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Mechanisms of Disease Resistance in Plants for Sustainable Agriculture

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ABSTRACT

Mainly biotic factors are responsible for plant discomfort and these diseases result in economic losses in term of crop yield, and environmental disruptions. Disease resistance in plants is crucial for mitigating these impacts and it involves complex interactions between plants and pathogens, with various resistance mechanisms, including R genes, vertical and horizontal resistance, and quantitative resistance. Physical barriers or resistance mechanisms involve strong cell walls, trichomes, and cuticle thickness while chemical resistance involved in production of phytochemicals, antimicrobial proteins, phytoalexins, hormonal signaling, cell wall reinforcement, detoxification enzymes, pathogenesis-related proteins, and secondary metabolites. Systemic Acquired Resistance (SAR) provides broad-spectrum, persistent resistance by priming plants to respond more effectively to various pathogens. Recognition of Pathogen Associated Molecular Patterns (PAMPs) initiates Pattern-Triggered Immunity (PTI), contributing to the plant's ability to recognize and respond to potential threats. Volatile Organic Compounds (VOCs) play roles in direct defense, signaling, and attracting beneficial organisms. Allelopathy, the release of chemicals affecting nearby plants, can contribute to disease resistance by inhibiting pathogen growth. Antimicrobial Peptides (AMPs) directly interact with and destroy a range of microorganisms, enhancing plant defense. This review will refine our knowledge about comprehensive understanding of plant diseases, resistance mechanisms, and their ecological implications are vital for sustainable agriculture, food security, and environmental health.

Keywords: *System Acquired Resistance (SAR), Antimicrobial Peptides (AMP), allelopathy, volatile organic compound (VOC), productive ecosystem and sustainable agriculture.*

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INTRODUCTION

Plant diseases refer to any abnormal condition affecting plants, leading to a disruption of their normal structure or function. These diseases can be caused by various pathogens, including fungi, bacteria, viruses, nematodes, and other microorganisms (Agrios, 2005; Ali et al., 2022a; & Safi et al., 2022). Additionally, abiotic factors such as environmental stress, nutrient deficiencies, and pollution can also contribute to plant diseases (Ali et al., 2022b; Zaib et al., 2023). There are different types of plant diseases, and they can manifest in various ways, including wilting, discoloration, lesions, stunted growth, and even death. Plant diseases can have significant economic and ecological impacts, affecting crop yields, food security, and natural ecosystems (Chase, 1987).

Understanding the importance of plant diseases is crucial for several reasons, as these diseases can have significant implications for agriculture, food security, and the overall health of ecosystems (Ali et al., 2022c; & James, 1974). Plant diseases can lead to reduced crop yields and quality, affecting the quantity and nutritional value of harvested produce. This has direct implications for global food security, as many communities rely on crops for sustenance (Sharma et al., 2017). Plant diseases result in economic losses for farmers and agricultural industries due to reduced productivity, increased input costs for disease management, and potential market losses. Plant diseases can disrupt natural ecosystems by affecting the health of wild plant species (James, 1974).

This, in turn, can impact the diversity and balance of ecosystems. Plant diseases can restrict international trade in agricultural products, as countries implement quarantine measures to prevent the spread of pathogens (Oerke, 2006). The introduction of exotic plant diseases to new regions can have severe consequences for local agriculture and ecosystems (Slusarenko et al., 2012). Plant diseases drive research and innovation in plant pathology, leading to the development of disease-resistant crop varieties, effective management strategies, and sustainable agricultural practices. Some plant diseases are associated with environmental changes, such as deforestation, climate change, and pollution, contributing to broader ecological issues (Ali et al., 2022d; & Ali et al., 2023).

