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Nutrient-Pathogen Interactions in Agriculture: Mechanisms, Relationships, and Sustainable Practices

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Abstract – Soil health contributes to environmental quality, supports biodiversity, maintains biological productivity, enhances water filtration, improves nutrient cycling, and promotes ecosystem resilience. Additionally, it is a pivotal driver in increasing plant growth and fortifying disease resistance. When the soil is inadequate, plants are particularly vulnerable to soil-borne bacterial and fungal diseases, which can be among the most harmful threats to agricultural productivity. Poor soil structure, nutrient imbalances, and low microbial diversity can weaken plant defenses, increasing susceptibility to pathogens. To manage these, balancing macro and micronutrients is essential. This review covers the critical roles of macro- and micronutrients not only in supporting fundamental plant processes but also in activating natural defense mechanisms against pathogens. Additionally, it focuses on how they strengthen physical and biochemical barriers, modulate the soil microbiome, and influence interactions with pathogens. Furthermore, it highlights organic amendments, biofertilizers, and integrated nutrient management (INM) approaches as effective strategies for balancing soil fertility while promoting disease suppression. It also discusses precision agriculture, which minimizes environmental impacts and improves crop resilience, while exploring innovative pathways to optimize nutrient use efficiency through the use of advanced technologies. Ultimately, the study concludes that maintaining soil health through balanced nutrient management is crucial for enhancing plant growth, disease resistance, and environmental sustainability. It recommends the adoption of integrated nutrient management (INM) practices, organic amendments, and the use of precision agriculture techniques to optimize nutrient use and mitigate disease risks. Further research is needed to explore the synergistic effects of soil amendments and microbial communities in supporting plant health and resilience, paving the way for more sustainable agricultural practices.

Keywords – Soil Health, Disease Resistance, Integrated Nutrient Management, Organic, Precision Agriculture.

I. INTRODUCTION

Soil is a key factor in preserving the balance of ecosystems on Earth, with soil productivity and fertility being essential for sustainable agriculture. A well-known relationship exists between microorganisms and soil fertility, which improves crop health, yield, and quality [1]. For example, rhizosphere microbes are some of the most well-known microbes found around plant roots and soil. These microbes can directly and indirectly influence plant growth [2-4]. This dynamic interaction not only supports agricultural productivity but also contributes to the sustainability of ecosystems. However, there are also soil-borne pathogens, including *Fusarium* spp., *Pythium* spp., *Verticillium dahliae*, *Xanthomonas* spp., Some strains of *Pseudomonas* spp., *Erwinia* spp., *Ralstonia solanacearum*, *Agrobacterium tumefaciens*, *Xylella fastidiosa*, *Meloidogyne* spp., and others, that compete for nutrients, space, and oxygen with beneficial microbes [5-14]. These soil-borne pathogens cause yield losses of 50 to 75%, or even total eradication, in susceptible horticultural and field crops [15-18]. These pathogens are found worldwide. For example, in the United States, 90% of the 2,000 significant diseases affecting major crops are caused by soil-borne pathogens [16, 19]. They frequently persist for extended periods in host plant debris, free-living organisms, soil organic matter, or in resilient structures such as chlamydospores, sclerotia, microsclerotia, or oospores [20]. Managing these pathogens is challenging due to their characteristics. However, it is believed that if cultural practices such as sanitation, quarantine, crop rotation, adding compost or organic matter to boost soil microbial diversity, removing infected plant debris, and minimizing soil disturbance are effectively applied, they can combine soil nutrient management with pathogen control strategies, thereby enhancing plant growth and natural resistance sustainably. This review covers the critical roles of macro- and micronutrients in supporting fundamental plant processes and activating natural defense mechanisms against pathogens. It also examines how these nutrients strengthen physical and biochemical barriers, modulate the soil microbiome, and influence interactions with pathogens. Finally, the review discusses how specific nutrients may inhibit particular pathogens and recommends the adoption of integrated nutrient management (INM) practices to reduce disease risks.

