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# Plant breeding and biotechnology's significance in sustainable agriculture

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**Abstract**

The agricultural industry is the primary economical driver, contributing 32% to the gross domestic product (GDP). To sustain the economy, the Agricultural Transformation Agenda is built on an organizational shift approach that prioritizes efficient production. Through the interplay of breeding and agronomy, higher worldwide yields of cereal crops were accomplished during the Green Revolution period. The need to study current Plant Breeding (PB) to develop fresh strains with the potential Despite this, there is still a developing ability to maintain yield stability under unpredictable climatic conditions while producing high yields in low-chemical-input systems thanks to genetic variety. Two such problems are the necessity to find new market niches and the effects of climate change. The time needed to create new cultivars, varieties, and hybrids has been considerably reduced because of biotechnology. Examples of modern breeding methods include doubled haploid state technology in order marker-assisted the breeding process, genetics, genetic counseling, and genome modification. These resources will be emphasized due to their critical function in hastening the creation of market-responsive types, which are essential to the upkeep of long-term agriculture.

**Keywords:** Genetics, Technology, Modern breeding tools, Crop improvement, agriculture, Plant Breeding (PB).

## 1. Introduction

Sustainable agriculture is greatly helped by PB and biotechnology. Developing crop varieties that are hardy, high-yielding, and adaptable to varied agricultural environments is essential in light of the continent's rapidly expanding population and accompanying rise in food demand. Breeding plants help farmers create new and better crop types with greater yield, disease resistance, drought tolerance, and nutrient quality. Breeders may improve the productivity and resilience of local crops by introducing these features via either traditional breeding methods or cutting-edge biotechnological technologies like genetic engineering. The agricultural output is seriously threatened by climate change. Drought, heat, and floods are just some of the climate change impacts that PB and biotechnology may help mitigate. These enhanced cultivars may help increase food security by maintaining yields in harsh conditions. Growing food sustainably requires fewer resources like water, fertilizer, and pesticides, and PB may help with this. Sustainable resource management is aided by the creation of drought-resistant agricultural types and the use of nitrogen more efficiently (Munawar *et al.,* 2020). The revenue of farmers may be increased via increased yields and productivity with the use of improved crop types. Crops engineered to be resistant to certain diseases or with enhanced agronomic qualities are two examples of the types of crops that might benefit from the use of biotechnology techniques like genetic modification. These characteristics have the potential to improve farmers' livelihoods and revitalize rural areas. PB aids in the conservation and use of agricultural genetic diversity via the use of traditional landraces and wild relatives. This preservation work guarantees the accessibility of various genetic resources that may be used in future breeding efforts to address new threats (Tirnaz*et al.,* 2022). A staggering 70-80% of the workforce is engaged in agriculture, which also contributes to a third of the continent's GDP. Produce from farms has the lowest production per acre of any other place on the planet. Therefore, the continent's food insecurity is a result of poor production and an unprecedented rise in population. Rain-fed agriculture accounts for 85-90% of SS's agricultural production, therefore climate change impacts have likely made an already difficult situation much worse (Hauptli *et al.,* 2020). As temperatures rise, the number of children suffering from undernourishment rises, and people eat much fewer calories as a result. To increase the consumption of calories to levels that can counteract the detrimental effects of the effects of climate change on children's health and welfare substantial increases in agricultural output are required. Now relies more on food that is grown in other areas of the globe due to the continent's low production. The limited cash is redirected from exports to purchases of food. This is unsustainable because it puts people at risk from fluctuations in food costs in foreign markets (Mbabazi *et al.,* 2021). Inadequate production, availability, and consumption aren't the only issues with food; food safety and nutrition are also growing problems. These difficulties also have the fewest available resources in terms of technology, institutions, and money with which to deal with them. Given these difficulties, it will need to increase its productivity by 2050, when the population is expected to have doubled, and this will be accomplished against the backdrop of decreasing arable property, the necessity to ensure water supplies, and the goal of reducing ecological impact (Du Preez *et al.,* 2020). The continent has to raise the amount of food grown by 70% by 2050 to fulfill its current and potential food demands, and this can only be done with increased investment in agricultural management and technology. Breeders have generally agreed that more funding for crop improvement technologies is essential to speeding up the process of producing new high-yielding varieties, which is necessary to address the continent's present food shortages. Advances in PB and biotechnology over the last 30 years have made feasible a wide variety of innovative uses (Hasan *et al.,* 2021). The innovative creation of a future that can survive the consequences of warming temperatures requires a comprehensive upgrade of the continent's crop enhancement framework to include and research cutting-edge technologies. To succeed in the increasingly competitive and specialized markets of the twenty-first century, new cultivars will need to exhibit desired qualities such as high or excellent yields (Munawar et al., 2020). Genetic engineering, product creation, and distribution methods are all areas that are now undergoing extensive study necessary to assure sustained food and nutrition security have all received significant funding in recent years, resulting in several efforts. PB, a centuries-old discipline, has been studied for decades, and recent improvements in crop development have been made possible by the quick adoption of innovative technologies like biotechnology. Regarding the last category, the Agricultural Technology Foundation (ATF) has served as an innovator in the search for food-stability-enhancing technology in the agricultural sector (Qaim, 2020). Therefore, this study focuses on the most important creative operations and several regional changes which is quickly leading the agricultural revolution.

