

*Microbial Science Archives (ISSN: 2583-1666)*

An International Research Journal

Journal homepage: [www.microbial.sciencearchives.org](http://www.microbial.sciencearchives.org)

<https://doi.org/10.47587/MSA.2026.6203>

Review Article



## Differential expression and induction of pathogenesis related proteins in response to plant pathogen infection

Narasimhamurthy Konappa<sup>1</sup>  , Soumya Krishnamurthy<sup>2</sup> , Fazilath Uzma<sup>1</sup> , Rajeshwari H Patil<sup>1</sup>  and Srinivas Chowdappa<sup>1</sup> 

<sup>1</sup>Department of Microbiology, Biotechnology and Food Technology, Jnana Bharathi Campus, Bangalore University, Bangalore-560 056, Karnataka, India

<sup>2</sup>Field Marshal K M Cariappa College, a Constituent College of Mangalore University, Madikeri 571 201, Karnataka, India

✉ Corresponding Author: [n.murthy10@gmail.com](mailto:n.murthy10@gmail.com)

Received: April 15, 2026/ Revised: May 20, 2026/Accepted: May 28, 2026

### Abstract

Plant diseases control is usually based on the usage of bactericides, fungicides and lethal to host invaders, causal agents of plants. Though, the harmful consequence of these synthetic pesticides on the environment and health of humans strongly enforces the exploration for new, safety means of plant disease management. Plants are continuously risked by phytopathogens, disturbing main crops conceding food safety. They have developed several mechanisms to defense pathogen disease, containing the of gene cascades, encoding several receptors, effectors, production of secondary metabolites, peptides and proteins having antimicrobial action and indicating and defensive compounds. Among these, production of pathogenesis related (PR) proteins from host plants in active resistance and their overexpression has directed to improved resistance to adverse situations is definite significant as PR proteins are an crucial constituent of innate immune reactions in host plants in abiotic or biotic pressure situations. Response proteins might also be enzymes in biosynthetic pathways for the synthesis of phytoalexins or lignification of cell walls, low molecular weight lethal compounds that inhibit the pathogens. Induction of PR proteins has been described in several plant types containing to several families signifying a common part for these prot PR proteins in variation to abiotic stress / biotic stress situations. The PR genes (defensin, thaumatin, glucanase, thionin, and chitinase) overexpression has significantly enhanced the level of resistance response in plants to a varied variety of phytopathogens, either independently or in combination.

**Keywords:** PR proteins; differential expression; immune responses; biotic stress; biocontrol; pathogens

### Introduction

The plant development and growth are caused by stresses like biotic and abiotic and they have possible toward pointedly decrease farming yield. Biotic pressures are affected by several phytopathogens (fungi, viruses and bacteria) (Cramer et al., 2011; Teixeira et al., 2019). These phytopathogens main to major decrease in yearly crop yield in addition to pose severe danger to the impending food safety. Hosts defend these pathogens by means of a

collection of resistance machineries in directive toward persist or maintain their capability (Singh et al., 2023; Roux et al., 2014). Abiotic stresses because of excesses in salinity, temperature, heavy metals and drought. These are not measured inducers of PR proteins, though some noninfectious physiological situations (toxin induced necrosis or chlorosis) often elicit stimulation of definite PR proteins (Khan et al., 2022). Plants use preformed

(biochemical and structural) and inducible resistance reactions to control several biotic pressures (Wani et al., 2018; Slusarenko et al., 2000). The active resistance structures contains waxes, cutin, deposition of lignin, and secretion of antipathogenic compounds like phytoanticipins and usually measured as primary route of resistance to stop more attack from phytopathogens (Osbourn, 1996). Induced protection apparatuses are intricate from the transduction of many indications intricate in the reactive oxygen species (ROS) synthesis, phytoalexin synthesis, strengthening of cell walls of host and the increase of the PR proteins, some acts as antipathogenic characteristics (Huffaker et al., 2011; Dos Santos and Franco 2023).

In host plants, induced resistance proteins have been defined upon diseased with viruses, bacteria, fungi, oomycetes or occurrence of insect and attended by improved production of resistance proteins often indicated to as pathogenesis related proteins (Gahlowt et al., 2023). The term "PR proteins" shows an collection of varied proteins influenced by phytopathogens also resistance related indicating compounds. The small proteins multigene classes, recognized as PR proteins are known for implementing a collection of biochemical reactions (Kumar et al., 2025; Javed et al., 2025; Bishi et al., 2025). After pathogen attack, stimulation of resistance indicating pathways such as, salicylic acid (SA) and jasmonic acid (JA) take place which more primes toward the buildup of pathogenesis related proteins that reduces infection onset or phytopathogen capacity in host healthy organs. The pathogenesis related proteins were initially revealed in leaves of tobacco responding hypersensitively to TMV. Primarily, simply five main PR proteins classes such as PR1- PR5 were described from tobacco host plants recognized based on the molecular and biochemical methods (Sharma et al., 2021; Bol et al., 1990). The pathogenesis related proteins are a varied cluster of host proteins that are measured to show key parts in host plant infection tolerance (Zribi et al., 2024). The low molecular weight PR proteins are, acid soluble compounds, these are comparatively resistant to endogenous plants and protease tolerance which accrues in developed plants through discordant connections from fungi, viruses, and bacteria (Adam et al., 2014). The PR-proteins can be basic or acidic compounds based on their isoelectric points, but they have similar functions. These are formed in the diseased and adjacent tissues as well as in the distant uninfected materials of the plant. The PR-proteins occur in intercellular spaces of host cells and subcellularly, mainly from the cell walls of several plant tissues (Shobade et al., 2025; Agrios, 2005; Ganguly et al., 2024; van Loon et al., 2006). Maximum acid PR-proteins are situated in the subcellular sections, while the basic PR-proteins are establish from plant vacuole. The

numerous groups of pathogenesis related proteins are categorized according to their serological association, role, molecular weight, sequences of amino acids, and some additional characteristics. The signal mixtures accountable for stimulation of pathogenesis related proteins contain ethylene, SA, polypeptide systemin, xylanase, JA etc. (Ouyang et al., 2024; Kheemji et al., 2026).

Currently, the pathogenesis related proteins are categorized into 19 families according to their sequence similarity, properties, and functions counting ribosome inactivating proteins, chitinases, thionins,  $\beta$ -1,3-glucanases, thaumatin-like proteins, peroxidases, defensins, oxalate oxidase like proteins and nonspecific lipid transfer proteins (Wang et al., 2011; Sels et al., 2008; Van Loon et al., 2006; Bai et al., 2013; Dobnik et al., 2013; Boccardo et al., 2019; Kaur et al., 2022; Cristiane dos Santos 2023; Islam et al., 2023; Javed et al., 2025) (Figure 1). These PR proteins contain PR-1 is unknown function, PR-2 is  $\beta$ -1,3- glucanase, PR3-4, PR-8 and PR-11 are endochitinases (Dos Santos and Franco 2023), PR-5 is thaumatin-like proteins, PR-6 is proteinase inhibitors, PR-7 is proteinase, PR-9 is peroxidase (Dos Santos and Franco, 2023), PR-10 is ribonuclease-like proteins, PR-12 is defensins, PR-13 is thionins, PR-14 is lipid transfer proteins, PR-15 and PR-16 are oxalate oxidase-like proteins and PR-17 is unknown function. The pathogenesis related proteins are stimulated by phytopathogen attack was described in wheat plant (Li et al., 2001), banana plant (Harish et al., 2009), apple plant (Li et al., 2014), mango tree (Ebrahim et al., 2011), grapevine plant (Hatmi et al., 2013), and European plum tree (El-kereamy et al., 2011). The PR-proteins like PR-1, PR-2, and PR-5 were stimulated in wheat plants after SA treatment was described by Niu et al., (2007), while PR-3, PR-4, PR-9 and PR-10 stimulated by JA activates (Perrot et al., 2022; Duan et al., 2014; Chen et al., 2023; Longsaward et al., 2023).

The families of pathogenesis related proteins have been described three antimicrobial peptides, specifically, PR-12 to PR-14 (van Loon et al., 2006). The PR-10 proteins acts directly on fungal plant pathogens (PR1-5, PR-8 and PR11-14), and the PR-1 and PR-5 families are antagonistic active towards oomycetes (Sharma et al., 2021; Campos et al., 2008; Han et al., 2023a). Usually, antimicrobial peptides are abundant and perform an important role of plant resistance to a wide-ranging of phytopathogens and insect pests in several existing types extending of microorganisms from hosts (Mehraj et al., 2024; Egorov et al., 2005). The pathogenesis related proteins family PR-2 is glucanases breaks existing fungal pathogenic cell wall and PR3, PR4, PR8 and PR11 proteins are acts as endo chitinases, that breaks cell wall chitin from fungal pathogens (Perrot et al., 2022; Mahajan et

al., 2025). The PR proteins displays antimicrobial properties target and damage the cell wall of phytopathogens and plasma membrane of plant pathogens; few of them target subcellular or make the enzyme production in microbes causing infections (Varma and Meena, 2020). The antimicrobial peptides (AMPs) from the PR-13, PR-12, and PR-14 proteins are categorized as thionins defensins, and lipid transfer proteins, correspondingly, action as recognized membrane disruption with antibacterial and antifungal actions (Lacerda et al., 2016; Shafee et al., 2017; Melnikova et al., 2022). The class PR-5 proteins, named osmotins, acts as glucan binding proteins and membrane permeabilizers that donate in encoded cell death and glucan degradation, correspondingly (Osmond et al., 2001; Sharma et al., 2021). Thus pathogenesis related proteins show vital role in the development of disease resistance, improves germination of seeds and facilitates the plants to adapt to the living and non living stress situations (Ngou et al., 2022; Ali et al., 2017, 2018).

There are two types of plant pathogens such as biotrophic (parasitic in nature) and necrotrophic pathogen, the primary biotrophic stimulates the salicylic acid pathway that excites the transcription of non-expressor of PR gene1 (NPR1), these indications to stimulation and buildup SA signal gene products in addition of steadily important to systemic acquired resistance (SAR) (Spoel et al., 2012). The necrotrophic phytopathogen activates JA signaling pathway that brings the activation of JA signal genes and indications to collection of their produce nearby and therefore deals individual local acquired resistance (LAR) (Ökmen et al., 2014; Ali et al., 2017; Yu et al., 2022). The SAR delivers improved defense to a varied variety of phytopathogens (Fu and Dong, 2013). Transcriptomic experiments have discovered that pathogenesis related genes are expressively stimulated by abiotic and biotic pressures and sorts them one of the greatest capable genes for developing numerous stress resistant crop types (Jiang et al., 2015; Kamran et al., 2025; Gupta et al., 2013; Fountain et al., 2010; Dai et al., 2016; Kumari et al., 2025; Ali et al., 2017, 2018). Genes accountable for the presence of PR proteins was expressively enhanced the defense against several phytopathogens from various agricultural yields (Ryals et al., 1994). The genes of  $\beta$ -1,3-glucanase include a great gene class that was divided to 3 main classes established on their main constructions (Ward et al., 1991) and described that hosts direct the  $\beta$ -glucanase genes in reaction to microbial diseases (Zavaliev et al., 2011; Dobnik et al., 2013). In this chapter, we highlighted on studies of differential expression and

induction of pathogenesis related proteins in reaction to different phytopathogens (Figure 1).

### PR proteins as signaling indicators of plant defense

Plants release a combination of plant hormones, such as JA, ethylene (ET), SA and xylanase in reaction to plant diseases (Table 1). The magnitude, conformation and development of these ingenious hormones mainly vary inside plants and are dependent on the mode, existence of microbial infection (Ngou et al., 2022; Shobade et al., 2025). Characteristically, SA signaling pathways deliver encounter against pathogens like biotrophic, while JA/ET signaling pathways enable defense to pathogens like necrotrophic also to pests like herbivorous (Bari and Jones, 2009). The pathogenesis related proteins are measured as marker genes from pathways of JA and SA from several agricultural crops. The PR1, PR2 and PR5 expression genes among PR genes are extremely stimulate upon pathogen attack through biotrophics (Delaure et al., 2008). The PR1, PR2, and PR5 symbolizes stimulation of salicylic acid indicating pathway (Zhang et al., 2010; Ali et al., 2017; Teng et al., 2026) and these PRs are used as indicators of the salicylic

acid pathway. Transcription of PR proteins and additional compounds induced is improved afterward JA or SA treatment subsequent in wide spectrum antimicrobial properties (Kaur et al., 2016). Also, SA mutants for example *nim1*, *npr1* and *sail*, *nahG* transgenic *Arabidopsis* with excluded expression of PR gene, a NPR1 locus was recognized (Shah et al., 1997). Afterwords, the NPR1 was establishing a dominant device of salicylic acid interceded host resistance. The presence of above 98% of salicylic acid controlled genes is reliant on NPR1 (Wang et al., 2006). Increased expressions of PR4, PR3 and PR-12 signify stimulation of pathway of jasmonic acid (JA) signaling from *Arabidopsis* plant. Remarkably, jasmonic acid mutants such as *fad3/7/8*, *jarland* *coil*, unsuccessful to make the appearance of PR12, PR4, PR3 and were occur designate vulnerable toward a great amount of phytopathogens (Ali et al., 2017). Several researchers have revealed that the plants JA and SA expressing PR genes central improved defense against a wide spectrum of phytopathogens (Kaur et al., 2016). Also resistance phytohormones such as SA and JA, and additional phytohormones for example auxins, brassinosteroids gibberellins, abscisic acid, and cytokinins, have been revealed to modify the host resistant system but the molecular mechanism residues mainly secretive (Dos Santos and Franco, 2023; Pieterse et al., 2012).

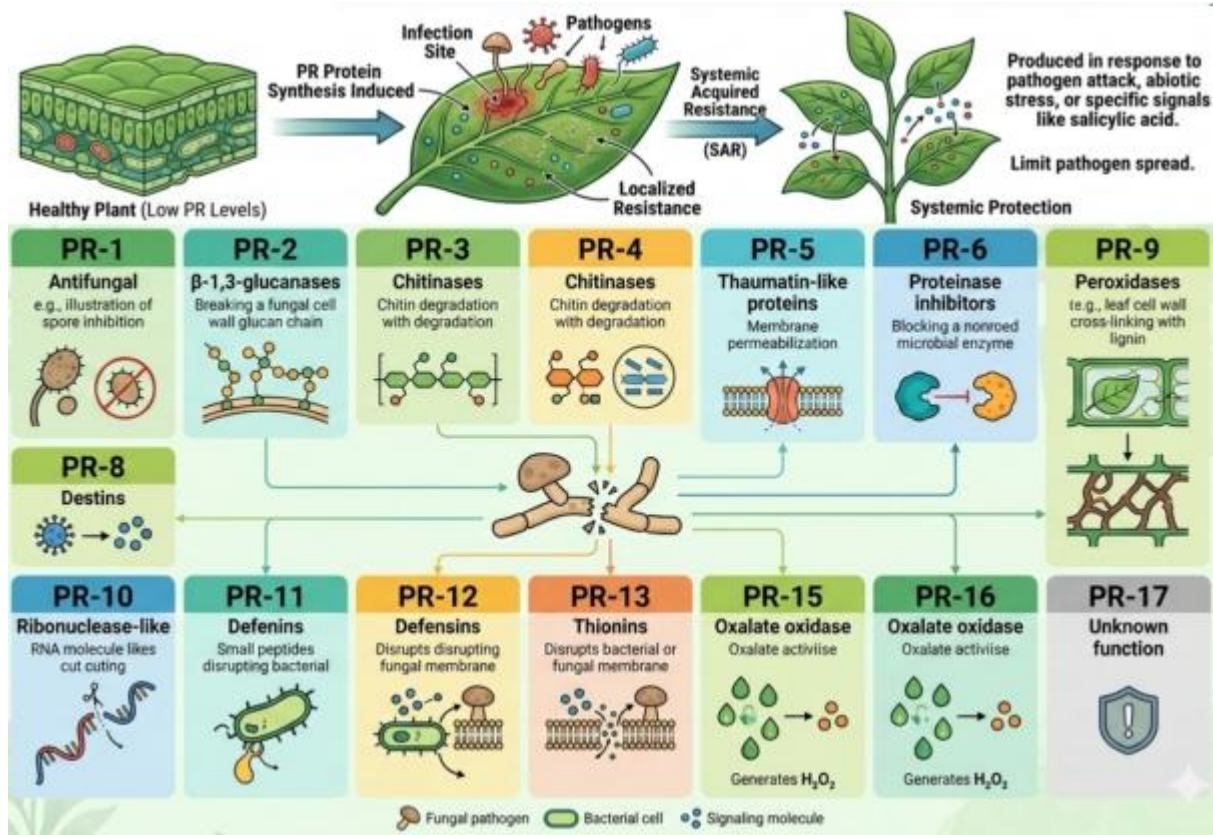


Figure 1 Different classification of PR proteins based on their properties, sequence similarity and functions

### Differential expression and induction of PR-proteins in response to bacterial phytopathogens

The interaction between hosts and bacteria among greatest remarkable associations and useful or detrimental to the plants. Plants associated with bacterial pathogens are identified since a period, nonetheless the initial established infection by bacteria was fire blight from pears and apples on 1878 (Burrill, 1878). In several types, infections associated bacteria rapidly move to the plant, for instance, stomata, lenticels, feeding insects and cuts, with the instruction of compounds on plant leaves. Afterwards, numerous bacterial phytopathogens were documented from several agronomic produces key to enormous crop damages. Plant pathogenic bacteria have been categorized into 3 families: *Pseudomonaceae*, *Xantomnadaceae*, and *Enterobacteriaceae*. Most of them belong to the following genera: *Acidovorax*, *Erwinia*, *Agrobacterium*, *Pectobacterium*, *Pantoea*, *Spiroplasma*, *Pseudomonas*, *Burkholderia*, *Xanthomonas*, *Clavibacter*, *Ralstonia*,

*Streptomyces*, *Phytoplasma* and *Xylella* (Agrios, 2005). The pathogenesis related proteins are well identified defense to bacterial plant pathogens which was used to improve resistant plants against bacteria. The antibacterial activity of the pathogenesis related proteins like PR10, PR12, PR13 and PR14 was shown numerous *in vitro* studies (Park et al., 2004; Jiang et al., 2015; Patkar and Chattoo, 2006). Numerous *in vitro* investigations presented the antimicrobial potential of PR proteins, for instance, ribonuclease-like proteins, lipid transfer proteins, and defensins, thionins (Jiang et al., 2015; Park et al., 2004). The *P. syringae*, *A. radiobacter*, *S. marcescens* *A. tumefaciens* and *P. aureofaciens* are between the microbes; PR10 shows wide variety antagonism against antibacteria (Ganguly et al., 2024; Jiang et al., 2015).

