant Growth by PGPR

1.2.2 Role of PGPR in the enhancement of Plant Growth

The plant growth is enhanced by direct and indirect mechanisms exhibited by PGPR. Plant development is highly affected by an assortment of stresses which can be classified into two types- biotic and abiotic. Biotic alludes to plant pathogens and pests, for example, such as fungi, viruses, bacteria, nematodes, and insects, while abiotic stresses focus on drought, salinity, the concentration of various heavy metals in soils, nutrient deficiency, temperature, and so on (Bhattacharyya and Jha, 2012; Grover et al., 2020; Leontidou et al., 2020). PGPR colonization profoundly improves the stress tolerance in plants and enables the enhancement of their growth.

1.2.3 PGPR and Plant Hormones

Phytohormones are crucial regulators of plant growth and development, acting as molecular signals to help plants adapt to environmental challenges that could otherwise hinder growth (Fahad et al., 2015). Numerous rhizospheres bacteria are known to secrete hormones and boost the growth of plants, stimulate agricultural production, and alter the stress response. Various microorganisms have the competence to produce growth regulators such as indoleacetic acid (IAA), gibberellic acid (GA), cytokinin, and ethylene.

According to Spaepen and Vanderleyden, IAA plays a role in plant growth and development including primary root elongation, enhances the root surface area and length (Spaepen and Vanderleyden, 2011). Auxin plays an important role in the beneficial plant–PGPR interaction. PGPR strains producing IAA such as *Aeromonas punctata* PNS-1, *Serratia marcescens* 90–166 and *Azospirillum brasilense* Sp245 stimulated growth and activated morphological changes in *A. thaliana* (Spaepen and Vanderleyden, 2011) (Shi et al., 2010; Iqbal and Hasnain, 2013; Spaepen et al., 2014).

The process of seed germination, flower, and fruit development, and leaf and stem growth involve the hormone gibberellin (GA), a type of phytohormone, which also plays a pivotal role in shoot elongation. Gibberellin-producing PGPR *Enterococcus faecium* LKE12 and *Leifsonia soli* SE134 activate shoot growth in mutant rice plants deficient in gibberellin synthesis (Kang et al., 2014). The gibberellin-producing PGPR strains of

Promicromonospora sp. SE188 and *Bacillus amyloliquefaciens* RWL-1 result in an increased amount of gibberellins in the plant.

Cytokinin enhances the plants vascular differentiation, cell division, and vascular cambium sensitivity, and increases root hairs proliferation, but inhibits primary root elongation (Jha and Saraf, 2015). Various PGPR strains synthesized cytokinin which enhances shoot growth and fruit formation of plants (Barea and Brown, 1974; Liu et al., 2013). *Bacillus megaterium* UMCV1 was reported to stimulate the growth of lateral roots in *Arabidopsis thaliana*, and the cytokinin receptor genes AHK2 and RPN12 are involved in the mechanism of this stimulation. Cytokinin producing PGPR strain *Pseudomonas fluorescens* stimulated main root growth and repressed lateral root formation in *Brassica napus* (Pallai et al., 2012). Bacterial cytokinin also have the property to exhibit plant resistance to various biotic and abiotic stresses. For example, The plant growth-promoting rhizobacterium (PGPR) *Pseudomonas fluorescens* G20–18 synthesizes cytokinin, which enhances the resistance of *Arabidopsis thaliana* to infection by *Pseudomonas syringae*. In contrast, a mutant strain of *Pseudomonas fluorescens* G20–18 that lacks cytokinin synthesis does not confer this improvement in plant resistance (Singh et al., 2022).

Ethylene is another hormone that regulates a variety of functions, such as fruit ripening, leaf abscission, shoot and root growth, and seed germination. However, excess of ethylene causes defoliation, early senescence, and reduced development of the roots and stem. Eventually, this results in limited plant development and growth. The synthesis of 1-aminocyclopropane-1-carboxylate (ACC), a precursor of ethylene, is triggered by several abiotic and biotic stressors, including floods, heavy metals, and infections. Premature senescence results from the ethylene's subsequent reduction of nitrogen fixation and root elongation (Khan et al., 2015).

PGPR degrades ACC and assists the growth of the root system. Glick (1995) has explained that PGPR-producing ACC deaminase and IAA facilitate the growth of plants to a greater extent. Ahmad et al., (2011) evidenced that *Pseudomonas* and *Rhizobium* ACC-deaminase-producing strains can augment the quality, growth, and physiology of mung beans under saline environments.

