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PLANT-FUNGAL INTERACTION: GLOBAL DIVERSE ROLE IN AGRICULTURE: A REVIEW

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The rapid growth of the global population demands an expansion of agricultural practices, supported by modernization and technological advancements. However, plant diseases have become more prevalent due to ongoing climate and environmental changes. The disease triangle, which includes the plant, pathogen, and environment, plays a key role in determining disease occurrence and severity. Abiotic factors such as climate primarily play an important role in new disease occurrence whereas, genetic alterations within the plant and pathogen result in resistance and susceptible varieties. The resistance and susceptibility of plants toward any disease are determined by multiple reactions between the genes carried in the plant and the pathogen. This describes how plant fungi interact with each other. The plant disease involves a series of steps including entry, inoculum potential, colonization, infection, multiplication, and several others during plant-fungal interaction. Here, we review the recent advances and progress toward the disease mechanism, etiological factors, and management techniques of plant-fungal interaction.

Keywords: Fungal, Infection, Pathogen, Resistance, Plant diseases.

Introduction

Plant diseases across the globe represent a critical problem and require prime attention to increase the quality and abundance of crops. Plant diseases are among the main constraints affecting the production and productivity of crops for both quality and quantity. Farmers rely on good agronomic and horticultural practices and raw materials for a healthy yield of crops. However, besides agricultural practices, inappropriate and excessive use of harmful chemical fertilizers is a worldwide concern. This overzealous and indiscriminate use of synthetic chemicals has created different environmental and toxicological problems[1].

Fungi can be defined as eukaryotes capable of digesting food externally and absorbing nutrition from a cell wall composed of chitin[2]. Fungal species hold a wide range of ecological roles, including decomposers, parasites, pathogens, mutualists, and symbionts. Research shows a total number of 1.5 million fungal species known to exist[2,3]. According to data, around 99,000 fungal species have been studied and described[4,5]. Plant diseases are known to be caused by several microorganisms. However, around 8,000 fungal and related species have been reported to cause plant diseases compared to other groups of microbes. Fungi can be both beneficial and pathogenic[6]. For example, *Trichoderma* is known as a biocontrol agent that promotes plant growth[7]. Similarly, another fungus, *Penicillin*, is well known to produce penicillin-G, which inhibits bacterial growth and cures deadly diseases in humans[6]. Conversely, several fungal species are infected by invasion, growth, and reproduction within the host plants and their parts. Many applications have been studied to control these fungal diseases, including genetic host resistance, cultural practices, chemical applications, government regulatory measures, and biological control[6]. However, biocontrol

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applications have been poorly emphasized and studied for the inhibition of fungal diseases and crop protection. The gross sale of biocontrol products for fungal diseases represents a very small fraction of the synthetic pesticides and fungicides. During the start of the modern era with technological improvements, total sales of $10-20 million have been reported of bio-control products compared to harmful chemicals[8].

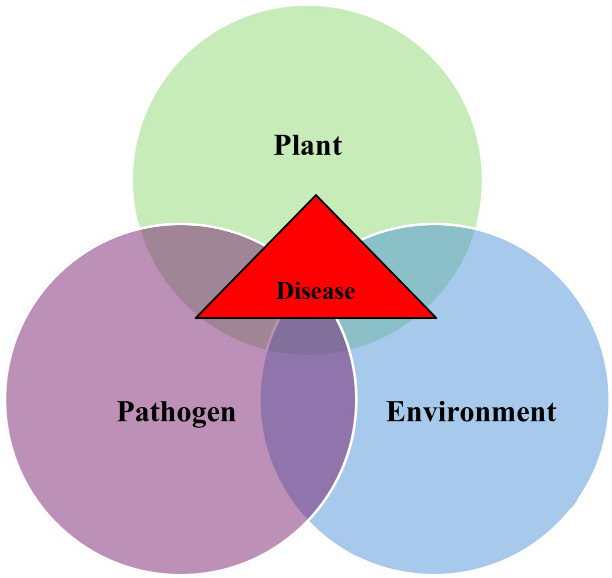

Figure 1. The three-way Plant-Pathogen-Environment interaction. The interaction explains the mechanism of disease during the equilibrium of the three components mainly pathogen, plant, and environment.

