REVIEW ARTICLE

The Impact of Antimicrobial Proteins on Plant Defense Strategies

Dipanshu Kumar Vishwas*

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Abstract

Antimicrobial proteins (APs) are short polypeptides and have an important piece of the innate defense network present in all lifeforms, including microbes, arthropods, animals, and plants. Our literature survey revealed that APs have an inherent immunological reaction in several creatures, including humans, but there is little knowledge on how they act as defense mechanisms in plants. As a result, the goal of this study is to the advancement of our understanding of how these plant peptides function as an immunological defense at the molecular level in plants. Thus, our research revealed how the anxious message created by the biological risk is recognized by plant cells and then eventually transformed into an effective defensive action. Moreover, APs might kill pathogenic microbes, fungi, and viruses, and promptly eradicate antibiotic-mediated multidrug-resistant infections. Further, our finding with these tiny peptides gives quick, regulated, and long-lasting immunity to a wide range of pathogenic organisms via stimulation of Ca^{2+} influx, reactive oxygen and nitrogen species generation, and activation of MAPK cascade for the expression of APs genes and also plant defense hormones, assure plant survival in nature. Therefore, it may be concluded that APs might be used as an admirable weapon for protecting plants from different infections and recommend a bright future in agricultural and therapeutic studies.

Keywords: Antimicrobial Proteins, Pathogenic agents, MAPK cascades, Phytohormones, Plant immunity.

Highlights

- Antimicrobial Proteins (APs) greatly impact on plant immunity
- APs eliminate antibiotic-mediated multidrug-resistant infections
- APs act as antibacterial, antifungal, and antiviral agents
- APs destroy their target physically or/and through MAPK cascades mechanism

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Introduction

Antimicrobial proteins (APs) are a piece of the innate defense network inborn in practically all lifeforms, including microbes, arthropods, creatures, and plants, and they play an essential role in pathogen defense (Hassan *et al.,* 2022). Generally, APs are a few particles of polypeptides (generally 12 -50 amino acids) produced by ribosomes, and non-ribosomal peptide synthetases can regulate some of them (Hurtado-Rios *et al.,* 2022). These peptides have a significant piece of the inborn defense response to infectious particles in humans and other animals, and thus they act as the first line of defense against numerous pathogenic microbes (Zhang and Gallo, 2016). They differ from species to species and generally are positively charged with amphipathic molecules. As a result, they often target several locations on the lipid membrane of the pathogens, with modest cytotoxicity to animals, including humans (Lei *et al.,* 2019).

Moreover, plants are a potential resource for APs, which have antibacterial efficacy on both human and plant infections. These are thought to be created at distinct locations of plants, such as leaves, roots, seedlings, petals, and shoots (Li *et al.,* 2021). Plant APs are thought to have an impact not only on plant defense against infections but also on plant growth and development. Thus, our numerous literature searches revealed that antimicrobial proteins have an inherent immunological response in several animals, including humans but there is little knowledge on how they act as defense mechanisms in plants. As a result, the goal of this study is to advance our understanding of how these plant peptides function as an immunological defense at the molecular level in plants.

Department of Botany, Brahmananda Keshab Chandra College, Bon-Hooghly, Kolkata, West Bengal, India.

***Corresponding author:** Dr. Dipanshu Kumar Vishwas, Assistant Professor, Department of Botany, Brahmananda Keshab Chandra College, Bon-Hooghly, Kolkata, West Bengal, India., Email: dipanshu.sls@gmail.com

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Plant Antimicrobial Proteins

APs are a type of polypeptides found throughout species that is essential in the inbuilt defense systems of different animals. In both plants and animals, they exhibit a broad spectrum of detrimental impacts on microbes, fungal and parasitic organisms, and viruses. Just one species may contain several APs having positively charged molecular masses that vary from 2 to 10 kilodaltons. These peptides have 4-12 molecules of cysteine that form disulfide bonds, which makes them extremely stable by stabilizing their three-dimensional structures. Xiao *et al.* (2011) extracted the shortest known AP with seven amino acids (Lys-Val-Phe-Leu-Gly-Leu-Lys). They are categorized as peptides having either positively or negatively charged and are often classified primarily on sequence likeness, the presence of disulfide motifs, and tertiary structures (Hafeez *et al.,* 2021). Since APs are less toxic and respond more efficiently in plants than fungicides (Galgoczy and Marx, 2019), thus they might be a better choice for plant pathogen management. Plants have various classes of APs such as α/β-thionins, defensins (γ-thionins), heveins, knottins, cyclotides, lipid transfer proteins, snakins, α-harpinins, 2S albumins, and short non-disulfide rich peptides/ glycine-rich proteins.