Bacterial pathogens are important pathogens, which cause huge yield loss in numerous crop plants. Afterward, an amount of bacteriological phytopathogens were identified in various significant agronomically yields primary to crop damages. They enter to the host through wounds, stomata;

mechanical injury or pest suckling on plants lenticels, also chemical captivate. Bacteria entered is primary line of resistance towards bacterial phytopathogen stimulates main immune reactions in plant viz. pattern recognition receptors (PPR) resulting in activation of pathogen associated molecular patterns (PAMPs) such as patterns triggered immunity (PTI) and effector trigger immunity (ETI). The infections were detected early and efficiently by PAMP and stop the pathogen from receiving recognized from the plants (Ali et al., 2024; Chen et al., 2025). The ETI clues to initiation of several indicating cascades such as stimulation of pathway of SA and SAR activation well as making of PR-proteins. The activation of SAR, SA pathways and PR-proteins are inclined by effector activate immunity (Jones and Dangl, 2006). Remarkably, immune reactions activated by PAMPa are an initial and active way to stop diseases prior the infection formation in the plant (Ngou et al., 2022).

Several *in vitro* experiments have exposed that activities of the PR-proteins like PR12, PR10, PR13 and PR14 are have capably confirmed their capacity to defend bacterial phytopathogens (Jiang et al., 2015). One of the PR proteins, antibacterial activity of PR-10 indications wide range of to *Serratia marcescens*, *Pseudomonas syringae*, *P. aureofaciens*, *Agrobacterium tumefaciens*, and *A. radiobacter* (Jiang et al., 2015; Xie et al., 2010; Lonjon et al., 2024). Greater expression in rice hosts, PR14 enhanced confrontation defense against bacterial pathogens and fungal phytopathogens (Patkar and Chattoo, 2006). The PR6 can prevent the activity of proteinases enzyme formed by different bacterial phytopathogens, proteinase obstruction was established toward control *Xanthomonas campestris* and *P. syringae* (Koiwa et al., 1997). Enzymatic activities, for example PR-2, PR-3, PR-4, PR-8, PR-11, PR-7 and PR-9 or PR-10 and hold both antibacterial and antifungal action (van Loon et al., 2006; Edreva, 2005). The pathogenesis related proteins from *C. annuum* was influenced by *X. campestris* infection (Jung and Hwang 2000) and gene have resistance was triggered differentially in pepper plant leaves injected with TMV (Huang et al., 2025; Shin et al., 200). Wheat endosperm Purothionin act against the pathogenic bacteria like *P. solanacearum*, *X. phaseoli*, *X. campestris*, *C. fascians*, *C. michiganese*, *C. sepedonicum* *C. poinsettiae* and *C. flaccumfaciens* (De Caley et al., 1972). The PR-13 thionins is used against bacteria *P. syringae* from tomato plants (Rayapuram et al., 2008). Antimicrobial peptide G3KL has been showed as a antimicrobial against *P. aeruginosa* and *A. baumannii* (Silva et al., 2016). The defensin, an antimicrobial peptide from *T. castaneum* presented both *in vivo* and *in vitro* activity against *S. aureus*

by disturbing the bacterial cell membrane (Lewies et al., 2017).

### Differential expression and induction of PR-proteins in response to fungal phytopathogens

Fungi are among main destructive phytopathogens which produce severe crop damages in maximum agronomically significant yields around the globally (Dean et al., 2012). The common of harmful plant pathogens are fungi diseased from numerous significant agricultural crops that activate considerable losses of crop yield (Dean et al., 2012). Based on existence of fungi, pathogens are classified into 3 types dependent on their existence such as, biotrophs hemibiotrophs and necrotrophs. To increase appearance, the fungal phytopathogens usually generate degrading enzymes such as pectinases, proteases, cutinases, and cellulases those lysis cell walls of plant. The fungi infecting plants gain access into its host by hydrolyzing the cell wall of fungal pathogens by production of variety of hydrolytic enzymes extracellularly like cellulases, proteases cutinases, and pectinases that degrades cell walls of the host. To protect from fungal phytopathogens, hosts utilise several resistant approaches initial from observation of pathogen, resistance indicator pathway activation and synthesis of molecules against fungal pathogens like pathogenesis related proteins, which additional control fungal infection, and its duplication (Sels et al., 2008). The genomic conversion of significant resistance compounds suggestions alternative approach intended for stopping diseases caused by fungi. One of pathogenesis related proteins that are excellent objectives for making strong and wide range infection, defense yield ranges to fungal phytopathogens (Ali et al., 2017, 2018).

The pathogenesis related proteins was helpful by way of numerous of PR proteins degrade fungal cell walls making death of the cell. Maximum active proteins against fungi establish from host plants was recognized under *in vitro* studies, for instance PR1- PR5, PR11, PR8, PR13 and PR12, effective antifungal proteins (Table 1). These PR proteins are utilised to improve extensive period and wide variety resistance to phytofungus from different crop plants (Ali et al., 2017). The PR genes overexpression, lone or mixture from numerous plants indications toward improve resistance to necrotrophic, biotrophic fungal pathogens (Wally and Punja, 2010; Dai et al., 2016; Jiang et al., 2015). Moreover, PR proteins affect the fungal cell walls; degrade in *in vitro* situations, important to death of fungal cell (Ali et al., 2017).

Several transcriptional reports have revealed the upregulation of PR genes from numerous agricultural crops later fungous contagions, additional expose their part in infection

tolerance. The PR proteins are brilliant compounds formed by hosts in reaction to pathogenic infection, which helps in forming extensive and enduring broad-spectrum resistance against fungal pathogens (Ahuja et al., 2012; Ali et al., 2017, 2018). PR-genes display basal level expression but afterward fungal contagion, they upsurges affectedly after fungal attack both at indigenous diseased spot in addition to in healthy parts of the plant thus triggering SAR pathway in control environments (Ali et al., 2017; Ahuja et al., 2012). The PR1 protein from tobacco and tomato showed antagonistic activity to *P. infestans* under *in vivo* trials, which showed reduced infected leaf disk surface and *in vitro* test, the inhibition of zoospore germination was identified (Munzert and Engelsdorf, 2025). The effective pathogenesis related proteins rated as excellent antagonistic activity against fungal agents such as PR2- PR5, and PR12 was indicated as the strong proteins against fungai from different hosts (Dai et al., 2016; Jiang et al., 2015). Also, improved PR genes expression solitary or in combination helps the plants to found in several crops mains to greater infection resistance to fungal necrotrophic and biotrophic plant pathogens (Dai et al., 2016; Jiang et al., 2015). Family PR1 has been related through antagonistic action to oomycetes (van Loon et al., 2006). From tea plant comprising overexpression of endo1, 3-d-glucanase gene maintaining a glucanase in potato developed tolerance to *Exobasidium vexans*, causes blister blight infection (Ranjit Singh et al., 2018).

Certain PR proteins groups such as PR3, PR4, PR8 and PR11 have activity of chitinase and canister influence on development and persistence of several fungi due to chitin is the main constituent from fungal cell wall (Kauffmann et al., 1987; Kasprzewska, 2003). Ceaser and Ignacimuthu (2012) effectively transformed *ch11* from rice in the regulator of maize ubiquitin promotor, discussing improved tolerance to leaf blast pathogen *Pyricularia oryzae*. The total 33chitinase genes from maize genome through sequence variety and expression designs, 7 chitinase genes had alleles related through improved defense to increase of aflatoxin and fungus *A. flavus* contamination under field experiment. The PR5 protein was described to prevent spore germination and growth of mycelia from pathogenic fungi (Acharya et al., 2013). The PR1 proteins in tomato plants, PR1a, and PR1b from tobacco plants showed antagonistic activity against *P. infestans*. The expression of PR1a proteins in transgenic tobacco host pointedly inhibited *P. tabacina*; the causative fungus causes blue mold disease (Sinha and Shukla, 2019). Additionally, *G. boninense* resistance from oil palm was supported by overexpression of glucanase from *Medicago sativa* (Hanin et al., 2020).

The PR-10 protein -CsPR10 from *C. sativus* with RNase action was revealed connected in the control development of several phytopathogens, for example *F. oxysporum* V. *dahilae*, and *Penicillium* sp. (Gomez-Gomez et al., 2011). PR-10 protein also identified in *Jatropha curcus* (JcPR10), exhibited both antifungal and RNase activities (Agarwal et al., 2013). The Radhajeyalakshmi et al., (2005), detected that greater activity of glucanase from leaves of tomato after treatment of *A. solani*. Mahatma et al., (2008) similarly reported the greater action of enzyme was  $\beta$ -1,3 glucanase from downy mildew leaves resistant pearl millet plants. Arabidopsis overexpression grapevine  $\beta$ -1,3-glucanase-VvGHF17 showed resistance against *C. higginsianum* and *B. cinerea* (Fujimori et al., 2016). The overexpression of gene LcCHI2 was increased the activity of chitinase from maize and tobacco plants, increasing defense to *A. alternata*, *C. lunata*, and *E. turcicum* (Liu et al., 2020).

The defense mechanism against several fungal phytopathogens from different plants because of  $\beta$ -1,3-glucanase overexpression, was detected against *R. solani* pathogen (Dong et al., 2007), *Phytophthora infestans* (Borkowska et al., 1998), *Fusarium* sp. (Wróbel-Kwiatkowska et al., 2004), *A. flavus* and *C. arachidicola* pathogen (Sundaresha et al., 2010). Antifungal pathogenesis related proteins have a different resistance from plant structure as PRs are triggered through SAR and hypersensitive (Ahuja et al., 2012). The expression of PRs generate upon exterior application of plant hormones or introduction to stress situation both abiotic and biotic (Sabater-Jara et al., 2011). Two PR-protein genes were combined in *Populus tomentosa* containing of motherwort lipid transfer protein-LJAMP2 and *B. bassiana* chitinase Bbchit1, resistance showing important greater decrease by *A. alternata* (Huang et al., 2012). The family PR1 protein from sugarcane plant shows a vital part for improving tolerance to fungal phytopathogens, *S. scitamineum* and *Phytophthora*, by creating epigenetic alterations, for instance increased H3K4me3, decreased H3K27me3 and reduced DNA methylation. These changes increase the SsnPR1 expression genes, enhancing protection to smut infection (Javed et al., 2024; Souza et al., 2017).

The wheat as transgenic plant, expression of rice chitinase gene with artificially induced, deliberated improved defense in wheat against *P. striiformis* causes stripe rust (Huang et al., 2013). Then Lacerda et al., (2016) described the antagonistic action of the defensin protein gene (rDrr230a) from transgenic *P. pastoris* to *F. tucumaniae* and *C. gossypii* and expressively repressed germination of spores and both fungal growth. Overexpression of thaumatococcal-like protein (TLPs) from plants has showed antagonistic against fungi and

resistance to different fungal phytopathogens (Wang et al., 2011; Liu et al., 2012; Singh et al., 2013). The thaumatin-like protein (AdTLP) expression from tobacco plant improved the defense to *R. solani* (Singh et al., 2013). The antagonistic activity of thaumatin like protein like the osmotins main to improved defense to *Fusarium* sp., *Bipolaris* sp., *Verticillium* sp., *Alternaria* sp., and *Phytophthora* sp. from barley, maize, oats, arabidopsis, parsley, and brassicae. Thaumatin like proteins have showed *in vitro* antifungal action to *Fusarium* sp, *Rhizoctonia* sp, *Botrytis* sp. and *Sclerotinia* sp. (Koiwa et al., 1997). The WRKY proteins from sugarcane plants, for example ScWRKY1-3, control protection apparatuses to numerous fungal phytopathogens, counting *C. falcatum*, *S. scitamineum* over epigenomic variations (Lopez-Galiano et al., 2018; Wang et al., 2024).

In mulberry plants, expression of the tobacco osmotin gene in the management of cauliflower mosaic virus 35S (CAM35S) deliberated better defense to fungal phytopathogens *F. pallidoroseum*, *C. dematium* and *C. gloeosporioides* (Das et al., 2011). Overexpression of glucanase gene from tobacco reported from groundnut plant tolerance against *C. arachidicola* and *A. flavus* (Sundaresha et al., 2010). The hevein like peptides (HLPs) was obtained in the *Hevea brasiliensis*, a rubber tree and it exhibited major antagonistic properties against fungi during *in vitro* studies. The hevein like peptides domain was described from numerous host lectins like pseudo hevein, *Urtica dioica* agglutinin, wheat germ agglutinin and AMPs (Choi et al., 2012). The Rs-AFP2 defensin gene overexpression from *R. sativus* presented antagonistic properties against fungi such as *R. solani* and *M. oryzae* (Jha and Chatto, 2010). Partridge Telenko et al., (2011) proved, oxalate oxidase expression gene from peanut deliberated improved resistance against blight caused by *Sclerotinia*. The transgenic rice oxalate oxidase 4 gene Osoxo4 was disruptions the important oxalic acid virulence factor produced by *R. solani* causes sheath blight disease. Similarly, many RNA-seq research discovered PR10 activated expression counting the ABR17 gene from *A. hypogaea* diseased by *A. flavus* (Soni et al., 2021), Betv1, RSPR10, PR10a, PBZ1, PR10b from Thai rice diseased infection as blast (Ngernmuen et al., 2020), numerous PR10 transcripts from *L. angustifolius* infected by *Diaporthe toxica* pathogen (Książkiewicz et al., 2021), PR10 transcripts from *B. distachyon* plant infected by *M. oryzae* pathogen (Zanini et al., 2021) and RrPR10-1, RrPR10-3 from *R. roxburghii* fruit causes top rot disease (Wang et al., 2024).