1.2.4 Nutrient availability for Plant Growth

Various PGPRs assist in fixing nitrogen into organic form that can be utilized by the plants. Several groups of soil and root-associated nitrogen-fixing microorganisms have been reported in literature such as *Azotobactervinelandii*, *Azospirillumbrasilense*, *Acetobacterdiazotrophicus*, *Achromobacterinsolitus*, *Bacillus rhizosphaerae*, *Burkholderiatropica*, *Burkholderiaxenovorans*, *Burkholderiasilvatlantica*, *Burkholderiacaballeronis*, *Bradyrhizobiumjaponicum,Bradyrhizobiumelkanii*, *Delftiatsuruhatensis,Enterobactersacchari*, *Bacillus megaterium*, *Gluconacetobacterdiazotrophicus*, *Stenotrophomonasmaltophilia*, *Pseudomonas stutzeri,Pseudomonas koreensis*, and *Pseudomonasentomophila* colonize different crops and enhance plant growth directly or indirectly. Their activity, however, is influenced by crop species, soil type, and soil condition (Antoun and Prévost, 2005; Bhattacharyya and Jha, 2012; Burdman et al., 2000).

Numerous PGPRs have been reported to have the ability to solubilize phosphate and increase the phosphate ion's availability and accessibility to the plants. Furthermore, *Kocuriatur fanensis* strains 2M4 PGPR is a phosphate solubilizer, a siderophore producer, and an IAA producer (Rashid et al., 2019). Kumar et al. (2014) have reported that employment of *Bacillus megaterium*, *Arthrobacter chloro phenolicus*, and *Enterobacter* resulted in a two-fold increase in wheat grain yield in greenhouse experiments (Kumar et al., 2014). PGPR with phosphate solubilizing capacity including *Bacillus megaterium* increased phosphate availability in soil by approximately 30% (Alzoubi and Gaibore, 2012), *Pseudomonas*, *Delftia sp.*, *Azotobacter, Xanthomonas and Rhodo coccus, Arthrobacter, Serratia, Phyllo bacterium, Chryseo bacterium,* and *Gordonia* (Sharma et al., 2013; Wani et al., 2005). Furthermore, phosphate deficiency was reported to reduce crop yield by 5 to 15% (Shenoy and Kalagudi, 2005). Phosphate-deficient plants show symptoms such as dark, dull, and reddish-colored leaves, necrosis in old leaf tips, and smaller size of new leaves (Malhotra et al., 2018; Raghothama, 2005). Employment of phosphate-solubilizing bacteria can prove to be highly cost-effective and lead to the enhancement of plant growth and development.

Another macronutrient in plant growth is potassium. Inoculation of seeds and seedlings of different plants with potassium solubilizing bacteria (KSB) generally displays significant enhancement of germination percentage, seedling vigor, plant growth, yield, and potassium uptake by plants under greenhouse and field conditions (Verma et al., 2017).

1.2.5 Enzymes by PGPR

PGPR produces key hydrolytic enzymes such as chitinase and glucans, which target chitin and beta-glucan, the main components of fungal cell walls. This enzymatic activity helps inhibit fungal growth and protects plants from pathogens. The *Pseudomonas fluorescens* LPK2 and *Sinorhizobiumfredii* KCC5 produce chitinase, beta-gluconates which reduces the fusarium wilt produced by *Fusariumudum* (Choure et al., 2012). Furthermore, *Pseudomonas* spp. a PGPR inhibits *Rhizoctoniasolani* and *Phytophthoracapsici* which are two of the most destructive crop pathogens in the world (Wang et al., 2021).

1.2.6 Abiotic Stress Tolerance in Plants

One of the main factors lowering agricultural output is abiotic stress. The impact of abiotic stressors depends on soil type and plant characteristics. For instance, Sarma and Saikia (2014) demonstrated that a strain of *Pseudomonas aeruginosa* significantly enhanced the growth of *Vigna radiata* (mung beans) under drought conditions. Moreover, the stomata of the leaves regulate both the amount of water in the leaf and the amount of water the roots absorb. Naveed et al., (2014) demonstrated that plants infected with PGPR had higher stomatal conductance of leaves under drought conditions than plants without PGPR. Furthermore, PGPR improves plants capacity to use water efficiently. Marulanda et al., (2010) reported that the *Bacillus megatertum* strain increases roots ability to absorb water in saline environments.