Plant antimicrobial proteins are the first line of defense against infections caused by pathogenic bacteria. They might possess various structures and action modes. *Thionins* are categorized into five categories with sizes ranging from 45 to 48 amino acids in both monocots and dicots. There are two different superfamilies: α/β-thionins and γ-thionins. α/β thionins share homologous amino acid sequences with significant quantities of arginine, cysteine, and lysine. γ-thionins are equivalent to defensins. Thionins exhibit a wide range of actions. They kill Gram-positive and Gram-negative bacteria, yeast, fungi, insect larvae, and nematodes and exhibit cytotoxic impacts on mammalian cells in vitro (Taveira *et al.,* 2017). *Defensins* may contain 45-54 amino acids and four disulfide bonds, having an antiparallel β sheet and an α-helix constrained by intrinsic disulfide bonds named cysteine-stabilized αβ motifs (Gao and Zhu, 2021). *Hevein*-like peptides may have 29-45 amino acids, containing six-glycine, eight-ten-cysteine, and aromatic residues. Antifungal action is linked to a chitin-binding domain, whereas 3-5 disulfide bonds strengthen antiparallel β-sheets and a short α-helix. Three aromatic amino acids anchor the hydrophobic C-H group, the π electron chain dictates van der Waals forces, and the hydrogen bonds between serine and N-acetylglucosamine promote chitin interaction (Slavokhotova *et al.,* 2017). *Knottins* referred to as "cysteine-knot peptides," are composed of 39 amino acids (six of which are cysteine residues), three disulfide bridges (cysteine-knot motifs), and can exist in two conformations (cyclic and linear). They are thermally stable and resistant to proteolysis, preventing α-amylase, trypsin, carboxypeptidase, and cysteine protease (Hellinger and Gruber, 2019). *Cyclotides* are macrocyclic and contain cyclic cystine knot structural motif sequences. Disulfide bonds support the head-to-tail helix. They are divided into two subfamilies: Mobius and Bracelet. Their function is based on the cystine knot structural motif, enhancing hydrophobic residue surface contact, with some forming a hydrophobic patch (de Veer *et al.,* 2019). *Snakins* are tiny (~7 kDa), cysteine-rich, positively charged proteins with antibacterial, antinematode, and antifungal actions (Rogozhin *et al.,* 2018). Lipid transfer proteins are tiny, cysteine-rich peptides of 100 amino acids with 4 to 5 helices held together by hydrogen bonds. They may transport lipids across membranes, create holes, and establish cell death (dos Santos-Silva *et al.,* 2020). Further, the overview of plant APs classification and its specific role in immune function are provided in Table 1.

Plant's Defense in Relation with Antimicrobial Protein

The networks constitute the barrier of protection necessary for the existence of plants, known as "plant immunity." Because of their potential function in plant survival, plant APs are becoming an increasingly popular area of research in agronomical and pharmacological domains. The biological processes involved in

Table 1: List of antimicrobial proteins and their specific role as immune function against various microbial agents

