



Predictive Breeding for Crop Improvement

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As global populations grow and climate change increasingly impacts agricultural productivity, there is an urgent need for more efficient and effective methods to develop crops that can meet the world's food demands. Traditional breeding methods, while successful in the past, often involve long and resource-intensive processes of selecting and crossbreeding plants over multiple generations. These methods rely heavily on phenotypic selection, where plants are chosen based on observable characteristics, which can be influenced by environmental factors and do not always accurately reflect the underlying genetic potential. In response to these challenges, predictive breeding has emerged as a transformative approach in modern agriculture. Predictive breeding integrates high-throughput genomic technologies, advanced phenotyping methods, and powerful computational tools to forecast the performance of plant progeny before they are even created. By analyzing large datasets that combine genetic information (genotypes) with observed traits (phenotypes), predictive breeding models can identify the most promising genetic combinations that are likely to produce desired traits, such as increased yield, enhanced nutritional quality, or improved resistance to pests and diseases.

This approach represents a significant shift from traditional breeding methods by focusing on the prediction and selection of genetic potential rather than solely on observable traits. The use of predictive models, which incorporate complex interactions between genes and environmental factors, enables breeders to make more informed decisions, accelerating the breeding process and increasing the likelihood of success.

Key Components of Predictive Breeding

- 1. Genomic Selection (GS):** A pivotal element in predictive breeding, genomic selection employs genome-wide marker data to predict the genetic potential of individuals within a breeding population. This technique enables breeders to choose parent plants based on anticipated genetic value, rather than relying solely on observable traits. Genomic selection has dramatically transformed breeding, particularly in crops with lengthy generation cycles, such as perennials, by significantly shortening the time needed to develop new varieties (Meuwissen *et al.*, 2001).
- 2. Machine Learning and Artificial Intelligence (AI):** The incorporation of AI and machine learning into predictive breeding enhances the accuracy of predictions by capturing complex interactions between genetic markers and environmental conditions. These advanced models process extensive datasets to uncover patterns and predict results that might be missed by traditional statistical methods. AI-based models have been utilized in various crops, including wheat, maize, and rice, to forecast traits like yield and disease resistance across different environments (Hickey *et al.*, 2017).
- 3. Phenotyping Technologies:** Cutting-edge phenotyping technologies, such as high-throughput field phenotyping and remote sensing, are vital to predictive breeding as they

offer precise, large-scale data on plant traits. This phenotypic information is crucial for training predictive models and verifying their accuracy. The deployment of drones, satellites, and ground-based sensors enables the collection of detailed phenotypic data over large areas and varied environments, further enhancing predictive breeding efforts (Cobb *et al.*, 2013).

4. **Genotype-by-Environment Interactions (GxE):** Predictive breeding models also integrate genotype-by-environment interactions, acknowledging that a plant's performance is shaped not just by its genetic composition but also by the environment in which it is cultivated. By including GxE interactions in predictive models, breeders can select crop varieties that are well-suited to specific environmental conditions, which is particularly crucial in the context of climate change (Cossa *et al.*, 2014).

Applications in Crop Improvement

Predictive breeding has demonstrated significant potential in enhancing major crops. For instance, in maize, predictive models have accelerated the development of hybrids with enhanced drought tolerance an increasingly critical trait as global climate patterns shift (Cooper *et al.*, 2014). In wheat, predictive breeding has facilitated the selection of varieties with better resistance to rust diseases, a major threat to global wheat production (Cossa *et al.*, 2014). Additionally, predictive breeding plays a crucial role in developing crops with improved nutritional profiles. By predicting and selecting for traits related to nutrient content, breeders can create varieties that address specific dietary deficiencies, contributing to global food security and nutrition (Zhao *et al.*, 2017). Predictive breeding is highly complementary to genome editing technologies such as CRISPR-Cas9. While predictive breeding identifies the most promising genetic combinations, genome editing can be used to introduce or enhance these traits with precision. This integration allows for the rapid development of improved crop varieties with desirable traits, such as increased yield or enhanced stress tolerance, thus addressing both current and future agricultural challenges.

Challenges and future prospects

Despite its potential, predictive breeding faces several challenges, including the need for large and high-quality datasets, the complexity of modeling GxE interactions, and the integration of different types of data (genomic, phenotypic, environmental). However, ongoing advancements in data collection, computational power, and breeding technologies are expected to address these challenges, making predictive breeding an indispensable tool in modern agriculture .

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