Disease resistance in plants refers to the ability of a plant to withstand or overcome infection by pathogens, such as fungi, bacteria, viruses, nematodes, and other harmful microorganisms (Clair, 2010). This resistance is often a result of complex interactions between the plant and the pathogen, involving genetic, biochemical, and physiological factors (Hammond-Kosack & Jones, 1997). Plants can exhibit different types of resistance mechanisms, and understanding these mechanisms is essential for developing crops with improved resilience to diseases (Flor, 1971). This type of resistance is usually controlled by one or a few major genes called vertical resistance and often lead to complete immunity against specific strains of pathogens. Examples include the resistance conferred by the R (resistance) genes in plants against certain races of pathogens. Vertical resistance is often specific to particular pathogen strains. Horizontal resistance involves multiple genes and provides a broader, partial resistance against a wide range of pathogen strains (Clair, 2010). It is a more durable form of resistance as it is less likely to be overcome by new pathogen races. Quantitative resistance is typically controlled by the cumulative effect of several genes, each contributing to a small degree of resistance (Flor, 1971)

The importance of disease resistance in plants is multifaceted and plays a crucial role in ensuring global food security, sustainable agriculture, and environmental health (James, 1974). Disease-resistant plants contribute to higher crop yields by minimizing the impact of pathogens on growth, development, and productivity. Improved crop quality is often associated with disease resistance, ensuring that harvested produce meets desired standards (Hammond-Kosack & Jones, 1997). Disease-resistant crops can reduce the reliance on chemical pesticides, promoting environmentally friendly and sustainable agricultural practices. This is particularly important for minimizing negative impacts on ecosystems and human health. Disease-resistant crops help mitigate economic losses for farmers by maintaining higher yields and reducing the costs associated with disease management (Mundt, 2014). Enhanced agricultural productivity contributes to the economic stability of farming communities.

Disease-resistant crops contribute to global food security by ensuring stable and reliable crop production, even in the presence of various pathogens (Slusarenko et al., 2012). This is essential for meeting the nutritional needs of a growing world population. Reduced reliance on chemical pesticides in disease-resistant crops contributes to the conservation of natural ecosystems and biodiversity. It helps maintain a healthier balance in agro ecosystems (Brown, 2015). Disease-resistant plants are a key component of sustainable agriculture, aligning with principles of environmental stewardship and long-term resource management (Mundt, 2014)

Physical Barriers in Disease Resistance of Plants

(i) Cell wall: Plants with stronger cell walls made of lignin and suberin form physical barriers that prevent the entry of pathogens (Barros et al., 2015; & Ali et al., 2021). Callose, a β-1,3-glucan, is deposited to reinforce cell walls and prevent pathogen entry (Ellinger & Voigt, 2014; & Malinovsky et al., 2014).

(ii) Trichomes: Plant surfaces have hair-like structures called trichomes, which are essential for defence. By acting as physical barriers, these structures keep pathogens from getting to delicate tissues (Wagner et al., 2004). Trichomes secrete secondary metabolites like terpenoids, which improves their ability to defend (Liakoura et al., 1997).

(iii) Cuticle thickness: The waxy layer that covers aerial surfaces of plants, known as the cuticle, serves as a hydrophobic barrier to keep pathogens out (Yeats & Rose, 2013). Thickness variations affect the cuticle's ability to function as a physical barrier, with thicker cuticles offering greater resistance (Chen et al., 2023).

(iv) Stomatal defense: The microscopic pores on the surface of leaves, called stomata, are possible entry points for pathogens. Plants use an intricate stomatal defense system to combat this vulnerability (Lawlor et al., 2012). When a pathogen is recognized, stomata close, limiting access and preventing the spread of illness (Melotto et al., 2006).

(v) Periderm formation: Periderm formation in woody plants acts as a barrier in the event of damage or infection. By taking the place of the epidermis, this corky tissue creates a barrier that keeps pathogens from penetrating deeper tissues (Heath, 2000). Suberin and lignin build up during the process, improving the material's resistance characteristics (Chakraborty et al., 2016) .

(vi) Formation of papillae: Papillae are tiny, localized plant cell wall outgrowths that appear where a pathogen has tried to enter the plant (Underwood, 2012). Infected plant cells may develop papillae, the formation of papillae involves the deposition of additional cell wall material that physically prevent the entry of pathogens (Faulkner & Robatzek, 2012).

