Agri Articles
(e-Magazine for Agricultural Articles)
Volume: 05, Issue: 06 (NOV-DEC, 2025)
Available online at http://www.agriarticles.com
©Agri Articles, ISSN: 2582-9882

Signal Transduction during Biotic Stress: Plant's Secret Crosstalk Network

*Sherin A Salam, Nisha N S, Viji M M and Heera G
College of Agriculture, Vellayani, Thiruvananthapuram-695522, India
*Corresponding Author's email: sherin.salam@kau.in

Plants constantly interact with their surrounding environment, using a variety of signals to adjust their growth and development. Every day, they face relentless attacks from fungi, bacteria, viruses, and herbivores. Unlike animals, plants are sessile and cannot escape danger; their survival depends on the ability to sense threats and mount rapid responses. This defense is orchestrated through signal transduction, a process in which external stimuli are converted into internal biochemical signals that activate protective mechanisms. During biotic stress, signal transduction involves receptors that recognize invaders, messengers that relay the alarm, and hormones that coordinate responses across tissues. Importantly, this communication system is not linear but highly interconnected, forming a complex web of interactions that balances growth with defense. In today's era of climate change and food insecurity, decoding these signaling pathways offers immense promise. By understanding how plants defend themselves, we can engineer crops that resist disease naturally, reducing reliance on toxic chemicals and pesticides. This article explores the intricate world of plant signal transduction under biotic stress, weaving together molecular biology, ecology, and agriculture into a compelling story of survival.

Biotic Stress

Biotic stress refers to damages inflicted by fungi, bacteria, and viruses that invade plant tissues, while herbivores like insects and nematodes feed on them. Each type of attacker presents unique challenges to the plants. The host pathogen interaction are of various types such as

- **Biotrophic pathogens** feed on living tissue, keeping host cells alive.
- **Necrotrophic pathogens** kill host cells and consume the remains.
- **Hemibiotrophs** switch strategies, starting as biotrophs before becoming necrotrophs.

The plants must distinguish between these attackers and tailor their responses accordingly to become resistant and resilient. For example, salicylic acid (SA)-mediated pathways are effective against biotrophs, while jasmonic acid (JA)-mediated pathways defend against necrotrophs and herbivores.

The challenge is compounded by beneficial microbes such as mycorrhizal fungi, rhizobia and other beneficial bacteria and fungi which enhance nutrient uptake, promote plant defense mechanism etc hence, the plants must avoid attacking them. Initially these organism enter the plants like any other pathogenic organism however they associate with the plant with the plant through a different signalling mechanism. Hence, plants must require a sophisticated recognition system that can discriminate between the friend and the foe.

The biotic stresses (weeds, insects, diseases, nematodes, mites etc.) cause colossal reduction of crop yield year after year, estimated to be around 40% due to pests and disease attack (FAO 2023). Crop losses due to pathogens and pests amount to billions of dollars annually. Thus, understanding how plants perceive and respond to biotic stress is critical for agriculture and food security.

How plants defend the biotic stress?

Signal Perception: The First Line of Defense

The first step in plant defense is perception of signals. Plants use pattern recognition receptors (PRRs) embedded in their cell membranes to detect invaders. These receptors recognize pathogen-associated molecular patterns (PAMPs which are conserved microbial signatures such as bacterial flagellin or fungal chitin. When PRRs bind PAMPs, they trigger PAMP-triggered immunity (PTI). This involves rapid cellular changes, including ion fluxes, production of reactive oxygen species (ROS), and activation of defense genes. PTI is broad-spectrum, providing resistance against many pathogens. However, pathogens also have their own mechanism to fight back by secreting effectors, such as molecules that suppress PTI. Plants will counter act with resistance (R) proteins that recognize effectors, leading to effector-triggered immunity (ETI). ETI is stronger and often involves localized cell death (hypersensitive response) to contain the infection. But if the pathogens are virulent they will produce more and evolved effectors to suppress the ETI that may lead to effector triggered susceptibility (ETI).This perception system is homologues to a security checkpoint. PRRs act like guards scanning for suspicious molecules, while R proteins are detectives trained to spot subtle tricks of biotic agents. Together, they form a layered defense system that ensures the plants are rarely caught off guard.