The transgenic rice plants exhibited greater oxalate oxidase enzyme activity and protection linked genes upregulation likened to non transformed hosts and strong defense to

sheath blight disease (Molla et al., 2013). The AceAMP1 gene in *Allium cepa* was overexpressed in *R. hybrida*, *T. aestivum*, *O. sativa* to deliberate defense to *S. pannosa* pathogen (Li et al., 2003), *N. indica*, *B. graminis* (Roy Barman et al., 2006), *R. solani*, *M. grisea* correspondingly (Patkar and Chattoo 2006). The class PR1 was revealed to be stops the *P. parasitica*, under laboratory antagonistic activity against fungi, pathogenesis related protein glucanase was exhibited to *P. infestans*, *F. solani*, *A. solani* *T. viridae*, and *C. fulvum* and establish designate exact effectiveness (Selitrennikoff, 2001). Snaking -1, 2 (STSN1 and 2) was reported to inhibit fungal pathogens such as *F. culmorum*, *F. solani*, *B. cinerea*, *F. oxysporum*, *C. graminicola*, *P. cucumerina*, *C. lagenarium*, *A. flavus* and *B. maydis* (Berrocal-Lobo et al., 2002). The PR5 ObTLP1 in *O. basilicum* was operatively labeled and its expression from *Arabidopsis* hosts developed resistance against *S. sclerotiorum*, *B. cinerea* diseases (Misra et al., 2016). Significance of the pathogenesis related proteins in plant resistance and transgenic expertise for over expression of various categories of induced or established antifungal proteins against phytopathogenic fungi (Ceasar and Ignacimuthu, 2012; Wally and Punja 2010; Filipenko et al., 2013). Various studies of gene expression was exposed PR10 increase through infection of fungi from plants, for instance *V. dahliae* treatment fast elicited GhPR10 together with protective genes from *G. hirsutum* (He et al., 2018), ZmPR10 from NK7328 maize plant antagonistic activity against *F. verticillioides* (Tran et al., 2021), PbrPR10, PbrMLP from *P. breitschneideri* plant antagonistic activity against pear anthracnose affected by *C. fruticola* pathogen (Su et al., 2024) and LhSorPR10-2 from *L. orientalis* diseased by *B. elliptica* and *F. oxysporum* pathogens (Wenting et al., 2023).

The enzymes like  $\beta$ -1, 3-glucanase, chitinases were occur in extensive range of plants such as, tobacco, peanut, chickpea etc. and have defense against numerous fungal phytopathogens for instance, *A. parasiticus*, *C. lagenarium*, *T. siyoensis*, *A. flava*, *M. phaseolina*, *F. oxysporum*, *Blumeria graminis*, *F. culmorum* and *F. udum* (Hong and Meng, 2004; Wrobel-Kwiatkowska et al., 2004; Liang et al., 2005; Roy-Barman et al., 2006). Chitin binding protein (CBP) expressions showed antagonistic activity against *Aspergillus* sp., *C. beticola*, *X. campestris* and several fungal phytopathogens (Vaaje-Kolstad et al., 2005). The basrai antifungal amphotericin B and Thaumatin like protein showed improved antagonistic activity against against *A. fumigatus* pathogen (Yasmin et al., 2017). Thionin genes (AT1G12660 and AT1G12663) acts as antifungal activity from *A. thaliana* plant was used to produce transgenic potato that was defensive to fungal pathogens like *F. solani* and *F. oxysporum* (Hammad et al.,

2017). Thionins are detected in both and expressed in several tissues in plants like roots, seeds, leaves. The thionins from dicots and monocots becomes expressed during microbial infections and also through release of methyl jasmonate hormone during microbial attack or wounding (Lai and Gallo 2009). The  $\alpha$ -purothionin is showed against *R. solani* (Oard et al., 2004); viscotoxin B and A3 in stems and leaves from *Viscum album* plant, was presented against *F. solani*, *S. sclerotiorum*, *P. infestans* (Giudici et al., 2004). The AsPR genes are putatively encoding PR1-PR5 from *A. sativum*; these genes were acts as plant protection against Fusarium infection (Anisimova et al., 2021). The PR10 -GbPR10-5D1 may support host resistance to *V. dahlia* for it influence suberin and wax creation in addition to function from metabolism of lipid (Guo et al., 2022a).

The Thionins from pearl millet is known to act against the fungi *S. graminicala* (Chandrashekhara et al., 2010); *T. aestivum* has represented against the fungi *F. solani* and AX1 in *Beta vulgaris* is described to act against fungi *C. beticola* (Kragh et al., 1995). The transgenic plants like rice and orange, PR5 influenced improved resistance to *R. solani* and *P. citrophthora* respectively (Fagoaga et al., 2001), whereas potato PR2 and PR3 overexpression was enhanced defense to *P. infestans* (Bachmann et al., 1998). The 12 clones demonstrating transcriptions intricate in oxidation decrease developments from wheat plants inoculated with *P. triticina* pathogen (Dmochowska-Boguta et al., 2015). The enzyme chitinase was described that intricate from wheat defence against stripe rust disease (Chen et al., 2013). The MeJA treatment stimulates the defense mechanism from banana plants and improved expression of PR1 (Tang et al., 2010). While from mandarins, the MeJA improved the PR5 and other PR proteins expression antagonist to *P. digitatum* pathogen (Wang et al., 2021). The fungicidal activity of *N. alata* defensin1-NaD1 was chiefly because of permeabilization of *F. oxysporum* hyphae into the cellular cytoplasm and induce ROS stress (Hughes et al., 2000). The association of the wheat PR-1, Lr35 determined mature host defense against leaf rust affected by *P. triticina* pathogen and PR-2 was described in wheat mature plant defense to *P. triticina* (Li et al., 2016). The PR1 and 3 proteins families have direct actions against Oomycete pathogens (Cui et al., 2024).

The different AMPs like defensins, Glycine rich proteins, lipid transfer proteins (LTPs), 2S albumin, Snakin, and Napid other fruit AMPs are reported from various fruits (Sani et al., 2019). Campos-Bermudez et al., (2013) studied the differential expression of chitinase from maize and silk representative to certain gene was kernel specific or as a minimum expressed from silk. The of enzyme  $\beta$ -1, 3-

glucanase from *V. flexuosa* plant was differentially induced and reliant against the fungal pathogens containing *E. ampelina*, *B. cinerea*, *C. acutatum*, and *R. vitis* (Soon Young Ahn et al., 2014). PR-2 and PR-5 proteins were solitary rapidly activated through the wheat blast (Ha et al., 2016). The puroindolines – PIN A and B isoforms are found from wheat and described to display antifungal activity against *B. cinerea*, *A. brassicola*, *V. dahliae*, *F. culmorum*, *C. heterostrophus*, *A. pisi*, (Zhang et al., 2011). Sterol auxotroph phytopathogens for example the *Phytophthora* are mainly subtle to PR1 and plants enhanced PR1 expression are mainly well resistance against Oomycete (Gamir et al., 2017). The PR1.2 transcript was influenced expressively from wheat Sumai 3 defense against *F. graminearum* pathogen (Soltanloo et al., 2010; Ray et al., 2003). Chitinases have important antifungal actions against *Bipolaris oryzae*, *F. udum*, *B. cinerea*, *Curvularia lunata*, *P. theae*, *Alternaria* sp., *R. solani* *M. arachidicola*, and *F. oxysporum* (Chu and Ng, 2005; Saikia et al., 2005; Kirubakaran and Sakthivel 2006). Ha et al. (2016) demonstrated genes for  $\beta$ -1,3-glucanase (PR2), peroxidase (Pox2), chitinase (Chi2), and plant defensin homolog (PRPI) are strongly upregulated in response to Fusarium head blight disease than by *Magnaporthe* wheat blast individually against the defense against the fungal pathogen. The PR5 improve defense against *S. scitamineum* and *C. falcatum* controlled through epigenetic alterations for instance DNA hypomethylation and histone acetylation (Sathyabhama et al., 2016).

#### Differential expression and induction of PR-proteins in response to viral phytopathogens

Plants are infested through different viruses that are obligate biotrophic phytopathogens capture the plant mechanism and affect the plant health by destroying the resistant reaction. From reaction against viral infection, yield of plants a range of antiviral components for example ribosome inactivating proteins (RIPs), RNA binding proteins (RBPs) and pathogenesis related proteins these can role as viral growth inhibitors (Ali et al., 2018; Liang et al., 2025). Later viral contagion, AMPs or pathogenesis related proteins get collected from healthy tissues thus stops more virus proliferation. Numerous studies have revealed that PR-2a and PR-3 which are generally identified as antifungal PR proteins in *N. tabacum* exhibited antagonistic activity against TMV (Sindelarova and Sindelar, 2005). The antiviral activities of PR proteins under *in vitro* studies, such as defensins, peroxidase, and lipid transfer proteins and thionins (Oskar et al., 2017).

**Table 1 Classification, molecular functions of pathogenesis related proteins and roles in plant defenses**

Family type / member	Activity/ Properties	Properties/Functions	References
PR-1 PR-1 a, b, c	Immune signaling, Lipid-binding Antifungal	Abundant proteins from the apoplast through pathogen plant communication and prevent growth of phytopathogens, antifungal and antiviral activity. PR1 has strong proteolytically sliced to produce a signaling peptide, important target of various fungal effector proteins, create extra pathogenesis related proteins, counting thaumatin like proteins and lipid transfer proteins, to rise pathogen tolerance. Inhibition of viral coat protein receptor binding.	Han et al., 2023b; Akbudak et al., 2020; Pečenková et al., 2023; Almeida-Silva et al., 2022; Sung et al., 2021; Guo et al., 2022b; Chen et al., 2023; Zhu and Gao 2025; Han and Schneider, 2024; Javed et al., 2025; Anuradha et al., 2024; Zhao et al., 2024; Wufuerjiang et al., 2025.
PR-2 PR-2 a, b, c (Classes: I, II, and III)	$\beta$ -1,3-glucanase	The hydrolysis of $\beta$ -1,3-glucan in plant cell wall and shows antibacterial, antifungal and antiviral activities. Degrade endogenous substrates to produce elicitors and start defense responses. ABA influences pathogen reactive callose deposition through PR2 transcriptional regulation. Initiation in plants delivers them resistance to biotrophic fungi and is controlled by SA to activate SAR.	Anisimova et al., 2021; Rabie et al., 2024; Bozbuga, 2021; Perrot et al., 2022; Wang et al., 2024; Zhu et al., 2024; Kumar et al., 2025.
PR-3 Chitinase type I, II, IV, V, VI, VII Endochitinase	Chitinase (GH19) Chitin binding Chitinase (GH18) Chitinase (GH18)	Hydrolysis of chitin in plant cell wall, decomposition of fungal cell wall, antifungal, antibacterial and salt tolerance. PR3 is recognized to confer tolerance in response to necrotrophs and is controlled through JA and ET to activate ISR.	Fukamizo and Shinya, 2019; Poria et al., 2021; Bozbuga, 2021; Omar et al., 2022; Mahajan et al., 2025.
PR-4 Tobacco "R"; PR-4a, b, c	Chitinase type I, II Endochitinase	Inhibition of fungal spore germination, suppression of hyphal development and assistance of degradation of cell wall. Ribonuclease activity induced not only by pathogens but furthermore through ethylene and peach plants and O <sub>3</sub> in Arabidopsis plants. The PR4 BARWIN homologs of numerous plant types were connected with the plant reactions against fungal disease and automatic wounding. PR4 aids in the deterioration of cell walls and may have RNase and DNase activity.	Maia et al., 2021; Chouhan et al., 2023; Singh et al., 2024.
PR-5 Tobacco S; PR-5	Thaumatin, antifungal, osmotin, Zeamatin and permatin	The antifungal activity and cause osmotic separation of fungal plasma membrane. Overexpression in plants has usually improved disease tolerance in several plant types. Usually utilize antifungal activity through degrade the lipid bilayer and creating pores in transmembrane from the pathogens plasma membrane, subsequent in a quick and dramatic rise in permeability. Prevents pathogen indication transduction pathways, rising fungal cell vulnerability. Repeatedly induced through ripening of fruit from fruit types for instance cherries, grapes, bananas, tomatoes, suggesting a potential secondary role from ripening. Prevents development of fungal	Zhang et al., 2018; de Jesús-Pires et al., 2020; Bashir et al., 2020; Bozbuga, 2021; Sharma et al., 2021; Anisimova et al., 2021; Aseel et al., 2022; Singh et al., 2024; Han and Schneider, 2024

		hyphae and germination of spore through producing fungal cell leakiness and disturbing of plasma membrane function receptor compounds intricate in signaling of cAMP/RAS.	
PR-6 Tomato inhibitor I	Protease inhibitor MEROPS family	Inhibition of pathogen protease, slice exopeptidases created via fungus insects, and bacteria and prevention of degradation host cell. Antiinsect and antinematode properties by deactivating the proteins produced by these parasites from attacked plant materials. Inhibitors of proteinase in host microbe and plant insect connections.	Rawlings et al., 2018; Rodríguez-Sifuentes et al., 2020; Kaur et al., 2022 Yarullina et al., 2024.; Han and Schneider, 2024.
PR-7 Tomato P69	Endoproteina se, Proteinase	Mechanism of action in antimicrobial such as degradation of pathogenic cell wall. Antifungal auxiliary protein that gives to the damage of fungal cell wall proteins, glucanases and chitinases. Main pathogen inducible protein from tomatoes, degradation of fungal structural proteins and damage of cell wall integrity.	Figueiredo et al., 2018; Rodríguez-Sifuentes et al., 2020; Yang et al., 2023; Kaur et al., 2022; Sabnam et al., 2023; Abdelkhalek et al., 2021; Bozbuga, 2022; Wang et al., 2024.
PR-8	Cucumber chitinase, Chitinase type III, Endochitinase	Gene coding designed for proteins counting class III chitinase, lysozyme with hydrolysis action on bacterial cell walls. Most plenteous chitinase from infected shares and cucumbers structural relationships with a lysozyme that can disturb a bacterial contagion. Triggered in reaction of apple fruit to microorganisms and the capacity of effectors of <i>B. cinerea</i> to inhibit with the reaction.	Liu et al., 2013; Chouhan et al., 2023; Derikvand et al., 2023; Dos Santos and Franco, 2023; Kumar et al., 2025.
PR-9 Tobacco "lignin-forming peroxidase"	Heme- containing Peroxidase	The catalyze hydrogen peroxide oxidation on organic and inorganic substrates. The ROS concentration variation, lignin mediated cell wall strengthening and creation of cytotoxic radical. Assistance of plants repel disease in a variation of behaviors, counting (i) reinforcement plant cell walls over the lignin deposition, which is supposed designate a general protection mechanism against a extensive variety of phytopathogens, and (ii) the formation of toxic radicals like hydrogen peroxide. In certain potato varieties, PR9 is lone locally induced and its initiation pattern is extremely related to that of peroxidases complicated from R gene mediated tolerance. Regulate ROS concentration; donate to lignification in cell wall.	Nawrot et al., 2014; Liu et al., 2018; Cesarino, 2019; Kim et al., 2020; Sellami et al., 2022; Wang et al., 2025a
PR-10 Parsley "PR1"	Ribonuclease- like, large hydrophobic cavity	The PR10 damage RNA, programmed cell death through hypersensitivity response, antifungal activity, antibacterial activity, secondary metabolite biosynthesis regulation, antinematode activity and antivirus activity and slat and cold stress resistance. Promoter driven actions were likewise perceived in vascular and floral tissue in plants, furthermore been established twas developmentally controlled. PR10 proteins developed the capacity for catalytic or/and ligand binding activities because of selective pressure and play main parts in non living pressure. RNA degradation that might damage in viruses.	Choi et al., 2012; Fernandes et al., 2013; Peng et al., 2017; Aglas et al., 2020; Mahmoud et al., 2020; Morris et al., 2021; Lopes et al., 2023; Regner et al., 2022; Wang et al., 2025b; Kumari et al., 2025.
PR-11 Tobacco "class V" chitinase	Chitinase, type I Endochitinase	It is aids in cell wall degradation, hydrolysis of $\beta$ -1, 4-chitin glycosidic bond, disruption of hyphal structure, inhibition of spore germination and pathogen protection improvement.	Anisimova et al., 2021; Chouhan et al., 2023; Han et al., 2024.
PR-12 Radish AFP3	Plant defensing, defensin	PR12 acts as ntimicrobial activity, systemic protection potentiation, pore formation in membrane and inhibition of pathogen protease. Formed constitutively in plant structures such as leaves, tubers, flowers, and seeds, pods. Improved plenty through interaction	Tam et al., 2015; Ali et al., 2018; Parisi et al., 2019; Westrick et al., 2021; Anisimova et al.,

