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Breeding for Durable Disease Resistance in the Era of Climate Change: Navigating a Shifting Landscape

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ABSTRACT

Climate change essentially is redefining the struggle against crop diseases that will make an already challenging fight a thousand times harder. The search of long-lasting resistance can no longer be thought of as a genetic puzzle, as pointed out in this review. These solutions, which are the pyramid of genes, the use of CRISPR, or the use of wild relatives are technically strong and are loaded with biological trade-offs, socio-economic hurdles, and the uncertainty of non-stationary climate itself. It is therefore not only fair to deploy new tools in the future but new philosophy of crop improvement that should be embraced. It is high time to create dynamic, interdependent, and equitable systems incorporating highly advanced science with the sound socio-economic support. By actively responding and trying to control such a vital problem proactively, we can not only come up with the climate resistant crops but the robust agricultural structures to sustain them by safeguarding the world food security in the succeeding generations.

Keywords: disease resistance, climate change, plant breeding, quantitative resistance loci (QRLs), gene editing (CRISPR), genomic selection

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Introduction

The Green Revolution in the 20th century was based on the use of high yielding cultivars that were often dependent on single gene resistance to the most common pathogenic risks. Whereas this policy has produced impressive agronomic benefits in the first place, it has also established a dynamic of boom and bust. The release of a dominant R-gene puts extreme selection pressure on populations of phytopathogenic species, and this has caused the rapid development of virulent races that can avoid the resistance, a good example being the Ug99 stem rust lineage of wheat [1]. The durable resistance (a characteristic that remains effective in the long-term through time and space) has emerged as a key goal in this milieu. This is a more stable broad-spectrum protection, which is quantitative and regulated by multiple quantitative resistance loci (QRLs), and is the most common form of resistance, such as Lr34 gene of wheat [2].

In the modern world, climate change is one of the most important factors that promote this cycle and predispose it to be more serious. That threat is not just no longer a potential issue but directly a disruptor, and a game-changer in the sense that it imposes new and unpredictable selection pressures not only on pathogens, but also on their host plants [3, 4]. Climate change does not only enlarge the geographical range of pathogens but also modifies the parameters of the interaction of hosts and pathogens entirely and even at the same time enhances the virulence of pathogens and silences the defense mechanisms of plants. The review challenges the multidimensional impacts of such forces and suggests that in order to address this new paradigm, it is not only necessary to have incremental progress in breeding but, also, a system change to pre-, not post-,emptive and integrated policies, with the express inclusion of climate-induced volatility, trade-offs associated with complex trait introgression, socio-economic syntheses to provide resilient crops to end-users.

As it may be even more pernicious, the indirect effects of climate change are quite strong as they undermine the well-being of the host plants. Important defensive signaling pathways may be inhibited by abiotic stresses such as drought, heat and waterlogging. As an example, heat stress was observed to suppress salicylic acid-mediated-defenses, which increases the vulnerability to biotrophic pathogens [5, 6]. The resultant effect is that a plant that is under a drought condition is more susceptible to infections like the Fusarium wilt. These legal forces that are growing populations of the pathogen, new environmental factors and stressed hosts eventually rate pathogen evolution. This multiplication of mutations that aid to bypass resistant cultivars increases the chances of the occurrence of adaptive mutations which is seen in the quick worldwide diffusion of wheat blast [3, 7].

Contemporary Breeding Procedures of Increased Durability

To address these changing threats breeding solutions need to go beyond single gene solutions. One of the foundational strategies involves introducing several R-genes into a single cultivar using marker-assisted selection (MAS) and, therefore, creates a multidimensional impediment of pathogen adaptation [8]. However, there is a growing focus on the exploitation of quantitative resistance loci (QRLs) which provide partial but more permanent and expanded protection. The adoption of genomic selection (GS) will play a central role in that respect, but it uses genome-wide markers to predict and select complex polygenic traits such as long-term resistance, and, in this way, significantly accelerates the breeding process [9, 10].

The rich genetic pool contained in the crop wild relatives (CWRs) and landraces is a priceless source of new resistance alleles, and this has been demonstrated by the use of the wheat rust resistance allele of the wheat strain, Aegilops tauschii [11, 12]. Meanwhile, biotechnological instruments provide accurate interventions in order to construct longevity. Breeders can also use CRISPR-based gene-editing techniques (like CRISPR-Cas9) to induce an effect of disrupting plant susceptibility (S) genes to produce a vast spectrum of resistance, as shown effectively by the editing of the powdery mildew resistance gene, the *MLO* gene, in wheat [13, 14].