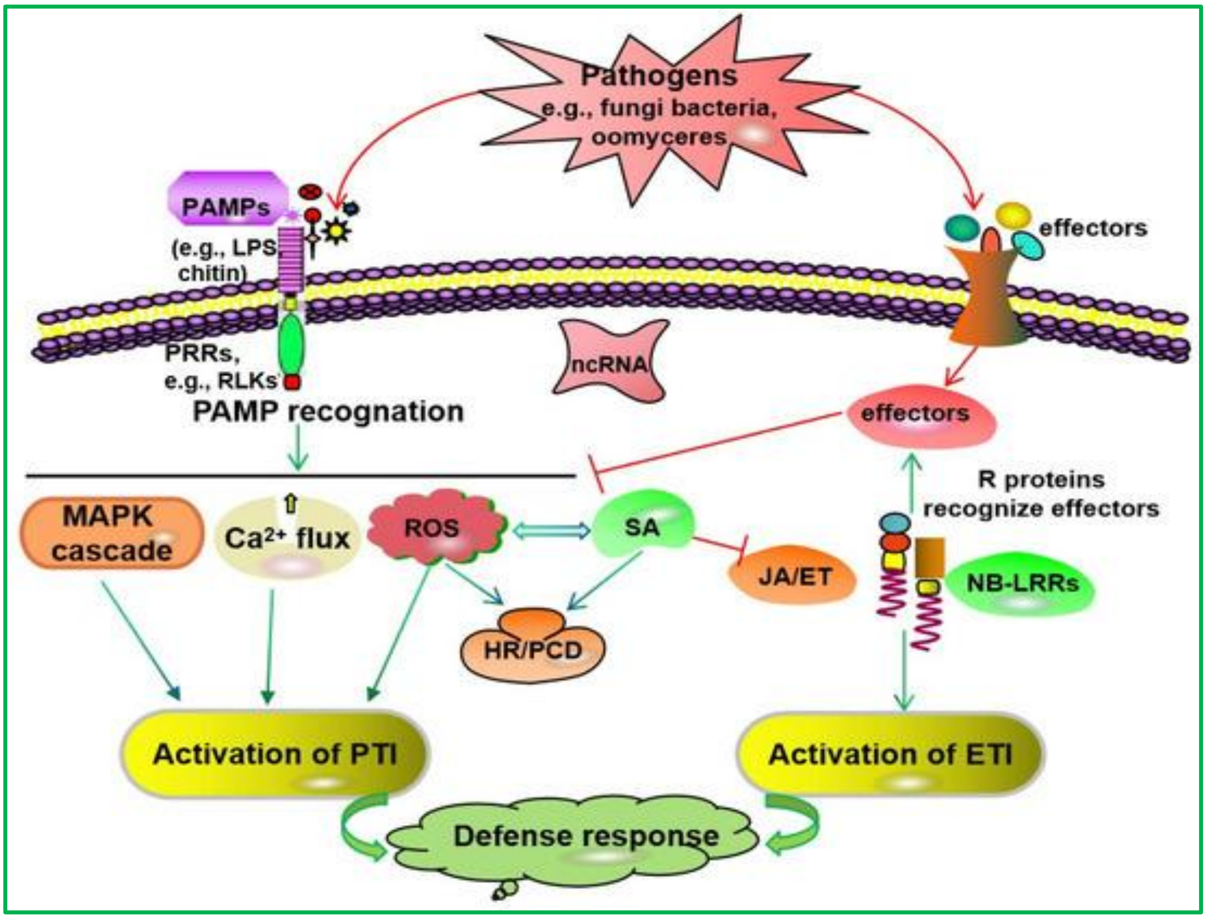

Fig 1.A model of immune responses in plant–pathogen interactions (Ding *et al.*, 2022)

NB-LRR, nucleotide-binding leucine-rich repeat; PRRs, pattern recognition receptors; SA, salicylic acid; JA/ET, jasmonic acid/ethylene; HR, hypersensitive response; PCD, programmed cell death; SAR, systemic acquired resistance; R, resistance; ROS, reactive oxygen species; MAPK, mitogen-activated protein kinase; PAMPs, pathogen-associated molecular pattern; PTI, PAMP-triggered immunity; ETI, effector-triggered immunity; ncRNAs, non-coding RNAs. The arrows indicate positive regulation, and open blocks indicate negative regulation.

Signal Transduction Pathways: From Detection to Response

Once a pathogen is detected, the signal must be transmitted inside the cell. This is achieved through a cascade of biochemical events.

