Innovative Strategies and Advances in Breeding Wheat for Rust Resistance

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Wheat (*Triticum aestivum* L.) is the primary staple meal for the majority of the world's population and was one of the crops farmed throughout the prehistoric period. Several variables contribute to the discrepancy between potential and harvested wheat yields. Crop diseases are the most significant barriers to reaching the goal of food security. Rust infections, caused by fungal pathogens of the genus Puccinia, are one of the most serious risks to worldwide wheat production. Three rust diseases-leaf rust *(Puccinia triticina*), stripe rust (*Puccinia striiformis* f. sp. *tritici*), and stem rust (*Puccinia graminis* f. sp. *tritici*) in wheat-are the main limitation in harvesting an abundance of crops, causing significant crop yield declines and significant damage in multiple regions at various times (Afzal *et al*., 2022). Rust stress reduces wheat grain production and affects other yield component qualities such grain size, weight, number of grains per head, plant biomass, vigor, and growth. Rust stress affects the developmental phases of plants. Characteristics of rust-induced infection include early tillering and jointing anthesis stage, few kernels per spike, and decreased grain weight and quality.

The dynamic nature of wheat rust means that it is always evolving, surpassing resistance in wheat varieties, making traditional breeding methods less successful, and requiring constant study and adaptation. Because of the dangers associated with broad fungicide usage, which can affect environmental sustainability and health, wheat rust research is important for ecological and environmental reasons in addition to agricultural economic ones. Evaluating these ecological consequences is crucial to creating coordinated and sustainable management methods. In order to maintain food security in the face of changing disease populations, breeding for rust resistance has proven essential to sustainable wheat production. This article examines the methods, difficulties and most recent developments in rust-resistant wheat breeding.

Significance of Rust Resistance in Wheat

Biffen (1905) made the first attempt to use breeding programs for wheat resistance to rust. Race-specific resistance (R) genes and non-race-specific resistance genes, which generally confer slow-rusting resistance, are the two types of genes that often govern the genetics of resistance in wheat. These genes do not discriminate between the two gene classes; they are designated *Lr*, *Sr* and *Yr* (for leaf, stem, and stripe or yellow rust resistance, respectively) (Ellis *et al*., 2014). Rust infections may spread quickly under favorable environmental conditions and can spread over vast distances due to their capacity to create significant amounts of airborne spores. New strains of stem rust (e.g., Ug99), leaf rust (*Lr21*), and stripe rust (*Yr27*) have been shown to be more virulent globally in a number of noteworthy outbreaks over the last ten years. One economical and sustainable way to fight these diseases is to create resistant cultivars, which will lessen the need for fungicides and have a less negative impact on the environment.

Diverse Sources of Rust Resistance

Rust resistance in wheat is classified into two categories:

1. **Race-Specific Resistance:** Also known as major-gene or qualitative resistance, Race-specific resistance, is granted by a single R gene and offers total protection; but, because of pathogen evolution, it is frequently transient (Ellis *et al*., 2014).
2. **Adult Plant Resistance (APR):** Also termed minor-gene or quantitative resistance. APR, provides partial but more resilient resistance and is controlled by numerous genes (Ellis *et al*., 2014).

APR may not offer sufficient protection on its own, even while its decreased effectiveness and delayed activation lessen the selection pressure on pathogens. Crop mixes or rotations that include APR and R genes can improve disease control and resistance persistence. According to molecular research, APR genes like *Lr34* and *Yr36* express a variety of proteins, including protein kinases and ABC transporters, whereas R genes normally encode NB-LRR proteins (Ellis *et al*., 2014). Resistance gene discovery has been sped up by complex methods including genome-wide association studies (GWAS) and genotyping-by-sequencing. Creating successful breeding plans requires an understanding of the molecular and genetic underpinnings of these resistance mechanisms.

Breeding Strategies

Advanced molecular techniques have replaced traditional methods in the breeding of wheat resistant to rust. While hybridization and selection are still significant traditional methods (Afzal *et al*., 2022), they are now supplemented by genomic selection, marker-assisted breeding and biotechnological tools (Savadi *et al*., 2018).

