“Genomics for Crop Improvement: From Genes to Fields"

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# ABSTRACT

The exploration of genomics has become a transformational one, transforming many areas of research, including agriculture. The genetic potential of crops has been unlocked in the field of agricultural improvement via genomics, enabling the creation of more durable, nutrient-rich, and sustainable cultivars. This chapter gives a broad overview of the use of genomics in crop development, emphasizing major technologies, difficulties, and potential future uses. Although traditional crop breeding techniques have been effective at enhancing agricultural attributes, they are frequently limited by laborious phenotypic selection and scant access to genetic diversity. With the use of high-throughput genome sequencing technologies, crop genomes can now be easily analyzed by scientists, revealing the genetic underpinnings of a variety of desirable features. Specific genes linked to qualities like resistance to diseases, drought tolerance, and nutritional content can be found by techniques like genomic mapping and quantitative trait locus (QTL) analysis, facilitating Marker-Assisted Selection (MAS) for more effective and precise breeding. In addition, the development of genome editing tools like CRISPR-Cas9 has given scientists the ability to modify specific crop genomes to produce crops with desired features without introducing foreign DNA. Utilizing the genetic variety found in crops and their wild cousins has been made possible by omics technologies, including genomics, transcriptomics, proteomics, and metabolomics. A new era of crop improvement has arrived thanks to genomics, which has made it possible for researchers and breeders to make better use of the huge genetic resources available in agriculture. The future of crop improvement is bright, bringing solutions to global issues like food security and climate change. This is due to ongoing advances in genomics and its combination with conventional breeding techniques.

**Keywords** :- Genomics, Omics, CRISPR/Cas, MAS, DNA Sequencing, etc.

# INTRODUCTION TO GENOMICS IN CROP IMPROVEMENT

A subfield of molecular biology called genomics focuses on understanding an organism's entire DNA sequence, including its genes and how they work. Genomic technologies have significantly impacted efforts to improve crops in a number of industries, including agriculture. Upcoming years are more critical for food production as we require more agricultural products to feed the world. Food and nutritional security depend on sustainable food production. Studies show that 821 million people globally are at or below the minimal nutritional level, including 151 million stunted children under the age of five. Additionally, two billion individuals do not get enough micronutrients to sustain a healthy lifestyle. To meet these objectives, the manufacturing and supply chain must run efficiently. It has been estimated that by 2050, the industrial system will need to raise its output by 60% in order to address a number of climate change-related challenges. The price of food is predicted to rise by 1-29% by 2050, which is projected to make these problems even worse. We now have less access to agriculturally productive land as a result of increased urbanization brought on by rising population [1]. We will need to increase food production for a number of other reasons besides population growth. Rapidly developing nations experienced significant income development that gave rise to an emerging middle class, which sped up the dietary shift toward higher consumption of meat, eggs, and dairy products and increased the need to farm more grain to feed more cattle, pigs, and poultry [2]. Agriculture would have to generate between 60 and 100 percent more food and feed than it does currently by 2050 [3]. Scientists can now quickly study the complete genome of crops thanks to the development of high-throughput DNA sequencing technologies, enabling a greater understanding of their genetic make-up and potential. Using methods like genetic mapping and quantitative trait locus (QTL) analysis, researchers can now pinpoint individual genes linked to important features like drought tolerance, disease resistance, and nutritional content. The discovery of these genes makes Marker-Assisted Selection (MAS) easier and enables breeders to more quickly choose plants with desired features.

# The Role of Genomic Selection in Crop Improvement:

By anticipating an individual's genetic worth based on its full genome, genomic selection advances the application of genomics in breeding. This makes it possible for breeders to make decisions early in a plant's development, even before particular features are completely manifested, leading to breeding cycles that are more precise and efficient. Recent advances in genome editing technologies, particularly CRISPR/Cas9, have opened up new avenues for quick and accurate genome modification, offering quick transfer of information from the lab to the field. In the target genome, genome editing enables the introduction of insertions, deletions, or a completely new sequence [4]. Genome editing enables the selective modification of known genes governing significant features, allowing for the alteration of phenotypes. Several genome-edited crop plants, such as waxy maize, drought- and salt-tolerant soybeans, and Camelina with more oil, have recently reached the end of the commercialization process in the United States of America [5].

# Classification of genomics based on the techniques

The three basic classification of genomics have been listed below along with the techniques and databases used (Fig.1)

# Structural Genomics:

 The study of the arrangement and sequencing of DNA throughout an organism's whole genome is known as structural genomics. Additionally, each protein encoded by genes has its three-dimensional structure evaluated. The primary goal of structural genomics is to identify all potential protein structures of an organism because it is crucial to learn new information about an organism's biological processes. The following are the structural genomics methodologies:

* + 1. Chromosomal maps
		2. Cytogenetic map
		3. Genetic map/Linkage map
		4. Physical map
		5. Transcriptome sequencing
		6. Expressed sequence tags (ESTs) and cDNA clones
		7. Full-length cDNA sequencing
		8. Whole genome sequencing

# Approaches of structural genomics

1. ***de novo* method (experimental approach):**

X-ray crystallography, NMR spectroscopy, or electron microscopy are common techniques for determining protein structure. The X-ray crystallography approach is the most accurate and is thought to have a higher degree of precision in determining the structure among all of these methods. For small- to medium-sized proteins, NMR spectroscopy can substitute X-ray crystallography. Heteronuclear Single Quantum Coherence, or HSQC, spectra are the primary tool in NMR spectroscopy for figuring out protein structures. The protein structure is first determined by electron microscopy at extremely low resolution, and it is then verified by the X-ray crystallography technique. New methods, such as transverse relaxation optimization spectroscopy, chilled probe technology, ultra-high field magnets, and isotope labeling methods, have been developed for quick determination.

# Modelling-based methods:

This method uses model building, threading, or profile-profile matching to compare proteins to the PDB (Protein Data Bank). Profile-profile matching is used in a PSI-Basic Local Alignment and Search Tool search to find closely related sequences of the query compound in the database. The most effective technique for protein projection is threading. By matching the new protein's main sequence to a related experimental structure in the PDB [6], it can determine the three-dimensional structure of the protein.

# Functional Genomics:

The study of the activities of genes, their products and interactions is known as functional genomics. It specifies the activities of an organism's entire genome before characterizing the genome in accordance with those functions. The primary goal of functional genomics is to investigate the connection between an organism's genome and phenotype. Techniques for functional genomics analysis include the following:

1. GTG banding (Giemsa banding) – GTG banding (Giemsa banding) - This technique is used to look at big chromosomal abnormalities (greater than 5 Mb) in karyotype.
2. Microarray-Based Comparative Genomic Hybridization, or aCGH, is used to analyze the gain or loss of genomic regions. Compared to conventional karyotyping, it is more accurate in detecting DNA gains or losses. To detect genomic alignments and copy-number changes, cCGH is a precise, delicate, and quick approach [7].
3. FISH (Fluorescence in situ Hybridization) – Using radiolabelled probes, this method is used to locate specific DNA sequences. The FISH technique was originally used to paint chromosomes [8].
4. Sanger or Next-Generation Sequencing – These techniques are used to find known and unknown variations in an organism's genomic DNA. Both approaches are based on similar principles. The complementary integration of fluorescently labeled deoxyribonucleotide 5'-triphosphates (dNTPs) into the DNA template is catalyzed by DNA polymerase during the polymerase chain reaction (PCR), which consists of several cycles of successive DNA replication. The nucleotide sequences of a labeled DNA fragment are identified by the detector based on the color of the fragment for each cycle. The fundamental distinction between Sanger and Next Generation sequencing is that the latter uses massively parallel sequencing technology to analyze millions of DNA fragments rather of only one [9].
5. Mass spectrometry – It consists of three components: an ion generator for forming ions from the gas-phase sample, a mass analyzer for using electromagnetic fields to separate those ions, and detectors. That permits proteins and peptides to move into the gaseous phase without considerable degradation has proved crucial for mass spectrometry in large proteome studies. The two most often utilized ionization methods are matrix-assisted laser electrospray ionization and desorption ionization. The most advanced mass spectrometer at the moment is the Orbitrap, which has a large dynamic range, high mass accuracy, and outstanding resolution that make it suitable for many proteomics and metabolomics applications.

# Comparative Genomics:

The genomic traits of several organisms are compared in the biological research discipline known as comparative genomics. The goal of comparative genomics is to discover the similarities between two organisms, which are frequently encoded in the DNA that is shared between species. The goal of comparative genomics is to analyze groups of genes that have a specific biological function in a given creature by differentiating gene counts, gene placements, and biological functions of genes in the genomes of various animals. We will be able to pinpoint the genes needed for essential processes in a wide range of species using comparative genomics. By comparing related species, it is crucial to study the evolutionary history of organisms. Because all living things have a common evolutionary ancestor, it is understandable that there are significant variances and overlaps within species as well as minute variations among individuals between species, which may affect disease susceptibility in some and resistance in others. It aids in establishing the connection between genotype and phenotype. On various databases, there are integrated resources for comparative genomics:

* + 1. PlantGDB and GreenPhylDB – for all plants.
		2. Gramene – for cereals.
		3. RoBuST – for root and bulb crop families Apiaceae and Alliaceae
		4. GRASSIUS – for grasses.

Aligning two genome sequences using a computational tool is the first step in doing a comparative genomics investigation. Recently developed tools include BLASTN and MEGABLAST, GLASS, MUMmer, PatternHunter, PipMaker, and VISTA for genome scale alignment and visualization.

Comparative analysis of genome structure - Examining global molecular structure, such as the nucleotide composition, syntenic linkages, or gene ordering, enables the understanding of similarities and differences between genomes. These comparisons shed light on the structure and evolution of a genome as well as its distinctive features. Three levels allow for comparisons between the structures of various genomes: a) Global nucleotide statistics b) DNA level genome structure c) gene level genome structure [10].



Fig. 1 Classification of genomics

# Harnessing Genetic Diversity through Omics Technologies:

Crop development relies heavily on genetic variety because it offers a pool of genes that may be used to create crop types that are more tolerant and adaptive. Omics technologies, including genomics, transcriptomics, proteomics, and metabolomics, allow for the thorough analysis of crop variety, making it easier to find important genes and the regulatory networks that control them.

# Challenges and Ethical Considerations:

There are challenges in integrating genomics into agricultural improvement. To ensure appropriate and sustainable use of genomic techniques in agriculture, issues like data management, intellectual property rights, and public acceptance of genetically modified crops need to be carefully considered and regulated.