- **Ion fluxes:** Rapid changes in calcium (Ca^{2+}) levels act as early signals.
- **ROS bursts:** Reactive oxygen species serve as both weapons and messengers.
- **MAPK cascades:** Protein kinases relay signals from membrane to nucleus.
- **Phytohormones:** Salicylic acid, jasmonic acid, and ethylene orchestrate defense strategies.

These pathways are interconnected. For example, calcium signaling can activate MAPKs, which in turn regulate hormone biosynthesis. The result is a finely tuned response that balances defense with growth. Signal transduction is not just about speed but specificity. Different pathogens trigger distinct signaling signatures, ensuring tailored responses. This prevents unnecessary energy expenditure and minimizes collateral damage to beneficial microbes.

Calcium Signaling: The Universal Messenger

Calcium ions are central to plant signaling. During pathogen attack, calcium channels open, allowing influx into the cytosol. This change is decoded by calcium-binding proteins such as calmodulins and calcineurin B-like proteins. Calcium signatures may vary in amplitude, frequency, and duration inorder to convey specific information. For example, a rapid spike may signal fungal invasion, while sustained oscillations may indicate bacterial attack. These signatures activate downstream kinases and transcription factors, leading to defense gene expression. Calcium signaling is versatile because it integrates with other pathways. It can modulate ROS production, hormone biosynthesis, and MAPK activation. This makes calcium a universal messenger, capable of coordinating diverse responses.

ROS and Nitric Oxide Bursts

One of the earliest responses to pathogen attack is the oxidative burst leading to rapid production of reactive oxygen species (ROS) such as hydrogen peroxide. ROS serve dual roles viz., they directly damage pathogens, act as signaling molecules in transduction pathway. ROS strengthen cell walls by cross-linking proteins, making it harder for pathogens to penetrate. They also activate defense genes and trigger programmed cell death in infected cells.

Nitric oxide (NO) works along with ROS often, it modulates gene expression, interacts with hormones, and regulates cell death. Together they form a powerful signaling duo that orchestrates cascade of defense signalling mechanism.

MAPK Cascades: The Signal Relay Race

Mitogen-activated protein kinases (MAPKs) are central to signal transduction. They form cascades like MAPKKKs activate MAPKKs, which activate MAPKs. This relay ensures amplification and specificity. MAPKs phosphorylate transcription factors, leading to defense gene expression. They also regulate hormone biosynthesis and ROS production. MAPK cascades are versatile, responding to diverse stresses. They integrate signals from PRRs, calcium, and hormones, ensuring coordinated responses.

Hormonal Cross-Talk: SA, JA, and ET

The cross talk between plant hormones fine-tune defense mechanism in plants when in stress. The hormones such as salicylic acid, jasmonic acid, ethylene are the key players in hormone signalling.

- **Salicylic acid (SA):** Effective against biotrophs.
- **Jasmonic acid (JA):** Defends against necrotrophs and herbivores.
- **Ethylene (ET):** Modulates both SA and JA pathways.

SA and JA often act antagonistically, ensuring tailored responses. ET acts as a mediator for balancing them. Hormonal cross-talk is crucial because plants face multiple stresses simultaneously. By integrating signals, they prioritize responses without compromising growth.

Systemic Acquired Resistance (SAR)

The plants not only just defend locally but also warn distant tissues. This is achieved through systemic acquired resistance (SAR). Mobile signals such as methyl salicylate and pipecolic acid travel through the phloem, activating defense in distant tissues. SAR provides whole plant immunity, akin to vaccination. SAR also involves memory. Plants "remember" past infections, responding faster next time. This priming ensures long-term protection.

Effector-Triggered Immunity (ETI)

Pathogens secrete effectors to suppress PTI. Plants counter with R proteins that recognize effectors, triggering effector-triggered immunity (ETI).ETI is stronger than PTI and often involves hypersensitive response—localized cell death to contain infection. This sacrificial strategy prevents pathogen spread. Sometimes this arms race continues until the pathogen or plant succeeds over one another. ETI and PTI together form a robust defense system in plants ensuring resistance to biotic stress.

Integration of Signals: A Complex Web

Signal transduction is not linear and it forms a network. Cross-talk between pathways ensures flexibility. Plants must balance defense with growth. Excessive defense wastes energy, while insufficient defense risks infection. Signal integration ensures optimal outcomes.