II. MAIN NUTRIENTS AND THEIR FUNCTIONS IN PLANT GROWTH

Plants, like humans and animals, require nourishment for healthy growth and development. Plant food contains several chemical components, known as plant nutrients, which include 18 essential elements [21]. Plant nutrients can be divided into two main categories: macronutrients and micronutrients. However, additional beneficial components are also required [22], as shown in **Figure 1** and **Table 1**. These nutrients depend on every step and process of a plant, including emergence, metabolism, productivity, and protection. The rate of nutrient requirements varies, with nitrogen (N), phosphorus (P), and potassium (K) as the primary macronutrients essential for plant growth and development. Sulfur (S), magnesium (Mg), and calcium (Ca) are secondary macronutrients needed in smaller amounts compared to N, P, and K [23]. Iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), boron (B), molybdenum (Mo), chlorine (Cl), nickel (Ni), and cobalt (Co) are micronutrients, required in much smaller quantities than macronutrients for crop growth and optimal yield [24].

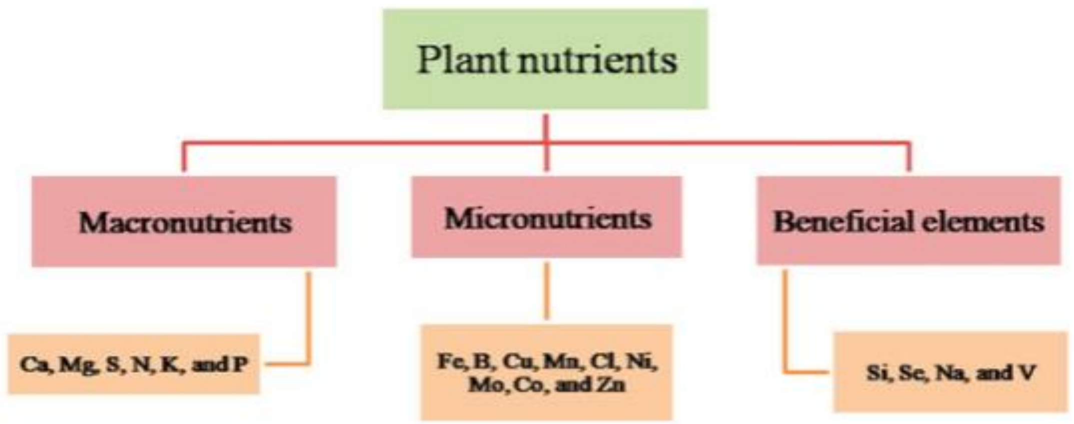

Figure 1. Classification of Plant Nutrients [22].

Table 1. The Role 18 essential elements for plant growth and protecting plant health

Nutrient	Symbol	Uptake form	Mobility in plant	Fundamental role	Reference
Nitrogen	N	NO_3^-, NH_4^+	Mobile	Essential for amino acids, proteins, and chlorophyll synthesis	[25, 26]
Phosphorus	P	$H_2PO_4^-$, HPO_4^{2-}	Mobile	Important for energy transfer (ATP), nucleic acids, and root development	[27]
Potassium	K	K^+	Mobile	Involved in enzyme activation, osmoregulation, and stomatal function	[28]
Calcium	Ca	Ca^{2+}	Immobile	Provides structural support in cell walls and membranes, involved in signal transduction	[29, 30]
Magnesium	Mg	Mg^{2+}	Mobile	Central atom in chlorophyll, important for enzyme activation	[31]
Sulfur	S	SO_4^{2-}	Mobile	Integral part of amino acids and vitamins; essential for protein synthesis	[32]
Iron	Fe	Fe^{2+}, Fe^{3+}	Immobile	Vital for chlorophyll synthesis and electron transport in photosynthesis	[33]
Manganese	Mn	Mn^{2+}	Immobile	Involved in photosynthesis, nitrogen metabolism, and enzyme activation	[34]
Zinc	Zn	Zn^{2+}	Immobile	Required for enzyme function, protein synthesis, and growth regulation	[35]
Copper	Cu	Cu^{2+}	Immobile	Plays a role in photosynthesis, lignin synthesis, and reproduction	[36]
Boron	B	H_3BO_3, $B(OH)_4^-$	Immobile	Essential for cell wall formation, reproductive development, and sugar transport	[37]
Molybdenum	Mo	MoO_4^{2-}	Immobile	Key for nitrogen fixation and nitrate reduction	[38]
Chlorine	Cl	Cl^-	Mobile	Important for osmosis, ionic balance, and photosynthesis	[39]
Nickel	Ni	Ni^{2+}	Mobile	Involved in nitrogen metabolism and enzyme activation	[40]
Cobalt	Co	Co^{2+}	Immobile	Needed for nitrogen fixation in legumes	[41]
Carbon	C	CO_2		Fundamental for organic molecules; major component of plant biomass	[42]
Hydrogen	H	H_2O		Involved in water transport, photosynthesis, and cell structure	[43, 44]
Oxygen	O	O_2, CO_2		Essential for respiration, energy transfer, and organic molecules	[43, 44]