# Unraveling the Genetic Blueprint: Genome Sequencing and Analysis

Unprecedented opportunities to interpret organisms' genetic codes have been made possible by advances in genomics, offering priceless insights into their features, functions, and evolutionary past. The primary technology of genomics, genome sequencing, has changed a number of scientific disciplines, from medicine to agriculture. In this article, we explore the importance of genome sequencing and analysis, its uses, and the significant influence it has had on both theoretical knowledge and real-world applications. Identifying the sequence of nucleotides (A, T, C, and G) that make up an organism's whole DNA entails genome sequencing. By decoding the human genome, which took more than a decade and the combined efforts of experts from all around the world, the Human Genome Project, which was finished in 2003, marked a key milestone in genomics. Since then, technical developments have significantly lowered the time and expense of genome sequencing, making it available to researchers and institutions around the world. Genome sequencing in agriculture has paved the road for crop development as researchers find genes linked to desired qualities like disease resistance and enhanced yield. With the help of links between organisms and the discovery of crucial moments in their divergence, it has thrown light on the evolutionary histories of numerous species. Scientists can track the evolutionary pathways of various species and identify the genetic alterations that led to speciation and adaptation by comparing the genomes of different species. Genome sequencing creates enormous amounts of data, making its management, analysis, and interpretation computationally challenging. High-performance computing and bioinformatics technologies are necessary for processing massive data and deriving relevant insights from genomes.

# Genome Sequencing

Genetics and genomics have undergone a major transformation thanks to the introduction of high-throughput sequencing tools. Whole genome sequencing (WGS) has become widely used for the first time, allowing detection of a full range of common and rare genetic variants of various types across almost the entire genome. This facilitates research and clinical applications for rare diseases and can enhance the discovery of common disease and annotation of the causal variants. We are at the beginning of a new age when WGS will be a dominating method for genetic analysis now that hundreds of thousands of genomes have been sequenced globally. In contrast to earlier decades of human genetic research, which relied on genetic markers that serve as indirect proxies of other genetic variations in the surrounding region, or sequencing data from the genome’s exonic regions only. In order to understand how variations affect phenotypes, functional interpretation of WGS-discovered variants is a crucial part of human genetics investigations. Assays for genome-wide functional genomics now make it possible to identify, characterize, and forecast variations' molecular effects with increasing accuracy. But since these impacts reveal the whole complexity of genome function, which we still don't fully understand, there is still much to learn about different molecular effects and how they could affect higher-level organismal phenotypes (Fig. 2).



Figure 2 :- General frame of WGS

A typical WGS study's primary goal is to provide a precise map of the samples' genomic variation. Since inaccurately detected and genotyped variations won't be directly evaluated in trait-focused studies, this critical step establishes the groundwork for all subsequent analyses geared at genome interpretation and genetic discovery. The technology utilized for sequencing and the level of coverage attained have a significant impact on the methodologies employed to map genomic variation [11]. Currently, there are three main WGS techniques : There are three types of whole genome sequencing (WGS): (1) short-read WGS using Illumina technology, which currently produces paired-end reads of 150 bp or less with error rates in the range of 0.1-0.5%; (2) long-read WGS using single molecule technologies from Pacific Biosciences (PacBio) or Oxford Nanopore Technologies (ONT), which produces reads of 10–100 kb or even longer on occasion; (3) linked-read WGS using technology from 10X Genomics We concentrate largely on the analysis of this data format because the vast majority of human genetics research use short-read WGS employing the Illumina HiSeq or NovaSeq platform due to factors like as cost, usability, and accuracy. The required amount of coverage is a key factor in the design of WGS investigations. Each nucleotide in the genome must be sequenced several times from randomly selected DNA molecules in order to identify variations from mistakes.

# Functional annotation and genetic variant impact forecasting consequences, both qualitative and quantitative

The simplest method for annotating genetic variations is based on the allele frequency and location of the variants in the genome's coding or noncoding regions. Diverse research communities have historically examined them. The majority of the attention in the rare and Mendelian illness community has been on exome-sequenced uncommon, strong-effect gene-disrupting coding mutations. The common illness community, on the other hand, has often concentrated on the investigation of non-coding variants with plausible regulatory implications driving GWAS relationships and common variants genotyped by SNP arrays. The basic coding/noncoding categorization, which frequently contains implicit assumptions that coding variants produce gene knockouts or affect protein structure, is challenged by a more nuanced knowledge of the functional impact of genetic variations. In truth, protein structure and dose may be affected in a variety of qualitative and quantitative ways by both coding and noncoding variations. In the end, annotation of variations according to their projected functional effects rather than their chromosomal location will have a stronger biological foundation and be more broadly applicable. For instance, loss-of-function effects from non-coding mutations that have a significant impact on gene expression should be comparable to those from coding variants that cause nonsense-mediated decay of the same gene.

The difficulties in predicting the impacts of variants are more complicated, and the plan and timetable are less distinct. There is general agreement, however, that a variety of techniques will be necessary and that they must be used on a variety of systems, including cellular, organoid, and animal models as well as human samples. Analysing ever-larger and more varied human populations as well as cell kinds is crucial [12]. To enable direct investigation of different impacts and more precise computational prediction techniques, we anticipate that advancements in experimental techniques, the generation of substantial and comprehensive data sets, and algorithm development will work hand in hand.

# Genome sequenced Agriculturally important plants

Reduced hunger is the main goal of the current boom in plant genome sequencing. Most of the plant genomes that have been sequenced are those of food crops, which are crucial for tropical nations. Various grains, pulses, tuber crops, fruits, vegetables, and oil plants are among these crops. For several of these crops, functional markers have been created, and genes affecting crucial agronomic features have been found. For a thorough knowledge of the genetic mechanisms underlying each attribute and to discover allelic variants, re-sequencing and gene expression experiments are still being carried out. Numerous genome studies are active or in the planned stages in addition to the crops that have been sequenced. Below is the list of some agriculturally important plants which are sequenced (Table 1). Genetics has undergone a radical transformation as a result of the development of sequencing technology and the mass sequencing of genomes and transcriptomes. Using the most latest technology, many crop genomes have been sequenced. However, the research is still in its infancy. Several crop genome assemblies still exist in draft form. The density of repeats in many plant genomes makes it difficult to assemble the short reads from NGS systems. It would be promising to launch third-generation sequencing technologies like Pacific Biosciences in order to get longer reads for the assembly of whole chromosomes. Another effective way to extract the whole genome assembly is by the purification of individual chromosomes, which may then be used for shotgun sequencing or the creation of BAC libraries [13]. The focus of this decade should be on information acquisition, with the expected application of that knowledge in the form of enhanced crop varieties with higher yields and resistance to biotic and abiotic stress in the following decades [62].

# Breeding for Resilience: Genomic Selection and Marker-Assisted Breeding

Breeding for resilience is a crucial strategy in modern agriculture and livestock management to enhance the ability of crops and animals to withstand various stressors and challenges. With the increasing impacts of climate change, emerging diseases, and changing environmental conditions, there is a growing need to develop resilient plant varieties and animal breeds that can thrive in these unpredictable circumstances. Two prominent techniques used in breeding for resilience are Genomic Selection (GS) and Marker-Assisted Breeding (MAB). These approaches leverage advancements in genomic technology to accelerate the breeding process, making it more efficient and targeted.

# Genomic Selection (GS):

A cutting-edge breeding technique called genomic selection makes use of genomic information to forecast a person's genetic potential for particular traits. It entails scanning an organism's complete genome to find areas connected to features that are desirable, such drought tolerance, disease resistance, or yield potential. These genomic areas, sometimes referred to as markers, act as signs of the existence of advantageous genes linked to the desired attributes. The GS process involves the following steps:

* + 1. Genotyping: The genome of a large population of plants or animals is analyzed using high-throughput genotyping technologies to detect markers associated with the desired traits.
		2. Phenotyping: The same individuals are phenotyped to measure their actual performance for the target traits.
		3. Training the model: A statistical model is developed to establish the relationship between the markers and the phenotypic data of the individuals in the population.
		4. Selection: The model is then used to predict the breeding value of untested individuals, allowing breeders to select candidates with the highest potential for desired traits.

Genomic Selection significantly accelerates the breeding process by allowing breeders to identify superior candidates at an early stage without the need for lengthy and resource-intensive field trials. This results in more efficient and precise breeding programs that can rapidly introduce desirable traits into new varieties and breeds. Numerous studies have been conducted to determine how well genomic selection (GS) may be used to enhance crops since the theory and conceptual underpinning for GS were first developed. However, marker-assisted selection has demonstrated its potential for improving qualitative characteristics with huge impacts regulated by one to few genes. It has a minor impact on the enhancement of quantitative traits that are controlled by a variety of small-effect genes**.** GS is a valuable technique for improving traits as it chooses candidates for the breeding cycleusing breeding values of individuals (genomic-estimated) derived from genome-wide markers. Over the past 20 years, GS has been widely implemented in animal breeding programs all over the world due to its capacity to maximize genetic gains, reduce phenotyping, shorten cycle times, and increase selection accuracy. The prospects of integrating GS in breeding crops are also being examined considering the positive preliminary findings of the GS evaluation for increasing production, stress tolerance both biotic and abiotic, and quality in cereal crops. For the success of GS-enabled breeding programs, improved statistical models are essential that employ genetic data to increase accuracy of prediction. The creation of production markers that can greatly speed up the generation of crop varieties. The figure below shows the major steps involved in genomic selection (Fig.4)



# Figure 4:- General Steps of Genomic Selection

# One of the advantages of GS, which predicts phenotype using data from genome-wide DNA markers, is a large cost decrease in repetitive phenotyping [63]. Breeding cycles can be shortened thanks to GS's excellent predictive accuracy in elite genetic materials, particularly in the early generations, and genomic estimated breeding values (GEBVs) [64]. The crop performance of hybrids may be accurately predicted using the GS models. Werner et al., for example, calculated general combining ability (GCA) and specific combining ability (SCA) based on RR-BLUP and Bayesian models to forecast hybrid performance in oilseed rape [65].

# Model for Genomic Selection Using Statistics

A basic linear model, often known as least-squares regression or ordinary least-squares regression (OLS), is the first step in the GS process of choosing the appropriate candidates:

Y=1nµ+Xβ+ε

Where, X is the design matrix of the order n×p (where each row represents the genotype/individuals/lines (n) and each column corresponds to the marker (p)), Y=n×1 vectors of observations, is the mean, β=p×1 vectors of marker effects,ε=n×1 vectors of random residual effects, and ε∼N(0,σ2e).

The number of markers (p) surpasses the number of observations (n), i.e., genotype/individuals/lines, causing the problem of over-parameterization (big "p" and small "n" problem (p >> n)). This is the main issue with linear models utilizing thousands of genome-wide markers. The big "p" and small "n" problem can be solved alternatively by using significant markers subset. For GS, Meuwissen et al. modified the least-squares regression [63]. Each marker was subjected to a separate least-squares regression analysis using the following model:

Y=Xjβj+ε,

where Xj is the jth column of the marker design matrix and βj is the genetic impact of the jth marker. This model's log likelihood is used to choose markers with significant effects, and those markers are subsequently used to estimate breeding values. It must be understood, nonetheless, that selection based on the subset of markers may result in the loss of some important information [66].