(vii) Hydrophobic Surface Coatings: Certain plants develop hydrophobic surfaces that inhibit the adherence and mobility of pathogens. Water droplets that bead up and roll off the leaves may carry away spores, preventing germination and infection (Riederer & Schreiber, 2001).

(viii) Silica Deposition: Herbivores and infections are discouraged by the abrasive barriers created by silica deposition in plant tissues, such as grasses (Riaz et al., 2022a; Ma & Yamaji, 2006; & Currie & Perry, 2007).

(ix) Callose Deposition in Plasmodesmata: The accumulation of cellulose in plasmodesmata can stop viruses from spreading among plant cells (Zavaliev et al., 2011).

Chemical defense mechanisms of Disease resistance in Plant

(i) Antimicrobial proteins: Production of fungal cell wall-rupturing enzymes, such as glucanases and chitinases. Pathogens are directly combated by antimicrobial proteins. For instance, tiny cationic peptides called plant defenses damage microbial membranes (Van der Weerden & Anderson, 2013). A direct defense mechanism is provided by certain antimicrobial proteins, such as chitinases and glucanases, which break down the cell walls of bacteria and fungus (Kubicek et al., 2014; & Durrant & Dong, 2004). Certain antimicrobial proteins possess antiviral properties, functioning to neutralize viral particles or disrupt the viral life cycle (Kumar, 2019). In order to ensure a coordinated defense response, antimicrobial proteins frequently interact with other defense pathways, such as effector-triggered immunity (ETI) and pattern-triggered immunity (PTI) (Jones & Dangl, 2006).

By inhibiting the growth of specific microorganisms, AMPs can affect the microbiome composition of plants. This modulation helps support disease resistance by maintaining a healthy, well-balanced microbial community (Martin et al., 2003). The integrity of microbial cell membranes is compromised by numerous AMPs. They can produce holes or channels in the membranes, which allows vital cell components to seep out and ultimately results in the pathogen's cell death. Certain AMPs, particularly those with enzymatic activity, have the ability to break down the bacterial and fungal cell walls (Van et al., 1998). AMPs weaken the pathogen's cell wall integrity by focusing on its structural elements, leaving it more vulnerable to other defense mechanisms. A few AMPs disrupt the pathogens' machinery for synthesising proteins. These proteins interfere with the pathogen's capacity to synthesise vital proteins for survival and replication by targeting ribosomes or other elements involved in protein synthesis (Van Der Biezen & Jones, 1998). Certain AMPs have the capacity to attach themselves to pathogen nucleic acids, such as DNA or RNA. Through this interaction, transcription and translation processes may be inhibited, which would ultimately stop the infection from replicating (Lacerda et al., 2014).

(ii) Phytoalexins: These are antimicrobial compounds synthesized in response to pathogen attack. Examples include resveratrol in grapes and pisatin in peas (Dixon & Paiva, 1995). Phytoalexins frequently exhibit direct antimicrobial activity against a variety of pathogens, such as bacteria, viruses, and fungi. They prevent the invasive pathogens from proliferating and developing (Dixon & Paiva, 1995). Certain phytoalexins help to strengthen plant cell walls, which increases the difficulty of pathogens entering plant tissues. One of the most important components of plant defense is this physical barrier (Naoumkina et al., 2008). By interfering with the cellular functions of pathogens, phytoalexins can be toxic to them. They could impede necessary enzymes, damage the integrity of the pathogen's membrane, or interfere with other critical processes (Pedras & Yaya, 2015). The synthesis of additional antimicrobial compounds and the up regulation of defense-related genes are two additional defense responses that are frequently linked to the production of phytoalexins. Jeandet et al. (2013) reported that plants that have acquired resistance (SAR), in which the entire system of the plant becomes more resilient to subsequent pathogen attacks, may benefit from phytoalexins. This entails eliciting defensive reactions in distant tissues (Mysore & Ryu, 2004). The production of phytoalexins is strictly controlled at the genetic level. Knowing the genetic regulation of phytoalexin synthesis sheds light on how plants synchronize defense mechanisms (Macoy et al., 2015). The variety of phytoalexins produced by different plant species adds to the adaptability of plant defense mechanisms against a broad spectrum of pathogens (Pedras & Yaya, 2015).