Plant-Fungal: Positive interaction:

Soil microbes, specifically the fungal community, interact with plants in various modes, including mutualism, parasitism, and symbiosis[9,10]. Fungi are categorized into positive and negative roles and play different characters in the environment. The fungal pathogens with negative responses impact the overall plant physiology, whereas the positive fungal taxa, including mutualistic fungi, are known to improve the plant's defense, growth, and development[11]. Fungal partners release bioactive compounds, including small peptide effectors, enzymes, and secondary metabolites, which aid in colonization and play roles in both symbiotic and pathogenic interactions.

Symbiotic fungal communities are associated with plants and the rhizosphere microbial community. Fungi interact with plants through varied mechanisms, including mutualism (reciprocal and mutual benefit of both) and commensalism (one benefits while the other remains neutral). The symbionts, mainly the mycorrhizal fungi belonging to Glomeromycota, are the most abundant and beneficial fungal community for plant-fungal interaction. Among these, Arbuscular mycorrhizal plays a significant role as a plant growth promoters[12-14]. Past studies have found that more than 80% of plant species are associated with Arbuscular Mycorrhizal Fungi (AMF)[15,16]. In recent years, advancements in agriculture, biotechnology, and molecular techniques have played a significant role in sustainable development and growth. In the global agriculture market, bioproducts such as biofertilizers, biopesticides, and bioremediation prepared out of AMF have tremendously increased in demand, utilization, and profits[17-19]. In addition, the global market demand for Arbuscular Mycorrhizal Fungi (AMF) in the mycorrhiza-based industry was valued at $268.8 million in 2019 and is expected to grow to $621.6 million by 2025, with a projected Compound Annual Growth Rate (CAGR) of 14.8% over the five years (Mycorrhiza-based Biofertilizer Market Growth Trends and Forecast 2020–2025)[19]. Moreover, AMFs are known to promote plant growth and improve the overall physiological responses of plants. Anli et al. (2021)[20] studied the role of Arbuscular Mycorrhizal Fungi on *Phoenix dactylifera* 'Boufgouss for growth and development. The research revealed a positive response of AMF on the overall plant growth, including root and shoot length. Moreover, nutrient improvement, physiological responses, and anatomical strengthening showed significant responses when treated with AMF strains. The research also showed positive effects as biofertilizers on *P. dactylifera*[20]. Therefore, based on studies conducted on the effect of fungal communities on plants, positive responses have been observed in relation to overall growth, development, soil health, rhizosphere environment, and physiological processes.

Table 1: Plant-fungal negative interaction and their impact on plants.

Disease Name	Pathogens	Host Plants	Symptoms	Impact on plant	Reference
Rust	*Uromyces, Phakopsora, Puccinia, Hemileia, Albugo*	Beans, Soyabean, Wheat, Coffee	Yellow spots on leaves, leading to necrosis and defoliation.	Reduces photosynthesis, weakening the plant and decreasing yield.	38-41
Smut	*Urocystis, Ustilago, Tilletia Sphacelotheca, Tolyposporium*	Monocot plants	White, soft galls may form on the plant parts including ears, tassels and leaves	large galls on various plant parts, diverting the plant's energy away from producing kernels, leading to yield losses	42,43
Powdery Mildew	*Erysiphe, Sphaerotheca, Phyllactinia, Microsphaera, Podosphaera, Uncinula, Oidium, Leveillula*	Angiosperms (cereals, fruits, vegetables, and ornamental plants, trees)	White-grey powdery patches on affected plant tissues	Affects overall plant vigor and can lead to crop loss if untreated.	40,44,45,46
Downy mildew	*Peronospora, Pseudo-peronospora, Plasmopara*	Cucurbits, Spinach, Grapes, Onion	yellow spots on the upper leaf and greyish-white fuzzy growth on the lower side	Exhibit stunted growth, wilting, and even defoliation, leading to reduced photosynthetic capacity	47-49
Blast	*Pyricularia (Syn. Magnaporthe)*	Rice, Wheat, Grasses	Lesions on the leaves, brown collar rot, nodes turn brown or black, neck rot in panicle	Exhibit lesions that can severely reduce leaf area, critical for grain filling, thereby diminishing yield	47
Anthracnose	*Colletotrichum*	Soyabean, Mango, Chilli, cereals, grasses	Dark, sunken lesions on leaves	Causes significant yield loss in fruits	50,51