# Table 1 : List of genome sequenced agriculturally important plants

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Scientific name** | **Common name** | **Economic importance** | **Haploid chromosome number** | **Estimated genomic size (Mb)** | **Size of Assembly (Mb)** | **Number of gene****predictions** | **Repeat (%)** | **Reference** |
| *Azadirachta indica* | Neem | Pesticides, medicine | 12 | 364.00 | – | 20,000 | 13.03 | [[14]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4807965/#b47-tlsr-27-1-93) |
| *Beta vulgaris* | Sugar beet | Sugar production | 9 | 714.00–758.00 | 567.00 | 27,421 | 63.00 | [[15]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4807965/#b47-tlsr-27-1-93) |
| *Brassica napus* | Rapeseed | Oil, animal feed, biodiesel | 19 | 1130.00 | 892.70 | 1,01,040 | 34.80 | [[16]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4807965/#b47-tlsr-27-1-93) |
| *Brassica oleracea var. capitata* | Cabbage | Food (vegetable) | 9 | 630.00 | 535.50 | 45,758 | 38.80 | [[17]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4807965/#b54-tlsr-27-1-93) |
| *Brassica rapa* | Chinese cabbage | Food (vegetable) | 10 | 529.00 | 283.80 | 4l,174 | 39.50 | [18] |
| *Cajanus cajan* | Pigeon pea | Food | 11 | 833.07 | 605.78 | 48,680 | 51.67 | [[19]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4807965/#b98-tlsr-27-1-93) |
| *Cametina sativa* | Camelina | Oil, animal feed, biodiesel | 20 | 785.00 | 641.45 | 89,418 | 28.00 | [[20]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4807965/#b42-tlsr-27-1-93) |
| *Carica papaya* | Papaya | Food (fruit, vegetable) | 9 | 372.00 | 271.00 | 24,746 | 52.00 | [21] |
| *Cannabis sativa* | Marijuana | Drug | 10 | ∼820.00 | 534.70 | 30,000 | – | [22] |
| Hemp | Fibre, oil |  |  | 220.80 | – | – |  |
| *Capsicum annum* | Hot pepper | Spice | 12 | 3,480.00 | 3,060.00 | 34,903 | 76.40 | [[23]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4807965/#b45-tlsr-27-1-93) |
| *Cicer arietinum* | Chickpea | Food | 8 | ∼738.00 | 532.29 | 28,269 | 49.41 | [24] |
| *Citrullus lanatus* | Water melon | Food (fruit) | 11 | ∼425.00 | 353.50 | 23,440 | 45.20 | [[25]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4807965/#b32-tlsr-27-1-93) |
| *Citrus clementina* | Clementine mandarin | Food (fruit) | 9 | 367.00 | 301.40 | 24,533 | 45.00 | [[26]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4807965/#b105-tlsr-27-1-93) |
| *Citrus sinensis* | Sweet orange | Food (fruit) | 9 | 367.00 | 320.50 | 29,445 | 20.50 | [[27]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4807965/#b108-tlsr-27-1-93) |
| *Coffea canephora* | Robusta coffee | Food | 11 | 710.00 | 568.60 | 25,574 | 50.00 | [[28]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4807965/#b108-tlsr-27-1-93) |
| *Cucumis melo* | Melon | Food (fruit) | 12 | 450.00 | 375.00 | 27,427 | 19.70 | [[29]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4807965/#b108-tlsr-27-1-93) |
| *Cucumis sativus* | Cucumber | Food (vegetable) | 7 | 367.00 | 243.50 | 26,682 | 24.00 | [[30]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4807965/#b108-tlsr-27-1-93) |
| *Elaeis guineensis* | Oil palm | Edible oil | 16 | 1,800.00 | 1,535.00 | 34,802 | 57.00 | [[31]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4807965/#b108-tlsr-27-1-93) |
| *Eragrostis tef* | Tef | Food | 20 | 772.00 | 672.00 | – | 14.00 | [[32]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4807965/#b108-tlsr-27-1-93) |
| *Eucalyptus, grandis* | Eucalyptus | Wood, biofuel, medicine | 11 | 640.00 | 605.00 | 36,796 | 50.00 | [[33]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4807965/#b108-tlsr-27-1-93) |
| *Fragaria vesca* | Strawberry | Food (fruit) | 7 | 240.00 | 209.8 | 34,809 | 16.00 | [[34]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4807965/#b108-tlsr-27-1-93) |
| *Glycine max* | Soybean | Food | 20 | 1,115.00 | 950.00 | 46.430 | 57.00 | [[35]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4807965/#b108-tlsr-27-1-93) |
| *Musa acuminata* | Banana | Food (fruit) | 11 | 523.00 | 472.20 | 36,542 | 43.72 | [[36]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4807965/#b108-tlsr-27-1-93) |
| *Nicotiana tabacum* | Tobacco | Smoking | 12 | 4,500.00 | 3,700.00 | 90,000 | 72.00–78.00 | [[37]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4807965/#b108-tlsr-27-1-93) |
| *Oryza sativa- spp indica* | Rice | Food | 12 | 430.00 | 466.00 | 46,022–55,615 | 42.20 | [[38]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4807965/#b108-tlsr-27-1-93) |
| *Oryza sativa-spp japonica* |  |  |  | 420.00 | 389.80 | 37,544 | 35.00 | [[39]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4807965/#b108-tlsr-27-1-93) |

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| *Phaseolus vulgaris* | Common bean | Food | 11 | 587.00 | 473.00 | 27,197 | 45.37 | [[40]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4807965/#b108-tlsr-27-1-93) |
| *Phoenix dactylifera* | Date palm | Food (fruit) | 18 | 671.00 | 605.40 | 41,660 | 21.99 | [[41, 42]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4807965/#b108-tlsr-27-1-93) |
| *Phyllostachys heterocycla* | Moso bamboo | Building material, furniture, pa per | 24 | 2,075.00 | 2,050.00 | 31,987 | 59.00 | [[43]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4807965/#b108-tlsr-27-1-93) |
| *Populus trichocarpa* | Poplar | Wood, paper | 19 | 485.00 | 410.00 | 45.555 | 44.00 | [[44]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4807965/#b108-tlsr-27-1-93) |
| *Prunus mume* | Chinese plum/Mei | Food (fruit) | 8 | 280.00 | 237.00 | 31,390 | 45.00 | [[45]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4807965/#b108-tlsr-27-1-93) |
| *Pyruss bretschneideri* | Pear | Food (fruit) | 8 | 265.00 | 226.60 | 27,852 | 29.60 | [[46]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4807965/#b108-tlsr-27-1-93) |
| *Pyruss bretschneideri* | Pear | Food (fruit) | 17 | 527.00 | 512.00 | 42,812 | 53.10 | [[47]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4807965/#b108-tlsr-27-1-93) |
| *Ricinus communis* | Castor bean | Oilseed | 10 | 320.00 | 350.00 | 31,237 | 50.33 | [[48]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4807965/#b108-tlsr-27-1-93) |
| *Setaria italica* | Foxtail millet | Food. fodder, biofuel | 9 | 490.00 | 423.00 | 38,801 | 46.00 | [[49, 50]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4807965/#b108-tlsr-27-1-93) |
| *Solanum lycopersicum* | Tomato | Food (vegetable) | 12 | 900.00 | 760.00 | 34,727 | 63.28 | [[51]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4807965/#b108-tlsr-27-1-93) |
| *Solanum melongena* | Eggplant | Food (vegetable) | 12 | 1126.00 | 833.10 | 85,446 | 70.40 | [[52]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4807965/#b108-tlsr-27-1-93) |
| *Solanum tuberosum* | Potato | Food | 12 | 844.00 | 727.00 | 39,031 | 62.20 | [[53]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4807965/#b108-tlsr-27-1-93) |
| *Sorghum bicolor* | Sorghum | Food, beverage | 10 | ∼730.00 | 698.00 | 27,640 | 62.00 | [[54]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4807965/#b108-tlsr-27-1-93) |
| *Theobroma cacao* | Cocoa | Food | 10 | 430.00 | 326.90 | 28,798 | 25.70 | [[55]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4807965/#b108-tlsr-27-1-93) |
| *Triticum aestivum* | Bread wheat | Food | 21 | 17,000.00 | 3,800.33 | 94,000–90,000 | 80.00 | [[56]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4807965/#b108-tlsr-27-1-93) |
| *Vaccinium macrocarpon* | Cranberry | Food (fruit) | 12 | 470.00 | 420.00 | 36,364 | 5.60 | [[57]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4807965/#b108-tlsr-27-1-93) |
| *Vigna radiata* | Mungbean | Food | 11 | 579.00 | 431.00 | 22,427 | 43.00 | [[58]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4807965/#b108-tlsr-27-1-93) |
| *Vitis vinifera* | Grape | Food (fruit), beverage | 19 | 475.00 | 487.00 | 30,434 | 41.40 | [[59]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4807965/#b108-tlsr-27-1-93) |
| *Zea mays* | Maize | Food | 10 | 2,300.00 | 2,048.00 | 32,540 | 85.00 | [[60]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4807965/#b108-tlsr-27-1-93) |
| *Ziziphus jujuba* | Jujube | Dry fruit, medicine | 12 | 444.00 | 437.65 | 32,808 | 49.49 | [[61]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4807965/#b108-tlsr-27-1-93) |

* 1. **Marker-Assisted Breeding (MAB):**

Marker-Assisted Breeding is an earlier version of genomic selection that employs markers associated with specific traits but doesn't involve complex prediction models. Instead, it directly targets specific genes or genomic regions known to influence desirable traits. MAB is particularly useful for traits controlled by major genes, which have a significant impact on the phenotype. The process of Marker-Assisted Breeding involves the following steps:

* + 1. Marker identification: Researchers identify markers that are closely linked to genes responsible for the target trait through genetic mapping and association studies.
		2. Marker-assisted selection: Breeders use these markers as a tool to select individuals that carry the desired genes during the breeding process.
		3. Phenotypic evaluation: The selected individuals are then subjected to rigorous phenotypic evaluation to validate their performance for the targeted trait.

While Marker-Assisted Breeding lacks the predictive power and efficiency of Genomic Selection, it remains a valuable technique for traits with known genetic markers. Additionally, it can be more cost-effective, especially in cases where genomic data for the entire genome is not necessary. In conclusion, both Genomic Selection and Marker-Assisted Breeding play crucial roles in breeding for resilience. They empower breeders with the knowledge of an organism's genetic makeup and aid in the selection of individuals with desired traits, ultimately leading to the development of more robust and resilient crops and animal breeds. As these technologies continue to advance, they will undoubtedly contribute significantly to food security and sustainable agriculture in the face of evolving challenges. The phenology of several agricultural species has been impacted by climate change, which has a negative impact on productivity and output. Climate change have resulted into various abiotic stresses including heat, cold, drought, and flood. Traditional breeding has been effective in achieving phenotypic selection-based genetic improvement of crops. However, recent advances in genomics have revealed a number of underlying genes and quantitative trait loci (QTLs) that confer tolerance to these particular environments and have been applied in marker-assisted selection (MAS). In an indirect selection procedure known as MAS, individuals are chosen based on the known markers associated with a certain characteristic of interest [67]. This technique has been successfully employed earlier to boost individual selection efficiency compared to the conventional phenotype-based selection approach [68].

