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Plant Antimicrobial Peptides: From Defense Mechanisms To Diverse Applications And Challenges.

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ABSTRACT

This comprehensive review Beginning with an overview of the historical context and evolution of research in this field, the review delves into the diverse types of plant AMPs, detailing their structures and activities. A thorough examination of the modes of action employed by these peptides reveals intricate strategies to disrupt microbial cells, reflecting the complexity of plant defense mechanisms. The review further investigates the applications of plant AMPs, emphasizing their potential in agriculture, medicine, and the food industry. Genetic engineering techniques to enhance crop resistance, the development of biopesticides, and the utilization of AMPs in food preservation underscore their pivotal roles in sustainable practices. In medicine, these peptides demonstrate promise as alternative antibacterial agents, antifungal treatments, and antiviral drugs, with potential applications in medical device coatings. The review discusses ongoing research endeavors aimed at overcoming these challenges, emphasizing the need for optimized production methods, regulatory approval processes, and innovative delivery systems. The future prospects section outlines potential advancements through genetic and protein engineering, combination therapies, targeted delivery systems, and efforts to enhance public awareness and acceptance. In conclusion, the review envisions a promising future for plant AMPs, provided that challenges are addressed through collaborative efforts across disciplines. The continuous innovation and translation of research findings into practical applications hold the key to unlocking the full potential of plant AMPs, offering sustainable solutions to contemporary challenges in agriculture, healthcare, and various industries.
Keywords: Cyclotides; Defensins; Hevein-like; Immune response; Knottin-like Peptides; Membrane integrity; Pharmaceuticals; Thionins;

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INTRODUCTION

Anti-microbial peptides (AMPs) are small, naturally occurring proteins that play a crucial role in the innate immune system of various organisms, including plants. Plants produce AMPs as a defense mechanism against microbial infections. These peptides exhibit antimicrobial activity against a wide range of pathogens, including bacteria, fungi, and viruses [1].

These AMPs play a crucial role in the plant's defense against pathogens by disrupting microbial cell membranes, interfering with cell wall synthesis, or other mechanisms. Researchers are studying these peptides for potential applications in agriculture, medicine, and food preservation due to their broad-spectrum antimicrobial activity and relatively low likelihood of inducing resistance compared to traditional antibiotics [2-4].

The history of plant anti-microbial peptides (AMPs) dates back to early observations of the innate defense mechanisms in plants. While the term "anti-microbial peptides" may not have been used historically, the understanding of plants producing substances with antimicrobial properties has been recognized for centuries. Traditional medicine in various cultures often involved the use of plant extracts to treat infections and wounds. People observed that certain plants appeared to have natural antimicrobial properties [5].

The 20th century saw advancements in microbiology, and scientists began to isolate and characterize substances responsible for the antimicrobial activity in plants. In the mid-20th century, the discovery of antibiotics from microbial sources, such as penicillin from fungi, shifted the focus away from plant-derived compounds for a period. Advances in molecular biology and biotechnology in the 1980s and 1990s led to a renewed interest in plant defenses at the molecular level. Researchers began to identify and characterize specific peptides and proteins in plants with antimicrobial properties. The late 20th century and early 21st century saw the identification and characterization of specific plant anti-microbial peptides (AMPs). Scientists began to isolate and study these peptides from various plant species. With the advent of molecular biology techniques, researchers started to explore the genetic basis of plant AMPs. Genetic engineering allowed the manipulation of plants to enhance their production of AMPs for increased resistance to pathogens. Functional studies helped elucidate the mechanisms of action of plant AMPs. Researchers investigated how these peptides interacted with microbial membranes, inhibited cell wall synthesis, and affected intracellular processes in pathogens [6-8].

As the understanding of plant AMPs grew, their potential applications in agriculture and medicine became evident. Plant AMPs were explored for crop protection, offering a sustainable alternative to chemical pesticides. Additionally, their antimicrobial properties made them attractive candidates for potential use in medicine. Ongoing research continues to uncover new plant AMPs, understand their roles in plant defense, and explore innovative applications in various industries. The history of plant anti-microbial peptides reflects a journey from traditional observations to modern molecular biology, showcasing the importance of these peptides in plant defense and their potential applications in addressing contemporary challenges in agriculture and healthcare [9-11].

Types of Plant Antimicrobial Proteins

Plant antimicrobial peptides (AMPs) are a diverse group of molecules that play a crucial role in the innate immune system of plants. These peptides exhibit antimicrobial activity against a broad spectrum of pathogens, including bacteria, fungi, and viruses [12,13]. Here are some common types of plant AMPs:

Defensins: Defensins are a major class of plant AMPs. They are small, cationic peptides stabilized by disulfide bonds. Defensins exhibit antimicrobial activity against bacteria, fungi, and some viruses [14,15].