			and stems, leaf drop.	and vegetables due to decay.	
Damping-off	*Pythium, Fusarium, Rhizoctonia, Thielaviopsis*	Wide range of plants (Cereals, vegetables and ornamental plants)	Seedling wilting and decay at the soil line.	High mortality rates in seedlings, affecting crop establishment.	52,53
Blight	*Phytophthora, Alternaria*	Potatoes, wheat	Water-soaked spots on leaves, target board symptoms	Can devastate crop yields	54-56
Canker	*Botryosphaeria, Cytospora, Nectria*, Neonectria, *Fusarium*	Oak, Pine, Juniper, Apple	Lesions on stems or branches, dieback of twigs.	Weakens the structural integrity of the plant, making it more susceptible to other diseases.	57,58
Wilt	*Fusarium, Verticillium*	Wide range of Plants	Yellowing of leaves, wilting, and stunted growth.	Reduces overall plant health and can lead to death in severe infestations.	59
Rot	*Botrytis, Sclerotium, Armillaria, Clitocybe tabescens, Fusarium, Rhizoctonia*	Strawberry, apple, herbs, cereals, Cucurbits and other vegetables	Darkening and decay of roots, wilting above-ground parts.	Impairs nutrient uptake, leading to poor growth and potentially plant death.	60,61
Wart	*Synchytrium*	Potato	Presence of gall and warty outgrowth on various plant parts	reduced vigor and small, greenish-yellow, warty growths at the stem base	47,62

Plant-Fungal: Negative interaction

Negative plant-microbe interactions involve detrimental effects on plant health caused by microbial pathogens. Anderson et al. (2004)[21] studied the emerging infectious diseases of plants and categorized them into three groups based on their relationship to anthropogenic food production. Several plant diseases, including potato late blight, tomato leaf curl, and citrus canker caused by *Phytophthora infestans*, *Puccinia kuehni*, and *Xanthomonas axonopodis,* respectively, were studied. Moreover, several emerging fungal diseases of wild plants, cash crops, and staple crops were also studied and analyzed for research[21]. Fungi are the most common cause of plant diseases, with over 19,000 species known to be pathogenic to plants[22]. Plant fungal diseases pose a significant threat to global food security, with pathogenic fungi capable of destroying a third of all harvests annually[23]. It is estimated that 10–23% of crops are lost each year due to fungal infections, despite the widespread use of antifungals, with an additional 10–20% lost post-harvest[24]. World agriculture sustains average losses of around 16% annually due to plant diseases and leading to economic losses of hundreds of billions of dollars annually[25]. Fungi damage plants by causing stress and killing the cells (Table 1).

Plant diseases and disorders

Plant disorders can be defined as any abnormal plant growth or development[26]. The affected plants are incapable of carrying out their normal physiological functions. These disorders can be studied in two main categories: abiotic disorders and biotic disorders. Abiotic disorders are caused by nonliving entities, such as adverse environmental effects or improper cultural practices. Biotic disorders include plant diseases caused by infectious organisms.

Plant diseases involve the interaction of the host, pathogen, and the environment. This interaction is known as a disease triangle. Specific conditions promote the development of biotic diseases. A three-way interaction of a susceptible host plant, a pathogen (fungi, bacteria, viruses, etc.), and environmental conditions contributes to the disease development. This three-way interaction forms the plant disease pyramid (Fig. 1)[27].

The use of chemicals continues to be a global concern, which reduces crop diseases but affects the environment and living organisms. However, environmental concerns are gaining worldwide importance against the harmful effects of chemicals, causing plant diseases[28]. The environmental pollution caused by the excessive utilization of agrochemicals has led to considerable changes in the attitudes of humans towards the use of bio-control methods in agriculture. Moreover, the health concern of humans, coupled with the development of resistance to pathogens, creates a worldwide awareness of the excessive use of synthetic chemicals in the agricultural sector.

