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Global Status, Scope and Future Prospects of Biotechnology in Vegetable Crops

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Abstract

Vegetable crops play an indispensable role in global food and nutritional security, yet their production is limited by many challenges. Biotechnology has revolutionised the improvement of vegetable crops worldwide through modern technologies such as genetic engineering, marker-assisted selection, CRISPR/Cas genome editing, tissue culture and molecular breeding, resulted in the development of climate-resilient, nutritionally enriched and high-yielding cultivars that have helped to reshape the vegetable production system. Landmark achievements in plant biotechnology, namely virus-free planting material, multiple disease resistance, Bt brinjal, Flavr Savr tomato, Purple Tomato™, genome-edited GABA tomato and high anthocyanin/carotene content have revolutionised vegetable production systems globally. In addition, new intervention options such as biofortification, edible vaccines, RNA interference and biotechnology-based hybrid breeding are not only creating possibilities at the interface of agriculture and nutrition but also in public health. This status paper highlights recent advances, successful applications and emerging opportunities of biotechnology to strengthen vegetable production under changing climatic conditions.

Keywords: Air Pollution, Meteorological, Opencast Coal Mine, Particulate Matter

Vegetables are of paramount importance in global agriculture and human dietary habits, providing a rich source of vitamins, minerals, dietary fibre and bioactive substances which help improve health and prevent diseases. Vegetable crops are an integral part of human diets and nutrition, but their production is constrained by a number of factors, including their short shelf life, susceptibility to pests and sensitivity to climatic fluctuations[1]. In the 21st century, food production should be increased by 70 per cent to meet the demands of the world's expected 9.7 billion people by 2050[2]. Therefore, for vegetable crops, biotechnology offers specific biotechnological approaches such as genetic engineering, marker-assisted selection and genome editing to improve flavour, texture, shelf life and micronutrient content while also adding resistance to diseases, pests and climate-related challenges[3].

Although traditional breeding has been crucial in developing improved vegetable varieties, it faces many inherent limitations. Conventional breeding techniques are generally hindered by "linkage drag" (the inheritance of undesirable traits) and sexual compatibility barriers between species and can frequently take decades to generate a single stable variety[4]. Biotechnology effectively overcomes these limitations through multiple key interventions. These advanced genetic tools and techniques have made it feasible to develop new durable, nutritious and high-

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yielding crop varieties[5]. Biotechnological potential applications in plant sciences have been enhanced by recent developments (for example, CRISPR-Cas genome editing and multi-omics approaches[6]. In 1994, the FDA first granted the commercial approval of genetically modified tomato (Flavr Savr) for human consumption. It has a unique trait of delayed softening (developed by additional PG gene expressed), resulting in slow ripening for better flavour and shelf-life.

This paper will emphasize the current trends of biotechnology in vegetable crops and its potential role in solving problems caused by population boom, shrinking land, climate change, nutritional security and increased demand for sustainable food supply and environmental sustainability. This also highlights the recent advancements made in biotechnology and future prospects of using plant biotechnology with traditional vegetable breeding programs to meet the demands of a growing population under changing climatic conditions. The main aim of this paper collectively is to demonstrate the essentiality of biotechnology in vegetable crops for a sustainable future.

SCOPE OF BIOTECHNOLOGY IN VEGETABLE CROPS

Its scope lies significantly from the development of vegetable crops that can better withstand biotic and abiotic stresses to accelerating vegetable breeding programmes to enhance fruit or seed quality for sustainable vegetable production.

- *Climate-resilient Crops*: Biotechnology helps in breeding climate-resilient crops using genome editing, marker-assisted selection and transgenic approaches that can withstand adverse extreme weather conditions such as salinity, heat, drought and flooding, *etc*. For instance, genetically modified chilli pepper plants overexpressing the tobacco *Osmotin* gene showed enhanced tolerance to salt (up to 300 mM NaCl) and showed better growth and fruit yield[7].
- *Biotic Stress Resistant Crops*: Biotechnology helps to breed vegetable cultivars that are resistant to biotic stresses such as pests and pathogens. It helps reduce farmers' dependency on chemical inputs and minimize their impact on the environment. For instance, RNA interference (RNAi) technology has been advanced by the introduction of spray-induced gene silencing (SIGS), in which the exogenous application of dsRNA is employed for regulating target genes without any manipulation of the genome. The technique has proven successful in managing fungi-related plant diseases and pest insects in vegetables through the development of targeted and eco-friendly crop protection measures[8].
- *Biofortification*: Biotechnology allows the biofortification of vegetables through genetic engineering that involves adding genes from different organisms into plants to boost the production of nutrients and vitamins. For example, Soyabean *Ferritin* gene is introduced in Lettuce for increasing Iron content in it[9]. The creation of Golden Tomato, which was genetically modified to have phytoene synthase (psy) and carotene desaturase (crt) genes, is one of the most famous examples of transgenic biofortification. This increased the amount of provitamin A (β-carotene) in the tomato fruits[10].
- *Use of Bio-pesticides and Bio-fertilisers*: These act as an alternative against adverse effects of synthetic chemicals on health, biodiversity and environment. For example, in cucumbers, a microbial consortium of *Trichoderma, Azotobacter* and *Bacillus* decreased the incidence of downy mildew and increased fruit set[11].
- *Prevention of Post-harvest Losses*: Worldwide, post-harvest losses can range from 30 to 50 per cent, particularly in tropical and subtropical regions[12]. Biotechnological measures can therefore be taken to lessen these losses. For instance, food ripening and softening may be delayed by altering ripening-associated transcription factors such as *RIN* and *NOR*[13].
- *Assistance in Hybrid Development*: Assist in hybrid development by adopting advanced technologies in the field of biotechnology such as molecular