Classification of Plant Antimicrobial Proteins	*Role as Immune Function*	*References*
α/β-thionins	Association with lipids in membranes leads to a surge in the permeability of cells and destruction.	Taveira *et al.,* 2017
Defensins (γ-thionins)	Contact with particular membrane elements induces intracellular signaling cascades that inhibit infection advancement. It can also prevent the function of insect digesting enzymes.	Lima *et al.,* 2022
Heveins	Limit the growth of bacteria and fungi by interacting with the mechanisms responsible for microbial cellular wall synthesis and toxicity. In addition, by acting as allergens, they boost protection against large mammals.	Tam *et al.,* 2015
Knottins	Bind to various molecular targets including microbial membrane and intracellular components. Also work as α-amylase or protease inhibitors.	Moore *et al.,* 2012
Cyclotides	Can disrupt the cell membranes of specific pathogens, interact with specific membrane lipids to internalize into the target cells to altering the activity of internal cellular components and alter the physiological features of arthropod digestive systems.	da Silva Lima *et al.,* 2017
Lipid transfer proteins	Potentially interact with membranes of microbes to 'cage' their fatty acids in the peptide lipid-binding site. Such interactions may decrease membrane integrity and enhance permeability.	dos Santos-Silva *et al.,* 2020
Snakins	Capacity to disrupt microbial membranes is ruled out due to their inability to interact with artificial lipid membranes.	Rodriguez *et al.,* 2018
α-harpinins	Present antibacterial and trypsin inhibitory action.	Tam *et al.,* 2015
2S albumins	Present antimicrobial and allergenic properties.	Maria-Neto *et al.,* 2011
Short non-disulfide rich peptides/ Glycine-rich proteins	Interact with many targets, including the microbial cell surface, internal cell structures, and nuclei, to influence pathogen metabolism.	Santana *et al.,* 2015

microbes' identification and stimulation of appropriate response mechanisms have been widely studied in plant immunity research. The plant immune structure is often referred to as a group of threat-recognition systems in which a stimulus from an anxious situation is identified and transformed by signaling molecules to trigger the necessary defense responses. In response to this theory, biological stresses create threat signals that are primarily detected by plant membrane-based pattern-recognizing receptors able to determine microbial-associated molecular patterns, which may generate variable inhibitory proteins that might be manufactured across the infection sites to boost virulence by imitating or hindering plant cellular processes (Li and Wu, 2021). Plants employ disease-fighting antimicrobial molecules to accurately identify infectious agents and stimulate stronger defensive reactions to cause hypersensitive cellular death at the spot of contamination to mitigate the effect of pathogenicity. In contrast, there is a plethora of information on spotting invaders and triggering plants' immunity. Antimicrobial peptides are one of the most significant universal chemical shields used to defend against infectious agents (Diamond *et al.,* 2009).

Moreover, the short peptides in the range of 100 amino acids of APs can be produced from inactive precursor protein zymogens. Most AP genes exhibit an "acclimation to infection" response, with its enhanced level of proteins in response to pathogens' attack, and overexpression of this gene is linked with greater resistance to infections (Zhang *et al.,* 2021). Furthermore, it has been established that APs operate as barriers to defense in their modes of action, enabling plants to use them as weapons against a wide range of bugs and infectious agents (Manniello *et al.,* 2021). These tiny peptides are defensive and provide immediate and long-lasting immunity to biological stress. This review will emphasize recent improvements in our knowledge of the importance of APs in plant immunity.

The capability of plant APs to function over a wide range of challenges is based on their varied mode of action and exceptional strength in structure. Plant APs are becoming a popular field of investigation because of their importance in helping plants to grow. However, APs are claimed as possible antibacterial and antifungal agents used in farming (Lobo and Boto, 2022). Therefore, microbes targeted by APs may serve as antifungal and antiviral APs. To eliminate infectious agents, APs specifically target and breach the cell membrane, while only a few APs may penetrate the cytosol, disturbing cellular physiological functions (Rahnamaeian *et al.,* 2015). AP membrane-targeting methods might be described using carpet, toroidal pore, and barrel-stave models (Benfield and Henriques, 2020).