		between plant and pathogen. Improved expression of PR3, PR4, and PR12 from Arabidopsis plant shows initiation of pathway related to JA, cold stress expressively induces the expression of AMps, specifically PR12 and PR13 from oxytropis and wheat plants, the overexpression of AMPs like PR12 and PR13 also improved disease tolerance against a wide variety of phytopathogens. Antifungal activity and antibacterial activity through relating with the biological membrane of the board bacterium, resultant in changed membrane permeability.	2021; Kumar et al., 2025; Zribi et al., 2021; Hawamda et al., 2022.
PR-13 (Classes: I, II, III and IV) Arabidopsis THI2.1	Thionin	The plant cell wall distribution, vacuole and protein bodies and resistance against an extensive variety of phytopathogens. Directly enters pathogen lipid bilayers, antibacterial activity and antifungal activity by relating with the biological membrane of the target bacterium, resultant in changed membrane permeability. Damage connected molecular pattern function	Tam et al., 2015; Ali et al., 2018; Höng et al., 2021; Zhang et al., 2021; Li et al., 2021; Srivastava et al., 2021.
PR-14 Barley LTP4	Non-specific lipid-transfer protein Protease inhibitor, Seed storage Lipid-transfer protein	The nonspecific lipids transfer proteins (ns-LTPs), synthesis of cuticle, and are connected through plant cell wall and resistance to an extensive variety of phytopathogens. Degraded pathogens membranes; the mechanism is unidentified, antibacterial activity and antifungal activity through interrelating with the biological membrane of the target bacterium, subsequent in changed permeability of membrane. Participation of membrane biosynthesis, disruption of pathogen membrane, modulation of lipid signals and SAR network interaction	Liu et al., 2015; Bao et al., 2018; Fleury et al., 2019; Wang et al., 2021; McLaughlin et al., 2021; Gao et al., 2022; Melnikova et al., 2022; Kaur et al., 2022; Islam et al., 2023.
PR-15 Barley Oxalate oxidase (germin)	Oxalate oxidase	Regulates the development of ROS, antimicrobial activities.	Li et al., 2015; Haider et al., 2021; Kaur et al., 2022.
PR-16, Barley OxOLP	Oxalate oxidase Oxalate oxidase-like	Controls the formation of ROS, antimicrobial properties. Development of ROS instantly once pathogen attack, which was antimicrobial action. Inhibition of fungal toxin, scavenging of SO mediated superoxide, activation of defense gene, H <sub>2</sub> O <sub>2</sub> dependent cell wall protection, improvement of ABA sensitivity, degradation of pathogen wall.	Krishna et al., 2015; Hu et al., 2018; Farvardin et al., 2020; Farvardin et al., 2020; Kaur et al., 2020; Joshi et al., 2021; Haider et al., 2021; Kaur et al., 2022; Govindan et al., 2024.
PR-17	Putative aminopeptidase	Resemblances with aminopeptidase such as that found from bacteria and eukaryotes, secretory protein, proteolytic action and antiviral activity and antifungal activity	Joshi et al., 2021; Kaur et al., 2022.
PR-17 Tobacco NtPRp27 (Q9XIY9)	Antifungal and antiviral	Extracellular protease activity, proteinase function is probable; mechanism is unidentified. Proteolytic enzyme functions an important part from fungal and viral defense.	Christensen et al., 2002; Kaur et al., 2022
PR-18 Carbohydrate oxidases	Carbohydrate oxidases, generating ROS	Carbohydrate oxidases properties, substrate specificity resultant in hydrogen peroxide as among reaction produces and antibacterial action. It regulates the development of ROS.	Kaur et al., 2022
PR-19 Antimicrobial protein	antifungal / antimicrobial protein	PR19 binds to fungal glucans, antimicrobial activity, altering cell wall organization and producing hypha morphological alteration.	Ali et al., 2018; dos Santos and Franco 2023; Kaur et al., 2022.

The PR9 protein (peroxidase) also possesses antiviral action (Nawrot et al., 2014). Preceding research was revealed that phosphorylation from *Capsicum annuum* PR10 (CaPR10) expressively improved antagonistic activity against TMV pathogen (Park et al., 2004). Previous reports have revealed that PR1b protein overexpression from tobacco plants indications that to improved defense against TMV (Cutt et al., 2005). The PR12-14 knottin and hevein peptides were recognized to presented antagonistic activity against viral action. The PR12-14 knottin and hevein peptides molecules not only prevent fusion of cell viral but also against virus envelope thus producing pores from the viral envelope and lastly the pathogen lysis (Nawrot et al., 2014). Furthermore, PR-12-PR-14 prevents fusion of viral cell; numerous pores produced and eradicate the viral pathogen (Nawrot et al., 2014). McKenzie et al., (2002) reported that, expression of pathogenesis related proteins for example chitinase,  $\beta$ -1, 3-glucanase, peroxidase increased stored to a greater level in reaction to Gemini virus infection and *Bemisia tabaci* contagion in tomato.

The peroxidase (PR-9) can acts from strengthening of cell wall by lignification mechanism, important to developed defense against several viral pathogens (Passardi et al., 2004), while certain PR10 proteins display a low

The investigation data connecting to defending role of PR proteins formed by plants diseased with parasitic nematodes are insufficient and conflicting. Certain Pattern Recognition Receptors are suitable for detecting apoplastic plant parasitic nematodes effectors and inducing pattern triggered immunity (Yusuf and Bello, 2025). Important alterations from the infection apparatuses from beet cyst and root knot nematodes control, PR protein creation and utilization inside vulnerable hosts (Hamamouch et al., 2011). Considerably study documentation supports the deficiency of PR protein release from plants attacked by pathogenic nematodes. Nevertheless the chitinase induction from soybean varieties developed greater defence to *Meloidogyne incognita*. The defensive function of chitinase could be because of its action against chitin it is significant constituent from cell walls of nematode and egg shells of nematode. Protection associated peptides for example host thionins, defensins and cysteine rich peptides contribute directly to inhibition of nematode growth through disturbing of membrane integrity or disturbing with nourishing place formation (Saber Riseh et al., 2025). From Arabidopsis, the expression of PR1, PR2, and PR5 were showed SA dependent systemic acquired resistance was produced from both the leaves, roots in diseased hosts throughout *H. schachtii* present in host (Hamamouch et al., 2011).

ribonuclease action, signifying a part in resistance to different viral plant pathogens (Park et al., 2004). Tobacco PR1b, wheat PR4a, and *L. radiata* amino acids (LrPR4) are intricated in activity of RNase, for instance R7 from wheat win1, H11, D92, and H113 even though the small association initiate among these proteins (Caporale et al., 2004). The tobacco senescent was revealing the accretion of PR proteins transcriptions capacity to connected to the usage of senescence and destruction of cellular mechanisms (van Loon et al., 2006), so that expression of pathogenesis related proteins may have a part from the association of nutrients from the tissues of virus spoiled or resistance to destruction of viral cells (Espinoza et al., 2007). Nonetheless, the action of ribonuclease of two histidine remains to the PR4 (Bertini et al., 2009). The PR4 has shown antagonistic activity against viral pathogens, its DNase delivers that the degradation of DNA, RNA through stress situations of the viral pathogen or necrosis might collect remains of the substance of the RNA and DNA inside the viral cell and PR4 protein into extracellular places. Furthermore, PR9 member of PR family also retains action against viral pathogens (Nawrot et al., 2014).

#### Differential expression and induction of PR-proteins in response to nematodes

The class PR6 may confer antiinsect and antinematode activity, disabling the proteins formed by insect and nematode parasites from the attacked plant tissues.

The capacity of PR 5, PR12- PR14 showed plasma membrane permeabilization, lysis of plasma membrane and destruction of different nematodes, preventing their growth and development (Selitrennikoff, 2001). Bent (2022) reported from soybean plant, Rhg1 and Rhg4 loci encode amino acid carrier and serine hydrox-ymethyltransferase, correspondingly, operative in performance to deliver resistance against soybean cyst of *H. glycines*.

The cyclotides was reported and extracted from plants from different families such as *Violaceae*, *Rubiaceae*, *Poaceae* and *Cucurbitaceae* (Gruber, 2010). The cyclotide peptides were designated to ensure immense biotic activities like antihelminthic, insecticidal, molluscidal, anti-viral and antimicrobial properties (Craik, 2010). The cyclotides like kalata (B1 and B2) obtained in *Oldenlandia affinis* plant revealed nematocidal, antibacterial, insecticidal activities (Craik, 2012); cyrulinA and cyrulinB found in *Collinsia parviflora* plant showed antiviral, nematocidal and antibacterial actions and cycloviolacin in *Viola odorata* inhibited bacterial pathogens (Pranting et al., 2010). Antinematode activity has been described for PR10 proteins from *Calcaritis pallida* roots indications nematocide and nematostatic properties to *M. incognita* causes root knot

nematode by preventing the papain- like enzymes existing from digestive tube and cuticles of nematodes (Flores et al., 2002). The transcription genes encoding PR10-SAM22 was improved 5-10 times after 12 days of infection and continued maximum after 10 weeks of infection (Andrade et al., 2010). The expression of PR10 was better defense from pine trees than in vulnerable host at 7 and 14 days after treatment of pine wood nematode *Bursaphelenchus xylophilus* (Ibrahim et al., 2011). The Combined expression of peroxidase with PR10 from resistant trees shows peroxidase gene can be stimulated through reactive oxygen species for example H<sub>2</sub>O<sub>2</sub> or this may functions as proteinase to certain enzymes for instance pectate lyases, cellulases, β-1, 3-glucanase, these are formed from pine wood nematode (Hirao et al., 2012). The disease from Arabidopsis plant roots by the *Heterodera schachtii* is beet cyst nematode, induces the existence of PR1, PR2 and PR5 from the roots of host and PR1 from shoots (Wubben et al., 2008).

#### Author Contributions

The author has significantly contributed to the study's conception, design, data collection, analysis, and interpretation. All authors were involved in writing the manuscript or critically reviewing it for its intellectual value. They have reviewed and approved the final version for submission and publication and accept full responsibility for the content and integrity of the work.

#### Financial Support

The authors declare that no external funding was received for this study.

#### Conflicts of Interest

The authors state that there are no financial, personal, or professional conflicts of interest associated with this research.

#### Ethical Approvals

This research did not involve the use of human participants or animal subjects and therefore did not require ethical clearance

#### Publisher's Note

The Journal stays neutral about jurisdictional claims in published maps and institutional affiliations

#### References

- Abdelkhalik A, Al-Askar AA, Alsubaie MM, Behiry SI. 2021. First report of protective activity of *Paronychia argentea* extract against tobacco mosaic virus infection. *Plants*. 10 (11):2435.
- Acharya K, Pal AK, Gulati A, Kumar S, Singh AK, Ahuja PS. 2013. Overexpression of *Camellia sinensis* thaumatin-like protein, CsTLP in potato confers enhanced resistance to *Macrophomina phaseolina* and *Phytophthora infestans* infection. *Mol Biotechnol*. 54:609–622.
- Adam M, Heuer H, Hallmann J. 2014. Bacterial antagonists of fungal pathogens also control root-knot nematodes by induced systemic resistance of tomato plants. *PLoS ONE* 9 (2), e90402.
- Agarwal P, Bhatt V, Singh R, Das M, Sopory SK, Chikara J. 2013. Pathogenesis related gene, JcPR-10a, from *Jatropha curcas* exhibit RNase and antifungal activity. *Mol. Biotechnol*. 54:412–425.
- Aglas L, Soh WT, Kraiem A, Wenger M, Brandstetter H, Ferreira F. 2020. Ligand binding of PR-10 proteins with a particular focus on the Bet v 1 allergen family. *Curr. Allergy Asthma Rep*. 20:25. doi: 10.1007/s11882-020-00918-4
- Agrios GN. 2005. *Plant Pathology* (5th ed.). Academic Press, London.
- Ahuja I, Kissen R, Bones AM. 2012. Phytoalexins in defense against pathogens. *Trends Plant Sci*. 17:73–90.
- Akbudak MA, Yildiz S, Filiz E. 2020. Pathogenesis related protein-1 (PR-1) genes in tomato (*Solanum lycopersicum* L.): Bioinformatics analyses and expression profiles in response to drought stress. *Genomics*. 112:4089–4099.
- Alcântara GDM, Silva GCB, Ocampo IYM, Kroger AA, de Oliveira RS, Gramacho KP, Alvim FC. 2025. Proteomic Analysis of plants with binding immunoglobulin protein overexpression reveals mechanisms related to defense against *Moniliophthora perniciosa*. *Plants*. 14(4):503.
- Ali M, Shi L, Khan MA, Ali A, Hu S, Shen J. 2025. Auxin biodynamics and its integral role in enhancing plant resilience to environmental cues. *Physiol. Plant* 177 (2), e70165.
- Ali S, Mir ZA, Bhat JA, Chandrashekar N, Papolu PK, Rawat S, Grover A. 2017. Identification and comparative analysis of *Brassica juncea* pathogenesis related genes in response to hormonal, biotic and abiotic stresses. *Acta Physiol. Plant*. 39: 1–15.
- Ali S, Mir ZA, Bhat JA, Tyagi A, Chandrashekar N, Yadav P, Rawat S, Sultana M, Grover A. 2018. Isolation and characterization of systemic acquired resistance marker gene PR1 and its promoter from *Brassica juncea*. 3. *Biotechnology* 8:10–23.
- Ali S, Tyagi A, Mir ZA. 2024. Plant immunity: at the crossroads of pathogen perception and defense response. *Plants*, 13(11):1434.
- Almeida-Silva F, Venancio TM. 2022. Pathogenesis-related protein 1 (PR-1) genes in soybean: Genome-wide identification, structural analysis and expression profiling under multiple biotic and abiotic stresses. *Gene*. 809:146013.
- Andrade LB, Oliveira, AS, Ribeiro JK et al., 2010. Effects of a novel pathogenesis- related class 10 (PR-10) protein from *Crotalaria pallida* roots with papain inhibitory activity against root-knot nematode *Meloidogyne incognita*. *J. Agric. Food Chem*. 58(7):4145–4152.
- Anisimova OK, Shchennikova AV, Kochieva EZ, Filyushin MA. 2021. Pathogenesis-related genes of PR1, PR2, PR4, and PR5 families are involved in the response to *Fusarium* infection in garlic (*Allium*

