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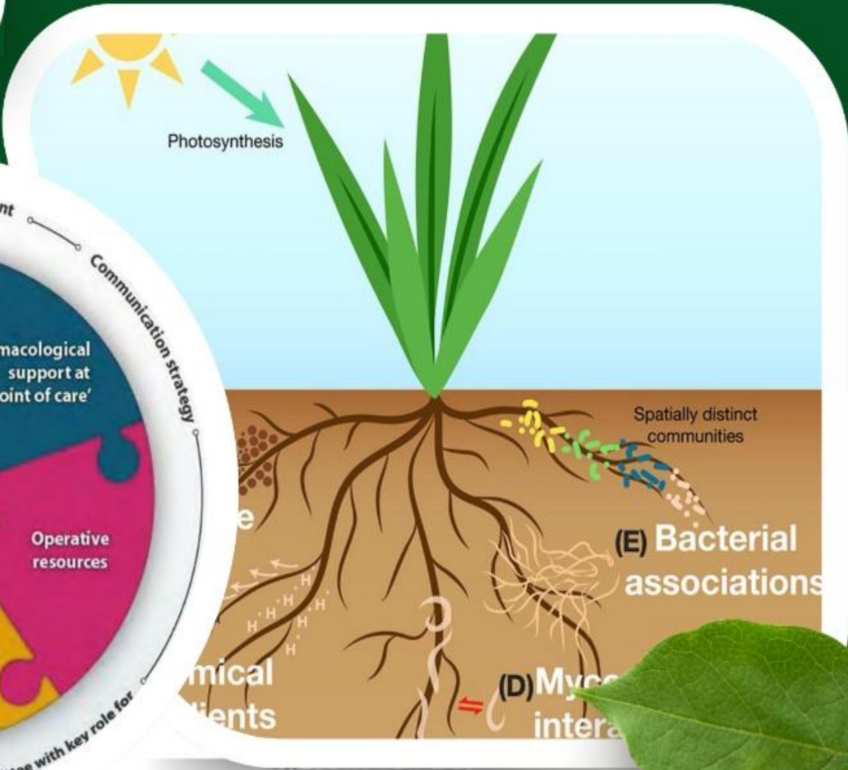

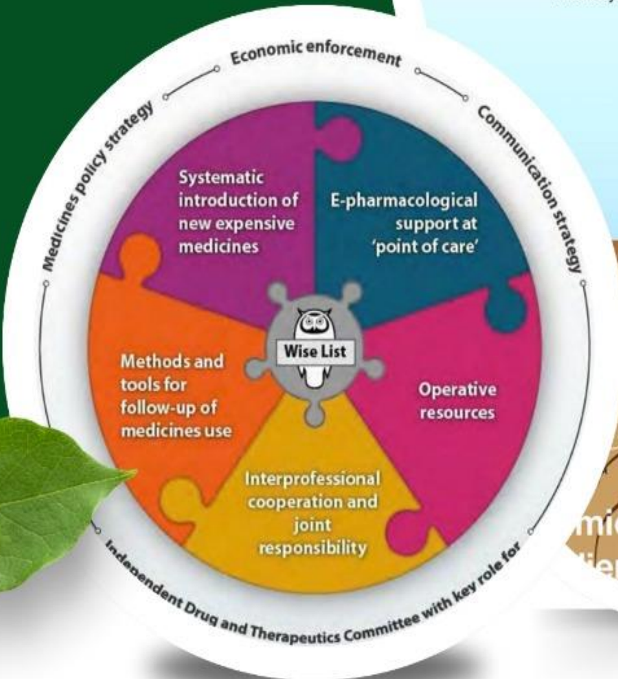

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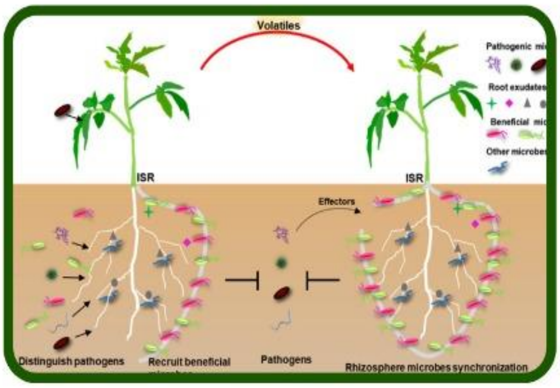
A Review of Agronomic and Pharmacological Relevance



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Functional Interactions Between Citrus Species and Rhizospheric Microbiomes: A Review of Agronomic and Pharmacological Relevance