Holzinger *et al.,*(2023) addressed several global issues and made significant contributions to the Sustainable Development Goals. When biotechnology and AI evolve together, unheard-of new potential solutions become accessible. Bain*et al.,*(2020) discussed research on sociotechnical imaginations to investigate the imagined consequences and advantages of gene editing for farmers. Agricultural goods and foods with a wide range of desirable features may now be delivered rapidly, simply, and inexpensively thanks to gene editing methods like Clustered Regularly Interspaced Short Palindromic Repeats. The paper by Jenkins*etal.,*(2021) provided a brief introduction to PB and the evolution of plant biotechnology policy, as well as an analysis of the various types of existing regulatory systems, how they treat genome-edited plants, and the benefits that may result from adopting these approaches. Zadokar*et al.,*(2023) provided a synopsis of the current state of molecules PB research being conducted at Agricultural Universities affiliated with the Indian Council of Agricultural Research with a focus on the enhancement of plants' resistance to both abiotic and biotic stressors, as well as their post-harvest stability and nutritional value. Pathirana and Carimi (2020) discussed the origins and range of produced species, the impacts of modern agriculture, strategies for maintaining them and employing them to increase the range of foods and manufacturing, and the use of crop wild relatives to breed variety that are climate-resilient and require fewer chemicals and mechanical input. Stevanato*et al.,* (2019) provided highlighted The accessibility of sugar beet cultivars possessing essential environmental characteristics, namely resilience and adaptability to reduced input methods, as well as tolerance to biotic and abiotic challenges, as one of the most important prerequisites. Nansamba*et al.,* (2020) compiled the latest information on how much water a banana needs to grow and produce optimally, how to identify drought-sensitive types, and how to manage your crop to mitigate the effects of drought. Campi*et al.,* (2021) provided a small number of tomato breeding institutes that are now capable of fueling the continent's thriving tomato sector and its downstream businesses. This is in addition to the negative consequences of climate change, the advent of pests and diseases, and poor breeding strategies for the release and protection of varieties, all of which influence tomato output. Capacity development presents a window of opportunity to make use of the variety already present in wild tomato relatives and to establish and enhance tomato breeding at diverse research centers.Raza*et al.,* (2022) provided a survey of the literature on agricultural plant responses to salt stress. Soil salinity is one of several environmental pressures brought on by climate change. Damage to many physiological, biochemical, and molecular processes is caused by salinity, making it the second most important abiotic factor impacting agricultural output across the globe. Roriz*et al.,* (2020) determined the use of plant growth-promoting bacteria to bio-fortify key crops like legumes are presented as an attractive strategy. There is an immediate need to create sustainable and environmentally acceptable agricultural ways to boost food output and nutritional value due to the world's expanding population, the effects of climate change, and the prevalence of hidden hunger. Chen *et al.,* (2021) provided a comprehensive survey of the literature on Horizontal gene transfer in the main green plant taxonomic groups, including the green algae, bryophytes, lycophytes, ferns, and seed plants. HGT describes the exchange of genetic material between species that do not occur via sexual reproduction. Lakhiar*et al.,* (2020) discussed the advantages, disadvantages, and real effects of New PB Technologies (NPBTs). By resolving some of the problems that plagued the green revolution, NPBTs including genetically modified and gene-edited crops hold great promise for the future of