- sativum* L.). International journal of molecular sciences, 22(13), 6688.
- Anuradha C, Mol PP, Chandrasekar A, Backiyarani S, Thangavelu R, Selvarajan R. 2024. Unveiling the dynamic expression of PR-1 during *Musa* spp. infection by *Fusarium oxysporum* fsp. *Cubense*: a cloning and characterization study. Mol. Biol Rep. 51(1):362.
- Aseel DG, Abdelkhalek A, Alotibi FO, Samy MA, Al-Askar AA, Arishi AA, Hafez EE. 2022. Foliar application of nanoclay promotes potato (*Solanum tuberosum* L.) growth and induces systemic resistance against potato virus Y. Viruses 14:2151.
- Bachmann D, Rezzonico E, Retelska D, Chételat A, Schaerer S, Beffa R. 1998. Improvement of potato resistance to *Phytophthora infestans* by overexpressing antifungal hydrolases. 5th International Workshop on pathogenesis-related proteins. Signalling pathways and biological activities. Aussois, France. Abstracts, P-57.
- Bai SH, Dong CH, Li BH, Dai HY. 2013. A PR-4 gene identified from *Malus domestica* is involved in the defense responses against *Botryosphaeria dothidea*. Plant Physiol. Bioch. 62:23–32.
- Bao Y, Pu Y, Yu X, Gregory BD, Srivastava R, Howell SH, Bassham DC. 2018. IRE1B degrades RNAs encoding proteins that interfere with the induction of autophagy by ER stress in Arabidopsis thaliana. Autophagy 14:1562–1573.
- Bari R, Jones JDG. 2009. Role of plant hormones in plant defense responses. Plant Mol. Biol. 69:473–488.
- Barre A, Damme E, Simplicien M, Benoist H, Rouge P. 2020. Are Dietary Lectins Relevant Allergens in Plant Food Allergy? Foods 9, 1724
- Bashir M.A, Silvestri C, Ahmad T, Hafiz IA, Abbasi NA, Manzoor A, Cristofori V, Rugini E. 2020. Osmotin: A cationic protein leads to improve biotic and abiotic stress tolerance in plants. Plants. 9:992.
- Bent AF. 2022. Exploring soybean resistance to soybean cyst nematode. Annu. Rev. Phytopathol. 60:379–409.
- Berrocal-Lobo M, Segura A, Moreno M, López G, Garcia-Olmedo F, Molina A. 2002. Snakin-2, an antimicrobial peptide from potato whose gene is locally induced by wounding and responds to pathogen infection. Plant physiol. 128(3): 951–961.
- Bertini L, Caporale C, Testa M, Proietti S, Caruso C. 2009. Structural basis of the antifungal activity of wheat PR4 proteins. FEBS Lett. 583:2865–2871.
- Bishi SK, Ranjan A, Pradhan B, Manik S, Vakharia D. 2025. Defense to *Sclerotium rolfsii* in groundnut (*Arachis hypogaea* L.) is associated with vascular tissue compactness and expression of genes coding for pathogenesis-related (PR) proteins. 3. Biotech. 15 (2):44.
- Boccardo NA, Segretin ME, Hernandez I, Mirkin FG, Chacón O. et al., 2019. Expression of pathogenesis-related proteins in transplastomic tobacco plants confers resistance to filamentous pathogens under field trials. Sci. Rep. 9:2019.
- Borkowska M, Krzymowska M, Talarczyk A, Awan MF, Yakovleva L, Kleczkowski K, Wielgat B. 1998. Transgenic potato plants expressing soybean  $\beta$ -1, 3-endoglucanase gene exhibit an increased resistance to *Phytophthora infestans*. Zeitschrift für Naturforschung C, 53(11-12):1012-1016.
- Bozbuga R. 2021. Commonalities of molecular response in tomato plants against parasitic nematodes. Biol. Bull. 48:S12–S21.
- Bozbuga R. 2022. Molecular analysis of nematode-responsive defense genes CRF1, WRKY45 and PR7 in *Solanum lycopersicum* tissues during the infection of plant-parasitic nematode species of the genus Meloidogyne. Genome 65:265–275.
- Burrill TJ. 1878. Pear blight. Trans. Ill State Hortic. Sci. 11:114–116.
- Campos A, Silva MS, Magalhaes CP, Ribeiro SG, Sarto RP, Vieira EA, Grosside-Sa MF. 2008. Expression in Escherichia coli purification, refolding and antifungal activity of an osmotin from *Solanum nigrum*, Microb. Cell Factories 7: 1–10.
- Campos-Bermudez VA, Fauguel CM, Tronconi MA, Casati P, Presell, DA, Andreo CS. 2013. Transcriptional and metabolic changes associated to the infection by *Fusarium verticillioides* in maize inbreds with contrasting ear rot resistance. PLoS One. 8:e61580.
- Caporale C, Di Bernardino I, Leonardi L, Bertini L, Cascone A, Buonocore V, Caruso C, 2004. Wheat pathogenesis-related proteins of class 4 have ribonuclease activity. FEBS Lett. 575 (1-3):71-6.
- Cesar SA, Ignacimuthu S. 2012. Genetic engineering of crop plants for fungal resistance: role of antifungal genes. Biotechnol. Lett. 34:995–1002.
- Cesarino I. 2019. Structural features and regulation of lignin deposited upon biotic and abiotic stresses. Curr. Opin. Biotechnol. 56, 209–214. doi: 10.1016/j.copbio.2018.12.012
- Chandrasekaran J, Brumin M, Wolf D, Leibman D, Klap C, Pearlsman M, Sherman A, Arazi T, Gal-On A. 2016. Development of broad virus resistance in non-transgenic cucumber using CRISPR/Cas9 technology. Mol. Plant Pathol. 17:1140–1153. doi: 10.1111/mpp.12375.
- Chandrashekhara, Niranjan Raj, S, Manjunath, G, Deepak, S, Shekar Shetty, H. 2010. Seed treatment with aqueous extract of *Viscum album* induces resistance to pearl millet downy mildew pathogen. J. Plant Interact. 5:283–291.
- Chen HC, Newton CJ, Diaz G, Zheng Y, Kong F, Yao Y, Yang L, Kvitko BH. 2025. Proteomic snapshot of pattern triggered immunity in the Arabidopsis leaf apoplast. Plant J. 123(6):e70498. doi: 10.1111/tpj.70498.
- Chen XM, Coram TE, Huang X.L, Wang MN, Dolezal A. 2013. Understanding molecular mechanisms of durable and non-durable resistance to stripe rust in wheat using a transcriptomics approach. Current Gen. 14:111–126.
- Chen YL, Lin FW, Cheng KT, Chang CH, Hung SC, Efferth T et al., 2023. XCP1 cleaves pathogenesis-related protein 1 into CAPE9 for systemic immunity in Arabidopsis. Nat. Commun. 14:4697. doi: 10.1038/s41467-023- 40406-7
- Choi DS, Hwang IS, Hwang BK. 2012. Requirement of the cytosolic interaction between pathogenesis-related protein10 and leucine-rich protein1 for cell death and defense signaling in pepper. Plant Cell. 24(4):1675–1690.
- Chouhan R, Ahmed S, Gandhi SG. 2023. Over-expression of PR proteins with chitinase activity in transgenic plants for alleviation of fungal pathogenesis. J. Plant Pathol. 105:69–81.
- Christensen AB, Cho BH, Næsby M, Gregersen PL, Brandt J, Madriz-Ordeñana K et al., 2002. The molecular characterization of two barley proteins establishes the novel PR-17 family of pathogenesis-related proteins. Mol. Plant Pathol. 3:135–144. doi: 10.1046/j.1364-3703.2002.00105.x
- Chu KT, Ng TB. 2005. Purification and Characterization of a Chitinase-Like Antifungal Protein from Black Turtle Bean With Stimulatory Effect on Nitric Oxide Production by Macrophages. Biol. chem. 386:19-24.
- Craik DJ. 2012. Host-Defense Activities of Cyclotides. Toxins 4 (2):139–156.

- Craik DJ. 2010. Discovery and applications of the plant cyclotides. *Toxicon*, 56(7):1092-1102.
- Cramer GR, Urano K, Delrot S, Pezzotti M, Shinozak, K. 2011. Effects of abiotic stress on plants: a systems biology perspective. *BMC Plant Biol.* 11–163.
- Cui Z, Shen S, Meng L, Sun X, Jin Y, Liu Y, Wang H. 2024. Evasion of wheat resistance gene Lr15 recognition by the leaf rust fungus is attributed to the coincidence of natural mutations and deletion in AvrLr15 gene. *Molecular Plant Pathology*, 25(7): e13490.
- Cutt JR, Harpster MH, Dixon DC, Carr J.P, Dunsmuir P, Klessig DF. 2005. Disease Response to tobacco mosaic virus in transgenic tobacco plants that constitutively express the pathogenesis-related PR1b gene. *Virology*. 173:89–97.
- Dai L, Wang Xie D, Zhang XC, Wang X, Xu Y, Wang Y, Zhang J. 2016. The novel gene vpPR4-1 from *Vitis pseudoreticulata* increases powdery mildew resistance in Transgenic *Vitis vinifera* L. *front. Plant Sci.* 7:695.
- Das M, Chauhan H, Chhibbar A, Haq QMR, Khurana P. 2011. High-efficiency transformation and selective tolerance against biotic and abiotic stress in mulberry, *Morus indica* cv. K2, by constitutive and inducible expression of tobacco osmotin. *Trans Res.* 20:231–246.
- De Caleyá RF, Gonzalez-Pascual B, Garcia-Olmedo F, Carbonero P. 1972. Susceptibility of phytopathogenic bacteria to wheat purothionins in vitro. *Appl. Microbiol.* 23(5):998–1000.
- de Jesus-Pires C, Ferreira-Neto JRC, Pacifico Bezerra-Neto J, Kido EA, de Oliveira Silva, RL, Pandolfi V, Wanderley-Nogueira AC, Binneck E, da Costa AF, Pio-Ribeiro G, et al., 2020. Plant Thaumatin-like Proteins: Function, Evolution and Biotechnological Applications. *Curr. Protein Pept. Sci.* 21:36–51.
- Dean R, Van Kan JA, Pretorius ZA, Hammond-Kosack KE, Di Pietro A, Spanu PD, Rudd JJ, Dickman M, Kahmann R, Ellis J. 2012. The Top 10 fungal pathogens in molecular plant pathology. *Mol. Plant Pathol.* 13:414–430.
- Delaware SL, Hemelrijck WV, Bolle MFCD, Cammue BPA, De Coninck BMA. 2008. Building up plant defenses by breaking down proteins. *Plant Sci.* 174:375–385.
- Derikvand F, Bazgir E, Darvishnia M, Mirzaei Najafgholi H. 2023. Evaluation the activity of peroxidase and catalase enzymes and the expression level of PR1 and PR8 genes in apple fruit following brown rot (*Monilinia laxa*) disease. *Plant Genet. Res.* 1: 29–42.
- Dmochowska-Boguta M, Alaba S, Yanushevska Y, Piechota U, Lasota E, Nadolska-Orczyk A, Karlowski WM, Orczyk W. 2015. Pathogen-regulated genes in wheat isogenic lines differing in resistance to brown rust *Puccinia triticina*. *BMC Genomics.* 16:742.
- Dobnik D, Baebler Š, Kogovšek P, Pompe-Novak M, Štebih D, Panter G, Janež N, Morisset D, Žel J, Gruden K. 2013.  $\beta$ -1, 3-glucanase class III promotes spread of PVYNTN and improves in planta protein production. *Plant Biotechnol. Rep.* 7: 547-555.
- Dong S, Tredway LP, Shew HD, Wang GL, Sivamani E, Qu R. 2007. Resistance of transgenic tall fescue to two major fungal diseases. *Plant Science.* 173:501–509.
- Dos Santos C, Franco OL. 2023. Pathogenesis-related proteins (PRs) with enzyme activity activating plant defense responses. *Plants.* 12 (11):2226. <https://doi.org/10.3390/plants12112226>.
- Duan Z, Guizhen LV, Shen C, Li Q, Qin Z, Niu J. 2014. The role of jasmonic acid signaling in wheat (*Triticum aestivum* L.) powdery mildew resistance reaction. *European J Plant Pathol.* 140: 169–183.
- Ebrahima S, Usha K, Singh B. 2011. Pathogenesis-related (PR)-proteins: Chitinase and  $\beta$  -1,3-glucanase in defense mechanism against malformation in mango (*Mangifera indica* L.). *Sci. Hortic. Amsterdam.* 130: 847–852.
- Edreva A. 2005. Pathogenesis-related proteins. Research progress in the last 15 years. *Gen. Appl. Plant Physiol.* 31: 105–124.
- Egorov TA, Odintsova TI, Pukhalsky VA, Grishin EV. 2005. Diversity of wheat antimicrobial peptides. *Peptides* 26:2064–2073.
- El-kereamy A, El-sharkway I, Ramamoorthy R, Taheri A, Errampalli D, Kumar P, Jayasankar S. 2011. *Prunus domestica* pathogenesis-related protein-5 activates the defense response pathway and enhances the resistance to fungal infection. *PLoS One* 6: e17973.
- Espinoza C, Medina C, Somerville S, Arce-Johnson P. 2007. Senescence-associated genes induced during compatible viral interactions with grapevine and Arabidopsis. *J. Exp. Botany* 58:3197–3212.
- Fagoaga C, Rodrigo I, Conejero V, Hinarejos C, Tuset JJ, Arnau J, Pina JA, Navarro L, Peña L. 2001. Increased tolerance to *Phytophthora citrophthora* in transgenic orange plants constitutively expressing a tomato pathogenesis related protein PR-5. *Mol. Breed.* 7:175–185.
- Farvardin A, González-Hernández AI, Llorens E, García-Agustín P, Scalschi L, Vicedo B. (2020). The apoplast: a key player in plant survival. *Antioxidants (Basel).* 9: 604. doi: 10.3390/antiox9070604
- Fernandes H, Michalska K, Sikorski M, Jaskolski M. 2013. Structural and functional aspects of PR-10 proteins. *FEBS J.* 280, 1169–1199. doi: 10.1111/febs.12114
- Figueiredo J, Sousa Silva M, Figueiredo A. 2018. Subtilisin-like proteases in plant defence: the past, the present and beyond. *Mol. Plant Pathol.* 19:1017–1028. doi: 10.1111/mpp.12567
- Filipenko EA, Kochetov AV, Kanayama Y, Malinovsky VI, Shumny VK. 2013. PR-proteins with ribonuclease activity and plant resistance against pathogenic fungi. *Russ. J. Genet. Appl. Res.* 3:474–480.
- Fleury C, Gracy J, Gautier MF, Pons JL, Dufayard JF, Labesse G, Ruiz M, De Lamotte F. 2019. Comprehensive classification of the plant non-specific lipid transfer protein superfamily towards its sequence–structure–function analysis. *Peer J*, 7:e7504.
- Flores T, Alape-Giron A, Flores-Diaz M. et al., 2002. Ocatin. A novel tuber storage protein from the Andean tuber crop oca with antibacterial and antifungal activities. *Plant Physiol.* 128(4):1291–1302.
- Fountain JC, Chen ZY, Scully BT, Kemerait RC, Lee RD, Guo BZ. 2010. Pathogenesis-related gene expressions in different maize genotypes under drought stressed condition. *Afr. J. Plant Sci.* 4: 433–440.
- Fu ZQ, Dong X. 2013. Systemic acquired resistance: turning local infection into global defense. *Annu. Rev. Plant Biol.* 64:839–863.
- Fujimori N, Enoki S, Suzuki A, Naznin HA, Shimizu M, Suzuki S. 2016. Grape apoplasmic  $\beta$ -1, 3-glucanase confers fungal disease resistance in Arabidopsis. *Sci Horti.* 200:105–110.
- Fukamizo T, Shinya S. 2019. Chitin/chitosan-active enzymes involved in plant-microbe interactions. *Adv. Exp. Med. Biol.* 1142:253–272. doi: 10.1007/978-981-13-7318-3\_12
- Gahlout P, Tripathi DK, Gupta R, Singh VP. 2023. Tsw: an NLR protein that keeps viruses away. *Plant Cell Reports*, 42(5):957-960.
- Gamir J, Darwiche R, van't Hof P, Choudhary V, Stumpe M, Schneider R, Mauch F. 2017. The sterol-binding activity of pathogenesis-

