

Plants Under Attack: How Modern Biotechnology Helps Crops Fight Disease

Sayali G. Magar¹ and Vaishnavi G. Magar²

¹Assistant Professor, VNGCAB, Yavatmal, (M.S.), India

²Independent Researcher

SUMMARY

Plant disease resistance depends on a multilayered immune surveillance system in which cell-surface and intracellular receptors recognize pathogen signals and activate defense signaling. Understanding pattern-triggered and effector-triggered immunity has opened new avenues for biotechnological crop protection, particularly in cereals, where fungal and bacterial diseases substantially reduce yield and grain quality. This review examines four complementary strategies: engineering pattern-recognition receptors and resistance genes, RNA interference through host-induced gene silencing, and CRISPR/Cas-mediated genome editing of susceptibility and defense-associated genes. Case studies, including HIGS-mediated resistance to *Fusarium*, TaMLO editing for powdery mildew resistance in wheat, and OsERF922 mutagenesis for rice blast resistance, illustrate how molecular precision can improve upon conventional breeding while reducing linkage drag. Together, these approaches suggest that integrating plant immune biology with molecular breeding and genome engineering offers a durable, sustainable path toward disease-resistant crops with reduced reliance on chemical controls.

INTRODUCTION

The outcome of a plant-pathogen interaction is largely determined by the ability of plant cells to recognize invading microorganisms and activate appropriate defense responses. Plant immunity relies on a multilayered surveillance system comprising cell-surface and intracellular immune receptors. Pattern-recognition receptors (PRRs) detect conserved pathogen-associated molecular patterns (PAMPs), triggering pattern-triggered immunity (PTI), while pathogen effectors that interfere with host defense can subsequently be recognized by intracellular immune receptors, resulting in effector-triggered immunity (ETI). These recognition events activate downstream signaling networks involving calcium fluxes, reactive oxygen species (ROS), phytohormones, and defense-associated transcriptional reprogramming, providing an important foundation for developing biotechnological approaches to enhance disease resistance in crops (Bigini et al., 2021). Rather than relying exclusively on external chemical treatments, modern crop-protection strategies increasingly aim to strengthen or modify a plant's own defense mechanisms. Biotechnological approaches include manipulation of immune receptors and resistance genes, RNA interference (RNAi), and targeted genome editing. These strategies hold particular promise for cereal crops, where fungal and bacterial diseases can cause substantial reductions in yield and grain quality (Bigini et al., 2021). This paper reviews these approaches, examining how advances in understanding plant immune recognition, RNA-based gene silencing, and genome editing are converging to enable more precise and durable disease resistance in crops.

Engineering Pattern-Recognition Receptors and Resistance Genes

One promising strategy involves manipulating pattern-recognition receptors to increase a plant's ability to perceive pathogen-derived signals. Engineering or transferring immune receptors can potentially expand pathogen recognition and activate conserved immune-signaling pathways, demonstrating how knowledge of plant immune recognition can be translated into strategies for developing crops with enhanced or broader-spectrum disease resistance (Bigini et al., 2021). Resistance (R) genes represent another important resource for crop improvement. In wheat, resistance-associated genes such as Lr34 and Lr67 have been linked to resistance against multiple fungal pathogens, and their contribution to broad-spectrum, durable resistance illustrates the value of naturally occurring resistance mechanisms for cereal improvement (Bigini et al., 2021; Sinha et al., 2022). Beyond conventional resistance genes, biotechnology can be used to introduce or modify genes encoding proteins involved in pathogen defense, offering additional opportunities to improve resistance against important fungal diseases.

RNA Interference and Host-Induced Gene Silencing

At the post-transcriptional level, RNA interference (RNAi) provides a sequence-specific mechanism for suppressing gene expression. Double-stranded RNA is processed into small interfering RNAs (siRNAs), which associate with Argonaute proteins and guide the silencing of complementary RNA molecules. This mechanism has been exploited through host-induced gene silencing (HIGS) to target essential genes within pathogens. Koch et al. (2013) demonstrated that HIGS targeting cytochrome P450 lanosterol C14 α -demethylase (CYP51) genes could confer strong resistance against *Fusarium* species, illustrating the potential of RNA-mediated approaches to interfere directly with essential pathogen processes and thereby reduce disease development.

CRISPR/CAS-Mediated Genome Editing

The development of CRISPR/Cas-mediated genome editing has further increased the precision with which disease-resistance traits can be manipulated, allowing specific genes associated with susceptibility or defense responses to be modified without requiring broad changes throughout the genome. In hexaploid bread wheat, Wang et al. (2014) simultaneously edited three homoeoalleles of the TaMLO gene and obtained heritable resistance to powdery mildew, a result made particularly notable by the successful simultaneous targeting of three homoeologous gene copies within the complex wheat genome. CRISPR/Cas technology has also been applied successfully in rice: Wang et al. (2016) demonstrated that targeted mutagenesis of the OsERF922 transcription factor gene enhanced resistance to rice blast caused by *Magnaporthe oryzae*, showing how targeted modification of a host regulatory gene can alter the plant's defense response and improve disease resistance. Together, these examples demonstrate the potential of genome editing to modify specific host genes involved in plant-pathogen interactions.

Advantages over Conventional Breeding

An additional advantage of targeted genetic approaches is their potential to reduce linkage drag, which can occur when resistance traits are introduced through conventional breeding, as traditional introgression may transfer undesirable genomic regions along with the desired resistance locus. Transgenic approaches and genome editing offer greater precision in introducing or modifying resistance-associated traits, allowing these technologies to complement conventional breeding and contribute to the development of disease-resistant elite cultivars (Bigini et al., 2021).

CONCLUSION

The integration of plant immune biology, molecular breeding, RNA-based technologies, and genome engineering represents an important direction for sustainable crop protection. Understanding the molecular mechanisms underlying host-pathogen interactions enables researchers to identify specific targets for improving disease resistance: RNAi-based approaches can suppress essential pathogen genes, while genome editing can modify host susceptibility or defense-associated genes. The combination of these technologies, alongside naturally occurring resistance genes and engineered immune receptors, could contribute to durable and broad-spectrum disease resistance in crops while reducing dependence on conventional chemical disease-control measures (Bigini et al., 2021; Sinha et al., 2022).

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