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Breeding strategies for vegetable improvement: An extensive analysis

Mahendra Kumar Yadav*[1], Juri Das[2]

[1]*Department of Agriculture, RNB Global University, Bikaner, Rajasthan, India*

[2]*Department of Agriculture, Teerthanker Mahaveer University, Moradabad, U.P, India*

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Abstract

In the face of a burgeoning global population, the imperative of ensuring food security looms large. This review critically examines the pivotal role of breeding strategies in enhancing crop yield, quality, and resilience, with a specific focus on vegetable improvement. Bridging the gap between traditional and modern methodologies, the study explores the historical successes of mass selection and crossbreeding, laying the groundwork for the transformative era ushered in by molecular breeding and genetic engineering. Biotechnology methods have additionally demonstrated to be insufficient to completely replace conventional breeding methods. Trait-specific breeding strategies are examined, emphasizing resilience to illness and abiotic stress, nutritional content, and post-harvest traits. This review analyzes the shortcomings of current breeding strategies, offering a realistic evaluation of the remaining challenges that must addressed overcome. It also discusses the possibility for breeding vegetables in the future, taking into account the need to address the consequences of climate change, incorporate new technology, and develop crops that can endure shifting environmental challenges. This review attempts to give a comprehensive picture of the state of vegetable improvement today and to direct future research efforts in the pursuit of sustainable vegetables production.

***Corresponding Author:** Mahendra Kumar Yadav ✉ mahendra.yadav@rnbglobal.edu.in

Introduction

Because they include a variety of vitamins, minerals, and antioxidants, vegetables are regarded as a protective food. Since the 1970s, India is currently ranked second in the world for vegetable output, having significantly boosted it, behind China, thanks to systematic effort on vegetable development that began in the 1970s (Aditika *et al.,* 2017). Vegetables constitute a crucial component of staple diet in India where more than 40% population is vegetarian (National Family Health Survey -2015-16). Vegetables were once thought of as a luxury item, but today they are valued as a valuable part of a healthy diet and a reliable source of revenue for farmers. Compared to other agronomical crops, vegetables are often short-duration crops, which allow a farmer to harvest more crops from a given area of land. Due to urbanization, industrialization and shrinkage of agricultural land, cultivation of vegetable crops will be more economical.

Vegetables are considered as "Protective supplementary food" as they contain large quantity of amino acids necessary for proper functioning of various metabolic processes in human body. They are an abundant supply of vitamins, minerals, phosphorus, iron, and calcium, as well as other nutrients and other nutraceutrical components that are vital to the body's continued good health. Emphasize how genetic advancements can improve the resilience, productivity, and quality of vegetable crops. Creating crop cultivars with enhanced genetic constitutions to meet a variety of human demands is the primary goal of plant breeding. Because of the rapid advancements in plant breeding, the majority of crop varieties with been generated to date share a common genetic background. This has resulted in a narrow genetic foundation, making them susceptible to both biotic and abiotic stress (Prakash *et al.* 2017). Even if they work well, traditional breeding techniques involve a sluggish, uncontrolled genetic improvement process that takes several generations in order to generate the desired features. Biotechnological techniques have the advantage of introducing particular genes, however, without having any unfavorable side effects (Wamiq *et al.* 2023).

Because of heterosis, which gives them an advantage over different parent kinds, hybrids are highly advantageous for enhancing the technological and economic elements of vegetable farming. Utilizing hybrids to their full potential is essential for tackling the new issues brought on With climate change, such lowering the disparity in access to food and nutrition. Additionally, hybrids give breeders a valuable tool to increase the potential output of vegetable crops. Heterosis has a significant effect on quality and productivity in a variety of vegetable crops, improving livelihoods by increasing production and producing high-quality goods and dietary options with better nutrition (Singh *et al.*, 2023). Mutation breeding is generally quite beneficial for vegetable crops. Some of the modern techniques that can yield mutant varieties with novel and desirable variation of agrometrical traits are mutagenesis, mutation breeding, and the isolation of better or novel phenotypes in conjunction with conventional breeding programs. This ground is ideal for induced mutations and similar technologies, and the overall approach aids in tracking agricultural genetic variation and maintaining biodiversity (Gupta, 2019).Vegetable crops were only produced via conventional breeding methods, which relied on random mutations created either naturally or through experiments, together with interspecific sexual hybridization of plants with desirable heritable traits, until recently.