- related protein 1 reveals the mode of action of an antimicrobial protein. *Plant J.* 89:502–509.
- Ganguly P, Ganguly N, Chakraborty B, Adhya TK. 2024. Pathogenesis related proteins: milestones in five decades of research. *Indian Phytopathology.* 77(4):899-923.
- Gao H, Ma K, Ji G, Pan L, Zhou Q. 2022. Lipid transfer proteins involved in plant-pathogen interactions and their molecular mechanisms. *Mol. Plant Pathol.* 23:1815–1829. doi: 10.1111/mpp.13264
- Garcia-Casado G, Collada C, Allona I, Casado R, Pacios LF, Aragoncillo C, Gomez L. 1998. Site-directed mutagenesis of active site residues in a class I endochitinase from chestnut seeds. *Glycobiology.* 18(10):1021-8.
- Giudici AM, Regente MC, Villalain J, Pfüller K, Pfüller U, De La Canal L. 2004. Mistletoe viscotoxins induce membrane permeabilization and spore death in phytopathogenic fungi. *Physiologia plantarum,* 121(1):2–7.
- Gomez-Gomez L, Rubio-Moraga A, Ahrazem O. 2011. Molecular cloning and characterization of a pathogenesis-related protein CsPR10 from *Crocus sativus*. *Plant Biol.* 13(2):297–303.
- Govindan G, Sandhiya KR, Alphonse V, Somasundram S. 2024. Role of Germin-Like Proteins (GLPs) in biotic and abiotic stress responses in major crops: A review on plant defense mechanisms and stress tolerance. *Plant Mol. Biol. Rep.* 42:450–468.
- Gruber CW. 2010. Global cyclotide adventure: a journey dedicated to the discovery of circular peptides from flowering plants. *Peptide Sci.* 94(5):565–572.
- Guo J, Cao P, Yuan L, Xia G, Zhang H, Li J, Wang F. 2022a. Revealing the contribution of GbPR10. 5D1 to resistance against *Verticillium dahliae* and its regulation for structural defense and immune signaling. *Plant Genome.* 15:e20271.
- Guo J, Bai Y, Wei Y, Dong Y, Zeng H, Reiter RJ, Shi H. 2022b. Fine-tuning of pathogenesis-related protein 1 (PR1) activity by the melatonin biosynthetic enzyme ASMT2 in defense response to cassava bacterial blight. *J. Pineal Res.* 72: e12784.
- Gupta P, Ravi I, Sharma V. 2013. Induction of  $\beta$ -1, 3-glucanase and chitinase activity in the defense response of *Eruca sativa* plants against the fungal pathogen *Alternaria brassicicola*. *J. Plant Interact.* 8:155–161.
- Ha X, Koopmann B, Von Tiedemann A. 2016. Wheat blast and Fusarium head blight display contrasting interaction patterns on ears of wheat genotypes differing in resistance. *Phytopathol.* 106(3):270–281.
- Haider MS, Jaskani MJ, Fang J. 2021. Overproduction of ROS: underlying molecular mechanism of scavenging and redox signaling. In *Biocontrol Agents and Secondary Metabolites* (pp. 347-382). Woodhead Publishing.
- Hamamouch N, Li C, Seo PJ, Park CM, Davis EL. 2011. Expression of Arabidopsis pathogenesis-related genes .during nematode infection. *Mol. Plant Pathol.* 12 (4):355–364.
- Hammad IA, Abdel-Razik AB, Soliman ER, Tawfik E (2017) Transgenic potato (*Solanum tuberosum*) expressing two antifungal thionin genes confer resistance to *Fusarium* spp. *J Pharm Biol Sci* 12:69–79.
- Han Z, Schneider R. 2024. Dual functionality of pathogenesis-related proteins: defensive role in plants versus immunosuppressive role in pathogens. *Front. Plant Sci.* 15:1368467. doi: 10.3389/fpls.2024.1368467
- Han X, Kui M, He K, Yang M, Du J, Jiang Y. Hu Y, 2023a. Jasmonate-regulated root growth inhibition and root hair elongation. *J. Exp. Botany.* 74(4):1176–1185. <https://doi.org/10.1093/jxb/erac441>
- Han Z, Xiong D, Schneider R, Tian C. 2023b. The function of plant PR1 and other members of the CAP protein superfamily in plant-pathogen interactions. *Mol. Plant Pathol.* 24: 651–668.
- Hanin AN, Parveez GK, Rasid OA, Masani MY. 2020. Biostimulant mediated oil palm transformation with alfalfa glucanase (AGLU1) and rice chitinase (RCH10) genes for increasing oil palm resistance towards *Ganoderma boninense*. *Ind Crops Prod* 144:112008
- Harish S, Kavino M, Kumar N, Balasubramanian P, Samiyappan R. 2009. Induction of defense-related proteins by mixtures of plant growth promoting endophytic bacteria against Banana bunchy top virus. *Biol. Control* 51:16–25.
- Hatmi S, Tritel-Aziz P, Villaume S, Couderchet M, Clément C, Aziz A. 2013. Osmotic stress-induced polyamines oxidation mediates defense responses and reduces stress-enhanced grapevine susceptibility to *Botrytis cinerea*. *J. Exp. Bot.* 65: 75–88.
- Hawamda AI, Reichert S, Ali MA, Nawaz MA, Austerlitz T, Schekahn P, Abbas A, Tenhaken R, Bohlmann H. 2022. Characterization of an Arabidopsis defensin-like gene conferring resistance against nematodes. *Plants* 11:280.
- Hawkins LK, Mylroie JE, Oliveira DA, Smith JS, Ozkan S, Windham GL, Williams WP, Warburton ML. 2015. Characterization of the maize chitinase genes and their effect on *Aspergillus flavus* and aflatoxin accumulation resistance. *PLoS One.* 10:e0126185.
- He X, Zhu L, Wassan GM, Wang Y, Miao Y, Shaban M, Hu H, Sun H, Zhang X. 2018. GhJAZ2 attenuates cotton resistance to biotic stresses via the inhibition of the transcriptional activity of GbhHLH171. *Mol. Plant Pathol.* 19, 896–908.
- Hirao T, Fukatsu E, Watanabe A. 2012. Characterization of resistance to pine wood nematode infection in *Pinus thunbergii* using suppression subtractive hybridization. *BMC Plant Biol.* 12:13.
- Höng K, Austerlitz T, Bohlmann T, Bohlmann H. 2021. The thionin family of antimicrobial peptides. *PLoS ONE.* 16:e0254549. doi: 10.1371/journal.pone.0254549.
- Hong TY, Meng M. 2004. Biochemical Characterization and Antifungal Activity of an endo-1,3- $\beta$ - glucanase of *Paenibacillus* sp. Isolated from Garden Soil. *Appl. Microbiol. Biotechnol.* 61(5-6): 472-478.
- Hu J, Jiang J, Wang N. 2018. Control of *Citrus Huanglongbing* via trunk injection of plant defense activators and antibiotics. *Phytopathol.* 108:186–195.
- Huang C, Zhao Z, Wu X, Zhao H, Wang M, He Z, Li Z, Wang L, Tang Y, Wang R, He L. 2025. Functional analysis of the pathogenesis-related protein 1 (CaPR1) gene in the pepper response to *Chilli veinal mottle virus* (ChiVMV) infection. *Viruses.* 17(11): 1456. <https://doi.org/10.3390/v17111456>
- Huang X, Wang J, Du Z, Zhang C, Li L, Xu Z. 2013. Enhanced resistance to stripe rust disease in transgenic wheat expressing the rice chitinase gene RC24. *Trans Res.* 22:939–947.
- Huang Y, Liu H, Jia Z, Fang Q, Luo K. 2012. Combined expression of antimicrobial genes (Bbchit1 and LJAMP2) in transgenic poplar enhances resistance to fungal pathogens. *Tree Physiol.* 32:1313–1320.
- Huffaker A, Kaplan F, Vaughan MM, Dafoe NJ, Ni X, Rocca JR, Alborn HT, Teal PEA, Schmelz EA. 2011. Novel acidic

- sesquiterpenoids constitute a dominant class of pathogen-induced phytoalexins in maize. *Plant Physiol.* 156: 2082–2097.
- Hughes P, Dennis E, Whitecross M, Llewellyn D, Gage P. 2000. The cytotoxic plant protein,  $\beta$ -purothionin, forms ion channels in lipid membranes. *J. Biol. Chem.* 275(2): 823–827.
- Ibrahim HM, Hosseini P, Alkharouf NW, Hussein EH, Gamal El-Din AE, Aly MA, Matthews BF. 2011. Analysis of Gene expression in soybean (*Glycine max*) roots in response to the root knot nematode *Meloidogyne incognita* using microarrays and KEGG pathways. *BMC Genomics.* 12:220.
- Islam MM, El-Sappah AH, Ali HM, Zandi P, Huang Q, Soaud SA, Alazizi EM, Wafa HA, Hossain MA, Liang Y. 2023. South African Journal of Botany 160: 414-427.
- Javed T, Wang W, Sun T, Shen L, Feng X, Huang J, Zhang S. 2024. Pathogenesis-related 1 (PR1) protein Family genes involved in sugarcane responses to *Ustilago scitaminea* stress. *Int. J. Mol. Sci.* 25 (12):6463.
- Javed T, Wang W, Yang B, Shen L, Sun T, Gao SJ, Zhang S. 2025. Pathogenesis related-1 proteins in plant defense: regulation and functional diversity. *Crit. Rev. Biotechnol.* 45 (2):305–313.
- Jha S, Chattoo BB. 2010. Expression of a plant defensin in rice confers resistance to fungal phytopathogens. *Trans Res.* 19:373–384.
- Jiang L, Wu J, Fan S, Li W, Dong L, Cheng Q. 2015. Isolation and characterization of a novel pathogenesis-Related protein gene (GmPRP) with induced expression in soybean (*Glycine max*) during infection with *Phytophthora sojae*. *PLoS One* 10: e0129932.
- Jones JDG, Dangl JL. 2006. The plant immune system. *Nature* 444:323–329.
- Joshi V, Joshi N, Vyas A, Jadhav SK. 2021. Pathogenesis-related proteins: Role in plant defense. *Biocontrol Agents Secondary Metabolites.* 573–590. doi: 10.1016/ B978-0-12-822919-4.00025-9
- Jung HW, Hwang BK. 2000. Pepper gene encoding a basic  $\beta$ -1, 3-glucanase is differentially expressed in pepper tissues upon pathogen infection and ethephon or methyl jasmonate treatment. *Plant Sci.* 159: 97–106.
- Kamran M, Burdiak P, Karpiński S. 2025. Crosstalk between abiotic and biotic stresses responses and the role of chloroplast retrograde signaling in the cross-tolerance phenomena in plants. *Cells*, 14(3): 176.
- Kasprzewska A. 2003. Plant chitinases-regulation and function. *Plant chitinases – regulation and function. Cellul. Mol. Bio. Let.* 8:809–824
- Kaur A, Kaur S, Kaur A, Sarao N.K, Sharma D. 2022. Plant breeding - new perspectives. intechopen; london, UK: pathogenesis-related proteins and their transgenic expression for developing disease-resistant crops: strategies progress and challenges; pp. 6–8.
- Kaur A, Pati PK, Pati AM, Nagpal AK. 2020. Physico-chemical characterization and topological analysis of pathogenesis-related proteins from *Arabidopsis thaliana* and *Oryza sativa* using in-silico approaches. *PLoS ONE.* 15:e0239836.
- Kaur A, Kaur S, Kaur A, Sarao NK, Sharma D. 2023. Pathogenesis-related proteins and their transgenic expression for developing disease-resistant. Case studies of breeding strategies in major plant species, 85.
- Kaur J, Fellers J, Adholeya A, Velivelli SL, El-Mounadi K, Nersesian N, Clemente T, Shah D. 2016. Expression of apoplast-targeted plant defensin MtDef4. 2 confers resistance to leaf rust pathogen *Puccinia triticina* but does not affect mycorrhizal symbiosis in transgenic wheat. *Trans Res.* 26:37–49.
- Kaur S, Samota MK, Choudhary M, Choudhary M, Pandey AK, Sharma A, Thakur J. 2022. How do plants defend themselves against pathogens-Biochemical mechanisms and genetic interventions. *Physiol. Mol. Biol. Plants* 28 (2):485–504. <https://doi.org/10.1007/s12298-022-01146-y>
- Khan MAU, Arshad H, Majid A. 2022. Transport mechanism from quantum dots to plant systems. *Quantum Dots for Plant Systems.* Springer International Publishing, Cham, pp. 103–136.
- Kheemji F, Shair G, Israr A, Farooq N, Hammad M, Shakeel M, Sherazi S. 2026. Pathogenesis-related proteins in plants: molecular features, functional diversity, and biotechnological applications. *J. Physical, Biomedical and Biological Sci.* 2026(1): 52-52.
- Kim YH, Kim HS, Park SC, Ji CY, Yang JW, Lee HU, Kwak SS. 2020. Overexpression of swpa4 peroxidase enhances tolerance to hydrogen peroxide and high salinity-mediated oxidative stress in transgenic sweet potato plants. *Plant Biotechnol. Rep.* 14:301–307. doi: 10.1007/s11816-020-00602-z.
- Kirubakaran SI, Sakthivel N. 2006. Cloning and overexpression of antifungal barley chitinase gene in *Escherichia coli*. *Pro. Express. Purific.* 52(1): 159-166.
- Koiwa H, Bressan RA, Hasegawa PM. 1997. Regulation of proteinase inhibitors in plant defense. *Trends Plant Sci.* 2:379–384.
- Krishna G, Singh BK, Kim EK, Morya VK, Ramteke PW. 2015. Progress in genetic engineering of peanut (*Arachis hypogaea* L.)—A review. *Plant Biotechnol. J.* 13: 147–162.
- Książkiewicz M, Rychel-Bielska S, Plewinski P, Nuc M, Irzykowski W, Jędrzycka M, Krajewski P. 2021. The resistance of narrow-leaved lupin to *Diaporthe toxica* is based on the rapid activation of defense response genes. *Int. J. Mol. Sci.* 22(2):574.
- Kumar P, Pandey S, Pati PK. 2025. Interaction between pathogenesis-related (PR) proteins and phytohormone signaling pathways in conferring disease tolerance in plants. *Physiol. Plant* 177 (2):e70174.
- Kumari M, Singh IK, Singh A. 2025. Pathogenesis related protein 10 (PR-10): A component of multiple defense systems against biotic and abiotic stresses. *Plant Stress.* 101141.
- Lacerda, AF, RP. Del Sarto MS. Silva EAR. Vasconcelos RR, Coelho VOE. Santos CV. Godoy CDS, Seixas MCM, Silva MF, Grossi-de-S. 2016. The recombinant pea defensin Drr230a is active against impacting soybean and cotton pathogenic fungi from the genera *Fusarium*, *Colletotrichum* and *Phakopsora*, 3 *Biotech.* 6:59.
- Lai Y, Gallo RL. 2009. AMPed up immunity: how antimicrobial peptides have multiple roles in immune defense. *Trends immunol.* 30(3):131-141.
- Lewies A, Wentzel JF, Jordaan A, Bezuidenhout C, Du Plessis LH (2017). Interactions of the antimicrobial peptide nisin Z with conventional antibiotics and the use of nanostructured lipid carriers to enhance antimicrobial activity. *Int. J. Pharma.* 526(1-2):244-253.
- Li Q, Xu F, Chen Z, Teng Z, Sun K, Li X, Yu J, Zhang G, Liang Y, Huang X, Du L, Qian Y, Wang Y, Chu C, Tang J. 2021. Synergistic interplay of ABA and BR signal in regulating plant growth and adaptation. *Nat. Plants.* 7:1108–1118.
- Li M, Xu J, Qiu Z, Zhang J, Ma F, Zhang J. 2014. Screening and identification of resistance related proteins from apple leaves inoculated with *Marssonina coronaria* (EII. and J. J. Davis). *Proteome Sci.* 12: 7.