Thionins: Thionins are cysteine-rich peptides that often form disulfide bonds. They have antimicrobial activity against bacteria and fungi and may also play a role in plant defense against pathogens [16].

Cyclotides: Cyclotides are cyclic peptides with a unique circular structure stabilized by disulfide bonds. They are found in certain plant families and exhibit antimicrobial, insecticidal, and cytotoxic activities [17].

Hevein-like Peptides: Hevein and hevein-like peptides are found in plants like rubber trees (Hevea brasiliensis). They often have chitin-binding domains and exhibit antifungal properties [18].

Knottin-like Peptides: Knottin-like peptides are small, cysteine-rich peptides with a knotted structure. Some of these peptides, like Ecballium elaterium trypsin inhibitor II (EETI-II), have antimicrobial activity [19, 20].

Mirabilis Jalapa Antimicrobial Peptides (MjAMPs): MjAMPs are a family of AMPs found in the plant *Mirabilis jalapa*. They exhibit antimicrobial activity against bacteria and fungi [21].

Lipid Transfer Proteins (LTPs): LTPs, also known as lipid-binding proteins, have been identified as plant AMPs. They are involved in transporting lipids and can also exhibit antimicrobial activity against bacteria and fungi [22-24].

Snakin Peptides: Snakin peptides are cysteine-rich AMPs found in various plant species. They possess antimicrobial activity against bacteria and fungi and are involved in plant defense responses [25].

Thaumatin-like Proteins (TLPs): Thaumatin-like proteins are a family of proteins that include some AMPs. While they are primarily known for their antifungal properties, some TLPs also exhibit antibacterial activity [26].

Ranacyclin: Ranacyclin is a cyclic peptide found in Ranunculus plants. It displays antimicrobial activity against bacteria and fungi [27, 28].

Ace-AMPs (Acacia epidermis Antimicrobial Peptides): Ace-AMPs are antimicrobial peptides found in the epidermal cells of Acacia plants. They exhibit activity against bacteria and fungi [29].

Plantaricin A: Plantaricin A is a bacteriocin produced by certain plants, such as chickpeas. It has antibacterial activity against specific pathogenic bacteria [30].

These plant AMPs contribute to the defense mechanisms of plants by inhibiting the growth of various pathogens. The diversity in their structures and activities reflects the complexity of plant immune responses [31-33].

Mode of Action of Plant Antimicrobial Proteins

The mode of action of plant antimicrobial proteins (AMPs) involves various mechanisms aimed at disrupting the integrity and function of microbial cells. Different AMPs may employ distinct strategies to target pathogens, including bacteria, fungi, and viruses. The diversity in the mode of action of plant antimicrobial proteins reflects the complexity of plant defense mechanisms [34, 35]. Here are some common modes of action for plant antimicrobial proteins:

Disruption of Cell Membranes: Many plant AMPs target microbial cell membranes. They may interact with the lipid bilayer of microbial membranes, leading to disruption and permeabilization. This can cause leakage of cellular contents and ultimately result in cell death [36].

Inhibition of Cell Wall Synthesis: Some plant AMPs interfere with the synthesis of microbial cell walls, particularly in bacteria and fungi. By disrupting the construction of cell walls, these AMPs compromise the structural integrity of the microorganism, leading to cell lysis [37].

Binding to Nucleic Acids: Certain plant AMPs can bind to microbial nucleic acids, such as DNA and RNA. This interaction may interfere with essential processes like transcription and replication, leading to the inhibition of microbial growth [38].

Inhibition of Protein Synthesis: Some AMPs target microbial protein synthesis machinery. By interacting with ribosomes or other components involved in protein synthesis, these AMPs disrupt the production of essential microbial proteins [39].

Generation of Reactive Oxygen Species (ROS): Some plant AMPs induce the production of reactive oxygen species within microbial cells. ROS can cause oxidative stress, damaging cellular components and leading to cell death [40].

Interaction with Intracellular Targets: Plant AMPs may enter microbial cells and interact with intracellular targets, such as enzymes or regulatory proteins. This interference with essential intracellular processes contributes to the inhibition of microbial growth [39].

Modulation of Immune Responses: Some plant AMPs play a role in modulating the plant's immune responses. They may act as signaling molecules, triggering the activation of defense pathways that enhance the plant's ability to resist microbial infections [41].