# Implications of Genomic Selection for crop improvement

1. **GS in Cereals**

Cereals such as wheat, rice, maize, and barley have been an important component of our daily diet with approximately 50% of the total energy supply. The production of these products is threatened by disasters brought on by climate change [69], and on top of that, it is made more challenging by the increased demand brought on by a growing population [70]. To overcome these encounters, the production system needs to be efficient, environmentally friendly, and sustainable. For such production systems to be able to meet the challenges, it is imperative to use crop kinds with high yields and minimal resource requirements. The creation of such varieties, however, is a laborious process because the majority of agricultural productivity attributes are governed by a complex genetic system (most genes have little or no influence), which is complicated by poor heritability and a high degree of epitasis [71]. Although traditional selection techniques have produced a lot of varieties, the genetic gain per unit of time is not as rewarding as GS, but they do offer a chance to speed up the selection cycle [72]. The feasibility of the technique can be assessed by how quickly GS selects individuals from early-generation populations with high breeding value without the requirement for considerable phenotyping. The first candidate crops where the efficiency of GS has been investigated are wheat, rice, maize, and barley.

# Improvements in Grain Yield and Related Characteristics

The thousand grain weight, the number of tillers bearing panicles, the number of grains per panicle, the number of filled grains per panicle, etc. are essential features that either directly or indirectly affect grain yield. It has been evaluated how well these variables can be predicted by genomics utilizing different training populations and model types. Variations in the heritability of the trait, the training population, and the models employed have all been linked to variations in the accuracy of genetic prediction. The genomic prediction accuracy ranged from 0.28 to 0.78 for a very complex and physiological trait-like distribution of weight to each individual grain in the panicle in rice [73]. Grain yield for maize ranged from 0.28 to 0.78 [74].

# Tolerance to Biotic Stress

As a result of shifting weather patterns, reports are being made on a global scale about the emergence/resurgence of novel disease races and insect biotypes [75]. Therefore, it is necessary to find resistance genes in the germplasm and incorporate them into the breeding program in order to create cultivars that can withstand biotic stress. While MAS has proven useful in the breeding of qualitative resistance, it has not been as successful in the breeding of quantitative resistance, which is controlled by a greater number of genes with less dramatic effects. Despite being used on a very small number of cereals, GS has demonstrated its effectiveness in increasing biotic stressor tolerance in cereals that are quantitatively controlled. The majority of studies on the application of GS for biotic stress tolerance have focused on wheat. Numerous diseases have been identified in wheat, including three different rust types, Fusarium head blight, *Septoria tritici* blotch, powdery mildew, tan spot, and *Stagonospora nodorum* blotch. Utilizing GS, blast-tolerant rice lines have been discovered [76]. In maize, GS has been successfully employed to select lines for superior productivity under heavy Striga infection [78] and for tolerance to the ear-rot-causing *Stenocarpella maydis* from wild populations.

# Tolerance to Abiotic Stress

Climate change has increased the likelihood of drought, high-temperature stress during agricultural growth phases, flood, etc., which results in large crop losses [79]. According to Liu et al.'s prediction, a 1°C increase in global temperature will cause a 6.4% yield decrease in wheat. In such circumstances, altering cropping patterns or creating cultivars that are resistant to abiotic stress are the affordable and sustainable solutions to make up for the losses. Conventional breeding techniques for abiotic stress have issues with precision and reproducibility. Molecular markers have been used to find and transfer yield QTLs under abiotic stress conditions [82], despite the fact that Beyene et al.'s [81] study on eight biparental populations of maize under drought conditions revealed a gain of 0.176 t/ha for grain yield after three cycles of selection using the rapid cycling GS strategy. Comparatively to the usual breeding technique, where phenotypic selection needed a selection time that was three times higher, this resulted in an increase in genetic gain.

# Quality Improvement

The genetic architecture of different quality vary; some, like grain color, are oligogenically controlled, whilst others, like grain size and protein content, are polygenic in origin [83]. When prediction accuracies in biparental and multifamily populations were compared, the multi-family populations showed superior prediction accuracies for quality-related variables, such as milling quality and flour quality[84]. It is well known that protein content and yield have a negative relationship because of physiological compensation [85]. With the help of several GS models, 110 Japanese rice cultivars were able to predict the length and breadth of rice grains with an accuracy range from 0.35 to 0.45 and 0.5 to 0.7, respectively [86].

# GS in oilseeds

Oilseeds are a major source of revenue for small-scale farmers in emerging Asian and African countries. Yield potential can still be realized by narrowing the yield gap and improving biotic and abiotic stressor resistance [87]. The report of GS in such potential crops is limited because to the qualitative nature of the bulk of the traits associated with biotic and abiotic stresses. The environment and GxE interactions influence oil quality and yield factors [88]. In order to make an accurate selection, it is crucial to employ the proper GS models that account for the GxE effects. The yield-related alleles were connected to the cultivated elite line, according to Beche et al.'s research, in contrast to the protein content alleles, which originated from the soybean's wild progenitor (G. max X G. sojae) [89]. Their ability to forecast outcomes is more affected by the variability in the distribution of the trait-contributing alleles in such crosses. When Hu et al. used GS to forecast the capacity of soybean embryogenesis, they received a satisfactory prediction accuracy (0.78) [90].

# GS in Pulses

Haile et al. showed that in the instance of lentils, single-trait GS (STGS) is appropriate in the absence of large-effect QTLs, whereas multi-trait-based Bayes B is the best GS model if large-effect QTLs are present in the population [91]. Additionally, they asserted that GxE interactions and MTGS improve prediction for low heritable traits. Diaz et al. investigated GS using multiple populations (RIL, Andean, MAGIC and Mesoamerican breeding lines) while taking into account quality qualities in Phaseolus, such as cooking time [92] in order to screen quick culinary genotypes. MAGIC population genomic prediction accuracy for cooking time was high and promising (0.55) compared to Mesoamerican genotypes' (0.22) accuracy, and the variable was substantially heritable (0.64-0.89).

# Horticultural Crops GS

In order to achieve nutritional security, fruit and vegetables are essential. However, the issue with their breeding, particularly with fruits, has its own drawbacks, namely a protracted juvenile phase and a highly heterozygous character. In an analysis of 537 genotypes of apples for fruit texture attributes using GS, Roth et al. reported an accuracy of up to 0.81 [93]. Using a factorial mating strategy, Kumar et al. demonstrated which is high prediction accuracy in apples for various quality parameters (0.70-0.90) [94].

# Statistical Tools for Implementing Genomic Selection

Several tools and packages have been developed for the evaluation of genomic prediction and implementation of GS, some of which are listed in table 3

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **S.No.** | **Tool** | **Description** | **Based** | **Availability** | **Access Website** |
| **1.** | GMStool | Genomic prediction tool ( Genome-wide association study (GWAS)-based) using genome-wide markerdata, identifies SNP markers  | R-based | freely available | ([http://cassavabase.org/solgs)](http://cassavabase.org/solgs%29) |
| 2. | solGS | Stores a large amount of phenotypic, genotypic and experimental data. | Linuxoperating system based | open-source tool | https://github.com/austin- putz/GenSel. |
| 3. | rrBLUP | For prediction of genome  | R based  | open-source tool | https://CRAN.R- project.org/package=rrBLUP. |
| 4. | BWGS | For estimation of GEBV forselection candidates. | R based  | freely available | https://CRAN.R- project.org/package=BWGS. |
| 5. | BGLR | Extension of the BLR package | used to implement several Bayesian models and also provides flexibility in terms of prior densitydistribution | freely available | https://CRAN.R- project.org/package=BGLR. |
| 6. | GenSel  | Used for estimation of molecular marker–based breeding values of animals for the trait of interest | Uses the Bayesian approach in the background | freely available user- friendly tool | https://github.com/austin- putz/GenSel. |
| 7. | GSelection | Estimating the GEBV and to select the important markers and  | R-based package | freely available | https://CRAN.R- project.org/package=GSelection |
| 8. | lme4GS | For fitting mixed models with covariance structures | R-based package | freely available | https://github.com/perpdgo/lme4GS |
| 9. | STGS | For genomic predictions by estimating marker effects, used for calculation of genotypic merit of individuals, i.e., GEBV | Performs genomic selectiononly for a single trait, hencenamed STGS | freely available | https://CRAN.R- project.org/package=STGS. |
| 10. | MTGS | Genomic selection using multi-trait information  | R-based package, only for a multiple trait | freely available | https://CRAN.R- project.org/package=MTGS |

# Next Generation Sequencing (NGS): The Secret to GS's Success

The most comprehensive method for studying polymorphism in any crop is to sequence or resequence the full genome (or a portion of it) of a large number of accessions. This was not conceivable prior to the development of the NGS platform, which has fundamentally changed the way genomic approaches to biology are carried out. The platform has dramatically increased the speed at which DNA sequence can be collected while sharply lowering the costs by several orders of magnitude. According to many scientists, NGS technologies have been extensively used for transcriptome and epigenetic analysis, whole genome sequencing (WGS), whole genome resequencing (WGRS), de novo sequencing, and GBS.

Third generation sequencing (TGS) technologies were created in recent years and are now being used to enhance NGS tactics. In less time and for less money each instrument run, these technologies yield longer sequence reads. NGS has grown to be a potent tool for genomic-estimated breeding (GAB) because of its ability to quickly detect a large number of DNA sequence polymorphism- based markers. Using NGS platforms, several targeted marker finding methods have been created. In GWAS and GS investigations, RAD-seq (or its variations) and GBS were often employed. These NGS technologies have already been demonstrated to be successful for GAB (Table 2).