- Li WL, Faris JD, Muthukrishnan S, Lui DJ, Chen PD, Gill BS. 2001. Isolation and characterization of novel cDNA clones of acidic chitinases and  $\beta$ -1, 3-glucanases from wheat spikes infected by *Fusarium graminearum*. *Theor. Appl. Genet.* 102: 353-362.
- Li XC, Liao YY, Leung DW, Wang HY, Chen BL, Peng XX, Liu EE. 2015. Divergent biochemical and enzymatic properties of oxalate oxidase isoforms encoded by four similar genes in rice. *Phytochemistry*, 118:216-223.
- Li X, Gasic K, Cammue B, Broekaert W, Korban SS. 2003. Transgenic rose lines harboring an antimicrobial protein gene, Ace-AMP1, demonstrate enhanced resistance to powdery mildew (*Sphaerotheca pannosa*). *Planta*. 218:226–232.
- Li X, Zhang Y, Zhang W, Zhang J, Wang H, Liu D. 2016. Expression profiles of pathogenesis-related gene, TaLr35PR1 as it relate to Lr35-mediated adult plant leaf rust resistance. *Plant Mol. Biol. Reporter*. 34:1127–1135.
- Liang P, Zeng Y, Ning J, Wu X, Wang W, Ren J, Zhang Y. 2025. A plant virus manipulates both its host plant and the insect that facilitates its transmission. *Science Advances*, 11(9), eadr4563.
- Liang XQ, Holbrook CC, Lynch RE, Guo BZ. 2005.  $\beta$ -1, 3-glucanase Activity in Peanut (*Arachis hypogaea*) seed is Induced by Inoculation with *Aspergillus flavus* and Copurifies with a Conglutin-like Protein. *Phytopathol.* 95(5): 506–511.
- Liu D, He X, Li W, Chen C, Ge F. 2012. Molecular cloning of a thaumatin-like protein gene from *Pyrus pyrifolia* and overexpression of this gene in tobacco increased resistance to pathogenic fungi. *Plant Cell Tiss Org Cul (PCTOC)*. 111:29–39.
- Liu F, Zhang X, Lu C, Zeng X, Li Y, Fu D et al., (2015). Non-specific lipid transfer proteins in plants: presenting new advances and an integrated functional analysis. *J. Exp. Bot.* 66, 5663–5681. doi: 10.1093/jxb/erv313
- Liu J, Wisniewski M, Artlip T, Sui Y, Droby S, Norelli J. 2013. The potential role of PR-8 gene of apple fruit in the mode of action of the yeast antagonist, *Candida oleophila*, in postharvest biocontrol of *Botrytis cinerea*. *Postharvest Biology and Technol.* 85: 203-209.
- Liu Q, Luo L, Zheng L. 2018. Lignins: Biosynthesis and biological functions in plants. *Int. J. Mol. Sci.* 19:335. doi: 10.3390/ijms19020335
- Longaward R, Sanguankiattichai N, Viboonjun U, van der Hoorn RAL. 2023. Letter to the editor: cautionary note on ribonuclease activity of recombinant PR-10 proteins. *Plant Cell Physiol.* 64:847–849. doi: 10.1093/pcp/pcad062
- Lonjon F, Lai Y, Askari N, Aiyar N, Bundalovic-Torma C, Laflamme B, Guttman DS. 2024. The effector-triggered immunity landscape of tomato against *Pseudomonas syringae*. *Nature Communications*. 15(1):5102.
- Lopes NDS, Santos AS, de Novais DPS, Pirovani CP, Micheli F. 2023. Pathogenesis-related protein 10 in resistance to biotic stress: Progress in elucidating functions, regulation and modes of action. *Front. Plant Sci.* 14:1193873.
- Lopez-Galiano MJ, Gonzalez-Hernandez AI, Crespo-Salvador O, Rausell C, Real MD, Escamilla M, Garcia-Robles I. 2018. Epigenetic regulation of the expression of WRKY75 transcription factor in response to biotic and abiotic stresses in Solanaceae plants. *Plant. Cell Rep.* 37:167–176.
- Mahajan G, Sharma N, Kaur M, Gupta R. 2025. Chitinases: Key players in plant defense mechanisms against fungal pathogens. *Physiol. Mol. Plant Pathol.* 138:102664.
- Mahatma MK, Bhatnagar R, Rawal P. 2008. Changes in enzymes and proline levels in leaves of downy mildew resistant and susceptible pearl millet genotypes. *J. Mycol. Pl. Pathol.* 38(2):277-281.
- Mahmoud F, Bondok A, Khalifa W, Abou Abbas F. 2020. Enhancing tomato plant resistance against Tobacco Mosaic Virus using riboflavin. *Arab Univ. J. Agric. Sci.* 28:1257–1270.
- Maia LB, Pereira HD, Garratt RC, Brandão-Neto J, Henrique-Silva F, Toyama D, Dias RO, Bachega JF, Peixoto JV, Silva-Filho MC. 2021. Structural and Evolutionary Analyses of PR-4 SUGARWINs Points to a different pattern of protein function. *Front. Plant Sci.* 12:734248.
- McLaughlin JE, Darwish NI, Garcia-Sanchez J, Tyagi N, Trick HN, McCormick S et al., 2021. A lipid transfer protein has antifungal and antioxidant activity and suppresses Fusarium head blight disease and DON accumulation in transgenic wheat. *Phytopathology* 111, 671–683. doi: 10.1094/PHYTO-04-20-0153-R
- Mehraj I, Hamid A, Gani U, Iralu N, Manzoor T, Saleem Bhat S. 2024. Combating antimicrobial resistance by employing antimicrobial peptides: immunomodulators and therapeutic agents against infectious diseases. *ACS Applied Bio. Materials.* 7(4): 2023-35.
- Melnikova DN, Finkina EI, Bogdanov IV, Tagaev AA, Ovchinnikova TV. 2022. Features and possible applications of plant lipid-binding and transfer proteins. *Membranes (Basel)* 13, 2. doi: 10.3390/membranes13010002
- Misra RC, Sandeep MK, Kumar S, Ghosh S. 2016. A thaumatin-like protein of *Ocimum basilicum* confers tolerance to fungal pathogen and abiotic stress in transgenic Arabidopsis. *Sci. Rep.* 6:25340.
- Molla KA, Karmakar S, Chanda PK, Ghosh S, Sarkar SN, Datta SK, Datta K. 2013. Rice oxalate oxidase gene driven by green tissue-specific promoter increases tolerance to sheath blight pathogen (*Rhizoctonia solani*) in transgenic rice. *Mol. Plant Pathol.* 14:910–22.
- Morris JS, Caldo KMP, Liang S, Facchini PJ. 2021. PR10/Bet v1-like proteins as novel contributors to plant biochemical diversity. *Chem Bio Chem.* 22:264–287.
- Munzert KS, Engelsdorf T. 2025. Plant cell wall structure and dynamics in plant–pathogen interactions and pathogen defence. *Journal of Experimental Botany.* 76:228–242.
- Nawrot R, Barylski J, Nowicki G, Broniarczyk J, Buchwald W, Gozdzicka-Jozefiak A. 2014. Plant antimicrobial peptides. *Folia Microbiol.* 59: 181–196.
- Ngermuen A, Suktrakul W, Kate-Ngam S, Jantasuriyarat C. 2020. Transcriptome comparison of defense responses in the rice variety ‘jao hom nin’ regarding two blast resistant genes, pish and pik. *Plants.* 9: 694.
- Ngou BPM, Ding P, Jones JDG. 2022. Thirty years of resistance: Zig-zag through the plant immune system. *Plant Cell.* 34:1447–1478. doi: 10.1093/plcell/koac041
- Niu JS, Liu R, Zheng L. 2007. Expression analysis of wheat PR-1, PR-2, PR-5 activated by Bgt and SA, and powdery mildew resistance. *J. Triticeae Crops,* 27:1132– 1137.
- Oard S, Rush MC, Oard JH. 2004. Characterization of antimicrobial peptides against a US strain of the rice pathogen *Rhizoctonia solani*. *J. Appl. Microbiol.* 97(1):169–180.
- Ökmen B, Doehlemann G. 2014. Inside plant: Biotrophic strategies to modulate host immunity and metabolism. *Curr. Opin. Plant Biol.* 20:19–25.

- Omar AZ, Hamdy E, Hamed EA, Hafez E, Abdelkhalek A. 2022. The curative activity of some arylidene dihydropyrimidine hydrazone against Tobacco mosaic virus infestation. *J. Saudi Chem. Soc.* 26:101504.
- Osbourn AE. 1996. Preformed antimicrobial compounds and plant defense against fungal attack. *Plant Cell* 8:1821–1831.
- Osmond RI, Hrmova M, Fontaine F, Imberty A, Fincher GB. 2001. Binding interactions between barley thaumatin-like proteins and (1, 3)- $\beta$ -D-glucans. Kinetics, specificity, structural analysis and biological implications, *Eur. J. Biochem.* 268 :4190–4199.
- Ouyang H, Sun G, Li K, Wang R, Lv X, Zhang Z, Wang Y. 2024. Profiling of *Phakopsora pachyrhizi* transcriptome revealed co-expressed virulence effectors as prospective RNA interference targets for soybean rust management. *J. Integrative Plant Biology.* 66(11):2543-2560.
- Parisi K, Shafee TM. A, Quimbar P, van der Weerden NL, Bleackley MR, Anderson MA. 2019. The evolution, function and mechanisms of action for plant defensins. *Semin. Cell Dev. Biol.* 88:107–118. doi: 10.1016/j.semcdb.2018.02.004
- Park CJ, Kim KJ, Shin R, Park JM, Shin YC. 2004. Pathogenesis related protein 10 Isolated from hot pepper functions as a ribonuclease in an antiviral pathway. *Plant J.* 37:186–198.
- Partridge-Telenko DE, Hu J, Livingstone DM, Shew BB, Phipps PM, Grabau EA. 2011. Sclerotinia blight resistance in Virginia-type peanut transformed with a barley oxalate oxidase gene. *Phytopathol.* 101:786–793.
- Patkar RN, Chattoo BB. 2006. Transgenic indica rice expressing ns-LTP-like protein shows enhanced resistance to both fungal and bacterial pathogens. *Mol. Breed.* 17:159–171.
- Pečenková T, Pejchar P, Moravec T, Drs M, Haluška S, Šantrůček J, Potocká A, Žárský V, Potocký M. 2022. Immunity functions of Arabidopsis pathogenesis-related 1 are coupled but not confined to its C-terminus processing and trafficking. *Mol. Plant Pathol.* 23:664–678.
- Pei Y, Xue Q, Zhang, Z, Shu P, Deng H, Bouzayen M, Hong Y, Liu M. 2023.  $\beta$ -1, 3-GLUCANASE10 regulates tomato development and disease resistance by modulating callose deposition. *Plant Physiol.* 192:2785–2802.
- Peng Q, Su Y, Ling H, Ahmad W, Gao S, Guo J, Que Y, Xu L. 2017. A sugarcane pathogenesis-related protein, ScPR10, plays a positive role in defense responses under *Sporisorium scitamineum*, SrMV, SA, and MeJA stresses. *Plant Cell Rep.* 36:1427–1440. doi: 10.1007/s00299-017-2166-4.
- Perrot T, Pauly M, Ramirez, V. 2022. Emerging roles of  $\beta$ -glucanases in plant development and adaptive responses. *Plants (Basel)* 11:1119. doi: 10.3390/plants11091119
- Pieterse CMJ, Van-der Does D, Zamioudis C, Leon-Reyes A, Van Wees SCM. 2012. Hormonal modulation of plant immunity. *Annu. Rev. Cell Dev. Biol.* 28:489–521.
- Poria V, Rana A, Kumari A, Grewal J, Pranaw K, Singh S. 2021. Current perspectives on chitinolytic enzymes and their agro-industrial applications. *Biol. (Basel)* 10:1319. doi: 10.3390/biology10121319
- Pränting M, Lööv C, Burman R, Göransson U, Andersson DI. 2010. The cyclotide cycloviolacin O2 from *Viola odorata* has potent bactericidal activity against Gram-negative bacteria. *J. Antimicrob. Chemother.* 65:1964–1971.
- Rabie M, Aseel DG, Younes HA, Behiry SI, Abdelkhalek A. 2024. Transcriptional responses and secondary metabolites variation of tomato plant in response to tobacco mosaic virus infestation. *Sci. Rep.* 14:19565.
- Radhajejalakshmi R, Velazhahan R, Balasubramanian P, Doraiswamy S. 2005. Overexpression of thaumatin-like protein in transgenic tomato plants confers enhanced resistance to *Alternaria solani*. *Arch. Phytopathol. Plant Prot.* 38:257–265.
- Ranjit Singh, H, Hazarika P, Agarwala N, Bhattacharyya N, Bhagawati P, Gohain B, Bandyopadhyay T, Raju B, Gupta S, Deka M, Das S. 2018. Transgenic tea over-expressing *Solanum tuberosum* endo-1, 3-beta-dglucanase gene conferred resistance against blister blight disease. *Plant Mol Biology Report.* 36(1):107–122.
- Rawlings ND, Barrett AJ, Thomas PD, Huang X, Bateman A, Finn RD. 2018. The MEROPS database of proteolytic enzymes, their substrates and inhibitors in 2017 and a comparison with peptidases in the PANTHER database. *Nucleic Acids Res.* 46: D624–D632. doi: 10.1093/nar/gkx1134
- Ray S, Anderson JM, Urmeev FI, Goodwin SB. 2003. Rapid induction of a protein disulfide isomerase and defense-related genes in wheat in response to the hemibiotrophic fungal pathogen *Mycosphaerella graminicola*. *Plant Mol. Biol.* 53: 701–714.
- Rayapuram C, Wu J, Haas, C, Baldwin IT. 2008. PR-13/Thionin but not PR-1 mediates bacterial resistance in *Nicotiana attenuata* in nature, and neither influences herbivore resistance. *Mol. Plant Microbe Int.* 21(7): 988–1000.
- Regner A, Szepannek N, Wiederstein M, Fakhimahmadi A, Paciosis LF, Blokhuis BR, Redegeld FA, Hofstetter G, Dvorak Z, Jensen-Jarolim E, Hufnagl K. 2022. Binding to iron quercetin complexes increases the antioxidant capacity of the major birch pollen allergen Bet v 1 and Reduces Its Allergenicity. *Antioxidants*, 12:42.
- Rodrigues JM, Coutinho FS, Dos Santos DS, Vital CE, Ramos JR, Reis PB, Oliveira MG, Mehta A, Fontes EP, Ramos HJ. 2021. BiP-overexpressing soybean plants display accelerated hypersensitivity response (HR) affecting the SA-dependent sphingolipid and flavonoid pathways. *Phytochemistry.* 185:112704.
- Rodríguez-Sifuentes L, Marszalek J.E, Chuck-Hernández C, Serna-Saldívar S.O. 2020. Legumes protease inhibitors as biopesticides and their defense mechanisms against biotic factors. *Int. J. Mol. Sci.* 21:3322. doi: 10.3390/ijms21093322.
- Roux, F, Voisin, D, Badet, T.C, Balagué, X, Barlet, C, Huard-Chauveau, et al., 2014. Resistance to phytopathogens e tutti quanti: placing plant quantitative disease resistance on the map. *Mol. Plant Pathol.* 15:427–432.
- Roy-Barman S, Sautter C, Chattoo BB. 2006. Expression of the lipid transfer protein Ace-AMP1 in transgenic wheat enhances antifungal activity and defense responses. *Trans Res.* 15:435–446.
- Ryals J, Uknes S, Ward E. 1994. Systemic Acquired Resistance. *Plant Physiol.* 104: 1109–1112.
- Sabater-Jara AB, Almagro L, Belchi-Navarro S, Ferrer MA, Barcelo AR, Pedreno MA. 2011. Methyl jasmonate induces extracellular pathogenesis-related proteins in cell cultures of *Capsicum chinense*. *Plant Sig. Behav.* 6:440–442.
- Saberi Riseh R, Fathi F, Vatankeh M, Kennedy JF. 2025. Thionins: potential use in plant defense against pathogens. *Plant Mol. Biol.* 115:77.