Both re-assorting and biochemical engineering, which were made feasible by improving breeding techniques through the use of randomly generated changes, have been utilized to generate entirely new opportunities and advancements (Miflin, 2000). In the future, it should be possible to improve crops by combining biotechnology with conventional breeding techniques (Dias, 2012). Technologies such as genome editing, transgenic, RNA interference, transcriptomics, and CRISPR/Cas-9 possess a tremendous deal of promise for boosting veggies' health-promoting ingredients (Singh *et al.*, 2021).

Need of vegetable improvement

Numerous issues, including the world's expanding population, shifting dietary habits, environmental concerns, and economic constraints, are driving the need for improved vegetables. The following are some major arguments in favor of vegetable improvement:

Population growth

With the world population continually increasing, the need for food, especially veggies, is rising. Vegetable improvement is crucial to enhance yields and ensure an adequate and nutritious food supply for the expanding population.

Nutritional security

A healthy, well-balanced diet must include vegetables since they are a great source of vitamins, minerals, and other nutrients. The goal of vegetable enhancement is to increase the nutritional value of crops in order to solve dietary inadequacies and advance general health.

Adaptation to climate change

Climate change affects temperature patterns, precipitation patterns, and the frequency of illnesses and pests, which presents serious difficulties to agriculture. The goal of vegetable development is to create cultivars that can withstand shifting weather patterns while maintaining steady yields and food security.

Pest and disease resistance

Vegetable crops are susceptible to significant yield losses due to pests and diseases. In order to minimize environmental impact and lessen reliance on chemical pesticides, improvement efforts are focused on developing cultivars with natural resistance or tolerance to common pests and diseases.

Abiotic stress tolerance

Vegetables often face challenges such as drought, salinity, and soil nutrient deficiencies. Breeding to withstand abiotic stress helps create crops that can thrive in adverse environmental conditions, expanding the range of areas where vegetables can be cultivated.

Post-harvest characteristics

Food waste can be decreased by improving post-harvest characteristics such shelf life, transportability, and storage life. Increased post-harvest quality and longer shelf life can boost vegetable production's financial sustainability.

Consumer preferences

Both consumer tastes and market demands are always changing. In order to meet customer tastes and market trends, vegetable development seeks to create cultivars with improved flavor, color, texture, and nutritional value.

Economic sustainability

Improved vegetable varieties can lead to increased yields, reduced production costs, and enhanced economic returns for farmers. This contributes to the economic sustainability of agriculture and the livelihoods of those involved in vegetable production.

Biotic and abiotic resistance

A more robust and resilient agricultural system is ensured by developing varieties that are resistant to both biotic (drought, salinity, and severe temperatures) and abiotic (pests and diseases) challenges.

Genetic diversity conservation

Genetic variety is frequently conserved and used in vegetable development initiatives. To ensure agriculture's long-term sustainability and to react to unanticipated problems, it is imperative to maintain a varied pool of genetic resources.

Traditional breeding methods for vegetables improvements

Traditional breeding methods for vegetable improvement involve controlled pollination, selection, and the emergence of new types across several generations. These techniques have been used for centuries and are still widely used in combination with modern techniques. The present scientific knowledge about crops and the discovery of an efficient hybrid seed production process has had a major impact on the agriculture industry. 1914 saw, American botanist and geneticist George Harrison Shull first used the term "heterosis" (Shull, 1952), (Kruse, 1964) to describe the higher performance of F1 hybrids above two mated inbreds while working with corn in Cold Harbor, New York. The use of the hybrid vigor of cucumbers (*Cucumis sativus*) was first suggested by Hayes and Jones Hayes 1916 during the second decade of the twentieth century. A noteworthy turning point for hybridization efforts was the creation of the F1 hybrid commercial eggplant in Japan in 1925 (Rai and Rai, 2006), (Kakizaki, 1931). According to the use of heterosis, four kinds of vegetables are documented. Due to their high production costs, hybrids were not widely used commercially at first. However, due to the growing availability of published data on the notable heterosis reported in several vegetable crops, breeders are now more motivated than ever to not only create new hybrids but also explore genetic pathways to enable more efficient and economic hybrid seed production.