The plant APs do not vary structurally from those found in animals. The expression of several plant and animal peptides in plants imparts both bactericidal and fungicidal activity (Iqbal *et al.,* 2019). Molecular synergy demonstrates that APs work with other antibacterial substances to destroy bacteria. Plant APs 2S albumins with thionins suppress the fungal growth, resulting in a 2- to 73-fold increase in lethal impact relative to a single AP (Terras *et al.,* 1993). Similarly, APs across diverse species have been determined in the elimination of bacteria, fungi, and parasites (Huan *et al.,* 2020). Additionally, APs have a synergistic effect with other antibiotics and fungicides. A combined action of APs may significantly decrease the overall number of particles necessary to destroy the infection. This suggests that using APs in the defense of plants might reduce the usage of farming-associated antibiotics and fungicides and reduce the total expense of cultivation. Furthermore, the combined impact of APs can slow drug-resistant progression and extend the life of agricultural pesticides (Maron *et al.,* 2022). Moreover, targeting different pathogen growth stages might result in a combined lethal impact. While, the majority of agricultural antibiotics, along with fungicides, depend only on infections during their growth stage, not the non-growing period. A prior study has shown that APs destroy non-germinating spores of fungi (Velivelli *et al.,* 2020), which can significantly inhibit the spread of diseases. APs might be employed as sporicidal agents to prevent plant infection from spreading and maintain farmers' health. Thus, APs have the potential to work together with different antimicrobials by reducing air spores and limiting infection rates and health hazards among farmers. APs also serve a crucial function in regulating interactions with microbes within legumes. Such antimicrobial proteins might both sustain and destroy the survival of nitrogen-fixing bacteria. During the root nodule's initial phase, lethal APs destroy most infectious molds and bacteria yet maintain symbiotic bacteria within the roots. Various cysteine-rich polypeptides peculiar to nodules are discharged into the roots of legumes to manage the growth of nitrogen-fixing bacteria (Van de Velde *et al.,* 2010).

Antimicrobial Proteins vs Antibiotics

Antibiotics have always had key roles in preventing microbial infections in humans, maintaining adequate nutrition, and increasing livestock productivity. However, the emergence of multi-drug resistance due to the overuse of antibiotics poses a significant risk to human health (Llor and Bjerrum, 2014). Multidrug-resistant microorganisms have expanded significantly over the globe causing increased infections and death rates along with huge societal costs. The limited occurrence of newly discovered antibiotics, along with the rapid development of resistance to conventional antibiotics, emphasizes the demand for innovative alternative therapies to antibiotics, especially antimicrobial proteins. Antimicrobial resistance is a growing worldwide health concern that makes it harder to combat bacterial illnesses (WHO, 2022). WHO studies advocate for immediate measures to prevent an antibiotic resistance catastrophe and emphasize the necessity of investigating and creating new medicines. Thus, novel drugs that are potent over infections while acquiring resistance to multiple drugs are required. To address this concern, numerous other therapies have been offered, including antimicrobial proteins, that were considered to be highly viable over two decades ago since they had lived naturally for many thousands of years with no or little resistance developed. Moreover, antibiotics are generated by secondary metabolic pathways, whereas APs are peptides synthesized through ribosomal-dependent/ -independent processes. APs kill pathogenic microbes, fungi, and viruses by a variety of methods (Huan *et al.,* 2020). Furthermore, classical antibiotics possess a broad range of activity and frequently develop drug resistance among microorganisms. Aside from direct antimicrobial action, APs also regulate the host's immune activities. Thus, APs have intriguing possibilities for replacing antibiotics in the suppression of some deadly infections that are easily resistant to antibiotics. Additionally, G3KL, a newly developed antimicrobial protein inhibits the growth of multidrug-resistant strains of *Acinetobacter* and *Pseudomonas*. Antimicrobial proteins work effectively against microorganisms that are resistant to antibiotics by damaging their cell wall (Xuan *et al.,* 2023). Thus, APs can promptly eradicate multidrug-resistant infections, and microbes have a negligible amount of resistance to them.

Biological Functions of Plant APs

APs bind directly with the microbial cell envelope or plasma membrane, disrupting its structural stability via penetration or lysis, and acting on molecular targets. They can combine with bacterial surfaces or be transported into the cell where they interact with the internal targets. APs act on their target according to the different biological infections, and they are as follows.

Plant APs as an Antiviral Agent

Few APs have been proven to serve a key role in reducing virion infections by interfering with nucleotides of cyst viruses. APs act as antiviral agents primarily by altering the virion replication pathway or by physically harming the phage envelope (Ahmed *et al.,* 2019). The exact connection between an AP and antiviral action is still under investigation. Moreover, APs' unique antiviral strategies are- to inhibit virion adhesion and invasion by interacting with virion-specific receptors on the plasma barrier of the host; they behave in the form of a "lectin-like" molecule to bind onto the phage's glycoprotein framework; they change the virion's genome by intervening with ribonucleotide combination; they also boost the concentration of the interferon or chemokine transcripts in the host (Elnagdy and AlKhazindar, 2020).