- Sabnam N, Hussain A, Saha, P. 2023. The secret password: Cell death-inducing proteins in filamentous phytopathogens- As versatile tools to develop disease-resistant crops. *Microb. Pathog.* 183:106276.
- Saikia R, Singh BP, Kumar R, Arora DK. 2005. Detection of Pathogenesis-related Proteins- Chitinase and  $\beta$ -1,3-Glucanase in Induced Chickpea. *Curr. Sci.* 89(4): 659–663.
- Sani I, Nwaogu J, Obafemi JI, Bello F, Abdulhamid A, Aminu H, Yanah YM. 2019. Antimicrobial phyto-peptides: Distribution, structural diversity and mechanisms of action. *World J. Pharm. Res.* 8:58-75.
- Sathyabhama M, Viswanathan R, Malathi P, Ramesh Sundar A. 2016. Identification of differentially expressed genes in sugarcane during pathogenesis of *Colletotrichum falcatum* by suppression subtractive hybridization (SSH). *Sugar Tech.* 18:176–183. <https://doi.org/10.1007/s12355-014-0364-8>.
- Selitrechnikoff CP. 2001. Antifungal proteins. *Appl. Environ. Microbiol.* 67:2883–2894.
- Sellami K, Couvert A, Nasrallah N, Maachi R, Abouseoud M, Amrane A. 2022. Peroxidase enzymes as green catalysts for bioremediation and biotechnological applications: A review. *Sci. Total Environ.* 806:150500. doi: 10.1016/j.scitotenv.2021.150500.
- Sellami K, Couvert A, Nasrallah N, Maachi R, Abouseoud M, Amrane A. 2022. Peroxidase enzymes as green catalysts for bioremediation and biotechnological applications: A review. *Sci. Total Environ.* 806:150500.
- Sels J, Mathys J, De Coninck B.M, Cammue BP, De Bolle MF. 2008. Plant pathogenesis-related (PR) proteins: a focus on PR peptides. *Plant Physiol. Biochem.* 46:941–950.
- Shafee TM, Lay FT, Phan TK, Anderson MA, Hulett MD. 2017. Convergent evolution of defensin sequence structure and function. *Cell. Mol. Life Sci.* 74: 663–682.
- Shah J, Tsui F, Klessig DF. 1997. Characterization of a salicylic acid-insensitive mutant (sai1) of *Arabidopsis thaliana*, identified in a selective screen utilizing the SA-inducible expression of the tms2 gene. *Mol. Plant Microbe Interact.* 10:69–78.
- Sharma A, Sharma A, Kumar R, Sharma I, Vats AK. 2021. PR proteins: key genes for engineering disease resistance in plants. In: *Crop improvement*. CRC Press, pp 81–98.
- Sharma A, Sharma H, Rajput R, Pandey A, Upadhyay SK. 2021. Molecular characterization revealed the role of thaumatin-like proteins of bread wheat in stress response. *Front. Plant Sci.* 12. doi: 10.3389/fpls.2021.807448
- Shin R, Lee G.J, Park CJ, Kim TY, You JS, Nam YW, Paek KH. 2001. Isolation of pepper mRNAs differentially expressed during the hypersensitive response to tobacco mosaic virus and characterization of a proteinase inhibitor gene. *Plant Science* 161:727–737.
- Shobade SO, Nilsen-Hamilton M, Zabolina OA. 2025. Plant Defense proteins: recent discoveries and applications. *Plants.* 14(13):2069. <https://doi.org/10.3390/plants14132069>
- Silva ON, De La Fuente-Núñez C, Haney EF, Fensterseifer ICM, Ribeiro SM, Porto WF, Lu TK. 2016. An anti-infective synthetic peptide with dual antimicrobial and immunomodulatory activities. *Sci. Rep.* 6(1):1-11.
- Sindelarova M, Sindelar L. 2005. Isolation of pathogenesis-related proteins from TMV- infected tobacco and their influence on infectivity of TMV. *Plant Prot. Sci.* 41:52–57.
- Singh BK, Delgado-Baquerizo M, Egidi E, Guirado E, Leach JE, Liu H, Trivedi P. 2023. Climate change impacts on plant pathogens, food security and paths forward. *Nat. Rev. Microbiol.* 21:640–656. doi: 10.1038/s41579-023-00900-7
- Singh NK, Kumar KRR, Kumar D, Shukla P, Kirti PB. 2013. Characterization of a pathogen induced thaumatin-like protein gene AdTLP from *Arachis diogeni*, a wild peanut. *PLoS One.* 8: e83963.
- Singh V, Hallan V, Pati PK. 2024. *Withania somnifera* osmotin (WsOsm) confers stress tolerance in tobacco and establishes novel interactions with the defensin protein (WsDF). *Physiol. Plant.* 176:e14513.
- Sinha R, Shukla P. 2019. Antimicrobial peptides: Recent insights on biotechnological interventions and future perspectives. *Protein and peptide let.* 26(2), 79-87.
- Slusarenko AJ, Fraser RSS, Van Loon LC. 2000. Mechanisms of resistance to plant diseases. Dordrecht, Kluwer (620 pp).
- Soltanloo H, Khorzoghi EG, Ramezanpour SS, Arabi MK, Pahlavani MH. 2010. The expression profile of Chi-1, Glu-2, Glu-3 and PR1.2 genes in scab-resistant and susceptible wheat cultivars during infection by *Fusarium graminearum*. *Plant Omics*, 3:162–166.
- Soni P, Pandey AK, Nayak SN, Pandey MK, Tolani P, Pandey S, Sudini HK, Bajaj P, Fountain JC, Singam P, Guo B. 2021. Global transcriptome profiling identified transcription factors, biological process, and associated pathways for pre-harvest aflatoxin contamination in groundnut. *J. Fungi.* 7:413.
- Souza TP, Dias RO, Silva-Filho MC. 2017. Defense-related proteins involved in sugarcane responses to biotic stress. *Genet. Mol. Biol.* 40 (1 suppl 1): 360–372.
- Spoel SH, Dong X. 2012. How do plants achieve immunity? Defence without specialized immune cells. *Nat. Rev. Immunol.* 12:89–100.
- Srivastava S, Dashora K, Ameta KL, Singh NP, El-Enshasy HA, Pagano MC, Hesham AE, Sharma GD, Sharma M, Bhargava A. 2021. Cysteine-rich antimicrobial peptides from plants: The future of antimicrobial therapy. *Phytother. Res.* 35:256–277.
- Stintzi A, Heitz T, Prasad V, Wiedemann-Merdinoglu S, Kauffmann S, Geoffroy P, Legrand M, Fritig B. 1993. Plant 'pathogenesis-related' proteins and their role in defense against pathogens. *Biochimie*, 75:687–706.
- Su Z, Han C, Qiao Q, Li C, Dong H, Wang X, Zhang S. 2024. Genome-wide analysis of the family 10 plant pathogenesis-related proteins in *Pyrus bretschneideri* and functional analysis of PbrMLP for *Colletotrichum fructicola* resistance. *Hortic. Adv.* 2(1):21.
- Sun T, Yan N, Liu Q, Bai T, Gao H, Chen J. 2025. Re-Examination Characterization and Screening of Stripe Rust Resistance Gene of Wheat TaPR1 Gene Family Based on the Transcriptome in Xinchun 32. *Int. J. Mol. Sci.* 26:640.
- Sundaresha S, Manoj Kumar A, Rohini S, Math SA, Keshamma E, Chandrashekar SC, Udayakumar M. 2010. Enhanced protection against two major fungal pathogens of groundnut, *Cercospora arachidicola* and *Aspergillus flavus* in transgenic groundnut over-expressing a tobacco  $\beta$  1–3 glucanase. *Eur. J. Plant Pathol.* 126: 497–508.
- Sung YC, Outram MA, Breen S, Wang C, Dagvadorj B, Winterberg B, Kobe B, Williams SJ, Solomon PS. 2021. PR1-mediated defence via C-terminal peptide release is targeted by a fungal pathogen effector. *New Phytol.* 229:3467–3480.
- Tam JP, Wang S, Wong KH, Tan WL. 2015. Antimicrobial peptides from plants. *Pharm. (Basel)* 8:711–757. doi: 10.3390/ph8040711

- Tang W, Zhu S, Li L, Liu D, Irving DE. 2010. Differential expressions of PR1 and chitinase genes in harvested bananas during ripening, and in response to ethephon, benzothiadiazole and methyl jasmonate. *Postharvest Biol. Technol.* 57(2):86–91. <https://doi.org/10.1016/j.postharvbio.2010.03.003>.
- Teixeira PJP, Colaianni NR, Fitzpatrick CR, Dangl JL. 2019. Beyond pathogens: microbiota interactions with the plant immune system. *Curr. Opin. Microbiol.* 49:7–17. doi: 10.1016/j.mib.2019.08.003
- Teng L, Liang S, Chen J, Kobe B, Ye N, Wang H, Song J. 2026. Genome-wide identification and analysis of expression of pathogenesis-related protein 1 (PR-1) gene family in brown algae. *Front Plant Sci.* 16:1754480. doi: 10.3389/fpls.2025.1754480. PMID: 41658544; PMCID: PMC12879055.
- Terras FR, Schoofs HM, Thevissen K, Osborn RW, Vanderleyden J, Cammue BP, Broekaert WF. 1993. Synergistic enhancement of the antifungal activity of wheat and barley thionins by radish and oilseed rape 2S albumins and by barley trypsin inhibitors. *Plant Physiol.* 103:1311–1319.
- Tomar P, Thakur D, Kamta S, Sharma S, Negi Y, Kaur N, Yadav AN. 2025. Integrating plant defense responses in managing nematode threats for sustainable farming: A potential review. *J. Natural Pesticide Research.* 15:100174.
- Tran TM, Ameye M, Landschoot S, Devlieghere F, De Saeger S, Eeckhout M, Audenaert K. 2021. Molecular insights into defense responses of Vietnamese maize varieties to *Fusarium verticillioides* isolates. *J. Fungi* 7:724.
- Vaaje-Kolstad G, Horn SJ, Aalten DMFV, Synstad B, Eijsink VGH. 2005. The Non-catalytic Chitin-binding Protein CBP21 from *Serratia marcescens* Is Essential for Chitin Degradation: *J. Biol. Chem.* 280(31):28492–28497.
- van Loon LC, Rep M, Pieterse CM. 2006. Significance of inducible defense-related proteins in infected plants. *Annu. Rev. Phytopathol.* 44:135–162.
- Varma S, Meena AK. Chapter-2 Integrated Defense Response of Plant against Pathogen. *Integrated Defense Response of Plant against Pathogen.* 2020.
- Velazhahan R, Cole KC, Anuratha CS, Muthukrishnan S. 1998. Induction of thaumatin-like proteins (TLPs) in *Rhizoctonia solani* infected rice and characterization of two new cDNA clones. *Physiol. Plant* 102:21–28.
- Wally O, Punja ZK. 2010. Genetic engineering for increasing fungal and bacterial disease resistance in crop plants. *GMCrops* 1:199–206.
- Wang C, Gao H, Chu Z, Ji C, Xu Y, Cao W, Zhou S, Song Y, Liu H, Zhu C. 2021. A nonspecific lipid transfer protein, StLTP10, mediates resistance to *Phytophthora infestans* in potato. *Mol. Plant Pathol.* 22:48–63. doi: 10.1111/mpp.13007.
- Wang C, Yin Z, Nie J, Lin Y, Huang L. 2021. Identification and virulence analysis of CAP superfamily genes in *Valsa mali*. *Scientia Agricultura Sin.* 54:3440–3450. doi: 10.3864/j.issn.0578-1752.2021.16.007
- Wang D, Amornsiripanitch N, Dong X. 2006. A genomic approach to identify regulatory nodes in the transcriptional network of systemic acquired resistance in plants. *PLoS Pathog.* 2:e123
- Wang L, Li R, Li K, Qu Z, Zhou R, Lu G, Li P, Li G. 2024. Genome-wide identification of the grapevine  $\beta$ -1,3-glucanase gene (*VviBG*) family and expression analysis under different stresses. *BMC Plant Biol* 24:911. <https://doi.org/10.1186/s12870-024-05597-1>
- Wang L, Wang G, Wang F, Chen Z, Wang X, Guo W. 2025a. Transcription factor GbTCP20 confers plant wilt resistance by regulating ACC biosynthesis pathway and lignin deposition. *Plant science international journal experimental plant biology* 359:112663.
- Wang N, Xiao B, Xiong L. 2011. Identification of a cluster of PR4-like genes involved in stress responses in rice. *J. Plant Physiol.* 168(18):2212–2224.
- Wang T, Xie M, Hou S, Ma J, Lin Y, Chen S, Li D, Yang G. 2025b. Walnut PR10/Bet v1-like proteins interact with chitinase in response to anthracnose stress. *J. Evol. Biol.* 38: 391–403.
- Wang Z, Zeng J, Deng J, Hou X, Zhang J, Yan W et al., 2023. Pathogen-derived extracellular vesicles: emerging mediators of plant-microbe interactions. *MPMI*, 36:218–227.
- Sun Z, Tan L, Chai N, Sui S, Liu D. 2023. Cloning and analysis of pathogenesis-related protein gene LhSorPR10-2 from 'Sorbonne' Lily. *J. Southwest Univ. (Natural Science)* 45:74–82.
- Wani MY, Mehraj S, Rather RA, Rani S, Hajam OA, Ganie NA, Mir MR, Baqal MF, Kamili AS. 2018. Systemic acquired resistance (SAR): A novel strategy for plant protection with reference to mulberry. *Int. J. Chem. Stud.* 2:1184-92.
- Westrick NM, Smith DL, Kabbage M. 2021. Disarming the host: detoxification of plant defense compounds during fungal necrotrophy. *Front. Plant Sci.* 12. doi: 10.3389/fpls.2021.651716
- Wrobel-Kwiatkowska M, Lorenc-Kukula K, Starzycki M, Oszmiański J, Kepczyńska E, Szopa J. 2004. Expression of  $\beta$ -1, 3-Glucanase in Flax Causes Increased Resistance to Fungi. *Physiol. Mol. Plant Pathol.* 65(5): 245-256.
- Wubben MJE, Jin J, Baum TJ. 2008. Cyst nematode parasitism of *Arabidopsis thaliana* is inhibited by salicylic acid (SA) and elicits uncoupled SA-independent pathogenesis-related gene expression in roots. *Mol. Plant-Microbe Interact.* 21:424–432.
- Wufuerjiang A, Sai J, Wen Y, Wang L, Chen C, Li X, et al., 2025. Genome-wide identification of the PR-1 gene family in *pyrus betulaeifolia bunge* and its expression analysis under fire blight stress. *Int. J. Mol. Sci.* 26, 5074. doi: 10.3390/ijms26115074.
- Xie YR, Chen ZY, Brown RL, Bhatnagar D. 2010. Expression and functional characterization of two pathogenesis-related protein 10 genes from *Zea mays*. *J. Plant Physiol.* 167:121–130.
- Yang H, Kim X, Sklenar J, Aubourg S, Sancho-Andrés G, Stahl E et al., 2023. Subtilase-mediated biogenesis of the expanded family of serine rich endogenous peptides. *Nat. Plants.* 9:2085–2094. doi: 10.1038/s41477-023-01583-x
- Yarullina L, Cherepanova EA, Burkhanova GF, Sorokan AV, Zaikina EA et al., 2023. Stimulation of the defense mechanisms of potatoes to a late blight causative agent when treated with *bacillus subtilis* bacteria and chitosan composites with hydroxycinnamic acids. *Microorganisms.* 11: 1993.
- Yarullina LG, Burkhanova GF, Tsvetkov VO, Cherepanova EA, Sorokan AV et al., 2024. The effect of Chitosan conjugates with hydroxycinnamic acids and *Bacillus subtilis* bacteria on the activity of protective proteins and resistance of potato plants to *Phytophthora infestans*. *Appl. Biochem. Microbiol.* 60:231–240.
- Yasmin N, Saleem M, Naz M, Gul R, Rehman, HM. 2017. Molecular characterization, structural modeling, and evaluation of antimicrobial activity of Basrai thaumatin-like protein against fungal infection. *Bio Med Res Int.* 2017.

- Yu DL, Song W, Tan EYJ, Liu L, Cao Y, Jirschitzka J et al., 2022. TIR domains of plant immune receptors are 2',3'-cAMP/cGMP synthetases mediating cell death. *Cell* 185 (13):2370–2386.e18. doi: 10.1016/j.cell.2022.04.032
- Yu Y, Gui Y, Li Z, Jiang C, Guo J, Niu D. 2022. Induced Systemic Resistance for Improving Plant Immunity by Beneficial Microbes. *Plants* (Basel Switz.) 11.
- Yusuf AG, Bello TT. 2025. Cellular plasticity and transcriptional reprogramming in plant-nematode interactions: insights into feeding site formation and plant defense. *Crop Health* 3:16.
- Zanini S, Secici E, Busche T, Galli M, Zheng Y, Kalinowski J, Kogel KH. 2021. Comparative analysis of transcriptome and sRNAs expression patterns in the *Brachypodium distachyon*—*Magnaporthe oryzae* pathosystems. *Int. J. Mol. Sci.* 22, 650.
- Zavaliev R, Ueki S, Epel BL, Citovsky V. 2011. Biology of callose ( $\beta$ -1, 3-glucan) turnover at plasmodesmata. *Protoplasma* 1:117-130.
- Zhang QY, Yan ZB, Meng YM, Hong XY, Shao G, Ma JJ, Cheng XR, Liu J, Kang J. 2021. Antimicrobial peptides: Mechanism of action, activity and clinical potential. *Mil. Med. Res.* 8:48. doi: 10.1186/s40779-021-00343-2.
- Zhang J, Du X, Wang Q, Chen X, Lv D, Xu K, Qu S, Zhang Z. 2010. Expression of pathogenesis related genes in response to salicylic acid, methyl jasmonate and 1-aminocyclopropane-1- carboxylic acid in *Malus hupehensis* (Pamp.) Rehd. *BMC Res. Notes* 3:208.
- Zhang J, Martin J. M, Balint-Kurti P, Huang L, Giroux MJ. 2011. The wheat puroindoline genes confer fungal resistance in transgenic corn. *J. Phytopathol.* 159(3):188–190.
- Zhang J, Wang F, Liang F, Zhang Y, Ma L, Wang H et al., 2018. Functional analysis of a pathogenesis-related thaumatin-like protein gene TaLr35PR5 from wheat induced by leaf rust fungus. *BMC Plant Biol.* 18:76. doi: 10.1186/s12870-018-1297-2
- Zhang Q, Xu C, Wei H, Fan W, Li T. 2021. Two pathogenesis-related proteins interact with leucine-rich repeat proteins to promote *Alternaria* leaf spot resistance in apple. *Hortic. Res.* 8.
- Zhao Y, Yang X, Zhang J, Huang L, Shi Z, Tian Z, Lu, G. 2024. Thaumatin-like protein family genes VfTLP4-3 and VfTLP5 are critical for faba bean's response to drought stress at the seedling stage. *Plant Physiology and Biochemistry*, 206:108243.
- Zhu F, Cao MY, Zhang QP, Mohan R, Schar J, Mitchell M, Chen H, Liu F, Wang D. Fu ZQ. 2024. Join the green team: Inducers of plant immunity in the plant disease sustainable control toolbox. *Journal of Advanced Research*, 57:15–42. <https://doi.org/10.1016/j.jare.2023.04.016>
- ZhuY, Gao F. 2025. Involvement of Pathogenesis-Related Proteins and Their Roles in Abiotic Stress Responses in Plants. *Biomolecules.* 15:1103. <https://doi.org/10.3390/biom15081103>
- Zribi I, Ghorbel M, Brini F. 2024. Pathogenesis-related proteins and plant defense response. In: Upadhyay SK (ed) *Defense-related proteins in plants*. Academic, New York, pp 53–97.
- Zribi I, Ghorbel M, Brini F. 2021. Pathogenesis Related Proteins (PRs): From Cellular Mechanisms to Plant Defense. *Curr. Protein Pept. Sci.* 22, 396–412.

#### How to cite this article

Konappa, N., Krishnamurthy, S., Uzma, F., Patil, R. H., & Chowdappa, S. (2026). Differential expression and induction of pathogenesis related proteins in response to plant pathogen infection. *Microbial Science Archives*, 6(2), 38–59. <https://doi.org/10.47587/MSA.2026.6203>

This work is licensed under a [Creative Commons Attribution 4.0 International License](https://creativecommons.org/licenses/by/4.0/)