1.3 Macronutrients and Micronutrients

Minerals are vital for completing the plant life cycle. While plants derive carbon, oxygen, and hydrogen from the air, the soil provides thirteen additional essential elements. These nutrients are categorized into macronutrients and micronutrients based on the quantities required by plants. Microorganisms play a significant role in enhancing the solubility of these minerals, thereby improving their availability for plant roots. Below is a discussion of some critical macro and micronutrients, along with their roles and effects on plant growth and development (İpek and Eşitken, 2017).

Potassium

Potassium contributes to various biochemical and physiological processes in plants, although it is not a component of their chemical structures. Its significance in plant development has been extensively documented (Ihtisham et al., 2021; Perrenoud, 1977; Prajapati and Modi, 2012; Sardans and Peñuelas, 2021). Potassium activates nearly 60 enzymes that are essential for plant growth and development. It plays a critical role in ion regulation and helps maintain the plant's pH level (7-8), which is necessary for enzymatic reactions. Potassium is also integral to stomatal function, facilitating nutrient transport, photosynthesis, and plant cooling mechanisms.

Additionally, potassium promotes water uptake in roots by creating an osmotic gradient. It supports sugar transport, starch and protein synthesis, and the movement of water and nutrients throughout the plant. Potassium also enhances crop quality and extends the post-harvest life of fruits and vegetables (Mengel and Kirkby, 1980; Mikkelsen, 2017; Sardans and Peñuelas, 2021; Tandon and Sekhon, 1988).

Phosphorus

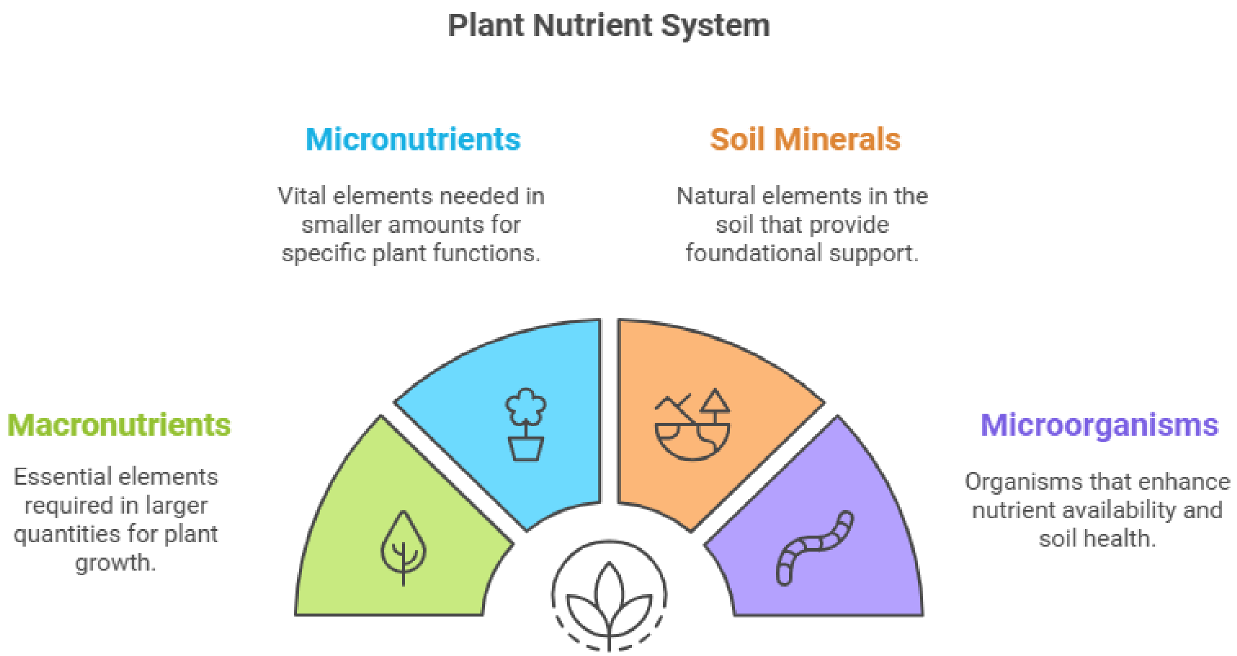

Figure 1.2: The role and function of various soil minerals, microorganisms, macronutrients, and micronutrients in plant growth and development

Phosphorus is a vital element for plants, participating in key cellular activities such as the production of DNA, RNA, sugar phosphates, and energy-carrying molecules like ATP. This nutrient is indispensable for photosynthesis and respiration, processes that are crucial for plant survival.