Synergy with Other Defense Mechanisms: Plant AMPs often work in conjunction with other defense mechanisms, such as the production of secondary metabolites or the activation of signaling pathways. This synergy contributes to a robust and effective defense response [42].

Specificity against Pathogens: Many plant AMPs exhibit a degree of specificity in their antimicrobial activity. They may selectively target certain pathogens while sparing beneficial microorganisms, contributing to a more tailored defense response [39].

Induction of Programmed Cell Death (Apoptosis): In response to microbial infection, some plant AMPs induce programmed cell death in infected cells. This process, known as apoptosis, helps contain the spread of pathogens within the plant tissues [43].

Application of Plant Antimicrobial Proteins

Plant antimicrobial proteins (AMPs) have various applications across different fields due to their broad-spectrum antimicrobial activity and potential benefits in areas such as agriculture, medicine, and biotechnology [44].

Application of Plant Antimicrobial Proteins in Agriculture

Incorporating plant AMPs into crops through genetic engineering can enhance their resistance to bacterial, fungal, and viral pathogens. This approach reduces the dependence on chemical pesticides and promotes sustainable agriculture. Treating seeds with plant AMPs can protect them from soil-borne pathogens, improving germination rates and overall crop yield. Plant AMPs can be formulated into biopesticides for application in agriculture. These biopesticides offer an environmentally friendly alternative to chemical pesticides [45].

Application of Plant Antimicrobial Proteins in Food Industry

Plant AMPs can be used as natural preservatives in food products to extend shelf life by inhibiting the growth of spoilage microorganisms. Incorporating plant AMPs into food packaging materials or food processing can help prevent the growth of pathogenic bacteria, enhancing food safety [46, 47].

Application of Plant Antimicrobial Proteins in Medicine

Some plant AMPs show promise as alternative antibacterial agents against drug-resistant bacteria. Research is ongoing to explore their potential in the development of new antibiotics. Plant AMPs with antifungal properties are being investigated for their potential use in treating fungal infections in humans and animals. Certain plant AMPs exhibit antiviral activity, and their development may contribute to the creation of novel antiviral drugs [39, 48]. Coating medical devices with plant AMPs can help prevent bacterial colonization and biofilm formation, reducing the risk of infections associated with medical implants. Plant-based expression systems can be used to produce recombinant plant AMPs for various applications, including therapeutic purposes [49-52].

Challenges for Application of Plant Antimicrobial Proteins

While the potential applications of plant AMPs are promising, challenges such as production costs, stability, and delivery methods need to be addressed for their successful implementation in various industries. Ongoing research aims to optimize and unlock the full potential of plant AMPs in addressing real-world challenges [53].

Large-scale production of plant AMPs can be expensive, limiting their commercial viability. Efficient production methods, such as plant-based expression systems or microbial fermentation, need to be optimized for cost-effective production. Besides, Regulatory approval for the use of plant AMPs in agriculture, food, and medicine is a complex process. Standardized testing protocols and clear guidelines are necessary to facilitate regulatory approvals and ensure safety [54].

Plant AMPs may be susceptible to degradation by proteases or other environmental factors, affecting their stability and shelf life. Formulation strategies and modifications to enhance stability are essential for practical applications. Efficient delivery of plant AMPs to target sites, such as plant tissues, microbial infections, or medical devices, is a challenge. Innovative delivery systems, including nanoparticles or encapsulation techniques, need to be developed for optimal efficacy [55, 56].

Future Prospects

Genetic engineering and protein engineering approaches can be employed to enhance the properties of plant AMPs, such as stability, specificity, and antimicrobial activity. This includes modifying amino acid sequences or introducing structural modifications. Combining plant AMPs with other antimicrobial agents, such as conventional antibiotics or other AMPs, may provide synergistic effects, reducing the risk of resistance and expanding the spectrum of activity.Developing advanced delivery systems that can target specific tissues or cells will enhance the efficiency of plant AMPs. These systems may include nanocarriers or controlled-release formulations. Raising awareness and fostering public acceptance of plant AMPs in food and other products are crucial. Public perception and acceptance play a significant role in the successful adoption of new technologies. Encouraging collaboration between researchers, industry, and regulatory agencies is essential for addressing challenges and advancing the field. Multidisciplinary approaches can accelerate progress in the development and application of plant AMPs [57]. Addressing these challenges and embracing future prospects will contribute to the successful translation of plant AMPs from research laboratories to practical applications, benefiting agriculture, healthcare, and various industries. Continuous innovation and collaboration will play a vital role in unlocking the full potential of plant AMPs.

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