Case Studies Highlighting the Importance of Biotic Stress and Signaling Pathways

Research on *Arabidopsis thaliana* revealed that the receptor Flagellin-Sensing 2 (FLS2) can recognize flg22, a highly conserved peptide fragment of bacterial flagellin. When FLS2 binds to flg22, it initiates a cascade of defense responses known as PAMP-triggered immunity (PTI). This discovery was ground breaking because it demonstrated that plants possess an innate immune system analogous to that of animals. Once activated, Arabidopsis cells undergo rapid changes: calcium ions flood the cytosol, reactive oxygen species (ROS) are generated, and mitogen-activated protein kinase (MAPK) cascades are triggered. These signals converge in the nucleus, activating genes that produce antimicrobial compounds and reinforce cell walls (Wyrsch *et al*., 2015).

In rice, the disease bacterial leaf blight caused by *Xanthomonas oryzae* pv. *oryzae* was studied through the receptor-like kinase XA21, embedded in the cell membrane. XA21 recognizes a conserved microbial molecule from *Xanthomonas* and, upon detection, activates downstream signaling cascades involving MAPKs and transcription factors. This leads to strong defense responses, and rice plants carrying XA21 exhibit remarkable resistance to bacterial blight, significantly reducing yield losses. The XA21 case also illustrates the evolutionary arms race between plants and pathogens: while plants evolve receptors like XA21, pathogens develop effectors to evade recognition (Moon *et al*., 2024).

Tomato plants defend themselves against chewing insects such as caterpillars by producing the hormone jasmonic acid (JA**.** When a caterpillar bites into a tomato leaf, the plant detects both mechanical damage and chemical cues from insect saliva. This triggers JA biosynthesis, which acts as a master regulator of defense. JA signaling activates genes that produce protease inhibitors, compounds that disrupt insect digestion, and induces the synthesis of toxic secondary metabolites that deter feeding. As a result, caterpillars feeding on JA-activated tomato leaves grow more slowly, experience digestive problems, and have reduced survival rates. In essence, the tomato makes itself a less palatable meal(Chen *et al*., 2019).

Applications in Agriculture

Understanding signal transduction offers practical benefits, including the development of disease- and pest-resistant crops, engineering plants with enhanced systemic acquired resistance (SAR), and breeding resilient varieties capable of withstanding diverse biotic stresses, thereby reducing pesticide use. Moreover, it contributes to the advancement of integrated pest management (IPM) strategies, fostering ecologically sustainable farming systems.

Conclusion

Signal transduction under biotic stress represents the cornerstone of plant defense, transforming external threats into coordinated internal responses. Through intricate networks of receptors, secondary messengers, and hormonal cascades, plants mobilize both localized and systemic immunity. Decoding these pathways not only deepens our understanding of plant biology but also provides actionable strategies for sustainable agriculture.

References

1. Chen, D., Shao, M., Sun, S., Liu, T., Zhang, H., Qin, N., Zeng, R., & Song, Y. (2019). *Enhancement of Jasmonate-Mediated Antiherbivore Defense Responses in Tomato by Acetic Acid, a Potent Inducer for Plant Protection.* Frontiers in Plant Science, 10: 764.
2. Ding, L.-N.; Li, Y.-T.; Wu, Y.-Z.; Li, T.; Geng, R.; Cao, J.; Zhang, W.; Tan, X.-L.(2022). Plant Disease Resistance-Related Signaling Pathways: Recent Progress and Future Prospects. *Int. J. Mol. Sci. 23*: 16200. https://doi.org/10.3390/ijms232416200
3. Food and Agriculture Organization of the United Nations. *Plant Production and Protection: Facts and Figures*. FAO. (2023). https://www.fao.org/plant-production-protection/about/en.
4. Moon, H., Jeong, A-R., & Park, C-J. (2024). *Rice NLR protein XinN1, induced by a pattern recognition receptor XA21, confers enhanced resistance to bacterial blight. Plant Cell Rep*. 43: 72.
5. Wyrsch, I., Domínguez-Ferreras, A., Geldner, N., & Boller, T. (2015). *Tissue-specific FLAGELLIN-SENSING 2 (FLS2) expression in roots restores immune responses in Arabidopsis fls2 mutants.* New Phytologist, 206(2): 774–784.