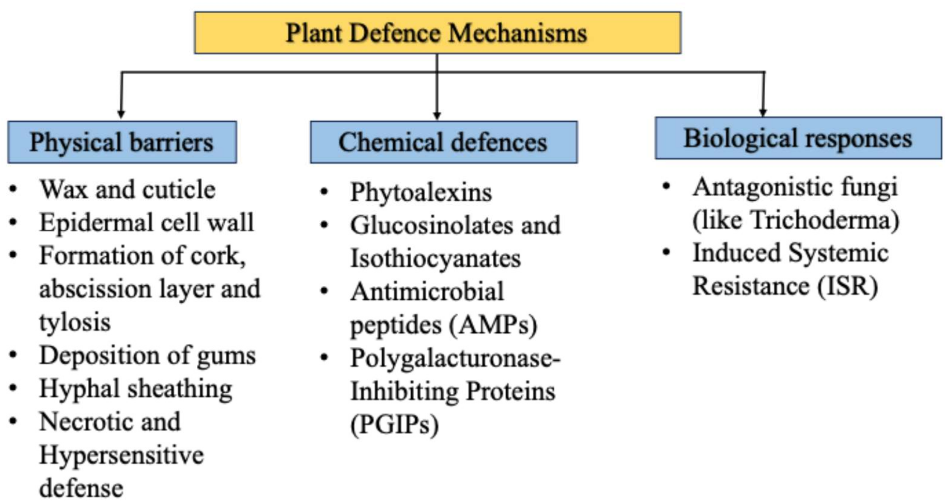

Figure 2. Plant defense mechanisms. The three defense systems, mainly physical, chemical, and biological described in brief.

Plant Defense Mechanism

The interaction between the host, mainly plants, and pathogens is known to be based on the molecular mechanisms of both. These molecules include essential primary metabolites including proteins and carbohydrates[29,30]. However, the functioning of molecules secreted from both organisms differs. Plant chemicals participate in pathogen recognition and defense mechanisms (Fig. 2). On the contrary, pathogen molecules are involved in successful infection and colonization in plant cells[30]. Past studies show that the first interaction of host-pathogens is initiated in the apoplast of cells. Moreover, the elicitors and receptor proteins of microbes and plants play a major role in the initial interaction process[31]. The identification and recognition of these microbial elicitors primarily initiate the defense mechanism in the host plants. This is known as the PAMP-Triggered Immunity (PTI) in the attacked plants[29,30]. The microbes in the counter mechanism are known to deliver essential components (proteins) in the host cells to suppress the effect of the PTI. In successive stages, the host plants develop a stronger defense mechanism known as the Effector-Triggered Immunity (ETI)[32]. The primary PTI and the secondary, stronger ETI defense system of the host plants results in recognition and consequently cell death of the pathogen. Therefore, it can be stated that the plants develop a multilayered and multifunctional defense system in response to the initial interaction of the attacking pathogen. This immune mechanism promotes resistance in plants and prevents the growth, development, and colonization of the pathogen[33,34]. However, research regarding the detailed role of pathogen proteins against the defense mechanism of the host plants is still unknown. Signal transduction during the host-pathogen interaction requires vast genetic investigation in the future. The resistance proteins of plants play a crucial role against the effector proteins of the pathogens during the process (Fig. 3).