# Table 2 :- Genomic selection (GS) initiatives for various traits in different crops

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **S.no****.** | **Species** | **NGS****marker platfor m** | **Trait** | **Populatio n size** | **Total SNP****marker s** | **Predictio n****accuracy** | **Model** | **Software packages** | **Referenc e** |
| 1 | Rice | GBS | Yield, flowering time | 363 | 73,147 | 0.31–0.63 | RR- BLUP | R package rrBLUP | [95] |
| 2 | Rice | DArTseq | Yield, plant height | 343 | 8,336 | 0.54 | G-BLUP,RR- BLUP | BGLR andASReml R packages | [[96]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5186759/#B32) |
| 3 | Wheat | GBS | Stem rust resistance | 365 | 4,040 | 0.61 | G-BLUP B | R package GAPIT | [[97]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5186759/#B61) |
| 4 | Wheat | GBS | Yield, plant height, pre-harvestsprouting | 365 | 38,412 | 0.54 | BLUP | R package rrBLUP | [[98]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5186759/#B35) |
| 5 | Wheat | GBS | Grain yield | 254 | 41,371 | 0.28–0.45 | BLUP | ASReml 3.0 | [[99]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5186759/#B54) |
| 6 | Wheat | GBS | Yield and yield related traits, proteincontent | 1127 | 38,893 | 0.20–0.59 | BLUP | rrBLUP version 4.2 | [[100]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5186759/#B37) |
| 7 | Wheat | GBS | Fusarium head blight resistance | 273 | 19,992 | 0.4–0.90 | RR- BLUP | R package GAPIT | [[101]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5186759/#B2) |
| 8 | Wheat | GBS | Grain yield, protein content andprotein yield | 659 | – | 0.19–0.51 | RR- BLUP | R package rrBLUP | [[102]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5186759/#B50) |
| 9 | Wheat | GBS | Grain yield | 1477 | 81,999 | 0.50 | G-BLUP | R packagerrBLUP | [[103]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5186759/#B42) |
| 10 | Wheat | DArTseq | Grain yield | 803 | – | 0.27–0.36 | G-BLUP | BGLR and ASReml Rpackages | [[104]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5186759/#B53) |
| 11 | Wheat | GBS | , Fusarium head blight resistance, yield softness equivalence and flouryield | 470 | 4858 | 0.35–0.62 | BLUP | BGLR R-package | [[105]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5186759/#B36) |
| 12 | Wheat | GBS | Heat and droughtstress | 10819 | 40000 | 0.18–0.65 | G-BLUP | BGLR R-package | [[106]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5186759/#B16) |
| 13 | Maize | GBS | Droughtstress | 3273 | 58 731 | 0.40–0.50 | G-BLUP | BGLR R-package | [[107]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5186759/#B75) |
| 14 | Maize | GBS | Grain yield, anthesis date, anthesis-silkimg interval | 504 | 158,281 | 0.51–0.59 | PGBLUP, PRKHS | R Software | [[108]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5186759/#B14) |
| 15 | Maize | GBS | Grain yield, anthesis date, anthesis-silkimg interval | 296 | 235,265 | 0.62 | PGBLUP, PRKHS | R software | [[108]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5186759/#B14) |
| 16 | Maize | DArTseq | Ear rotdisease resistance | 238 | 23.154Dart-seq markers | 0.25–0.59 | RR- BLUP | R package rrBLUP | [[77]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5186759/#B21) |
| 17 | Soybean | GBS | Yield and other agronomictraits | 301 | 52,349 | 0.43–0.64 | G-BLUP | MissForest R package, TASSEL 5.0 | [[109]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5186759/#B40) |
| 18 | Canola | DArTseq | Floweringtime | 182 | 18, 804 | 0.64 | RR-BLUP | R packageGAPIT | [[110]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5186759/#B56) |
| 19 | Alfalfa | GBS | Biomass yield | 190 | 10,000 | 0.66 | BLUP | R package, TAASELsoftware | [[111]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5186759/#B43) |
| 20 | Alfalfa | GBS | Biomass yield | 278 | 10,000 | 0.50 | SVR | R package rrBLUP, Rpackage BGLR, Rpackage ‘RandomFores t | [[112]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5186759/#B1) |
| 21 | Miscanthus | RADseq | Phenology, biomass, cell wall composition traits | 138 | 20,000 | 0.57 | BLUP | R package rrBLUP | [[113]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5186759/#B63) |
| 22 | Switchgrass | GBS | Biomass yield | 540 | 16,669 | 0.52 | BLUP | glmnet R package, Rpackage rrBLUP | [[114]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5186759/#B44) |
| 23 | Grapevine | GBS | Yield and related traits | 800 | 90,000 | 0.50 | RR- BLUP | R package BLR, Rpackage rrBLUP | [[115]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5186759/#B26) |
| 24 | Intermediat e wheatgrass | GBS | Yield and otheragronomic traits | 1126 | 3883 | 0.67 | RR- BLUP | R package rrBLUP, BGLR R-package | [[116]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5186759/#B76) |
| 25 | Perennial ryegrass | GBS | Plant herbage dry weight and days-to-heading | 211 | 10,885 | 0.16–0.56 | RR- BLUP | R software | [[117]](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5186759/#B23) |

1. **BIOTECHNOLOGICAL APPLICATIONS IN CROP IMPROVEMENT**

The whole genomes of model species like human, yeast, Caenorhabditis elegans, Arabidopsis thaliana, and rice have all been sequenced over the past ten years. *Zea mays, Sorghum bicolor, Medicago sativa,* and *Musa* spp. are among the other plant species that will probably have their whole genomes sequenced. Systematic whole genome sequencing will transform our understanding of the structure and function of genes and genomes, allowing us to better manage the traits that result in high agricultural productivity [118]. It takes five to six generations of conventional breeding to transfer a trait from a species into high-yielding, locally adapted cultivars, and choosing the plants with the optimal combination of qualities necessitates planting a large number of children. The improved lines required to undergo a round of multi-location tests before the farmers could select a variety for production. It takes this process at least seven to ten years. Genetic transformation, which also provides access to genes from other species that can be utilized to make transgenic crops, enables the variation of the level of gene expression as well as the geographical and temporal pattern of gene expression. After the necessary genes are transferred into the target crops or cultivars, it takes five to six years for cultivars with stable gene expression to be developed (Figure 5).



Figure 5 :- A diagram showing crop development biotechnology approaches. Genetically modified lines might be released as new kinds or used as donor parents in traditional breeding. It may take multiple generations (BCFn) to obtain homozygous and stable lines from wide-crossing lines, and such material can be used as improved lines or as a donor parent in traditional breeding or marker-assisted selection.

# Resistance against pests, diseases, and herbicides

In 1987, the first transgenic plants containing Bt (Bacillus thuringiensis) genes were developed. Although Bt d-endotoxin genes have been used to construct the bulk of insect-resistant transgenic plants, several experiments are currently being carried out to use non-Bt genes that interfere with the nutritional requirements of the insects. Lectins, chitinases, secondary plant metabolites, and protease inhibitor are a few of the genes in this group. There are currently a number of transgenic plants that can be grown in fields or for on-farm production. Cotton bollworms have been successfully managed with the use of transgenic cotton. To protect against lepidopterous pests, the Bt genes have also been successfully expressed in tomato, potato, brinjal, groundnut, and chickpea. Sorghum, pigeonpea, and chickpea are currently being genetically modified with Bt, trypsin inhibitor, and lectin genes to provide insect resistance. Transgenic sorghum and pigeonpea plants with Bt and trypsin inhibitor genes are presently being investigated in glasshouse confinement conditions. In addition, scientists are aiming to create groundnut plants that are resistant to viruses and fungi. The adoption of transgenic plants in conjunction with integrated pest management (IPM) strategies will considerably help the environment. Insecticide treatments will be decreased, natural enemies' activity will rise, and secondary pests will be managed through Integrated Pest Management (IPM) as a result of the development and usage of transgenic plants carrying insecticidal genes [118].

# Abiotic stress tolerance

The creation of crops with the ability to endure abiotic stressors would aid in crop output stabilization and considerably improve food security in underdeveloped nations. Barley late embryogenesis (LEA) gene-transformed rice plants have reportedly shown improved performance [48]. Acid soil tolerance for aluminum is provided by plants with the capacity to create more citric acid in their roots [49]. By introducing a gene that makes plant farnesyltransferase [51] and inhibitors of this enzyme when created in plants, drought tolerance is increased, senescence is delayed, and the growth habit is altered, all of which together give tolerance to salinity [50].

# Metabolism of starches and sugars

The enzyme known as sucrose phosphate synthase (SPS) is essential for regulating the metabolism of sucrose. To express the maize SPS, transgenic plants are controlled by a promoter from the tobacco small subunit. Rubisco has shown improved foliar sucrose/starch ratios in leaves and lower levels of foliar carbohydrates when cultivated with CO 2 enrichment. This has opened up intriguing possibilities for altering the chemical composition of dietary grains to meet specific demands.

# Enhanced yield and photosynthetic effectiveness

Making the transition from C3 to C4 photosynthesis in C3 plants like Arabidopsis [63] and potatoes [64] is an intriguing experimental strategy for considerably increasing crop output. The oxygenase reaction of ribulose 1, 5-biophosphate carboxylase/oxygenase (Rubisco) and the accompanying loss of CO 2 from photorespiration cause O 2 to limit C3 photosynthesis. Phosphoenolpyruvate carboxylase (PEPC), an enzyme which fixes atmospheric carbon dioxide in the cytoplasm of mesophyll cells, is an essential part of this system. Incorporating the entire maize PEPC into the C 3 plants has recently been accomplished by Agrobacterium-mediated transformation. Sublethal freezing can reduce the type I photosynthetic pigment a/b binding protein of light harvesting complex II in oilseed rape during seed development.

# Vaccines and Pharmaceuticals

Several different vaccines can be made by plants. To create vaccinations against infectious gastrointestinal illnesses, potatoes and bananas have been employed. Biotechnology has produced plants that have genes from human infections.The diagnosis and therapy of this disorder may benefit from the anti-cancer antibodies contained in wheat and rice. The output of drugs made from plants (like salicylic acid) has a great chance of being increased through the use of transgenic technology.

# Nutritional factor

It is possible to improve the nutritional value of crop products by focusing on a number of quality attributes. These include sugars, proteins, and fats. By concentrating on a variety of quality characteristics, crop products' nutritional value can be increased. These include vitamins, iron, carbohydrates, proteins, lipids, proteins, and amino acids, among other nutrients. The producers, the agro-based sector, and the ultimate consumers all have an impact on the choice of target qualities. Transgenic rice with more iron has been developed using genes that build an iron-binding protein that increases the availability of iron in the human diet. Digestibility is increased by lowering the quantity of oligosaccharides (such raffinose and stachyose), which result in flatulence during digestion. Transgenic technology can also be used to remove antinutritional elements [118].

# FUTURE CHALLENGES

As we move into the future, the field of genomics holds immense promise for revolutionizing crop improvement and agricultural practices. Genomics, the study of an organism's complete set of DNA, offers valuable insights into the genetic makeup of crops, enabling scientists and researchers to understand the underlying genetic mechanisms responsible for specific traits. This knowledge opens up exciting possibilities for developing improved crop varieties with enhanced productivity, resilience, and nutritional content. Here are some of the future directions, innovations, and prospects in genomics for crop improvement: **Precision Breeding:** Genomics allows for precise identification and selection of desirable genetic traits in crops. With advancements in genome sequencing technologies and data analytics, breeders can now identify specific genes or gene variants associated with traits such as drought resistance, disease tolerance, or increased yield. This targeted approach enables the development of crops tailored to specific environmental conditions and consumer demands.