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agriculture and global food supplies.

## 2. Classical breeding to biotechnology agricultural enhancement

Crop improvement and development have always made use of traditional PB, which relies on phenotypic selection. Several traditional approaches to breeding have emerged during the last century and are now widely used across the world. They employed the most popular and effective strategies for increasing agricultural yields. This means that classical breeding was used for the majority of released crop types. The series, developed by Rice Centre from interspecificm lines resulting from crossings between cultivated rice species and cultivated rice species, is one of the most successful crops released in recent years. Classical breeding techniques have also been employed by Harvest Plus to create nutritionally superior crops. Early breeding attempts were mostly on improving yield and component attributes. The focus then switched to industrial features, with a change to quality traits catering to farmer tastes to increase adoption and ultimately improve markets. One way in which breeding operations evolved throughout time is with the addition of screening for uncommon traits in the groups, which allows for the discovery of new properties beyond only yields, illness, and resistance to pests. **Figure 1** show how recent trends have shifted attention to the development of climate-resilient crops in light of the growing threat presented by global warming. The traditional methods of breeding such as germplasm collection and population enhancement, recurring selection, production of genetic stocks, and hybrid formation through heterotic, have all been used.

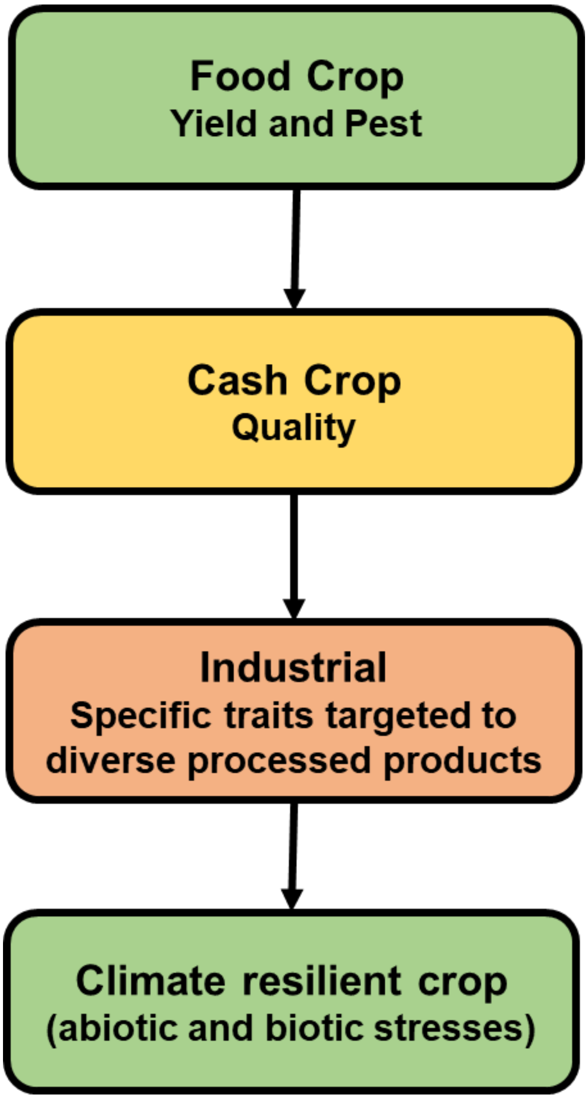

***Figure1:*** *Crop breeding trait generations*

### Germplasm and population growth

Different alleles found in a population's genetic variety may be used to produce elite lines with improved fitness, resistance to disease, and other desirable characteristics. Many breeding initiatives are hampered by a lack of diversity in the population's genetic foundation, which is a serious problem. The collected massive germplasms, and this trend is predicted to continue to keep up with the ever-evolving demands of humans and the expanding commercial and cash crop markets.