Plant APs as an Antibacterial Action

The chemical reaction between positively-charged APs and anion-rich lipid bilayer of infectious microbes is thought to be linked to antimicrobial action. Particular APs engage with the microbial cell membrane, limiting cellular wall formation which leads to cell death. Defective integrity of the lipid bilayer develops when AP binds with the anionic membrane and also interacts with specific molecular targets to inhibit the production of nucleotides and proteins (Singh *et al.,* 2022). The electrostatic attraction between the positive APs and the negatively charged lipids is the main interacting spot between the peptide and the microbe's membrane. Microbial plasma coats are rich in phospholipids and phosphatidylglycerol with anionic groups that effectively attract cationic APs (Rashid *et al.,* 2016). The advancement of investigations and the discovery of APs suggest that these peptides share a variety of models, including the barrel-stave pore, carpet mechanism, toroidal pore, and disordered toroidal pore are the most common models of AP association with the cytoplasmic barrier (Kumar *et al.,* 2018).

Yet, expanding evidence suggests that, in instead of interacting with the lipid barrier, APs may also interact with cellular locations to impair infectious microbe's basic physiological functions, resulting in antimicrobial benefits. Furthermore, APs may hamper the development of biofilm by affecting the cascade mechanism, minimizing the transcripts of binding protein transport genes; and overproduction of guanosine tetra-phosphate and penta-phosphate in microorganisms might hinder nucleic acid production. It can also damage the pre-formed biofilms by impacting the membrane potential of bacteria (Yasir *et al.,* 2018).

Plant AP as an Antifungal Action

Numerous undesirable negative effects of antifungal pharmaceuticals have made researchers aware to investigate the antifungal action of APs and seek novel options in medication. Cell destruction due to increasing fungal cytolysis, disruption of chitin wall formation, and stimulated breakdown of actin cytoskeleton are all possible mechanisms of AP antifungal action (Buda De Cesare *et al.,* 2020). The proposed procedures appear to be identical to antibacterial AP concepts. Additionally, the occurrence of primary and secondary structures of these peptides may enhance the hydrophilic and hydrophobic nature of the APs, allowing them to interact precisely with the specific sites in the fungal barrier. Several distinct APs are currently being explored for antifungal action till date. Therefore, APs might form an entirely novel category of antifungal medicines. Thus, the antifungal nature of APs has the potential to damage or kill fungi by restricting the formation of fungus chitin walls, interfering with the fungal plasma membrane and deterioration of its structure and functions, causing fungal mitochondria to vacuolate and then hampering respiration, and affecting fungal proteins, DNA and RNA to impact fungal metabolism (Struyfs *et al.,* 2021).

Mechanism of Action of APs as a Weapon of Defence

Anxious circumstances caused by biological invasion generate threat signals that can be detected through the pattern-recognition receptors on the plant's cell interface. The signaling circuits are subsequently active, triggering significant transcriptional modifications and producing stress-response peptides or molecules to cope with the adverse situations caused by these infections (Saijo *et al.,* 2018). Antimicrobial short peptides are one of the more frequent distress-responsive peptides, especially for biological reactions to stress. These AP gene sequences are incorporated into the plant's defense signaling network, leading to an elevation in the level of cellular Ca^{2+} along with the synthesis of a variety of defense hormones like abscisic acid, gibberellic acid, and jasmonic acid, and might have an important role to activate a variety of transcription factors through the cascades of MAP kinase pathway (Goyal and Mattoo, 2014). Thus, the routes of these networks result in the production of defense protein (*i.e.,* antimicrobial peptide). Further, reactive free radical species may additionally develop in the contaminated plant tissues, inducing cells to death in the infected site to restrict the transmission of pathogens (Vatansever *et al.,* 2013).