**Gene Editing Techniques:** The emergence of gene editing techniques, particularly CRISPR-Cas9, has revolutionized crop improvement. CRISPR-Cas9 allows precise modifications of specific genes, enabling the development of crops with desired traits without introducing foreign DNA. This technology has the potential to accelerate the breeding process significantly and overcome some of the challenges associated with conventional breeding methods.

**Omics Integration:** Genomics is just one aspect of the larger "omics" family, which includes transcriptomics, proteomics, and metabolomics. Integrating these different layers of biological information provides a more comprehensive understanding of crop biology and how genes interact with various cellular processes. This integrated approach can uncover novel targets for crop improvement and reveal previously unknown relationships between genes and traits. The vast amounts of genomic data generated from various sources require sophisticated data analysis tools. Artificial intelligence (AI) and machine learning algorithms play a crucial role in analyzing these datasets efficiently. AI can identify patterns and correlations in genomic data, predict crop performance under different conditions, and optimize breeding strategies for faster and more effective crop improvement.

**Resilience to Climate Change:** Climate change poses significant challenges to global agriculture. Genomics can aid in the identification of genetic traits that confer resilience to extreme weather events, temperature fluctuations, and water scarcity.

Developing climate-resilient crop varieties is crucial for ensuring food security in the face of a changing climate. As genomics advances, it is vital to ensure its inclusive and ethical application in crop improvement. Balancing the benefits of genetic technologies with concerns related to biodiversity, intellectual property rights, and ethical considerations is essential to fostering public acceptance and sustainable agricultural practices.

# Conclusion

Access to information and expertise in underdeveloped nations, where the need to boost food production is most pressing, will be crucial for the deployment of biotechnology for long-term food security. The Rockefeller Foundation, UNESCO, the International Cooperation Program of the European Union, the International Service for National Agricultural Research (ISNAR), and the International Service for the Acquisition of Agrobiotech Applications (ISAAA) are a few of the agencies attempting to play an important part in the technology transfer from public and private sector institutions in the development These efforts, as well as the creation of several others, will require international help in order to meet the demands of end-users in developing, notably in Africa.

 The creation of appropriate regulations and a legal framework for the application of biotechnology in the production of sustainable food requires assistance and encouragement from the national governments. Crop production and food security will face significant challenges due to the projected increase in global population as well as the expected effects of climate change, especially in developing nations. Transgenic plants and marker-assisted selection combined with conventional breeding have the potential to significantly boost food production. However, understanding plant physiology and biochemistry will be crucial for creating new and more effective paradigms for plant breeding as well as for interpreting the data from molecular markers. Utilizing the massive and largely untapped pool of advantageous alleles found in crops' wild relatives will allow for the use of DNA marker technologies, opening up a vast new source of genetic variety that will power the subsequent stage of crop improvement. The transfer of genes crucial for crop quality and crop protection will yield the greatest benefits. However, a thorough understanding of how genes interact with their genomic context and the environment in which their given phenotype must interact will be necessary for the quick and cost-effective development and adoption of biotechnology-derived products.

In conclusion, the future of genomics in crop improvement is incredibly promising. As we gain a deeper understanding of crop genetics and harness the potential of gene editing and omics technologies, we can develop crops that are more resilient, nutritious, and sustainable. Leveraging big data and AI, along with advances in synthetic biology, will further accelerate progress in this field. Ultimately, the responsible and equitable application of genomics in agriculture will play a critical role in meeting the challenges of feeding a growing global population while safeguarding the environment**.**