markers, tissue culture, genetic engineering and genome editing. Through molecular markers, early parental line selection with improved traits at the seedling stage reduces the time required for the breeding cycle. Also, we can develop CMS lines through genetic engineering for efficient hybrid seed production. Use of *Solanum aethiopicum* as female parent with *S. melongena* led to the development of a CGMS line in brinjal[14].

- *Edible Vaccines*: These are plant-based vaccines made by identifying and inserting genes for 'antigen' into plants through genetic engineering, and when these antigenic proteins are ingested, they trigger an immune response for a targeted pathogen in our body. Many vegetable plant species such as potatoes, tomatoes and lettuce are being utilized for making edible vaccines against several infectious diseases[15].
- *Pre-breeding*: Pre-breeding necessarily means locating beneficial genes from non-domesticated sources and incorporating them into a transitional set of materials. These materials can later be used by breeders for the creation of new varieties. Using molecular-assisted selection and QTL mapping, the efficacy of pre-breeding can be increased.

STATUS OF BIOTECHNOLOGY IN VEGETABLE SCIENCE

Biotechnology can assist in vegetable production in two ways: firstly, as an aid to conventional breeding programs and secondly, to transfer genes between different organisms[16]. The key biotechnological areas that are currently used for vegetable crop improvement are:

(A) Plant Tissue Culture

It is a collection of techniques used to maintain or grow plant cells, tissues or organs under sterile conditions on a nutrient-rich medium of known composition. It is based on the principle of Totipotency. The various types of plant tissue culture are described below:

(a) Micropropagation

Typically, utilized in crops that are propagated vegetatively, like onion, garlic and sweet potato and fail to generate true seeds[17]. For instance, in modern potato seed production, virus-free plants with better multiplication rates and efficiency were achieved using techniques like micropropagation, microtubers and minitubers under sterile conditions[18].

(i) *Meristem Culture*: This is described as a technique in which somatic meristematic tissues are taken as explants to get genetically true-to-type plants. This is generally used for recovery of virus-free stocks. Major achievements are presented in Table 1.

Table 1. Success of meristem culture in vegetable crops

Crop	Purpose	References
Potato	Elimination of potato virus Y	19
Potato	Elimination of Potato Y potyvirus	20
Chilli	Production of chilli plants free from leaf curl virus	21
Tomato	Elimination of Tomato Yellow Leaf Curl Virus	22
Sweet potato	Elimination of sweet potato viruses for production of disease-free planting material	23
Cassava	Elimination of cassava mosaic disease (CMD) and cassava brown streak disease (CBSD) causal viruses	24
Garlic	Elimination of Onion Yellow Dwarf Virus (OYDV), Garlic Common Latent Virus and Shallot Latent Virus (SLV)	25

(ii) Anther Culture: Utilization of microspore culture on broccoli and cabbage has led to the development of DH (Double Haploids) lines that exhibit improved uniformity and desired traits[26]. The sweet pepper cultivar "*Haihua 3*" has been developed from anther culture, featuring broader adaptability and disease tolerance.

(iii) *Embryo Rescue*: In this technique, immature embryos are used as explants to aid in their growth to form a viable plant. It is used for controlling post-fertilization obstacles (Embryo abortion) during wide hybridization. A few important events are summarized in Table 2.