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Abstract

Citrus fruits (*Citrus* spp.) are prized throughout the world for their therapeutic qualities, such as their anti-inflammatory, anti-cancer, and antioxidant capabilities, in addition to their nutritional value, which includes a high concentration of vitamin C, flavonoids, and essential oils. The importance of rhizospheric microbiota in citrus cultivation has been clarified by recent developments in plant-microbe interactions. Plant growth, nutrient uptake, abiotic stress tolerance, and disease resistance are all facilitated by the diverse community of bacteria, fungi, archaea, and protozoa found in the rhizosphere, a dynamic soil-root interface. *Pseudomonas*, *Bacillus*, and *Azospirillum* species are examples of plant growth-promoting rhizobacteria (PGPR), which improve nutrient cycling by fixing nitrogen, solubilizing phosphate, and producing siderophores. Additionally, a variety of secondary metabolites and enzymes produced by rhizospheric microorganisms have potential uses in industry, medicine, and agriculture. These consist of chitinases, flavonoids, and lipopeptides.

Keywords: Rhizosphere, *Fusarium*, Citrus

1. INTRODUCTION

Citrus fruits, belonging to the genes citrus, are globally recognized for their nutritional, economic, and medicinal importance. Species such as oranges (*Citrus sinesis*), lemons (*Citrus limon*), limes (*Citrus aurantifolia*), and grapefruits (*Citrus paradisi*) are rich sources of vitamin C, antioxidants, and bioactive compounds like flavonoids, carotenoids, and polyphenols, which contribute to their health-promoting properties. These fruits are known to boost immunity, reduce inflammation, and prevent chronic diseases such as cardiovascular disorders, diabetes, and cancer [1]. Beyond their direct health benefits, citrus fruits are deeply interconnected with their rhizospheric microbome, a complex community of bacteria, fungi, and other microorganisms that inhabit the soil surrounding their roots. These microorganisms play a critical role in enhancing plant growth, nutrient uptake, and stress tolerance through mechanisms such as nitrogen fixation,phosphate solubilization, and the production of phytohormone and secondary metabolites [2]. Recent studies have revealed that the rhizospheric bacteria associated with citrus plants not only support plant health but also produce bioactive compounds with significant medicinal potential, including antimicrobial, anticancer, and anti-inflammatory properties [3].

Citrus fruits are a powerhouse of nutrient and bioactive compounds that contribute to their extensive medicinal properties. They are particularly rich in vitamin C, a potent antioxidant that strengthens the immune system and protects cells from oxidative stress [1]. Additionally, citrus fruits contain flavonoids such as hesperidin, naringenin, and quercetin, which exhibit anti-inflammatory, antiviral, and anticancer activities [4]. The essential oils derived from citrus peels, such as limonene, have also been shown to possess antimicrobial and anticancer properties [5]. These bioactive compounds make citrus fruits valuable not only as dietary components but also as sources of natural therapeutics for various diseases.

The rhizosphere, the soil region influenced by plants roots, harbors a diverse microbial community that plays a crucial role in plant health and productivity. In citrus plants, rhizospheric bacteria such as

Pseudomonas, *Bacillus*, and *Azospirillum* contribute to nutrient acquisition, disease suppression, and stress tolerance [6]. These bacteria fix atmospheric nitrogen, solubilize phosphate, and produce phytohormone like auxins and cytokinins, which promote root growth and overall plant vigor [3]. Moreover, rhizospheric bacteria produce antimicrobial compounds that protect citrus plants from soil-borne pathogens, reducing the need for chemical pesticides [7] The symbiotic relationship between citrus plants and their rhizospheric microbiome enhances the plants' resilience to environmental stresses, such as drought and salinity, making these bacteria indispensable for sustainable citrus cultivation.

Recent research has uncovered the medicinal potential of rhizospheric bacteria associated with citrus plants. These bacteria produce a wide range of bioactive compounds, including antimicrobial peptide, enzymes, and secondary metabolites, which have application in human health [8]. For example, certain Bacillus species isolated from citrus rhizospheres produce lipopeptides with potent antimicrobial activity against multidrug-resistant pathogens, offering a promising alternative to conventional antibiotics. Additionally, rhizospheric bacteria synthesize flavonoids, terpenoids, and other secondary metabolites that exhibit anticancer properties by inducing apoptosis in cancer cells [2]. The exploration of these microbial resources for drug discovery represents a growing field of interest in pharmacology and biotechnology.