(iii) Hormonal Signaling: Induction of systemic acquired resistance (SAR) through signaling molecules like salicylic acid, which activates defense responses (Pieterse et al., 2012). One of the main defense mechanisms for plants against bio trophic pathogens is salicylic acid. It causes systemic acquired resistance (SAR), which protects against further pathogen attacks by creating a state of increased defense readiness outside of the infection site (Vlot et al., 2009). Jasmonic acid is linked to protection from herbivores and necrotrophic pathogens. It controls the expression of genes that produce protease inhibitors, antimicrobial compounds, and other proteins related to defense (Wasternack & Hause, 2013). Ethylene is involved in the regulation of various defense responses, including the induction of modulation of cell wall composition and induction of pathogenesis-related (PR) proteins. It frequently works in concert with Jasmonic Acid signalling pathways to precisely control the plant's defensive reactions (Pieterse et al., 2012). Known for its part in stress reactions, abscisic acid (ABA) interacts intricately with the signaling pathways of ethylene, salicylic acid, and jasmonic acid. Depending on the situation, it can either strengthen or suppress defense reactions, helping to maintain a balance between growth and defense (Ton et al., 2009). Auxins are involved in defense reactions in addition to their well-known function in plant growth and development. By adjusting the ratio of defense to growth, they can affect how a plant interacts with a pathogen (Kazan & Manners, 2009). By controlling the expression of genes linked to defense and modifying the actions of other hormones, brassinosteroids contribute to the improvement of plant immunity. They help make plants resistant to a range of diseases (Belkhadir et al., 2012).

(iv) Strengthening of cell wall: Pathogens frequently try to penetrate cell walls when they are infected. Plants use the deposition of lignin, callose, and other strengthening substances to strengthen their cell walls (Voxeur & Höfte, 2016). The plant cell's structural strength comes from the stiff network of cellulose micro fibrils in the cell wall. As the first line of defense, this physical barrier keeps pathogens out of plant cells (Malinovsky et al., 2014). Plants have the ability to store callose, a β-1,3-glucan polymer, in their cell walls in reaction to pathogen invasion. By strengthening the cell wall and functioning as a physical barrier, cellulose deposition prevents infections from spreading (Showalter, 1993). A complex polymer called lignin can be deposited in the cell wall to increase its resistance to pathogen degradation (Voxeur & Höfte, 2016). Lignification strengthens cell walls and offers more defenses. The enzymes known as Xyloglucan Endotransglucosylases/Hydrolases (XTHs) and expansions are involved in the remodelling of cell walls (Bellincampi et al., 2014). Cell walls can be altered during an infection to prevent the pathogen from moving as much and to strengthen the physical barrier (Underwood, 2012).

(v) Pathogenesis-related (PR) proteins: Plants produce a class of proteins known as pathogenesis-related (PR) proteins in reaction to pathogen invasion. These proteins are essential to plants' defense mechanisms against illness. Numerous PR proteins have direct antibacterial action on pathogens (Jain & Khurana, 2018). For instance, some PR proteins, like chitinases and glucanases, have the ability to break down the bacterial and fungal cell walls, which helps to prevent the spread of pathogens. The plant cell wall is strengthened in part by certain PR proteins (Saboki Ebrahim & Singh, 2011). In order to build a physical barrier against pathogen invasion, this reinforcement is necessary. Plant cells become more resistant to pathogen penetration when more cell wall material is deposited, which is facilitated by PR proteins (Loon et al., 2006). Certain components of pathogen cell walls are hydrolyzed by enzymes belonging to the PR protein family, such as glucanases and chitinases. The pathogen's ability to infect plant tissues is hampered by this hydrolysis, which erodes the pathogen's structural integrity (Dangl & Jones, 2001). At the site of infection, certain PR proteins play a role in triggering programmed cell death (PCD). PCD sometimes referred to as the hypersensitive response (HR), is a defense mechanism that eliminates diseased plant cells to stop infections from spreading.