Numerous breeding strategies can be used to enhance edible colors and nutraceuticals, including recurrent selection, backcrossing, pedigree, F1 hybridization, polyploidy breeding, and mutation breeding. The F1 hybrid muskmelon's beta-carotene content has multiplied (Moon *et al.* 2002). India has historically had attempts to produce biotic stress resistant types because these have been acknowledged as providing a more sustainable method of agricultural production. Many variants were created, as noted by Meena and Meena (2014), Singh and Chaubey (2013), and Kalloo (1998). In the past, the most widely used techniques for producing hybrid seeds were hand pollination and hand emasculation. However, hand pollination produces very little seed, thus crops cannot profit from this practice. Thus, the cost of hybrid seed can be reduced if techniques that are realistically important to maximize out-crossing and inhibit selfing in the field of manufacturing hybrid seeds are available (Kumar and Singh, 2004).

Mutation breeding for vegetables improvements

Vegetable breeding categorized into three sub-types as mutation breeding, recombination breeding and transgenic breeding. In case of mutation breeding, the basic fundamental and the unique feature is the generation of new mutated alleles. Hugo de Vries coined the term "mutation" in 1900 to refer to heritable phenotypic alterations. Mutation breeding is the use of induced mutations for crop enhancement (Kalloo, 1998). In addition to changing linkage groups, mutations can cause both qualitative and quantitative variation quite quickly by changing both alleles at recognized locations and newly unidentified loci (Konzak *et al.,* 1977). Utilizing induced mutagenesis has been obtain direct mutants or by using these mutants in hybridization (Ahloowalia *et al.*, 2004) to overcome yield plateaus and generate desirable horticultural traits. Utilizing viable morphological mutations and induced variability for chlorophyll in the M2 generation proved to be the most reliable method for utilizing beneficial mutations for effective crop improvement (Kumar *et al.,* 2007). Mutation is an effective way to create variation rapidly in a genotype. Cauliflower-Spontaneous mutation results in ‘orange curd’ (Li *et al.,* 2001). In tomatoes (*Solanum lycopersicum*), five high pigment (hp) variants have been found: hp-1, hp-1w, hp-2, hp-2j, and hp-2 dg. The tomato Damaged DNA-binding protein locus (SlDDB1) was utilized to map hp-1 and hp-1w.

Increased carotenoid content in fruits and higher anthocyanin (7.1 mg/100 g) content are characteristics of mutant plants expressing these mutations in SlDDB1. The high pigment2 (hp2) tomato mutant is caused by point mutations to DEETIOLATED1 (DET1), which led to increased levels of carotenoid (0.82g/100g) and phenyl propanoid phytonutrients in mature fruit (Jones *et al.,* 2012). Curds and a few other tissues exhibit a remarkable mutant phenotype of vivid purple color due to an aberrant pattern of anthocyanin accumulation (42.1 mg/kg) caused by a mutation in the purple (Pr) gene.

Molecular breeding for vegetable improvement

Utilizing molecular biology techniques, molecular breeding is a sophisticated approach to plant breeding that enhances the accuracy and efficiency of breeding programs.

This methodology has been widely applied to enhance various traits in vegetables, including yield, quality, disease resistance, and stress tolerance. Molecular markers, also referred to as DNA markers, are little segments of DNA that are suitable for easy tracking and identification. It has been investigated how molecular markers might apply to vegetable crops by Ansari (2015). Marker aided selection, according to Foolad and Sharma (2005), is the process of choosing a trait based more on genetics than phenotype. Using markers could speed up selection and increase the productivity of breeding cycles (Holland, 2015).The male sterility and fertility restorer genes in chilies were found using the RAPD technique (Kumar *et al.,* 2002). In the Indian long-day onion population, a DNA marker for male sterility and hybrid production has been produced and found for the first time. Using marker-assisted selection, we can use the detected marker for hybrid production and male sterility transfer to other onion lines or genotypes in the future (Saini *et al.,* 2015).Through marker-assisted selection, the Ty2 and Ty3 genes were inserted into the plant, producing tomato hybrids that are immune to the tomato leaf curl virus (Prasanna *et al.,* 2015).