2. Citrus Fruits

2.1. Classification of citrus

The classification of citrus species has been a subject of debate among researchers.Some have divided the genus Citrus into 16 species, while others have identified up to 159 species. The difficulty in accurately determining the number of species arises from ease with which citrus species can hybridize and the presence of clonal and apomictic variations [9]. Among the most well-known species are *Citrus sinensis* (sweet orange), *C. aurantium* (bitter orange), *C. reticulata* (mandarian orange, tangerine), and *C. lemon* (lemon) and *C. paradise* (grapefruit) having exceptional medicinal values (Figure 1).

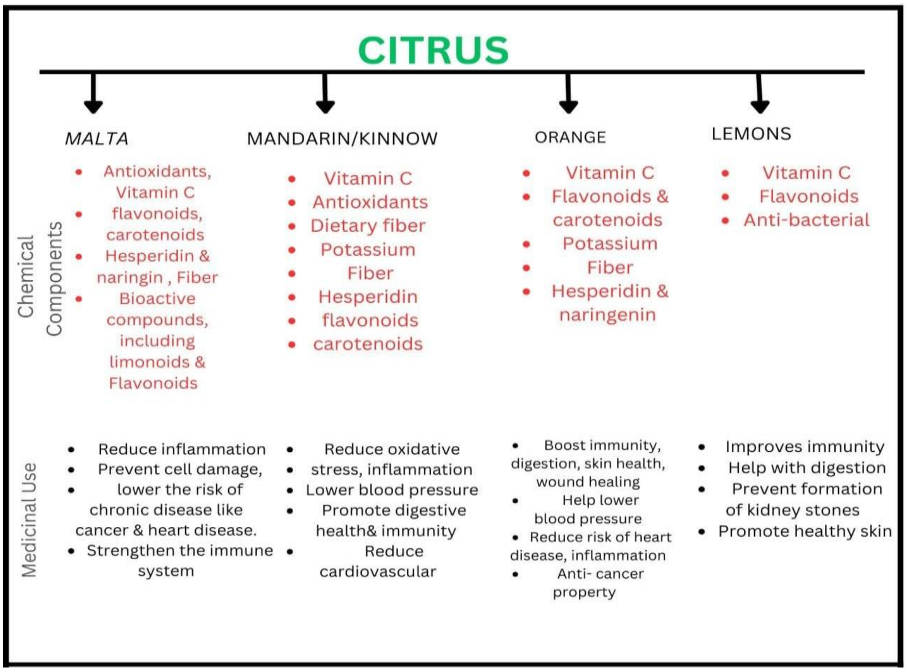

Figure 1: Chemical components present in various citrus plants and its medicinal use.

3. Rhizospheric Bacteria

The rhizosphere, the narrow region of soil directly influenced by root secretion and associated soil microorganisms, plays a pivotal role in determining the health, growth, and productivity of citrus plants. This dynamic zone is a hotspot for microbial activity, hosting a diverse community of bacteria, fungi,

archaea, and protozoa that interact in intricate ways to influence nutrient availability, disease resistance and stress tolerance in citrus plants. Beneficial bacteria such as *Pseudomonas* and *Bacillus* are known to produce antibiotics, sideophores, and phytohormones that protect citrus roots from pathogens like *Phytophthora* and *Fusarium* while promoting root growth and nutrient uptake [2].
Similarly, arbuscular mycorrhizal fungi (AMF), such as *Glomus* and *Rhizophagus*, form symbiotic relationships with citrus roots, extending their hyphal networks to enhance the absorption of phosphorus, zinc, and other micro-nutrient, particularly in nutrient - deficient soils [10]. These fungi also improve water uptake, making citrus plants more resilient to drought conditions. The rhizosphere also harbors ammonia -oxidizing archaea (AOA) that contribute to nitrogen cycling, converting ammonia into nitrite, a crucial step in making nitrogen available to plants [11]. Additionally, protozoa and nematodes regulate microbial populations by preying on bacteria , releasing nitrogen and other nutrients in plant - available forms. However, the health of the rhizosphere can be compromised by factors such as soil salinity, acidity, and the overuse of chemical fertilizers, which can disrupt microbial balance and reduce beneficial interactions. For instance , excessive nitrogen fertilization can lead to the accumulations of salts, negatively impacting microbial diversity and root function. Conversely, sustainable practices like the application of organic amendments, compost, and microbial inoculation can enhance rhizosphere health by promoting microbial diversity and activity [12].