This aids in infection containment by reducing the pathogen's resources (Linthorst & Van Loon, 1991). Some PR proteins function as signal molecules in the initiation of systemic acquired resistance (SAR), especially those that are induced by salicylic acid (SA). They support the plant's overall defense mechanism and get it ready for any future pathogen attacks (Jain & Khurana, 2018). Certain pathogen-produced compounds are detoxified by certain PR proteins. These proteins aid the plant in withstand the deleterious effects of molecules derived from pathogens by neutralizing or breaking down harmful compounds. The defense against viral infections involves PR proteins (Ebrahim & Singh, 2011). Research is currently being conducted to determine the precise function of PR-1 proteins in antiviral defense, as they are known to accumulate in response to viral pathogens (Edreva, 2005). PR proteins are frequently linked to other defense mechanisms, including effector-triggered immunity (ETI) and the identification of pathogen-associated molecular patterns (PAMPs) (Jain & Khurana, 2018).

(vi) Secondary metabolites: Secondary metabolites with antimicrobial qualities, such as phenolics, terpenoids, and alkaloids, are produced by plants. For example, tobacco's alkaloids function as a defense against infections (Wink, 2003). Flavonoids and tannins are examples of phenolic compounds that support plant defense by serving as antioxidants and preventing the growth of pathogens. Plant cell walls are a common place to find them (Nicholson & Hammerschmidt, 1992).

Alkaloids, like quinine and nicotine, are produced by plants and are toxic to infections. For instance, nicotine is a neurotoxin to insects (Ye et al., 2019). Antimicrobial properties are possessed by essential oils and other terpenoids. When a pathogen attacks, certain terpenoids function as signaling molecules that activate defense mechanisms (Dixon & Paiva, 1995). Plants produce glycosides, which when attacked by pathogens can decompose into toxic compounds. For example, cruciferous plants use their glucosinolates to protect themselves from infections and herbivores (Papadopoulou et al., 1999). Lignin serves mainly as a structural element, but it also offers defense against microbial invasions. It fortifies cell walls, increasing their resistance to pathogen degradation (Zaib et al., 2023; & Wink, 2003).

(vii) Systemic Acquired Resistance (SAR): Plants can acquire broad-spectrum, persistent resistance known as systemic acquired resistance (SAR) after being exposed to specific pathogens or their byproducts (Durrant & Dong, 2004). The plant immune system relies heavily on SAR, which gives plants a higher level of preparedness to fight off a variety of infections. When a pathogen or any of its constituents are introduced to a plant, defense mechanisms are activated both locally at the site of infection and systemically throughout the entire plant. This process is known as self-defense reaction (SAR) (Fu & Dong, 2013).

Plant cells are primed through SAR to activate defense mechanisms more quickly and forcefully in the event of a pathogen attack. The plant can react to possible threats more skillfully when it is primed (Kamle et al., 2020). The movement of signaling molecules throughout the body is linked to SAR; these signals are also known as "mobile signals" or "systemic signals." One of the main signaling molecules in SAR is salicylic acid (SA), which travels from the infection site to other areas of the plant and triggers a systemic response (Durrant & Dong, 2004). Throughout the plant, SAR causes the up regulation of a number of genes linked to defense. These genes encode proteins involved in the synthesis of antimicrobial compounds, cell wall reinforcement, and hypersensitive response (HR) activation, among other defense mechanisms (Ryals et al., 1996). SAR offers defense against a wide range of pathogens, such as viruses, fungi, and bacteria.