Short DNA sequences that are readily detectable and tracked in inheritance are known as molecular markers, or DNA markers. Ansari (2015), conducted a review about the potential application of molecular markers in vegetable crops. It was possible to identify seven SSR producers that are practical in marker assisted breeding to create cucumber germplasm whose fruits have high beta carotene content. According to Song and colleagues (2010), the carotenoid content in common cucumbers are low, ranging from 22 to 48 ìg/100 g. On the other hand, the Xishuangbanna gourd has a high carotenoid content, with 700 ìg/100 g measured on a flesh weight basis. Therefore, the Xishuangbanna gourd offers a special advantage as a germplasm that can be utilized to increase the nutritional content of cucumbers. The development of superior vegetable varieties with desirable features has advanced substantially faster thanks to molecular breeding. It's crucial to remember, nevertheless, that legal frameworks and public acceptance of creatures with altered genetic makeup (GMOs) may have an impact on the uptake and application of specific molecular breeding methods.

Biotechnological approaches for vegetable improvement

Biotechnological approaches play a crucial role in vegetable improvement by harnessing the tools and techniques of biotechnology to enhance traits such as yield, quality, nutritional content, and adaptability to both biotic and abiotic stimuli. Examine how biotechnological tools-like gene editing and genetic engineering are used to improve vegetables. Unlike gametic fusion, somatic fusion provides a means of integrating both complete genomes at intra- and interspecific, as well as intra-and/or intergeneric levels, by means of the asexual hybridization of two somatic protoplasts. Tissue culture offers several ways to quickly multiply true-to-type, virus-free propagating material and maintain healthy stocks through meristem culture (Pandey et al. 2010). Using a particular MS media, the potato cultivars Kufri Jyoti, Phulwa, and C-13 were kept in vitro so that true to types could regenerate and provide nutrient-rich seed stock (Tiwari. Ultrasound, 2015). Dwivedi *et al.* (2015) state that double haploids are used in self-fertilizing species to produce cultivars and in cross-fertilizing species to encourage the emergence of inbreeding. Technology utilizing recombinant DNA (r-DNA) assists in resolving both biotic and abiotic problems. Likewise, tissue culture methods and quantitative trait loci (QTL) mapping are enhancing crop quality at the molecular level. The current understanding of new tools for deciphering encoded genetic languages underpins the potential applications of this technology in vegetable crop breeding (Pradhan *et al.,* 2021). Tissue culture is the in vitro regeneration of plants from disease-free plant components (cells, tissue). Producing agricultural planting material free of diseases is made possible by this technique. Compared to other crop species, potatoes have been the subject of more cell and tissue culture techniques in the past 50 years. Potato in vitro cultures been produced using a range of plant parts, including petioles, ovaries, stems, roots, and shoot tips since 1951 (Steward and Caplin, 1951), as mentioned by Srivastava *et al.* (2012), Bajaj (1987), Kumar *et al.* (2015).

This crop has been improved over the years using a range of techniques due to its high adaptability to in vitro alterations. These methods encompass a wide range of technology and differ in their degrees of sophistication. While some of these technologies—like disease eradication and micro-propagation—have already been applied to boost potato yields, others are still in the development and improvement stages. Utilizing in vitro methods for clonal mass multiplication (micro-propagation) and viral elimination (meristem culture) is the most popular use in potato research. In vitro-generated, disease-free potato clones combined with conventional multiplication techniques have become a crucial component of seed production in several regions (Naik and Sarkar, 2000).

Transgenic or genetically modified of vegetable crops

Transgenic or genetically modified (GM) Vegetable crops are plants that have had alien genes introduced into their genetic makeup. Usually, the purpose of this method is to improve a particular trait—like tolerance to pests, diseases, or herbicides—or to raise the yield or nutritional value of vegetable crops. Farmers of vegetables in the United States are reaping benefits from the commercialization and deregulation of transgenic squash cultivars resistant to the cucumber, watermelon, and yellow mosaic viruses that affect zucchini. since 1996. In the United States, Bt-sweet corn is still permitted for use in the fresh corn market, and nearly yearly releases of hybrids intended for this market are made possible by the crop's shown ability to suppress certain lepidopteran species. Similarly, farmers in Bangladesh are currently cultivating transgenic Bt eggplant, which was designed to use fewer pesticides (Dias, 2014).