Any microelement deficiency may significantly hinder crop growth and production. Most of these elements can be found in the soil and air in the form can be taken up by plants or not. Additionally, some nutrients are mobile, meaning they can move within a plant or soil, while others are immobile [45]. Understanding nutrient mobility can help determine which deficiency is occurring and identify the root cause. Several of these mineral nutrients may protect agricultural plants from biotic and abiotic stressors by boosting plant resistance and controlling mineral nutritional status [43, 46]. Therefore, plant nutritional problems including low soil fertility, insufficient nutrient availability, or imbalances might threaten world food production and security. Proper agricultural and integrated nutrient management are essential to safeguard crop production from various stresses [47-49].

III. NUTRIENT-PATHOGEN INTERACTIONS

Plants interact with pathogens and microorganisms, and these interactions can be either beneficial or harmful [50-54]. For example, some beneficial microbes, including bacteria and fungi, promote plant growth and help resist pathogenic agents [50, 55, 56]. This promotion can occur through two mechanisms: direct and indirect. Direct mechanisms include nitrogen fixation, phosphorus and potassium solubilization, phytohormone production, and siderophore production. Indirect mechanisms include competition for nutrients and space, induced systemic resistance (ISR) and systemic acquired resistance (SAR), HCN production, as well as biofilm formation [57-61]. This type of interaction is more familiar than the interaction between soil nutrients and pathogens, which also contributes to disease incidence and severity [62]. Additionally, the relationship between nutrients and pathogens plays a significant role in determining a plant's ability to resist or be susceptible to diseases. Nutrient availability influences plant growth, immunity, and overall vigor, which, in turn, affects how plants respond to infections [63, 64].

As is well known, the occurrence of a disease depends on the presence of a triad consisting of the pathogen, the environment, and the plant host. Each of these factors is essential for disease development. A disease can only manifest when a susceptible host, favorable environmental conditions, and a virulent pathogen coexist in the field [65], as shown in Figure 2.

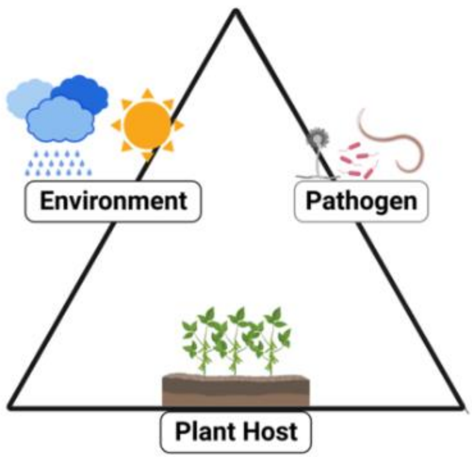

Figure 2. Disease triangle [66].

Some plant pathologists also include time and human activities as additional factors, referring to this model as the 'disease pyramid [67, 68]. In this model, the pathogen, environment, plant host, man, and time are essential components for disease development.

As stated earlier, plants require a balanced supply of macro- and micronutrients to maintain optimal health [69, 70]. Insufficient nutrient uptake from the soil can make plants more susceptible to diseases and pests. For example, nitrogen is essential for the synthesis of amino acids, proteins, starch in leaf, chlorophyll, and crop yield [69]. Its deficiency leads to reduced photosynthesis, lower protein contents, stunted growth, and weakened plant defenses, making plants more susceptible to bacterial, virus, and fungal diseases [70]. On the other hand, an excess of nitrogen can promote rapid pathogen growth. Additionally, nutrient imbalances can influence the production of secondary metabolites, such as phytoalexins, which play crucial roles in plant defense mechanisms, resulting in poor growth and weakened defenses [44]. Therefore, it is essential to apply and place nutrients in the proper amount. Furthermore, soil-borne pathogens can directly impact the plant's nutrient and water uptake by altering the root structure, inhibiting nutrient transport, or modifying nutrient allocation within the plant [70].