Since the generated defense reactions are not pathogen-specific, SAR is a flexible and potent defensive tactic against a range of microbial threats. After undergoing SAR, plants "remember" the pathogens they were previously exposed to (Fu & Dong, 2013). When the same or related pathogens re-infect the plant, this memory enables it to react to those infections more swiftly and efficiently. Other plant defense mechanisms, such as Effector-Triggered Immunity (ETI) and Pattern-Triggered Immunity (PTI), are linked to SAR. An effective and well-coordinated immune response is facilitated by the communication amongst these defense pathways (Kamle et al., 2020). Through the provision of a systemic defense mechanism that can offer protection against a range of pathogens for an extended period of time, SAR improves the overall fitness and adaptability of plants (Durrant & Dong, 2004)

(viii) Recognition of Pathogen-Associated Molecular Patterns (PAMPs): A key element of the plant immune system is the recognition of Pathogen-Associated Molecular Patterns (PAMPs), which is a component of PAMP-triggered immunity (PTI), the first line of defense (Akira & Hemmi, 2003). The ability of a plant to identify pathogen-associated molecular structures is essential for disease resistance. Upon identifying PAMPs, a plant initiates a sequence of signaling reactions that culminate in the initiation of diverse defense mechanisms (Zipfel, 2014). Reactive oxygen species (ROS), defense-related genes being triggered, and the creation of antimicrobial compounds are examples of these reactions (Nürnberger & Kemmerling, 2009). Pattern Recognition Receptors (PRRs) are specialized receptors found in plants that are able to identify PAMPs.

Plant cell surfaces are home to PRRs, which have the ability to attach to pathogens' conserved molecular patterns (Postel & Kemmerling, 2009). An essential first step in PAMP-triggered immunity activation is this recognition. Various PRRs identify particular PAMPs linked to various pathogen kinds. Because of this specificity, plants are able to adjust their defense mechanisms according to the kind of pathogen they come across (Macho & Zipfel, 2014). Fungal chitin, bacterial flagellin, and other conserved motifs in pathogens are examples of common PAMPs. Systemic acquired resistance (SAR), a type of long-lasting, broad-spectrum resistance that readies the entire plant for upcoming pathogen attacks, can be induced by PAMP recognition (Akira & Hemmi, 2003). Systemic defense mechanisms beyond the initial infection site are activated as part of SAR.

When PAMPs are recognized, defense mechanisms are frequently triggered, which directly inhibits the growth and development of pathogens. At the site of infection, this can involve the initiation of hypersensitive response, the reinforcement of cell walls, and the synthesis of antimicrobial compounds. Effector Triggered Immunity (ETI), a different layer of plant immunity, is linked to PAMP recognition (Nürnberger & Kemmerling, 2009). Effective delivery of effectors—molecules that weaken host defenses by the pathogen to the plant cell may enable the plant to identify these molecules and mount a more focused and potent immune response (Zipfel, 2014). An essential component of the plant's capacity to identify and react to possible pathogens is the recognition of PAMPs. Plants that use this multi-layered defense system are better able to withstand a variety of diseases and adjust to changing environmental conditions (Macho & Zipfel, 2014)

(ix) Volatile Organic Compounds (VOCs): Plant defense against disease is significantly influenced by volatile organic compounds. Plants release these chemicals into the atmosphere, and they can serve a number of purposes, such as direct defense against pathogens and signaling (Possell & Loreto, 2013). VOCs can be released by plants in reaction to pathogen invasion. These volatile organic compounds (VOCs) act as signaling molecules, informing nearby plants when pathogens are present (Liu et al., 2020). Plants in the vicinity may activate defense mechanisms as a result of this communication, readying them for possible threats. Certain volatile organic compounds (VOCs) released by plants attract natural enemies of pathogens or herbivores. Plants have an indirect defense mechanism in which they can attract predators or parasitoids that feed on herbivores or pathogens by releasing certain compounds (Srikamwang et al., 2023).