### Recurrent selection

Recurrent selection has greatly increased yield and genetic gain. It entails reselecting generations and intermixing chosen plants to create the next selection population. This strategy improves the average efficiency of a plant group while maintaining genetic diversity for further selection. It works well for cross-pollinating crops. Given its enormous gene count, it has helped manipulate and enhance complex features and increase population allele frequency. This method has become valuable when genotypes incorporate more features. This strategy's breeding success relies on the trait's heritability, gene action types regarded crucial in influencing it, selection efficiency, and trait complexity. Recurrent selection has enhanced maize, cassava, and other staples.

### Heterotic as a Mechanism for developing hybrids

One of the most often used ideas in commercial PB is the study of heterotic to improve plant performance. The method relies on investigating a particular set of two heterotic groups that, when crossed, display exceptional hybrid performance (heterotic). Analyses of pedigrees, numbers, and locations are the main tools used to classify heterotic groupings. To maximize the results of a hybrid breeding program, it is helpful for breeders to categorize their germplasm into relevant heterotic groups so that they may consistently and efficiently utilize their germplasm via the exploitation of complementing lines. Since the private sector owns the parental stock, they are in a unique position to reap the financial benefits of this breeding strategy for yield enhancement. Using parents from inbred lines effectively for generating hybrids requires specialized knowledge. One of the most fruitful crops that gain from this strategy is maize. It has been used in public as well as private breeding initiatives.

### Generation of genetic stocks

According to the crop, the kind of genetic stock, and the user community, the genetic resources represented by genetic stocks may be either fleeting or permanent. Cytological stocks, mutant and germplasm sets, inbred, haploids, and test lines are the main types of genetic stocks. PB has become an important field for members of both of these groups. To speed up breeding and better understand the genetics of the features, these stocks, where biologically created, are invaluable. Genetic research and the creation of superior elite lines have made use of newly created and/or carefully chosen genetic pools. Due to biological limitations, the availability of certain genetic stock varieties of some crops is limited.

## 3. Biotechnology for agricultural improvement

Biotechnology refers to the application of scientific principles to the modification and enhancement of living creatures. Controlled and sustained screening of progeny is made possible, and potentially new markers and features that are challenging to cross in nature may be introduced. Biotechnology in the form of genetic modifications is increasingly acknowledged as a potent instrument for not only hastening the process but also improving our understanding of the underlying mechanisms involved in genomics at the levels of cells and molecules. Due to these limitations, **Table 1** shows how biotechnology has produced tools and techniques that considerably complement conventional breeding. We are now using a plethora of cutting-edge biotechnology technologies to improve the ability to create ideotypes for novel genotypes based on our current understanding of genetics and genomics. These biotechnology applications have had a significant impact on breeding, leading to a massive shift in agriculture; they are now the subject of extensive research on a worldwide scale and are being quickly incorporated into the crop development processes.