The metabolic pathways in rhizospheric microbes are essential for nutrient acquisition, stress tolerance, and pathogens defence. For instance, ammonia -oxidizing archaea and bacteria play a crucial role in nitrogen cycling by converting ammonia into nitrite and then nitrate, making nitrogen available to plants.Many rhizospheric bacteria, such as Pseudomonas and Bacillus, produce organic acids like citric acid and gluconic acid that solubilize insoluble phosphates in the soil, making phosphorus available to plants. This is particularly important in citrus cultivation, as phosphorus is a key nutrient for root development and fruit quality. Rhizospheric microbes also decompose organic matter, releasing carbon compounds that serve as energy sources for both microbes and plants, enhancing soil structure and fertility. Some bacteria produce sideophores, which are iron- chelating compounds that bind to iron in the soil, making it available to plants and preventing pathogenic microbes from accessing this essential nutrient. Certain help plant cope with abiotic stresses such as drought, salinity, and heavy metal toxicity by stabilizing plant cells and improving water retention in the rhizosphere [13].

Rhizospheric microbes produce a variety of enzymes that benefit both plants and humans. Enzymes such as chitinase and glucanase degrade the cell walls of pathogenic fungi, providing biocontrol benefits to citrus plants. For example, *Pseudomonas* species produce chitinase, which breaks down chitin in fungal cell walls, protecting citrus roots from pathogens like *Phytophthora* and *Fusarium.* These enzymes also have industrial applications, such as in the production of bioactive compounds and biofertilizers.Phosphatases hydrolyze organic phosphorus compounds, releasing inorganic phosphate that plants can absorb, which is particularly beneficial in phosphorus-deficient soils.Cellulase and pectinase break down cellulose and pectin, respectively, and are used in the food industry for fruit juice extraction and clarification, including ammonia, making nitrogen available to plants and reducing the need for chemical nitrogen fertilizers. Amylase and protease are involved in the breakdown of starch and proteins, respectively, and have applications in the food and beverage industry, including the processing of citrus- based products [14].

Plant Growth-Promoting Rhizobacteria (PGPR) are beneficial bacteria that enhance plant growth through various mechanisms. In citrus cultivation, PGPR play a vital role in improving nutrient uptake, disease resistance, and stress tolerance. PGPR such as *Pseudomonas* and *Bacillus* solubilize phosphorus, potassium, and zinc, making these nutrients available to citrus plants. They also fix atmospheric nitrogen, reducing the need for chemical fertilizers. PGPR produce phytohormones like auxins, cytokinins, and gibberellins, which promote root growth, cell division, and fruit development. For example, auxins produce produced by *Azospirillum* species enhance root elongation, improving nutrient and water uptake. PGPR also produce antibiotic sideophores, and lytic enzymes that suppress soil-borne pathogens. For instance, *Bacillus subtilis* produces lipopeptides that inhibit the growth of *Phytophthora* species, a major pathogen in citrus cultivation. Additionally, PGPR can prime citrus plants to activate their defence mechanisms against pathogens, reducing the need for chemical pesticides and enhancing plant resilience [15].

The use of rhizospheric microbes in citrus cultivation offers numerous economic and industrial benefits. By using PGPR and microbial inoculants, farmers can reduce their reliance on chemical fertilizers, lowering production costs and minimizing environmental impact. Microbial- based products, such as biofertilizers and bio-pesticides, are cost-effective and environmentally friendly alternatives to chemical inputs. For example, *Trichoderma*- based biopesticides are widely used to control fungal pathogens in citrus orchards. Enzymes produced by rhizospheric microbes, such as cellulase, pectinase, and chitinase, have applications in the food beverage, and biofuel industries.For instance, pectinase is used in the clarification of citrus juices, while cellulase is used in biofuel production. Rhizospheric microbes can also be used to remediate soils contaminated with heavy metals or pesticides. For example, *Pseudomonas* species can degrade organic pollutants, making them valuable for cleaning up industrial waste sites [16].

Sustainable practices are essential for maintaining a healthy rhizosphere and ensuring long-term citrus productivity. The application of compost, manure, and other organic materials improves soil structure, enhances microbial diversity, and provides a slow- release source of nutrients. Inoculating citrus plants with beneficial microbes, such as PGPR and AMF, enhances nutrient uptake and disease resistance, which is particularly beneficial in nutrient- deficient soils. Advanced technologies, such as soil sensors and drones, can be used to monitor soil health and optimize the application of fertilizers and water, reducing waste and improving efficiency [6]. However, challenges such as climate change, soil degradation, and the emergence of resistant pathogens pose ongoing threats to citrus health. Addressing these challenges requires innovative management strategies, such as rhizosphere engineering and the development of microbial consortia tailored to specific soil conditions .

