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Molecular dialogues: Signaling pathways in plant microbe communication.

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Introduction

Recent studies reveal that small RNAs (sRNAs) and epigenetic modifications play roles in plant–microbe signaling. Pathogens can deliver sRNAs to silence host genes, while plants use sRNAs to regulate immunity. Epigenetic changes, such as DNA methylation and histone modifications, can alter gene expression in response to microbial signals, contributing to immune memory and stress adaptation. Plants and microbes are engaged in a constant molecular conversation an intricate exchange of signals that determines whether the relationship will be beneficial, neutral, or antagonistic. These signaling pathways are central to plant–microbe interactions, orchestrating everything from nutrient exchange to immune responses. Understanding these molecular dialogues is key to advancing sustainable agriculture, improving crop resilience, and unlocking new biotechnological applications [1, 2].

Advances in omics technologies genomics, transcriptomics, proteomics, and metabolomics have revolutionized our understanding of plant–microbe signaling. Techniques like CRISPR-Cas9, RNA-seq, and fluorescent biosensors allow precise manipulation and visualization of signaling components. Understanding signaling pathways enables the development of microbial inoculants, biocontrol agents, and stress-resilient crops. By enhancing beneficial interactions and suppressing pathogens, farmers can reduce chemical inputs and improve sustainability. At the heart of plant microbe communication lies a sophisticated system of chemical signaling. Plants detect microbial presence through conserved molecules known as microbe-associated molecular patterns (MAMPs). These include bacterial flagellin, fungal chitin, and lipopolysaccharides. In response, plants activate pattern-triggered immunity (PTI), a broad-spectrum defense mechanism [3, 4].

Rhizobia produce Nod factors, which are lipochitooligosaccharides recognized by Nod factor receptors (NFRs) on legume roots. Conversely, beneficial microbes produce symbiotic signals such as nodulation (Nod) factors and mycorrhizal (Myc) factors that suppress immune responses and initiate symbiosis. The plant's ability to distinguish between friend and foe depends on its repertoire of pattern recognition receptors (PRRs) and receptor-like kinases (RLKs). For example, the receptor FLS2 detects bacterial flagellin and initiates PTI through interaction with the co-receptor BAK1, leading to MAPK activation and transcriptional reprogramming [5, 6].

Beneficial microbes like rhizobia and arbuscular mycorrhizal fungi (AMF) initiate symbiosis through specialized signaling molecules. Pathogens often secrete effectors molecules that suppress PTI and facilitate infection. In response, plants have evolved resistance (R) proteins that recognize specific effectors, triggering effector-triggered immunity (ETI). ETI is typically stronger and faster than PTI and often involves a hypersensitive response (HR) localized cell death to contain the pathogen. The NLR (nucleotide-binding leucine-rich repeat) proteins are key players in ETI. For instance, the RPM1 protein in Arabidopsis detects effectors from *Pseudomonas syringae*, activating defense responses [7, 8].

This triggers: AMF release Myc factors, which are structurally similar to Nod factors. Plants recognize these via LysM domain receptors, initiating a signaling cascade that leads to fungal colonization and enhanced nutrient uptake.Both pathways converge on a common symbiosis signaling pathway (CSSP), involving CCaMK and transcription factors like CYCLOPS. Microbial signals can induce systemic acquired resistance (SAR) or induced systemic resistance (ISR), preparing distant tissues for future attacks. ISR, often triggered by beneficial rhizobacteria, involves JA and ET signaling without direct pathogen contact. Priming enhances the plant's ability to respond quickly and robustly to subsequent stress, offering long-term protection [9, 10].

Conclusion

Plant microbe communication is a molecular symphony an elegant interplay of signals that determines the fate of interactions. From defense to symbiosis, these pathways shape plant health and productivity. As research continues to unravel these dialogues, we move closer to harnessing them for ecological restoration, food security, and climate resilience.

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