With only 11.6 million hectares of bt cotton, India ranks fourth in the world in terms of the overall area under GM crop, behind the US, Brazil, and Argentina (Anonymous, 2015). While public protests and anti-GM groups forced the release of the first genetically modified (GM) food crop in India, the ban on the release of the crop (available at Nature http://doi.org/bkt7dh; 2010) has not prevented research into improving the nutritional value of various vegetable crops or mitigating biotic and abiotic stresses, and successful adoption of these crops is anticipated in the near future. The Annual Report IIVR, 2012–13 states that brinjal (Solanum melongena) cv. Kashi Taru plants were found to have a notable level of fruit and shoot borer. ProTato, a transgenic potato line, expresses the AMA1 gene, which results in a 48% higher total protein content than non-transformed potatoes (Chakraborty *et al.,* 2010). In the Network Project on Transgenic Crops (NPTC), a transgenic tomato that is resistant to water scarcity stress was created using the AtDREB1A gene. Due to high levels of Cry1Aa3 protein expression, brindal (*Solanum melongena*) cv. Kashi Taru plants had considerable levels of fruit and shoot borer. You can see the IIVR Annual Report for 2012–2013 at www.iivr.org.in/annual-reports. You can also view the 2012 IIHR Annual Report at www.iihr.res.in/content/annual-reports. Trial using the transgenic watermelon CV's T4 offspring. Watermelon bud necrosis virus resistance in Arka Manik; every transgenic line examined showed complete resistance to the illness. The transgenic potato line ProTato has an overall protein content that is 48% higher than non-transformed potatoes because the AMA1 gene is expressed in it (Chakraborty *et al.*, 2010).

The Fuchs *et al.* (2004), study examined the fitness costs of transgenic squash bearing CMV, ZYMV, and WMV potyvirus coat protein genes (Tricoli *et al.,* 1995). It was discovered that aphid-borne viruses resistant to transgenic plants were widespread. As an example of the selective utility of transgenes, the authors indicate that CMV, ZYMV, and WMV can significantly impair the growth and reproduction of wild squash populations. Tomato fruits have two main characteristics: their nutritional worth and their organoleptic qualities (taste, fragrance, etc.). The texture, flavor, and scent of the fruit are all organoleptic. Tomato fruits are a terrific nutritional choice since they are an excellent source of many vitamins and minerals, sugars, flavonoids, ascorbic acids, folate, and carotenoids. They also contain about five grams of dietary fiber, one gram of fat, one hundred calories, and almost no sodium. A study using genetically modified tomatoes showed how the fruit's firmness and softness are affected by expansin or b-galactosidase according to the findings of Brummell *et al.* (1999) and Smith *et al.* (2002). Along with their organoleptic properties, scientists are paying more and more attention to the nutritional aspects of tomato fruits. Zanor *et al.* (2009) demonstrated that cell wall invertase (LIN5) is involved in controlling the amount of soluble solids in transgenic tomato plants using the RNA interference approach.

Future prospects

Overall, the future of vegetable improvement involves a multidisciplinary approach, combining traditional breeding with innovative technologies to address the challenges of a changing climate, population growth, and evolving consumer needs. It requires a balance between sustainability, nutritional quality, and economic viability in vegetable production. India's vegetable industry has a promising future thanks to several key areas of focus that could both address current problems and promote long-term agricultural growth. While boosting yield will remain the main objective of breeding to meet the growing global demand for food, producing nutrient-rich cultivars is essential to ensure health security.

Conclusion

In conclusion, the future of vegetable improvement lies in a holistic and multidisciplinary approach that balances the need for increased yields, nutritional quality, and environmental sustainability. As technological advancements continue, the field of vegetable breeding is poised to make significant contributions to global food security and the overall well-being of the growing population. Continued research, collaboration, and the responsible application of biotechnological tools will play pivotal roles in shaping the future of vegetable improvement. It has also been demonstrated that biotechnology technologies cannot fully replace traditional breeding practices.

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