Phosphorus contributes to the stability of cell membranes through its role in forming phospholipids. It is also essential for seed germination, root development, and overall plant growth, including root and shoot elongation, flowering, and seed production (He et al., 2001; Malhotra et al., 2018; Raghothama, 2005).

Calcium

Calcium is a key element that significantly influences plant growth and development (Jones and Lunt, 1967). Though widely recognized as a second messenger in animal cells, calcium plays an equally critical and indispensable role in plant cells. It contributes to the structural integrity of the cell wall and regulates the selective permeability of the membrane. Additionally, calcium has been shown to stimulate root hair growth in several plants. Calcium uptake is also vital in helping plants resist heavy metal toxicity and combat pathogenic microorganisms such as bacteria and yeast. Its functions extend across numerous developmental processes, including pollen tube elongation, cell division, seed germination, apoptosis, stomatal closure, and responses to auxins (Albrecht, 1970; He et al., 2001; Hepler and Wayne, 1985; Jones and Lunt, 1967).

Magnesium

Magnesium plays an essential role in both plant and animal biology, particularly as a dissociable cofactor for enzymes involved in phosphorylation. In plants, magnesium is a central component of the chlorophyll molecule, which is crucial for photosynthesis. Its levels influence processes such as photorespiration within chloroplasts. Magnesium also supports protein synthesis and helps maintain the stability of ribosomal subunits. Furthermore, magnesium is required for the activation of metabolic pathways involved in lipid and carbohydrate metabolism, and it has been linked to improved crop quality and yield (Ahmed et al., 2023).

Iron

Iron is vital for chlorophyll synthesis and the maintenance of chloroplasts. The concentration of iron in plants is directly associated with chlorophyll levels. Iron plays a critical role in energy-producing processes such as photosynthesis and cellular respiration, and is involved in nitrogen fixation, hormone production, and nutrient uptake. As a component of numerous electron carriers and enzymes, iron also contributes to essential metabolic pathways, enhancing the nutritional quality and yield of plants (Briat et al., 2015).

Zinc

Zinc is a crucial element in plant enzymes, acting as a cofactor for enzymes like peroxidases and oxidases. It is also involved in the regulation of nitrogen metabolism, seed formation, cell multiplication, and photosynthesis (Camp, 1945; Hafeez et al., 2013). Zinc plays a pivotal role in various metabolic pathways, including starch and carbohydrate metabolism, hormone activity (e.g., indole acetic acid and auxin), and protein synthesis. Additionally, zinc supports the integrity and function of cell membranes, and its presence in plants has been shown to reduce heavy metal accumulation (Rudani et al., 2018; Tsonev and Cebola Lidon, 2012).

Manganese

Manganese acts as a cofactor in plant cells, facilitating the function of metalloproteins such as superoxide dismutase and oxalate oxidase. It plays a key role in enzyme activation, particularly phosphokinase and phosphotransferase. Manganese is involved in several metabolic processes, including glycosylation and reactive oxygen species (ROS) scavenging. It also serves as an antioxidant, helping to mitigate oxidative damage in plants. Manganese is critical for processes like water splitting, chlorophyll production, lignin biosynthesis, and photosynthesis (Alejandro et al., 2020).

Copper

Copper is essential for various physiological processes in plants, including photosynthesis, electron transport, respiration, and metabolism of cell walls, carbohydrates, nitrogen, and hormones. It also helps plants manage oxidative stress. At the cellular level, copper plays a role in protein trafficking, transcription, and the mobilization of iron. Copper is vital for activating enzymes like superoxide dismutase, cytochrome c oxidase, and laccase. It has been shown to enhance disease resistance, improve fertility, and contribute to fruit development (Mir et al., 2021).

1.3.1 Nanotechnology and Plant Growth-Promoting Rhizobacteria (PGPR)

Nanotechnology, which focuses on materials with dimensions in the nanometre range, has become a significant tool in various fields, including agriculture, medicine, and engineering (McNeil, 2005). Recent advances in nanotechnology hold great potential for improving agricultural practices. Metal and metal oxide nanoparticles are particularly attractive due to their large surface area and enhanced reactivity. These nanoparticles can boost plant nutrient uptake, improve metabolism, and enhance growth parameters such as root and shoot biomass, leaf area, and overall plant weight (Siddiqui et al., 2015). The synergy between nanomaterials and PGPR is currently being explored for better crop production and nutrient utilization.