A few volatile organic compounds (VOCs) have direct antimicrobial qualities and can stop the spread of pathogens. These substances help the plant fight off a range of illnesses by having the ability to combat a wide range of microorganisms (Niinemets & Monson, 2013). VOCs can prime plants to mount more effective defenses. Plants that are exposed to specific volatile compounds may develop a state of readiness that will help them react to upcoming pathogen attacks more quickly and skillfully. Additionally, VOCs are involved in intra plant communication (Maffei et al., 2011). They have the ability to transfer signals between various plant sections, enabling the activation of defense mechanisms in distant plant tissues and a systemic response to pathogen infection (Maffei et al., 2011). Additionally, VOCs are involved in intra plant communication. They have the ability to transfer signals between various plant sections, enabling the activation of defence mechanisms in distant plant tissues and a systemic response to pathogen infection (Niinemets & Monson, 2013).

(x) Allelopathy: Allelopathy is a biological phenomenon in which a plant releases chemicals into its surroundings that have the ability to affect the germination, growth, or development of other plants in the area (Rice, 2012). Allelopathy can contribute to plant disease resistance even though it is frequently linked to resource competition (Farooq et al., 2011). Certain plants emit compounds called allelochemicals that have antimicrobial qualities. These substances offer a type of chemical defense against illnesses by preventing the development and activity of plant pathogens (Rice, 2012). Allelopathic substances have the ability to impede the germination and development of pathogenic microorganisms, thereby restricting their colonization and dissemination. Given that the compounds are released into the soil in the rhizosphere, this may be particularly important (Halbrendt, 1996). Plants that are exposed to allelopathic substances have the ability to express genes linked to defense. By triggering a variety of defense mechanisms, this stimulation of plant defense pathways improves the capacity of plants to withstand diseases (Blum & Blum, 2011). Plant-released allelopathic compounds have the ability to affect the make-up and activity of soil microbial communities.

This may result in alterations in the population of advantageous microorganisms that aid in suppression of disease and lessen the favorable conditions for the growth of pathogens (Riaz et al., 2022c; & Blum & Blum, 2011). The decrease of pathogen inoculum in the soil or on plant surfaces may be facilitated by allelopathy. Plants can lower the likelihood of disease outbreaks by reducing the presence of pathogens (Riaz et al., 2022b).

(xi) Antimicrobial Peptides: Antimicrobial peptides are essential for plants to defend themselves against infections. These peptides are small, amphipathic, cationic molecules that have the ability to directly interact with and destroy a variety of microorganisms, such as viruses, fungi, and bacteria (Bahar & Ren, 2013). Pathogenic microorganisms' membranes can be directly targeted by antimicrobial peptides, which can cause cell lysis. Plants are able to repel pathogen invasions thanks to this direct antimicrobial action (Izadpanah & Gallo, 2005). At the site of infection, certain antimicrobial peptides cause plant cells to undergo programmed cell death. The hypersensitive response (HR), which is characterized by localized cell death, aids in limiting the pathogen's ability to spread and increases overall disease resistance (Izadpanah & Gallo, 2005).

Antimicrobial peptides have the ability to alter a number of signaling pathways connected to defense responses in plants**.** To strengthen the plant's resistance to infections, they could turn on genes linked to defense, produce reactive oxygen species (ROS), and affect other signaling molecules (Lacerda et al., 2014). AMPs frequently cooperate with other defense mechanisms, like secondary metabolite synthesis and plant immune system activation. This partnership offers a strong, multi-layered defense against various pathogen kinds (Bahar & Ren, 2013; & Zeeshan et al., 2023). The ability of plants to adapt to shifting environmental conditions and pathogen diversity is facilitated by antimicrobial peptides. They are an active and adaptable part of the plant defense armament (Lacerda et al., 2014).

CONCLUSION

For sustainable agriculture, environmental health, and global food security, it is essential to understand and utilize plant disease resistance. A strong plant immune system is a result of a variety of tactics, including chemical defense mechanisms, physical barriers, systemic acquired resistance, and the identification of molecular patterns linked to pathogens. Disease-resistant plants are essential for attaining resilient and sustainable agricultural practices because they increase crop yield, lessen the need for pesticides, and maintain ecological equilibrium.

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