Essential Factors and Issues that Remain

Although the technological approaches mentioned above have a potential, their effective execution depends on overcoming deep biological, economic and systemic impediments that often lack adequate focus. The Yield -Durability Trade-off: The breeding cost of durable, quantitative resistance is that it is commonly linked to yield penalties, otherwise known as yield drag. Alleles with broad spectrum resistance may also be energetically expensive or associated with other unrelated traits. An example is the introgression of crop wild relatives (CWRs) that can bring both detrimental and advantageous genes with it, such as linkage drag, and thus requires extensive backcrossing to eliminate undesirable loci [15]. Moreover, the susceptibility (S) genes could have a pleiotropic effect; although, MLO gene knockout provides resistance against powdery mildew, it may also induce untimely senescence of the leaf in particular environmental conditions [16]. As a result, breeding programmes should strictly consider the agronomic performance of the resistant lines in various environment to see that durability does not reduce the productivity. The Socio-Economic and Regulatory Disjuncture: The expensive nature of genomic selection, high-throughput phenotyping and CRISPR technology could lead to increased inequality in the world. A large technological and capacity disparity may arise whereby government breeding projects in the developing countries, that feed large proportions of the most vulnerable groups in the world, cannot compete with highly financed private organizations [17]. This is further worsened by a complicated intellectual property policy on the major technologies like CRISPR that may hinder their free application by researchers. In addition, gene-edited crops create a cloud of uncertainty over regulatory rules that are usually restraining, discouraging investments, especially among staple crops that are the pillars of food security [18].

Durability in a Non-Stationary Climate: The very meaning of the term of durability is being thrown into question. A currently stable pyramid of

resistance gene combinations that is quantitatively represented as quantitative resistance locus (QRL) may not be as stable in future climatic conditions. As an illustration, a character that is resistant to heat stress in moderate situations might not be resistant to heat waves that further diminish host immunity. This demands a radical change of thought to a non permanent and non-stable solution in developing dynamic and responsive breeding systems which can constantly be altered.

The Requirement of Real Integration: Finally, the shout of the multidisciplinary collaboration must be made out of the words. It necessitates structural incorporation. The data of genomic surveillance of pathogens should be immediately received and processed into the decision to breed (pre-emptive breeding). The choice of target environments to be used in phenotyping requires climate models. The decision about the priorities in socio-economic studies should be to direct the kind of traits that farmers will be willing to adopt. It needs new data sharing platforms and collaborative forms of governance that break disciplinary silos. Facilitating Technologies and a Coordinated Way. These advanced strategies are implemented with the backing of enabling technologies. Large-scale, real-time screening of disease resistance and abiotic stress tolerance can be performed on a large scale with high-throughput phenotyping platforms, which use drones and satellites with spectral and thermal sensors [19, 20]. At the same time, it is important to genetically monitor the populations of pathogens to trace their evolution and provide pre-emptive breeding [21]. It is expected to create a climate-resilient ideotype- model plant combines long-lasting disease resistance with properties of heat tolerance, water use efficiency and high yield potential [22]. This principle is demonstrated by such examples as the heat and stripe rust-resistant wheat variety Kharchia 65.

The four pillars that form the basis of the integration framework are:

- Climate-Informed Breeding Pipelines: Use predictive climate models to designate hotspots of future abiotic and biotic stress and give breeding emphasis there.
- Open -Sources: Have common digital platforms on genomic data, pathogen monitoring and phenotyping, to reduce barriers to entry to all breeders.
- Policy and Regulatory Harmonization: Support science-founded, relative regulations of gene-edited crops to encourage innovation and global availability of the innovation.

Farmer-Centric Delivery: Empower seed systems and involve farmers in early stages of breeding process to ensure that emerging varieties address their needs and are affordable to them hence a reduction in adoption gap.

Conclusion

Climate change essentially is redefining the struggle against crop diseases that will make an already challenging fight a thousand times harder. The search of long-lasting resistance can no longer be thought of as a genetic puzzle, as pointed out in this review. These solutions, which are the pyramid of genes, the use of CRISPR, or the use of wild relatives are technically strong and are loaded with biological trade-offs, socio-economic hurdles, and the uncertainty of non-stationary climate itself. It is therefore not only fair to deploy new tools in the future but new philosophy of crop improvement that should be embraced. It is high time to create dynamic, interdependent, and equitable systems incorporating highly advanced science with the sound socio-economic support. By actively responding and trying to control such a vital problem proactively, we can not only come up with the climate resistant crops but the robust agricultural structures to sustain them by safeguarding the world food security in the succeeding generations.

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