1. **Conventional Breeding -** Conventional breeding relies on hybridization and selection to transfer resistance genes from donor lines to elite wheat cultivars. In order to include resistance genes while preserving desired agronomic traits backcrossing and pedigree selection are frequently employed (Afzal *et al*., 2022).
2. **Gene Pyramiding -** Resistance durability is increased when many R or APR genes are combined in a single cultivar (gene pyramiding). Precise stacking of these genes is made possible by marker-assisted selection (MAS), which guarantees complete defense against a variety of rust races. Combining many resistance genes to increase durability and expand protection against various rust races is known as gene pyramiding (Baranwal, 2022).
3. **Genomic Selection (GS) -**The creation of rust-resistant cultivars is accelerated by GS, which predicts breeding values using genome-wide markers. GS supports both marker-assisted and conventional breeding methods by capturing both significant and minor gene effects (Newell and Jannink, 2014).
4. **Marker-Assisted Breeding (MAB) -** With integrating molecular markers connected to rust resistance genes, MAB makes it possible to select resistant lines early and precisely. The time and resources required for phenotypic screening in the field are decreased by this method (Savadi *et al*., 2018).
5. **Biotechnological Approaches -** New approaches to rust resistance breeding have been made possible by developments in genetic engineering and gene-editing technologies like CRISPR-Cas9. According to Afzal *et al*. (2024), these techniques enable the introduction of new resistance genes from various sources as well as the exact alteration of target genes.

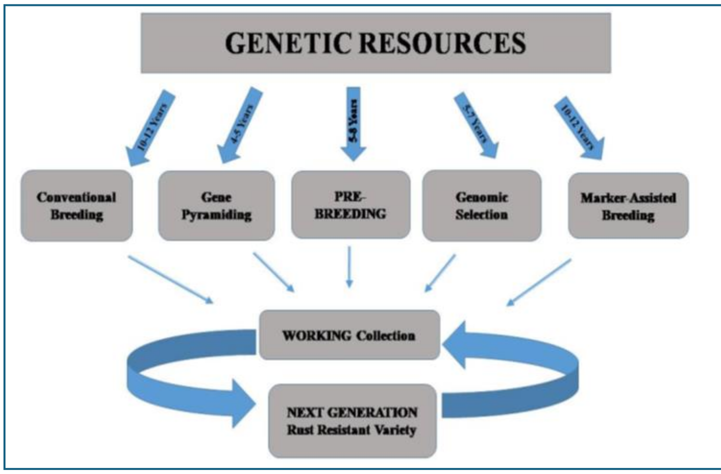

Fig. 1. Breeding Strategies for development of Rust Resistant Wheat Varieties

Challenges in Breeding for Rust Resistance

Wheat rust resistance breeding presents continual problems due to the fast emergence of novel pathogenic races (Bhavani *et al*., 2019). This is rapid and continues process which makes resistant varieties to susceptible within short span. Some challenges are listed below: -

- **Pathogen Variability**: The fast emergence of new virulent rust races, such as Ug99 and derivatives, hampers resistance deployment (Bhavani *et al*., 2019).
- **Trade-offs with Agronomic Traits**: Genes for resistance may have an adverse effect on grain quality, yield, or other desired characteristics (Brevis *et al*., 2008).
- **Climate Change**: Resistance breeding is a dynamic objective because rust epidemiology is influenced by shifting climatic circumstances (Park, 2008).

- **Durability of Resistance**: Diverse resistance sources must be deployed and continuously monitored to ensure the long-term efficacy of resistance genes (Park, 2008).

Recent Advances and Future Prospects

Recent advances in wheat genetics and breeding technology provide interesting techniques for improving rust resistance. High-throughput phenotyping technologies allow for precise evaluation of rust resistance features (Keller *et al*., 2018).

- **High-Throughput Phenotyping**: Accurate and extensive evaluation of rust resistance is made possible by automated phenotyping tools (Keller *et al.*, 2018).
- **Pan-Genome Resources**: Novel resistance genes and structural variants can be found more easily because to the availability of wheat pan-genomes (Sanjay and Prakash, 2024).
- **Genomic-Assisted Breeding**: Breeding is accelerated by the integration of transcriptome data, genomic selection, and GWAS (Sanjay and Prakash, 2024).
- **Pre-Breeding Programs**: The goal of cooperative efforts is to introduce resistance genes from exotic germplasm and wild relatives (Keller *et al*., 2018).

Conclusion

Global food security depends on breeding wheat to be resistant to rust since it is a significant source of protein and calories. To create long-lasting, rust-resistant cultivars, contemporary techniques have been combined with traditional breeding techniques based on Mendelian genetics. These consist of genetic engineering, RNA interference, CRISPR-Cas9 gene editing, and marker-assisted selection. Combining traditional and cutting-edge breeding techniques is necessary to address the persistent problems caused by the continual development of rust pathogens and climate change. Achieving sustainable wheat production and satisfying the world's food demands requires international cooperation and the application of cutting-edge technologies. To improve rust resistance and guarantee steady output under shifting climatic circumstances, it is also essential to develop wheat types that are climate-resilient. These initiatives support the environmental sustainability and food security Millennium Development Goals of the United Nations.

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