**Table1**: Agricultural Enhancement with Biotechnology

| Applications | Techniques |
|---|---|
| Interspecific crosses | Embryo rescue |
| characteristic transmission to elite lines is expedited | MABC |
| Effectively combining the finest alleles | MARS, genomic selection |
| Classifying ancestry and family trees as heterotic | Heterotic groups |
| Interspecies gene transfer | Genome editing, GE |
| Maintenance and preservation | Tissue culture/ cryopreservation |
| Accelerating seed development | In vitro |
| Searching for Useful Characteristics in Wild Species | MABC |
| Faster generational progress | DH |
| Genetic relatedness may be determined by cluster analysis. | Genotyping |

### Doubled Haploid (DH)

Doubled Haploid (DH) is an innovative technology that has significantly shortened the time it takes to establish hybrid lines from inbred stock. When Colchicine is used in vivo to induce chromosomal doubling in haploid cells, a DH genotype is produced. By using DH technology, plant breeders may speed up the process of creating new cultivars by producing pure lines in a single generation. In contrast to traditional pedigree procedures, which need six to ten generations of selfing heterozygous material to generate 96.9% homozygous lines, Using DH technology, the process of creating inbred lines may be sped up to a minimum of two generations.

## 4. Applications of Molecular Markers in Genetic Analysis, Trait Selection, and Improvement

### Genetic Engineering (GE)

A significant obstacle for classical breeding was the difficulty or impossibility to transfer characteristics across species, which is particularly problematic in species with low levels of genetic diversity for the trait of interest. Genetic Engineering (GE) facilitates the exchange of genetic material between species that are more distantly related than would be achievable via conventional breeding methods alone. Transgenic organisms (or GMOs) are the result of this kind of genetic modification. The co-transformation of several linked or unlinked genes has proven effective in GE for both the transmission of basic characteristics and multi-gene transfers.

### The Improvement and Selection of Traits

Marker-Aided Breeding (MAB) is one of the most rapidly developing subfields in plant biotechnology, which has had a profound impact on farming. With the help of MAB, just the DNA sequences encoding a desired trait need to be recombined into the new creature. When the genetic code underlying a desired feature has been located, other genes that contribute to their absence may be eliminated.

### Gene discovery (GD)

The identification of genes involved in the development of a certain phenotype or trait is known as genetic dissection (GD). DNA-based methods and statistical genetic discovery procedures based on recombination events as measures of genetic distance between two loci provide the backbone of many GD investigations. These researchers analyze the participants' DNA to determine the specific marker on each participant's chromosomes. GD and breeding have made extensive use of various markers, including Single Nucleotide Polymorphisms (SNPs), expressed sequence tags (ESTs), diversity arrays technology (DArT), Amplification Of Fragment Length Polymorphism (AFLP), restriction of fragments length polymorphisms (RFLP), Simple Sequence Repeats (SSR), and Inter Basic Sequences Repeats (ISSR)

### The crop improvement programs: status and Problems

Crop improvement involves genetically altering current crop kinds to create new, more productive ones. However, the growth of crops demands human, germplasm, and physical resources. Despite encouraging progress, inadequate funding has slowed the distribution of better crop varieties and the expansion of agricultural improvement capacity in the area. Therefore, agricultural progress in SSA countries depends on the sum of its NARs' abilities and the way money is allocated among groups.

### Agricultural Development Programs

Agricultural enhancement is the practice of developing or modifying crop types via genetic means to increase their productivity over their ancestors. However, improving crops involves human and physical resources, as well as access to and utilization of adequate genetic resources. Plant Genetic Resources (PGR) diversity has aided these crop improvement initiatives and is essential to the long-term success of crop development. PGRs are the source of useful agronomic features and the repository of genetic variation used to develop new plant types. The continent's significant genetic variety has been mined for its helpful genes, leading to the identification of novel features that may be used to adapt crops to shifting climates and the introduction of new pests and illnesses. Ecological variability and variety in the continent are significantly responsible for the continent's richness and resilience in terms of plant genetic resources.

## 5. Crop improvement

The various crop enhancement programs in **Table 2** handle new agricultural issues. Such projects have relied on the synergistic collaboration of International Agricultural Research Centers (IARC), Regional Resource Centers (RRC), and National Agricultural Research Systems (NARS). **Figure 2** displays the distribution of Water and Environment Management 's (WEM) 109 Climate-smart Hybrids (containing 104 classic DroughtTEGO® hybrids and MLN-tolerant hybrids). In addition to these hybrids, the WEM Project generated additional inbred lines that seed firms may license to supply efficiently.