Silver Nanoparticles

Silver nanoparticles (Ag NPs) have been extensively studied for their antimicrobial properties and their ability to promote plant growth, often in combination with PGPR. Research has shown that Ag NPs can significantly improve plant growth, including root and shoot length, leaf number, and the production of phytochemicals such as diosgenin in fenugreek seedlings (Siddiqi and Husen, 2021). In maize, the combination of Ag NPs and PGPR strains like *Pseudomonas* and *Bacillus* species enhances root growth and the production of growth hormones (Khan and Bano, 2016). Studies on *Brassica juncea* seedlings have also demonstrated the benefits of Ag NPs and PGPR in reducing stress levels (Vishwakarma et al., 2020).

Zinc Oxide Nanoparticles

Zinc is a critical micronutrient involved in plant growth, especially in the synthesis of tryptophan, which is a precursor to indoleacetic acid (IAA), a key plant hormone (Camp, 1945; Hafeez et al., 2013). Furthermore, Zinc oxide nanoparticles (ZnO NPs) have been shown to enhance plant growth, but their effectiveness depends on the concentration and plant species. At lower concentrations, ZnO NPs improve biomass and photosynthesis, while higher concentrations can inhibit root growth and photosynthesis efficiency (Rout and Das, 2009). In drought-stressed plants like *Sorghum*, ZnO NPs help mitigate the negative effects of water stress (Dimkpa et al., 2019).

Silicon Oxide Nanoparticles

Silicon oxide nanoparticles (SiO_2 NPs) have been shown to improve plant growth and help plants cope with abiotic stresses such as drought and salinity. SiO_2 NPs promote seed germination, root elongation, and overall plant biomass, even under challenging environmental conditions. In cucumber plants, SiO_2 NPs improved water regulation and ion balance, which helped mitigate the effects of drought (Mahdavi et al., 2016). Similarly, tomato seed germination is enhanced with low concentrations of SiO_2 NPs (Mahmoodzadeh et al., 2013).

Iron Oxide Nanoparticles

Iron oxide nanoparticles are beneficial for plant growth by enhancing nutrient uptake and reducing oxidative stress. They have been shown to improve plant yield and yield components, as well as boost photosynthesis. Furthermore, zero-valent iron in combination with PGPR can enhance phytoremediation in contaminated soils. Studies have indicated that iron oxide nanoparticles reduce ROS damage and improve the oxidative defense system in plants like Brassica napus (Gulaim et al., 2017) and *Vigna unguiculata* (Rahimi et al., 2016)

1.3.2 Other Nanomaterials

Nanoparticles of essential elements like calcium and manganese have been developed as potential growth enhancers. Calcium nanoparticles, in particular, are promising for reducing fertilizer use and minimizing environmental pollution. They also promote better germination, growth, and yield in various plants. For instance, calcium phosphate nanoparticles have improved the quality and storability of fruits in strawberry plants (Zakaria et al., 2018). Manganese nanoparticles are also used to enhance plant growth, photosynthesis, and reduce oxidative stress, making them an effective supplement in crop management (Pradhan et al., 2013).

1.4 Research Objectives

The application of nanomaterials with PGPR holds great promise. Co-application of iron nanoparticles and PGPR to improve the growth of groundnut plants was investigated in this study. Plant growth of groundnut exposed to nanoparticles and the PGPR separately and in combination to observe the effect on plant growth.

1. **Objective-1 Isolation of bacteria(s) from the selected soil and screen isolates for various plant growth-promoting (PGP) traits.**
2. **Objective 2 Identify the selected isolates by their molecular (16s rRNA technique) study.**
3. **Objectives-3 Optimization of synthesis and concentration of nanoparticles (NPs) on plant growth.**
4. **Objective-4 To perform a pot experiment using selected PGPR individually and with nanoparticles to check their plant growth-promoting ability.**

1.5 Implications

Groundnut (*Arachis hypogaea* L.) is a highly valuable crop grown for its oil, food, and feed purposes, primarily in tropical and subtropical regions across the globe (Variath and Janila, 2017). The Saurashtra region is considered the core area for groundnut cultivation in both Gujarat and India. This research was focused on enhancing groundnut yield through the use of effective PGPR and synthesized nanoparticles.

The integration of PGPRs as biofertilizers alongside nanoparticles offers a biological method to sustainably intensify agricultural production. PGPRs play a vital role in regulating plant hormone levels, balancing nutrition, boosting resistance to pathogens, and making nutrients more accessible to plants. Compared to traditional chemical fertilizers, PGPRs are more cost-effective and environmentally friendly. When combined with metal oxide nanoparticles, PGPRs can provide a gradual and controlled release of nutrients, improving the efficiency of biofertilizer use, reducing volatilization and nutrient leaching, and minimizing environmental impact.