# REFERENCES

1. Satterthwaite David, McGranahan Gordon and Tacoli Cecilia. Urbanization and its implications for food and farming. Phil. Trans. R. Soc. 2010. B3652809–2820
2. Tilman D, Clark M. Global diets link environmental sustainability and human health. Nature. 2014;515(7528):518-522.
3. Tilman D, Balzer C, Hill J, Befort BL. Global food demand and the sustainable intensification of agriculture. Proc Natl Acad Sci U S A. 2011;108(50):20260-20264.
4. Scheben A, Batley J, Edwards D. Genotyping-by-sequencing approaches to characterize crop genomes: choosing the right tool for the right application. Plant Biotechnol J. 2017;15(2):149-161.
5. Waltz E. With a free pass, CRISPR-edited plants reach market in record time. Nat Biotechnol. 2018;36(1):6-7.
6. Peng, J., & Xu, J. Boosting protein threading accuracy. In Research in Computational Molecular Biology: 13th Annual International Conference, RECOMB 2009, Tucson, AZ, USA, May 18-21, 2009. Proceedings 13 (pp. 31-45). Springer Berlin Heidelberg
7. De Paz JF, Benito R, Bajo J, Rodríguez AE, Abáigar M. aCGH-MAS: analysis of aCGH by means of multiagent system. Biomed Res Int. 2015;2015:194624.
8. Shakoori AR. Fluorescence In Situ Hybridization (FISH) and Its Applications. Chromosome Structure and Aberrations. 2017;343-367.
9. Gasperskaja E, Kučinskas V. The most common technologies and tools for functional genome analysis. Acta Med Litu. 2017;24(1):1-11.
10. Wei L, Liu Y, Dubchak I, Shon J, Park J. Comparative genomics approaches to study organism similarities and differences. J Biomed Inform. 2002;35(2):142-150.
11. Lappalainen T, Scott AJ, Brandt M, Hall IM. Genomic Analysis in the Age of Human Genome Sequencing. *Cell*. 2019;177(1):70-84. doi:10.1016/j.cell.2019.02.032
12. Phillips KA, Trosman JR, Kelley RK, Pletcher MJ, Douglas MP, Weldon CB. Genomic sequencing: assessing the health care system, policy, and big-data implications. Health Aff (Millwood). 2014;33(7):1246-1253.
13. Bolger ME, Weisshaar B, Scholz U, Stein N, Usadel B, Mayer KF. Plant genome sequencing—Applications for crop improvement. Current Opinion in Biotechnology. 2014;26:31–37.
14. Krishnan NM, Pattnaik S, Jain P, Gaur P, Choudhary R, Vaidyanathan S, Deepak S, et al. A draft of the genome and four transcriptomes of a medicinal and pesticidal angiosperm Azadirachta indica. BMC Genomics. 2012;13(1):464.
15. Dohm JC, Minoche AE, Holtgräwe D, Capella-Gutiérrez S, Zakrzewski F, Tafer H, Rupp O, et al. The genome of the recently domesticated crop plant sugar beet (Beta vulgaris) Nature. 2014;505(7484):546–549.
16. Chalhoub B, Denoeud F, Liu S, Parkin IA, Tang H, Wang X, Chiquet J, et al. Early allopolyploid evolution in the post-Neolithic Brassica napus oilseed genome. Science. 2014;345(6199):950–953.
17. Liu S, Liu Y, Yang X, Tong C, Edwards D, Parkin IA, Zhao M, et al. The Brassica oleracea genome reveals the asymmetrical evolution of polyploid genomes. Nature Communications. 2014b;5:3930. doi: 10.1038/ncomms4930.
18. The Brassica rapa Genome Sequencing Project Consortium The genome of the mesopolyploid crop species Brassica rapa. Nature Genetics. 2011;43(10):1035– 1039.
19. Varshney RK, Chen W, Li Y, Bharti AK, Saxena RK, Schlueter JA, Donoghue MTA, et al. Draft genome sequence of pigeonpea (Cajanus cajan), an orphan legume crop of resource-poor farmers. Nature Biotechnology. 2011;30(1):83–90.
20. Kagale S, Koh C, Nixon J, Bollina V, Clarke WE, Tuteja R, Spillane C, et al. The emerging biofuel crop Camelina sativa retains a highly undifferentiated hexaploid genome structure. Nature Communications. 2014;5:3706. doi: 10.1038/ncomms4706.
21. Ming R, Hou S, Feng Y, Yu Q, Dionne-Laporte A, Saw JH, Senin P, et al. The draft genome of the transgenic tropical fruit tree papaya (Carica papaya Linnaeus) Nature. 2008;452(7190):991–996.
22. van Bakel H, Stout JM, Cote AG, Tallon CM, Sharpe AG, Hughes TR, Page JE. The draft genome and transcriptome of Cannabis sativa. Genome Biology. 2011;12(10):102.
23. Kim S, Park M, Yeom SI, Kim YM, Lee JM, Lee HA, Seo A, et al. Genome sequence of the hot pepper provides insights into the evolution of pungency in Capsicum species. Nature Genetics. 2014;46(3):270–278.
24. Varshney RK, Song C, Saxena RK, Azam S, Yu S, Sharpe AG, Cannon S, et al. Draft genome sequence of chickpea (Cicer arietinum) provides a resource for trait improvement. Nature Biotechnology. 2013;31(3):240–248.
25. Guo S, Zhang J, Sun H, Salse J, Lucas WJ, Zhang H, Zheng Y, et al. The draft genome of watermelon (Citrullus lanatus) and resequencing of 20 diverse accessions. Nature Genetics. 2013;45(1):51–58.
26. Wu GA, Prochnik S, Jenkins J, Salse J, Hellsten U, Murat F, Perrier X, et al. Sequencing of diverse mandarin, pummelo and orange genomes reveals complex history of admixture during citrus domestication. Nature Biotechnology. 2014;32(7):656–662.
27. Xu Q, Chen LL, Ruan X, Chen D, Zhu A, Chen C, Bertrand D, et al. The draft genome of sweet orange (Citrus sinensis) Nature Genetics. 2013;45(1):59–66.
28. Denoeud F, Carretero-Paulet L, Dereeper A, Droc G, Guyot R, Pietrella M, Zheng C, et al. The coffee genome provides insight into the convergent evolution of caffeine biosynthesis. Science. 2014;345(6201):1181–1184.
29. González VM, Benjak A, Hénaff EM, Mir G, Casacuberta JM, Garcia-Mas J, Puigdomènech P. Sequencing of 6.7 Mb of the melon genome using a BAC pooling strategy. BMCPlant Biology. 2010;10(1):246.
30. Huang X, Lu T, Han B. Resequencing rice genomes: An emerging new era of rice genomics. Trends in Genetics. 2013b;29(4):225–232.
31. Singh R, Ong-Abdullah M, Low E-TL, Mana MAA, Rosli R, Nookiah R, Ooi LC-L, et al. Oil palm genome sequence reveals divergence of interfertile species in Old and New worlds. Nature. 2013b;500(7462):335–339.
32. Cannarozzi G, Plaza-Wüthrich S, Esfeld K, Larti S, Wilson YS, Girma D, De Castro E, et al. Genome and transcriptome sequencing identifies breeding targets in the orphan crop tef (Eragrostis tef) BMC Genomics. 2014;15(1):581–600.
33. Myburg A, Grattapaglia D, Tuskan G, Jenkins J, Schmutz J, Mizrachi E, Hefer C, et al. The Eucalyptus grandis Genome Project: Genome and transcriptome resources for comparative analysis of woody plant biology. BMC Proceedings; IUFRO Tree Biotechnology Conference 2011: From Genomes to Integration and Delivery; Arraial d’Ajuda, Bahia, Brazil. 26 June – 2 July 2011; 2011. p. I20.
34. Shulaev V, Sargent DJ, Crowhurst RN, Mockler TC, Folkerts O, Delcher AL, Jaiswa P, et al. The genome of woodland strawberry (Fragaria vesca) Nature Genetics. 2011;43(2):109–116.
35. Schmutz J, Cannon SB, Schlueter J, Ma J, Mitros T, Nelson W, Hyten DL, et al. Genome sequence of the palaeopolyploid soybean. Nature. 2010;463(7278):178– 183.
36. D’Hont A, Denoeud F, Aury J-M, Baurens F-C, Carreel F, Garsmeur O, Noel B, et al. The banana (Musa acuminata) genome and the evolution of monocotyledonous plants. Nature. 2012;488(7410):213–217.
37. Sierro N, Battey JN, Ouadi S, Bakaher N, Bovet L, Willig A, Geopfert S, Peitsch MC, Ivanov NV. The tobacco genome sequence and its comparison with those of tomato and potato. Nature Communications. 2014;5:3833.
38. Yu J, Hu S, Wang J, Wong KS, Li S, Liu B, Deng Y, et al. A draft sequence of the rice genome (Oryza sativa L. ssp. indica) Science. 2002;296(5565):79–92.
39. Goff SA, Ricke D, Lan T, Presting G, Wang R, Dunn M, Glazebrook J, et al. A draft sequence of the rice genome (Oryza sativa L. ssp. japonica) Science. 2002;296(5565):92–100.
40. Schmutz J, McClean PE, Mamidi S, Wu GA, Cannon SB, Grimwood J, Jenkins J, et al. A reference genome for common bean and genome-wide analysis of dual domestications. Nature Genetics. 2014;46(7):707–713.
41. Al-Dous EK, George B, Al-Mahmoud ME, Al-Jaber MY, Wang H, Salameh YM, Al-Azwani EK, et al. De novo genome sequencing and comparative genomics of date palm (Phoenix dactylifera) Nature Biotechnology. 2011;29(6):521–527.
42. Al-Mssallem IS, Hu S, Zhang X, Lin Q, Liu W, Tan J, Yu X, et al. Genome sequence of the date palm Phoenix dactylifera L. Nature Communications. 2013;4:2274.
43. Peng Z, Lu Y, Li L, Zhao Q, Feng Q, Gao Z, Lu H, et al. The draft genome of the fast-growing non-timber forest species moso bamboo (Phyllostachys heterocycla) Nature Genetics. 2013;45(4):456–461.
44. Tuskan GA, Difazio S, Jansson S, Bohlmann J, Grigoriev I, Hellsten U, Putnam N, et al. The genome of black cottonwood, Populus trichocarpa (Torr. & Gray) Science. 2006;313(5793):1596–1604.
45. Zhang Q, Chen W, Sun L, Zhao F, Huang B, Yang W, Tao Y, et al. The genome of Prunus mume. Nature Communications. 2012b;3:1318.
46. The International Peach Genome Initiative The high-quality draft genome of peach (Prunus persica) identifies unique patterns of genetic diversity, domestication and genome evolution. Nature Genetics. 2013;45(5):487–494.
47. Wu J, Wang Z, Shi Z, Zhang S, Ming R, Zhu S, Khan MA, et al. The genome of the pear (Pyrus bretschneideri Rehd.) Genome Research. 2013;23(2):396–408.
48. Chan AP, Crabtree J, Zhao Q, Lorenzi H, Orvis J, Puiu D, Melake-Berhan A, et al. Draft genome sequence of the oilseed species Ricinus communis. Nature Biotechnology. 2010;28(9):951–956.
49. Zhang G, Liu X, Quan Z, Cheng S, Xu X, Pan S, Xie M, et al. Genome sequence of foxtail millet (Setaria italica) provides insights into grass evolution and biofuel potential. Nature Biotechnology. 2012a;30(6):549–554.
50. Bennetzen JL, Schmutz J, Wang H, Percifield R, Hawkins J, Pontaroli AC, Estep M, et al. Reference genome sequence of the model plant Setaria. Nature Biotechnology. 2012;30(6):555–561.
51. The Tomato Genome Consortium The tomato genome sequence provides insights into fleshy fruit evolution. Nature. 2012;485(7400):635–641.
52. Hirakawa H, Shirasawa K, Miyatake K, Nunome T, Negoro S, Ohyama A, Yamaguchi H, et al. Draft genome sequence of eggplant (Solanum melongena L.): The representative solanum species indigenous to the old world. DNA Research. 2014;21(6):649–660.
53. The Potato Genome Sequencing Consortium Genome sequence and analysis of the tuber crop potato. Nature. 2011;475(7355):189–195.
54. Paterson AH, Bowers JE, Bruggmann R, Dubchak I, Grimwood J, Gundlach H, Haberer G, et al. The Sorghum bicolor genome and the diversification of grasses. Nature. 2009;457(7229):551–556.
55. Argout X, Salse J, Aury JM, Guiltinan MJ, Droc G, Gouzy J, Allegre M, et al. The genome of Theobroma cacao. Nature Genetics. 2011;43(2):101–108.
56. Brenchley R, Spannag M, Pfeifer M, Barker GLA, D’Amore R, Allen AM, McKenzie N, et al. Analysis of the bread wheat genome using whole-genome shotgun sequencing. Nature. 2012;491(7426):705–710.
57. Polashock J, Zelzion E, Fajardo D, Zalapa J, Georgi L, Bhattacharya D, Vorsa N. The American cranberry: First insights into the whole genome of a species adapted to bog habitat. BMCPlant Biology. 2014;14(1):165–181.
58. Kang YJ, Kim SK, Kim MY, Lestari P, Kim KH, Ha BK, Jun TH, et al. Genome sequence of mungbean and insights into evolution within Vigna species. Nature Communications. 2014;5:5443.
59. The French–Italian Public Consortium for Grapevine Genome Characterization The grapevine genome sequence suggests ancestral hexaploidization in major angiosperm phyla. Nature. 2007;449(7161):463–467.
60. Schnable PS, Ware D, Fulton RS, Stein JC, Wei F, Pasternak S, Liang C, et al. The B73 maize genome: Complexity, diversity and dynamics. Science. 2009;326(5956):1112–1115.
61. Liu MJ, Zhao J, Cai QL, Liu GC, Wang JR, Zhao ZH, Liu P, et al. The complex jujube genome provides insights into fruit tree biology. Nature Communications. 2014a;5:5315.
62. Thottathil GP, Jayasekaran K, Othman AS. Sequencing Crop Genomes: A Gateway to Improve Tropical Agriculture. Trop Life Sci Res. 2016;27(1):93-114.
63. Meuwissen TH, Hayes BJ, Goddard M. Prediction of total genetic value using genome-wide dense marker maps. genetics. 2001 Apr 1;157(4):1819-29.
64. Crossa J, Pérez-Rodríguez P, Cuevas J, Montesinos-López O, Jarquín D, De Los Campos G, et al. Genomic selection in plant breeding: methods, models, and perspectives. Trends in plant science. 2017 Nov 1;22(11):961-75.