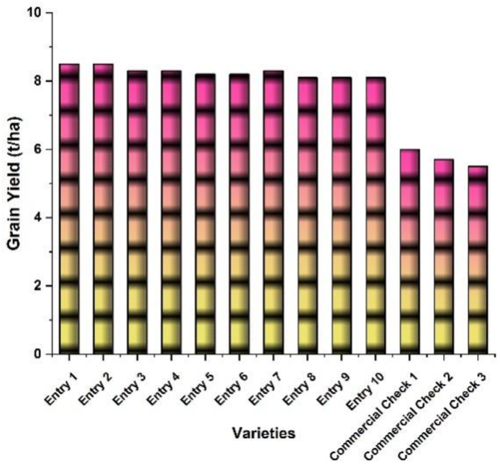


***Figure 2:****Outstanding drought-tolerant three-way hybrids' performance*

**Table 2**: Accessed Technologies and ATF-led Initiatives

| Product/Genes | Trait | Project |
|---|---|---|
| Pflp, EFR genes<br>Gene for Imazypayr Resistance<br>Hrap, Pflp genes<br>Hrap, Pflp genes<br>Cry1Ab | Herbicide resistance<br>Resistance to bacterial wilt<br>Bacterial resistance to Blight<br>Maruca vitrata resistance | Potato<br>Striga,<br>Banana,<br>Casava,<br>Cowpea, |
| Parental lines (S and P) | Quality<br>Milling value<br>elevated yields of aroma | Hybrid Rice |
| CSPs<br>Bt | Drought tolerance<br>Stem Borer resistance | WEM |
| OsNHX1<br>HvAlaAT<br>AtuIPT | Salt Tolerance<br>Nitrogen Use Efficient<br>Water Use Efficient | NEWEST Rice |

**Figure 3** shows that under natural Fall Armyworm (FAW) and stem borer infestations in Kerala, Madhya Pradesh, and West Bengal with stacking drought-resistant and insect-resistant (Bt) characteristics produced 9 to 98% over isogenic hybrids. These efforts to enhance crop quality are providing the continent with access to cutting-edge goods. Included in the mission to adapt farming to commercial principles, further investment by breeders and scientists in state-of-the-art crop enhancement through traditional and biotech treatments, as well as in increased

knowledge and enhanced infrastructure, has been encouraged by ATF. This will help select the best hybrids to enter into more advanced evaluations.

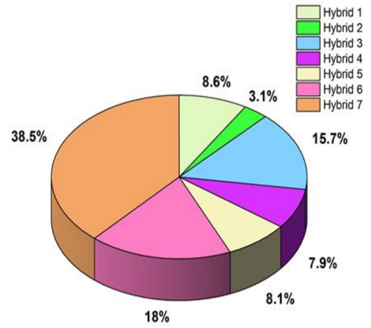


*Figure 3:Stacking drought-tolerant and insect-resistant hybrids' performance*

**6. Creating an environment and sustainable mechanisms for the uptake, spread, and scaling of novel types**

**Capacity building**

The extent to which advancements in biotechnology and genomics may be incorporated into ongoing PB projects is sometimes constrained by available funding. Molecular PB requires substantial expenditures in new research infrastructure and intellectual talent, therefore its development, implementation, and operation will cost more than traditional PB approaches. The PB Academy was also instrumental in educating plant breeders on cutting-edge methods and research. As a result of these initiatives, the continent's PB capability has increased to some extent. If is going to be able to address its food security issues, it will need to form a multidisciplinary plant development team capable of conducting cutting-edge integrated breeding. The effectiveness experiments were carried out in the west of the continent, and the findings revealed that under strong Maruca infestation pressure, transgenic cowpea events provided almost complete control of caused just 0-6% pod damage, and enhanced grain output per plant by a factor of three in **Figure 4**.