AP and Reactive Oxygen Species

The beginning phases of bacterial and fungal infections in plants enhance the generation of radicals such as hyperoxide ($O_2^{\bullet -}$), hydrogen dioxide (HO_2), hydroxide radical ($HO^{\bullet}$), and dihydrogen dioxide (H_2O_2). The formation of reactive oxygen species within

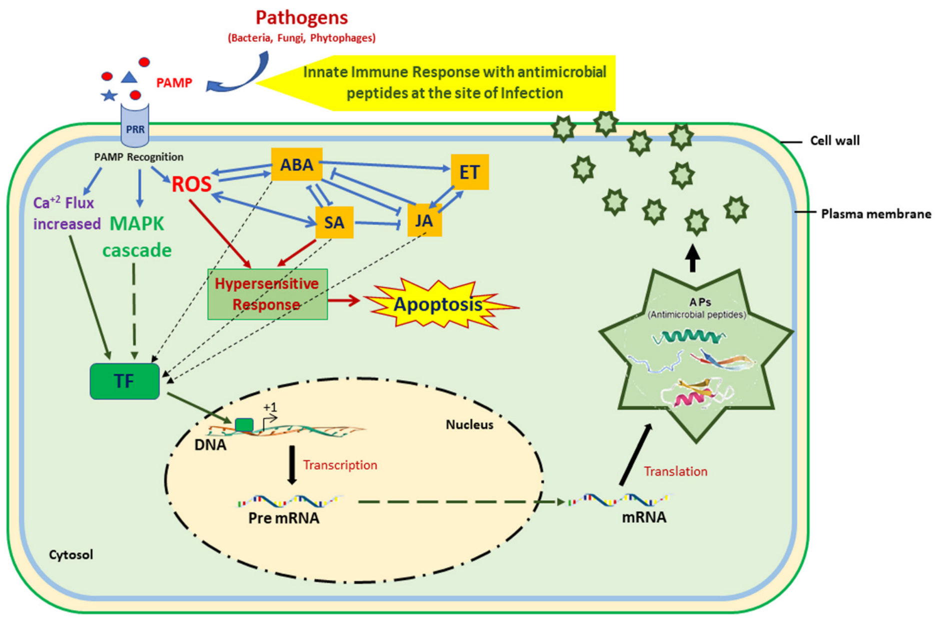

Fig. 1: Summarized view showing the molecular action of antimicrobial proteins against pathogenic interactions to develop innate immune response in plant cells/tissue (PAMP= Pathogen Associated Molecular Pattern; ROS= Reactive Oxygen Species; ABA= Abscisic acid; SA= Salicylate; JA= Jasmonate; ET=Ethylene; APs= Antimicrobial Peptides/proteins)

infected cells is a critical aspect of plant defensive response that eventually leads to programmed cell death (Tripathy and Oelmuller, 2012), and antimicrobial proteins in diverse plant genera might trigger it. The rising level of ROS in fungi infecting cells influences the cellular cascade network, triggering membrane perforation and growth inhibition (Schieber and Chandel, 2014). To avoid cell injury, plants additionally synthesize antioxidative enzymes (GPx, ascorbate, SOD, and catalase) to neutralize these reactive species (Hasanuzzaman, 2020). Similarly, certain AP molecules may function as antioxidative proteins, modulating the cell's redox balance directly. They also especially, increase the concentration of H_2O_2, which might stimulate the genes associated with stress, such as salicylate and jasmonate, for the protection of plant cell walls (Moghaddam *et al.,* 2016).

Moreover, reactive nitrogen species and reactive oxygen radicals facilitate innate defensive reactions against plant-borne pathogenic organisms (Al-Shehri, 2021). Nitric oxide can either directly or indirectly influence the MAPK network by altering receptors that are linked to MAPK (Doronzo *et al.,* 2011). The contribution of reactive nitrogen species to AP action remains unclear, and such relationships need to be investigated thoroughly. While AP-induced nitric oxide deposits tend to serve as a more potent signal for innate defensive actions by generating lethal doses of reactive oxygen/nitrogen species in the infectious agents and collaborating with antioxidants to regulate the cell's oxidative state along with defense mechanisms (Chen *et al.,* 2022).