65. Werner CR, Voss‐Fels KP, Miller CN, Qian W, Hua W, Guan CY, Snowdon RJ, Qian L. Effective genomic selection in a narrow‐genepool crop with low‐density markers: Asian rapeseed as an example. The plant genome. 2018 Jul;11(2):170084.
66. Budhlakoti N, Kushwaha AK, Rai A, Chaturvedi KK, Kumar A, Pradhan AK, Kumar U, Kumar RR, Juliana P, Mishra DC, Kumar S. Genomic selection: a tool for accelerating the efficiency of molecular breeding for development of climate-resilient crops. Frontiers in Genetics. 2022 Feb 9;13:832153.
67. Fernando, R., and Grossman, M.. Marker Assisted Selection Using Best Linear Unbiased Prediction. *Genet. Selection Evol.* 1989. 21 (421), 467–477.
68. Mohan, M., Nair, S., Bhagwat, A., Krishna, T. G., Yano, M., Bhatia, C. R., et al. Genome Mapping, Molecular Markers and Marker-Assisted Selection in Crop Plants. Mol. Breed. 1997. 3, 87–103.
69. Reynolds MP, Ortiz R. Adapting crops to climate change: a summary. InClimate change and crop production 2010 (pp. 1-8). Wallingford UK: CABI.
70. Furbank RT, Tester M. Phenomics–technologies to relieve the phenotyping bottleneck. Trends in plant science. 2011 Dec 1;16(12):635-44.
71. Mackay TF. The genetic architecture of quantitative traits. Annual review of genetics. 2001 Dec;35(1):303-39.
72. Lorenz AJ, Chao S, Asoro FG, Heffner EL, Hayashi T, Iwata H, Smith KP, Sorrells ME, Jannink JL. Genomic selection in plant breeding: knowledge and prospects. Advances in agronomy. 2011 Jan 1;110:77-123.
73. Yabe S, Yoshida H, Kajiya-Kanegae H, Yamasaki M, Iwata H, Ebana K, Hayashi T, Nakagawa H. Description of grain weight distribution leading to genomic selection for grain-filling characteristics in rice. PLoS One. 2018 Nov 20;13(11):e0207627.
74. Rio S, Mary-Huard T, Moreau L, Charcosset A. Genomic selection efficiency and a priori estimation of accuracy in a structured dent maize panel. Theoretical and Applied Genetics. 2019 Jan;132:81-96.
75. Fones HN, Bebber DP, Chaloner TM, Kay WT, Steinberg G, Gurr SJ. Threats to global food security from emerging fungal and oomycete crop pathogens. Nature Food. 2020 Jun 2;1(6):332-42.
76. Huang M, Balimponya EG, Mgonja EM, McHale LK, Luzi-Kihupi A, Wang GL, Sneller CH. Use of genomic selection in breeding rice (Oryza sativa L.) for resistance to rice blast (Magnaporthe oryzae). Molecular Breeding. 2019 Aug;39:1-6.
77. Dos Santos JP, Pires LP, de Castro Vasconcellos RC, Pereira GS, Von Pinho RG, Balestre M. Genomic selection to resistance to Stenocarpella maydis in maize lines using DArTseq markers. BMC genetics. 2016 Dec;17(1):1-0.
78. Badu-Apraku B, Talabi AO, Fakorede MA, Fasanmade Y, Gedil M, Magorokosho C, Asiedu R. Yield gains and associated changes in an early yellow bi-parental maize population following genomic selection for Striga resistance and drought tolerance. BMC Plant Biology. 2019 Dec;19(1):1-7.
79. Qin F, Shinozaki K, Yamaguchi-Shinozaki K. Achievements and challenges in understanding plant abiotic stress responses and tolerance. Plant and Cell Physiology. 2011 Sep 1;52(9):1569-82.
80. Liu B, Asseng S, Müller C, Ewert F, Elliott J, Lobell DB, Martre P, Ruane AC, Wallach D, Jones JW, Rosenzweig C. Similar estimates of temperature impacts on global wheat yield by three independent methods. Nature Climate Change. 2016 Dec;6(12):1130-6.
81. Beyene Y, Semagn K, Mugo S, Tarekegne A, Babu R, Meisel B, Sehabiague P, Makumbi D, Magorokosho C, Oikeh S, Gakunga J. Genetic gains in grain yield through genomic selection in eight bi‐parental maize populations under drought stress. Crop Science. 2015 Jan;55(1):154-63.
82. Almeida GD, Makumbi D, Magorokosho C, Nair S, Borém A, Ribaut JM, Bänziger M, Prasanna BM, Crossa J, Babu R. QTL mapping in three tropical maize populations reveals a set of constitutive and adaptive genomic regions for drought tolerance. Theoretical and Applied Genetics. 2013 Mar;126:583-600.
83. Battenfield SD, Guzmán C, Gaynor RC, Singh RP, Peña RJ, Dreisigacker S, Fritz AK, Poland JA. Genomic selection for processing and end-use quality traits in the CIMMYT spring bread wheat breeding program. Plant Genome 2016, 9.
84. Heffner EL, Lorenz AJ, Jannink JL, Sorrells ME. Plant breeding with genomic selection: gain per unit time and cost. Crop science. 2010 Sep;50(5):1681-90.
85. Lam HM, Coschigano KT, Oliveira IC, Melo-Oliveira R, Coruzzi GM. The molecular-genetics of nitrogen assimilation into amino acids in higher plants. Annual review of plant biology. 1996 Jun;47(1):569-93.
86. Onogi A, Ideta O, Inoshita Y, Ebana K, Yoshioka T, Yamasaki M, Iwata H. Exploring the areas of applicability of whole-genome prediction methods for Asian rice (Oryza sativa L.). Theoretical and applied genetics. 2015 Jan;128:41-53.
87. Janila P, Variath MT, Pandey MK, Desmae H, Motagi BN, Okori P, Manohar SS, Rathnakumar AL, Radhakrishnan T, Liao B, Varshney RK. Genomic tools in groundnut breeding program: status and perspectives. Frontiers in Plant Science. 2016 Mar 17;7:289.
88. Pandey MK, Chaudhari S, Jarquin D, Janila P, Crossa J, Patil SC, Sundravadana S, Khare D, Bhat RS, Radhakrishnan T, Hickey JM. Genome-based trait prediction in multi-environment breeding trials in groundnut. Theoretical and Applied Genetics. 2020 Nov;133:3101-17.
89. Beche E, Gillman JD, Song Q, Nelson R, Beissinger T, Decker J, Shannon G, Scaboo AM. Genomic prediction using training population design in interspecific soybean populations. Molecular Breeding. 2021 Feb;41:1-5.
90. Hu Z, Li Y, Song X, Han Y, Cai X, Xu S, Li W. Genomic value prediction for quantitative traits under the epistatic model. BMC genetics. 2011 Dec;12(1):1-1.
91. Haile TA, Heidecker T, Wright D, Neupane S, Ramsay L, Vandenberg A, Bett KE. Genomic selection for lentil breeding: Empirical evidence. The Plant Genome. 2020 Mar;13(1):e20002.
92. Diaz S, Ariza-Suarez D, Ramdeen R, Aparicio J, Arunachalam N, Hernandez C, Diaz H, Ruiz H, Piepho HP, Raatz B. Genetic architecture and genomic prediction of cooking time in common bean (Phaseolus vulgaris L.). Frontiers in Plant Science. 2021 Feb 11;11:622213.
93. Roth M, Muranty H, Di Guardo M, Guerra W, Patocchi A, Costa F. Genomic prediction of fruit texture and training population optimization towards the application of genomic selection in apple. Horticulture research. 2020 Dec 1;7.
94. Kumar S, Chagné D, Bink MC, Volz RK, Whitworth C, Carlisle C. Genomic selection for fruit quality traits in apple (Malus× domestica Borkh.). PloS one. 2012 May 4;7(5):e36674.
95. Spindel J, Begum H, Akdemir D, Virk P, Collard B, Redoña E, Atlin G, Jannink JL, McCouch SR. Genomic selection and association mapping in rice (Oryza sativa): effect of trait genetic architecture, training population composition, marker number and statistical model on accuracy of rice genomic selection in elite, tropical rice breeding lines. PLoS genetics. 2015 Feb 17;11(2):e1004982.
96. Grenier C, Cao TV, Ospina Y, Quintero C, Châtel MH, Tohme J, Courtois B, Ahmadi N. Accuracy of genomic selection in a rice synthetic population developed for recurrent selection breeding. PloS one. 2015 Aug 27;10(8):e0136594.
97. Rutkoski JE, Heffner EL, Sorrells ME. Genomic selection for durable stem rust resistance in wheat. Euphytica. 2011 May;179:161-73.
98. Heslot N, Rutkoski J, Poland J, Jannink JL, Sorrells ME. Impact of marker ascertainment bias on genomic selection accuracy and estimates of genetic diversity. PloS one. 2013 Sep 5;8(9):e74612.
99. Poland J, Endelman J, Dawson J, Rutkoski J, Wu S, Manes Y, Dreisigacker S, Crossa J, Sánchez‐Villeda H, Sorrells M, Jannink JL. Genomic selection in wheat breeding using genotyping‐by‐sequencing. The Plant Genome. 2012 Nov;5(3).
100. Isidro J, Jannink JL, Akdemir D, Poland J, Heslot N, Sorrells ME. Training set optimization under population structure in genomic selection. Theoretical and applied genetics. 2015 Jan;128:145-58.
101. Arruda MP, Lipka AE, Brown PJ, Krill AM, Thurber C, Brown-Guedira G, Dong Y, Foresman BJ, Kolb FL. Comparing genomic selection and marker-assisted selection for Fusarium head blight resistance in wheat (Triticum aestivum L.). Molecular Breeding. 2016 Jul;36:1-1.
102. Michel S, Ametz C, Gungor H, Epure D, Grausgruber H, Löschenberger F, Buerstmayr H. Genomic selection across multiple breeding cycles in applied bread wheat breeding. Theoretical and Applied Genetics. 2016 Jun;129:1179-89.
103. Lado B, Barrios PG, Quincke M, Silva P, Gutiérrez L. Modeling genotype× environment interaction for genomic selection with unbalanced data from a wheat breeding program. Crop Science. 2016 Sep;56(5):2165-79.
104. Saint Pierre, C., J. Burgueño, J. Crossa, G. Fuentes Dávila, and P. Figueroa López. "Genomic prediction models for grain yield of spring bread wheat in diverse agro-ecological zones. Sci. Rep. 2016. 6: 27312." .
105. Hoffstetter A, Cabrera A, Huang M, Sneller C. Optimizing training population data and validation of genomic selection for economic traits in soft winter wheat. G3: Genes, Genomes, Genetics. 2016 Sep 1;6(9):2919-28.
106. Crossa J, Jarquín D, Franco J, Pérez-Rodríguez P, Burgueño J, Saint-Pierre C, Vikram P, Sansaloni C, Petroli C, Akdemir D, Sneller C. Genomic prediction of gene bank wheat landraces. G3: Genes, Genomes, Genetics. 2016 Jul 1;6(7):1819-34.
107. Zhang X, Sallam A, Gao L, Kantarski T, Poland J, DeHaan LR, Wyse DL, Anderson JA. Establishment and optimization of genomic selection to accelerate the domestication and improvement of intermediate wheatgrass. Plant Genome 2016 9: 1–18.
108. Crossa J, Beyene Y, Kassa S, Pérez P, Hickey JM, Chen C, De Los Campos G, Burgueño J, Windhausen VS, Buckler E, Jannink JL. Genomic prediction in maize breeding populations with genotyping-by-sequencing. G3: Genes, genomes, genetics. 2013 Nov 1;3(11):1903-26.
109. Jarquín D, Kocak K, Posadas L, Hyma K, Jedlicka J, Graef G, Lorenz A. Genotyping by sequencing for genomic prediction in a soybean breeding population. BMC genomics. 2014 Dec;15(1):1-0.
110. Raman H, Raman R, Coombes N, Song J, Prangnell R, Bandaranayake C, Tahira R, Sundaramoorthi V, Killian A, Meng J, Dennis ES. Genome‐wide association analyses reveal complex genetic architecture underlying natural variation for flowering time in canola. Plant, Cell & Environment. 2016 Jun;39(6):1228-39.
111. Li X, Wei Y, Acharya A, Hansen JL, Crawford JL, Viands DR, Michaud R, Claessens A, Brummer EC. Genomic prediction of biomass yield in two selection cycles of a tetraploid alfalfa breeding population. Plant Genome 2015 8.
112. Annicchiarico P, Nazzicari N, Li X, Wei Y, Pecetti L, Brummer EC. Accuracy of genomic selection for alfalfa biomass yield in different reference populations. BMC genomics. 2015 Dec;16:1-3.
113. Slavov GT, Nipper R, Robson P, Farrar K, Allison GG, Bosch M, Clifton‐Brown JC, Donnison IS, Jensen E. Genome‐wide association studies and prediction of 17 traits related to phenology, biomass and cell wall composition in the energy grass Miscanthus sinensis. New phytologist. 2014 Mar;201(4):1227-39.
114. Lipka AE, Lu F, Cherney JH, Buckler ES, Casler MD, Costich DE. Accelerating the switchgrass (Panicum virgatum L.) breeding cycle using genomic selection approaches. PloS one. 2014 Nov 12;9(11):e112227.
115. Fodor A, Segura V, Denis M, Neuenschwander S, Fournier-Level A, Chatelet P, Homa FA, Lacombe T, This P, Le Cunff L. Genome-wide prediction methods in highly diverse and heterozygous species: proof-of-concept through simulation in grapevine. PLoS One. 2014 Nov 3;9(11):e110436.
116. Zhang X, Sallam A, Gao L, Kantarski T, Poland J, DeHaan LR, Wyse DL, Anderson JA. Establishment and optimization of genomic selection to accelerate the domestication and improvement of intermediate wheatgrass. Plant Genome 2016 9: 1–18.
117. Faville MJ, Ganesh S, Moraga R, Easton HS, Jahufer MZ, Elshire RE, Asp T, Barrett BA. Development of genomic selection for perennial ryegrass. InBreeding in a World of Scarcity: Proceedings of the 2015 Meeting of the Section “Forage Crops and Amenity Grasses” of Eucarpia 2016 (pp. 139-143). Springer International Publishing.
118. Sharma HC, Crouch JH, Sharma KK, Seetharama N, Hash CT. Applications of biotechnology for crop improvement: prospects and constraints. Plant Science. 2002 Sep 1;163(3):381-95.