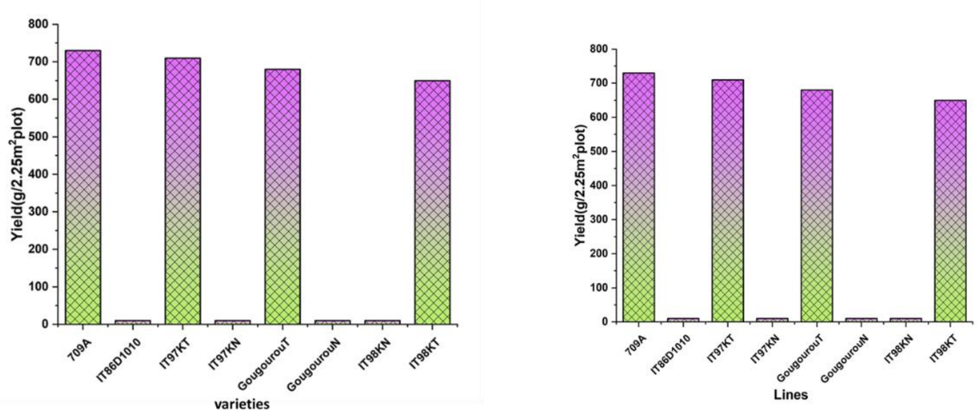


*Figure 4:Conventional isogenic PBR-Cowpea lines*

**Guidelines and Rules**

The success of the end-users for whom biotech products were designed requires the formulation and implementation of appropriate laws and regulations. A significant issue is still the lack of effective strategies to promote agricultural growth. The endorsement of significant choice makers, influencers, and allied organizations is necessary to gather political support for releasing products including target technology. In keeping with its purpose, ATF has achieved notable advancement toward its goal of seeing evidence-based risk assessments included in a wide range of regulatory structures and policies. ATF has found that the topic is typically weighty and prone to political overtones since the final choice on the broad distribution of transgenic crops rests largely on product safety data and the availability of regulatory regulations. A favorable legislative and legal structure that encourages the adoption of Genetically Modified (GM) crops in may take time to materialize, given the different regulatory statuses of GM technology.

**Agricultural Capitalism and widened consumer bases**

The economy must be rapidly expanded and farmers and others in the agricultural supply chain have to receive greater possibilities to sustain their families in addition to solving food and nutrition issues. The increased earnings that will ensue will provide these farmers the buying power they need to invest in cutting-edge farming equipment and use cutting-edge farming methods to maximize output. For farmers to make the transition from subsistence to commercial agriculture, this is a crucial factor. Developing market mechanisms to support the new breeding paradigm is of utmost importance as the power of biotechnology quickly drives goods with high value-added. Improving farmers' access to both domestic and global markets is, thus, essential. The agricultural exports would benefit from improved breeding for food safety and quality qualities.

**Stewardship**

Breeding and biotechnology methods have been very helpful in developing seed-based innovations. As a biological product, seed is the most efficient and effective means of delivering innovations to low-income farmers. Therefore, stewardship functions aid in ensuring that technologies are utilized responsibly to promote the long-term reliability of similar technology for farmers and to prevent losing costly created technologies. Some agricultural strains have developed resistance to pests due, for instance, to incorrect usage of Bt crops.

## 7. Conclusion

An improved understanding of genetics allowed for the creation of better 20th-century variants. To address the problem of feeding the continent's rising population in the context of new dangers including global warming, novel diseases and pests, and a requirement to fill new market segments, there is an increasing desire to examine current discoveries in PB and plant biotechnology. The creation of novel crop varieties with the potential to produce high yields requires a plethora of decision support systems, including but not limited to regulatory, technology, and product stewardship, seed supply chain, lobbying, and outreach. Public and commercial sectors should work together to form robust partnerships for the systems' development of sustainable agricultural value chains. Breeding technologies used to increase food and nutrition security must be scalable and replicable, with efficient distribution to farmers and the backing of value chain development in the continent if they are to have a lasting impact.

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