AP and MAP Kinase Cascade

In every species of eukaryotes, especially higher plants, MAPK cascades convey exogenous inputs and activate effective reactions within cells. MAP Kinases phosphorylate the targets (regulatory/transcription factors), triggering the expression of transcripts associated with the defense network gene. Pattern-recognition receptors on the plant cell detect various microbial-associated molecular patterns and generate polymorphic effector proteins (danger signals) at the pathogen-plant cell interface, and activate the production ROS, secondary messengers, release of Ca^{2+}, and MAPK pathway as a defense response (Saijo *et al.,* 2018). Ca^{2+}-linked kinases and MAPK complexes subsequently modulate the unique targeted genes in the microbial-associated molecular pattern network. MAPKs can activate certain transcription factors that specifically bind to the promoter sequence of defense-related genes, enabling the production of antifungal chemicals (Bigeard and Hirt, 2018). Additionally, the increased production of defense proteins as a reaction to such infection might be linked to the stimulation of antimicrobial peptides. Thus, the interplay involving APs and MAPKs looks to be essential for plants' defenses.

APs and Plant Defense Hormones

The growth hormones of plants perform as immunological modulators and have key functions in the natural defense system networking. The main defense hormones are salicylate, jasmonate, ethene, ABA, gibberellic acid, IAA, and cytokinin (Bari and Jones, 2009). It has been proposed that reactive species-induced abscisic acid favors the immune-mediated network and influences the cross-talk between the jasmonate and salicylate pathways. These defense hormones influence tolerance or sensitivity to necrotrophic microbes, oomycetes, or fungal organisms through activating immune reactions (Burger and Chory, 2019). Disease tolerance or sensitivity is determined by the harmed tissue, invasion phase, as well as infecting strategy in the host. Furthermore, several transmitting signal mechanisms, including defensive hormone-mediated signaling, might trigger the formation of antimicrobial substances like secondary metabolism products (phytoanticipins and phytoalexins), infection-linked peptides, and tiny polypeptides that are antimicrobial (Isah, 2019). As a result of the network, AMP overproduction in plants promotes abiotic (salt and drought) tolerance. Thus, it appears that AP-regulated biotic and abiotic stress adaptations coincide with the diverse defensive hormones (Kulaeva *et al.,* 2020), and , therefore might be used to organize actions against multiple stimuli, thereby performing plant immunity.

Conclusion and Future Prospects

Thus, our understanding is that the biological processes of immunity to plant infectious reactions are extremely complicated and variable. A plethora of regulators and genes have an impact on plant-microbial communications, tolerance to infection signaling, and defensive actions, forming a complicated structure of regulation. An extensive knowledge of AP-linked defensive reactions is critical for managing agricultural infections and bugs. Plant tolerance to infectious signals is not distinct but is linked together by extensive regulated circuits. Learning the way plants systematize multiple elements of signaling is expected to be essential for future investigations. Several scientists have made attempts to uncover the regulators that act across the cascades of circuits in the past few years. Still, the outcomes have needed to be more logical, or their precise actions and roles in hormonal networking circuits need to remain explored deeply.

Furthermore, antibiotics, along with antimicrobial proteins, might be an excellent future pharmaceutical technique to combat superbugs, boost lethal impact, and diminish adverse reactions of antibiotics. This technique may boost microbial lipid bilayer permeation, reduce drug leakages, interfere with cytoplasmic ions balance, and therefore hinder biofilm development and thus limit the growth of bacteria. Another promising prospect is APs grafting with an antibody that specifically targets pathogens; synthetic APs to upgraded antimicrobial chemotherapies; AP immobilization onto contact lens surfaces to ensure prolonged antimicrobial effectiveness; and next-generation human therapeutic antibodies from plant hairy root cultures. Such novel treatments and biomedical tools might be successfully battle infections and improve human health.

Therefore, we can determine how the anxious message created by the biological risk is recognized by plant cells and then eventually transformed into an effective defensive action. In this regard, APs are considered the greatest frequently encountered defenses used by plants to defend themselves (Fig. 1). The finding that such tiny peptides give quick, regulated, and long-lasting immunity to a wide range of pathogenic organisms and bugs explains their widespread distribution across varieties of plants. Plant APs have grown to be a prominent area of study because of their significance in making sure of plant survival in nature, as well as their immense potential for use in agricultural and therapeutic domains of study. Its diverse range of actions, flexibility to adapt, and various modes of operation make antibacterial peptides an admirable weapon for protecting plants from infections and definitely recommend a bright future for study with such peptides.

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Author'scontribution

The author confirms sole responsibility for the study conception, design, and manuscript preparation.

Conflict of interest

There is no conflict of interest.

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