Several researchers have emphasized a significant link between disease resistance and the mineral nutrition of plants [71-73]. For example, Tomatoes are affected by early blight and gray mold, two destructive diseases caused by *Alternaria solani* and *Botrytis cinerea*, respectively. A high nitrogen supply can help reduce disease severity and incidence, as well as enhance plant resistance [74, 75]. *Rhizoctonia solani*, which induces sheath blight on rice, can have its severity reduced by increasing the supply of potassium [76]. Additionally, low potassium supply increases the susceptibility of soybeans to pod and stem blight diseases [77]. When phosphorus was applied to cucumber plants, it was observed to reduce the severity of powdery mildew disease [78]. Other studies have highlighted that phosphorus can also increase plant resistance to bacterial leaf blight in rice, but may increase flag smut severity in wheat [79, 80]. A 2009 study reported that nutrient imbalances can alter plant metabolism, creating favorable conditions for pathogens. Calcium deficiency, for instance, can lead to membrane leakage, releasing sugars and amino acids that support pathogen growth [72]. Furthermore, Ca application decreases the severity and incidence of Phytophthora stem rot and clubroot disease in soybean and crucifers, respectively [81, 82]. Many other researchers have also reported that the application of sulfur and magnesium reduces the severity of powdery mildew in grapes and brown spot in rice [83, 84]. Based on these studies, applying nutrients through integrated nutrient management is essential for sustainable agricultural practices.

IV. SUSTAINABLE NUTRIENT MANAGEMENT FOR ENHANCED GROWTH AND RESISTANCE

Climate change, pests, and disease outbreaks impact plant nutrient uptake and availability by altering water and soil conditions. Therefore, practicing Integrated and Sustainable Nutrient Management is a key strategy for achieving food security while ensuring both environmental and agricultural sustainability [85-87]. Sustainable nutrient management (SNM) is vital for improving crop yield and quality, reducing environmental pollution, preventing soil degradation and erosion, as well as enhancing soil health and fertility [88-90]. Additionally, it supports diverse agricultural practices, such as mixed cropping and agroecological approaches, which promote biodiversity [91, 92].Proper nutrient management not only protects the environment but also strengthens plant defense mechanisms against plant pathogens. Plants that receive the right balance of nutrients, such as nitrogen, phosphorus, potassium, and micronutrients, are more resilient to pests and diseases [69, 71, 73]. It also boosts the plant's natural immunity, reducing the need for chemical pesticides and promoting sustainable pest and disease control.

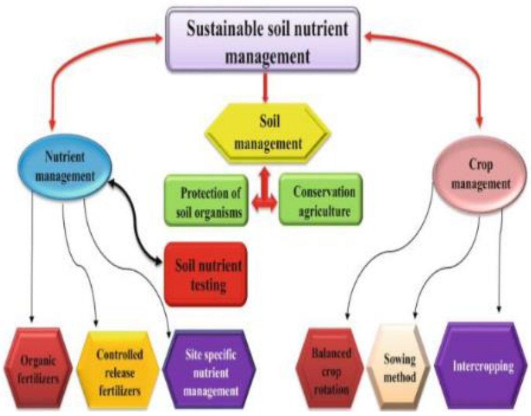

Figure 3. Sustainable management of soil nutrients [90]

Some pathogens can manipulate and alter plant cell membrane permeability to access more nutrients. However, adequate nutrient levels can enhance the production of phenolic compounds and other antimicrobial substances, which strengthen plant defenses against such manipulation. Furthermore, when plants receive proper nutrients, they can even better withstand environmental stresses, such as drought or extreme weather, which could otherwise weaken the plant and make it more susceptible to pathogens [79, 93]. So, ensuring a balanced supply of nutrients and implementing sustainable agricultural practices can improve soil fertility and productivity, ultimately enhancing plant resilience against pathogens.

V. CONCLUSION

Soil nutrients are one of the key factors that contribute to increased crop yield and resilience against plant pathogens. This review highlights the role of proper nutrients in plant production and their resistance to bacterial and fungal diseases. Additionally, it evaluates the availability and balance of essential macro- and micronutrients that directly influence plant health, metabolic processes, and defense mechanisms against both biotic and abiotic stresses. Furthermore, nutrient imbalances can make plants more susceptible to pathogens, which harm crop yields, ultimately leading to food insecurity. Integrated nutrient management and organic farming are significant potential in enhancing soil fertility, increasing crop productivity, and reducing the reliance on chemical pesticides. Therefore, farmers must make an effort to provide plants with the proper nutrients, at the right time, and in suitable areas to sustain the environment and ensure long-term agricultural productivity. Finally, further research on the interactions between soil nutrients, plant health, and disease resistance is essential to develop more effective and sustainable agricultural strategies.

CONFLICT OF INTEREST

The authors declare no conflict of interest regarding the publication of this paper.

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