4. Conclusion

In conclusion, the rhizosphere is a critical zone for the health and productivity of citrus plants, where complex interactions between roots,soil, and microorganisms occur. By optimizing the rhizospheric environment through sustainable pratices and leveraging the metabolic capabilities of beneficial microbes, it is possible to enhance citrus health, improve fruit quality, and ensure long-term productivity while minimizing environmental impacts.
These studies provide a comprehensive understanding of the roles and benefits of rhizospheric microbes in citrus cultivation, highlighting the importance of sustainable practices and innovative management strategies for long-term agricultural productivity and environmental health.

5. Acknowledgement

The authors would like to acknowledge the Founder & CEO of Rapture Biotech International Pvt. Ltd., Noida, Uttar Pradesh, India, for granting the opportunity to undertake this review article. We are also sincerely thankful to the Director of Rapture Biotech, Bengaluru, Karnataka, India, for the valuable guidance, insightful suggestions, and consistent support extended throughout the course of this work. We gratefully acknowledge the Scientist at Rapture Biotech, Bengaluru, for their supervision and invaluable assistance during the execution of this study.

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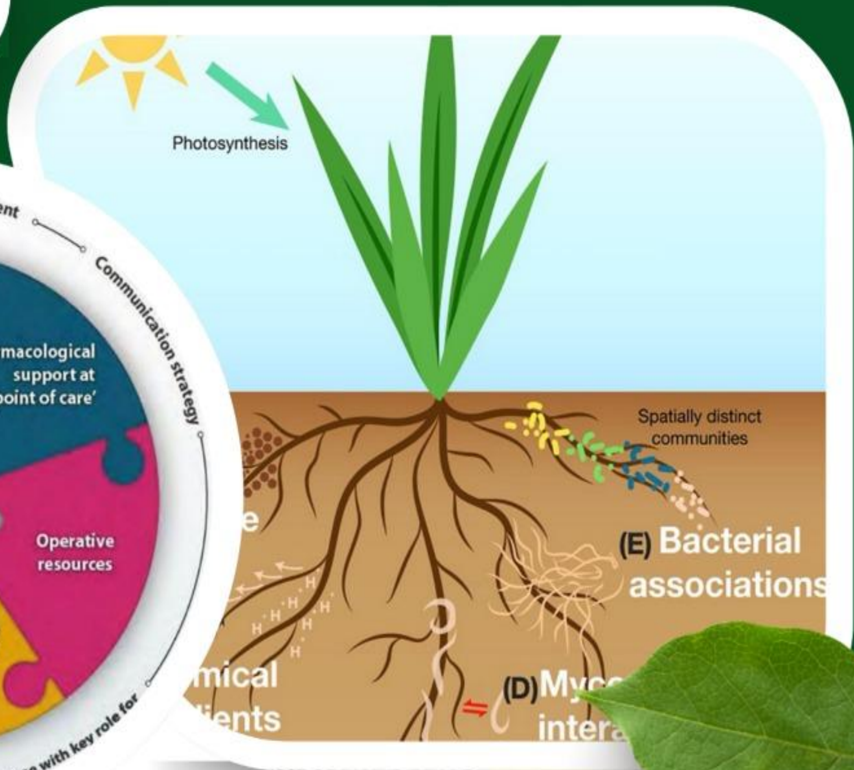

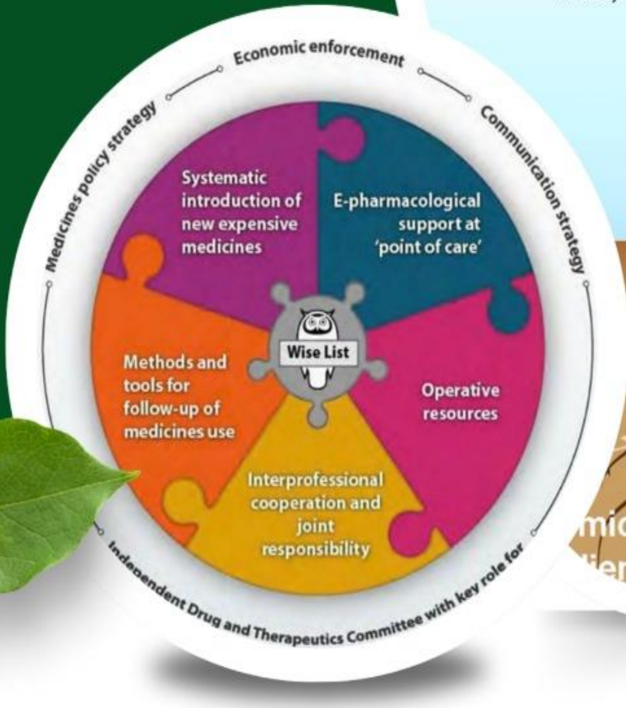

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