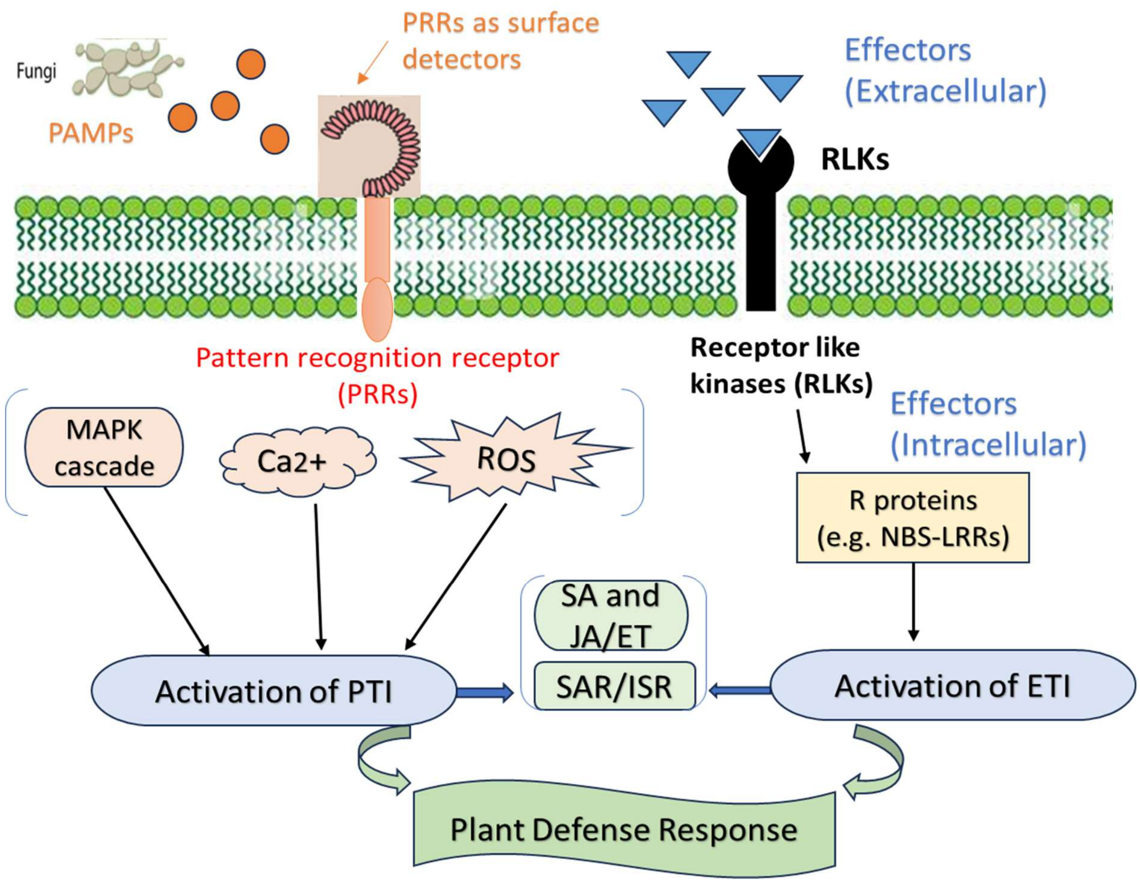

Figure 3. A model of defense response in plant-fungal interaction.

This model includes Pathogen-Associated Molecular Patterns (PAMPs) and effectors produced by fungi. PAMPs bind to Pattern Recognition Receptors (PRRs) on the cell surface. Plant Trigger Immunity (PTI) is induced through the recognition of PAMPs. The signaling pathways such as MAPK cascade, calcium signaling, and Reactive Oxygen Species (ROS) signaling are activated. Some fungi can release effectors (enzymes, toxins, and growth regulators) to interfere with PTI, causing susceptibility triggered by effectors and causing a Hypersensitive Response (HR) at the infection site. When effectors bind with R proteins, induced effector-triggered immunity. The salicylic acid and Jasmonate/ethylene signaling pathways are involved in PTI and ETI activation. Systemic Acquired Resistance (SAR) is activated by pathogenic fungi and induced systemic resistance is activated by nonpathogenic fungi. The figure was developed using BioRender: Scientific image and illustration software.

Factors affecting plant-fungal interaction

Plant-fungal interaction has also been known to be affected by various environmental parameters, including temperature, precipitation, and humidity. These climatic factors unintentionally create favorable conditions for an increase in pathogen virulence, which consequently leads to plant diseases. However, besides virulence, post-harvest management, disease-management approaches, and agricultural disease control strategies also get affected by changes in climatic conditions. With global changes in environmental parameters, the growth and development of plants are highly influenced. Genetic, morphological, and physiological alterations and nutrient deficiencies are some of the known factors affecting the host plants. The survival, dispersal, distribution, inoculum potential, and virulence of the pathogens, in turn, are highly dependent on the mentioned plant factors[35]. Moreover, modifications and alterations in the concentration of environmental carbon dioxide are known to play a crucial role in host-pathogen interaction. Vital plant mechanisms, including growth, development, defense, and resistance, are highly influenced by the carbon-di-oxide (CO_2) concentration in the environment[35,36]. Therefore, a combined effect of increased CO_2 with climate changes can highly influence the evolution, virulence, potential, and genetics of the pathogens regarding plant diseases[35,37].

Future perspectives on agriculture

Recent advances in molecular and genetic areas of plant pathology and biotechnology have revolutionized crop protection by improving resistance to diseases and enabling more effective biological control strategies. Innovations in molecular technologies, including next-generation and Illumina sequencing, have significantly improved research studies in the past few years. Advanced research in biological sciences offers great opportunities to understand the molecular networks of plant-pathogen interactions that could be beneficial in the development of innovative genetic engineering strategies, to ensure food safety and sustainable agricultural development in the future.

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