Table 2. Applications of embryo rescue in vegetable crops

Crop	Target gene	Cross combination	Improved trait/ purpose	References
Tomato (***Solanum lycopersicum***)	***HsfA1***	***S. lycopersicum* × *S. habrochaites***	Introgression of heat tolerance and disease resistance through embryo rescue	[27]
Tomato (***Solanum lycopersicum***)	***Ty-1***	***S. lycopersicum* × *S. peruvianum***	Transfer of resistance to Tomato yellow leaf curl virus (TYLCV)	[28]
Brinjal (***Solanum melongena***)	***Rfo-sa1***	***S. melongena* × *S. torvum***	Development of resistant rootstocks against bacterial wilt and nematodes	[29]
Brinjal (***Solanum melongena***)	***SmMyb1***	***S. melongena* × *S. aethiopicum***	Improvement of biotic stress resistance using embryo rescue	[30]
Chilli (***Capsicum annuum***)	***Pvr4***	***C. annuum* × *C. chinense***	Recovery of interspecific hybrids for virus and pungency traits	[31]
Cucumber (***Cucumis sativus***)	***dmR1.2***	***C. sativus* × *C. hystrix***	Development of downy mildew-resistant introgression lines	[32]
Muskmelon (***Cucumis melo***)	***Pm-W***	***C. melo* × *wild Cucumis spp.***	Improvement of resistance to powdery mildew and drought tolerance	[33]
Onion (***Allium cepa***)	***Pd1***	***A. cepa* × *A. roylei***	Transfer of downy mildew resistance through embryo rescue	[34]
Carrot (***Daucus carota***)	***DcDREB1***	Wild ***Daucus*** species crosses	Enhancement of abiotic stress tolerance and root quality	[35]
Cabbage (***Brassica oleracea*** var. capitata)	***Ogura CMS-associated gene***	***B. oleracea* × *B. rapa***	Production of distant hybrids and CMS-based breeding material	[36]

(b) Somatic Hybridization

It is used for controlling pre fertilization obstacle in an isolated hybridization. It is possible to change cytoplasmic organelles like chloroplasts and mitochondria through this technique. For instance, the mt of *R. sativus* and cp of *B. campestris* have been transferred to *B. oleracea* to exploit organelle heterosis for enhanced productivity[37]. The introgression of Ogura Cytoplasmic Male Sterility (CMS) from Japanese wild radish into cole crops and its refinement through somatic hybridization to overcome low-temperature-related leaf chlorosis transformed hybrid breeding in cole crops[38]. Some other important applications have been shown in Table 3.

Table 3. Applications of somatic hybridization in different vegetable and tuber crops

Somatic hybrid	Trait	References
S. bulbocastanum + *S. tuberosum*	Haploid plants	39
S. melongena + *S. tuberosum*	Resistance to bacterial wilt	40
S. tuberosum + *S. chacoense*	Resistance to bacterial wilt	41
Brassica carinata + *B. oleracea* var. *italica*	Introgression of the '*Rb*' resistance gene into broccoli	42
Celeriac + carrot	Recovery of CMS hybrids through asymmetric protoplast fusion	43

(c) Somaclonal Variations

Somaclonal variations happen because of the conditions of culture, the components of the medium, the addition of plant growth regulators, or may be triggered by *in vitro* mutagenesis[44]. Gene mutations and changes in the structure and number of chromosomes are the main cause of these variations which led to some useful traits in crops (Table 4).

Table 4. Applications of somaclonal variations in different vegetable and tuber crops

Crop	Characteristic of somaclones	References
Sweet potato	Variety 'Scarlet' developed, which is resistant to *Fusarium oxysporum* f. *batatis* and gives higher tuber yields.	45
Potato	Increased phytonutrient content and antioxidant components over cv. 'Russet Burbank'.	46
Potato	Somaclones IBP-10, IBP-27 and IBP-30, derived from cultivar *Desiree*, showed higher resistance to *Alternaria solani* and *Streptomyces scabiei*.	47
Potato	'White Baron': a non-browning somaclonal variant of Danshakuimo (Irish cobbler).	48
Eggplant	Salt tolerance via somaclonal variants	49

(d) Cryopreservation

It provides a reliable method for the long-term preservation of high-quality germplasm and breeding materials, especially those that are unsuitable for traditional seed storage. Generally, agents used for preservation are glycerol, PEG and DMSO to protect against ice damage that usually occurs at -100°C. The cryopreservation of chilli pepper seeds (Huareo n° 13) was performed using the vitrification method with a survival rate of 100 per cent[50].

(e) *Synthetic Seed*

Synthetic seeds are artificially coated plant propagules, including somatic embryos, shoot buds or other types of meristematic tissues, that can develop into complete plants in both *in-vitro* and *ex-vitro* environments[51]. Some important examples are illustrated in Table 5.

B. Genetic Engineering (GE) and GMOs

It is used to describe a process through which the genetic makeup of an organism is altered to introduce beneficial agronomic, processing and nutritional traits for enhanced adaptability to environmental stresses. In vegetable crops, GE has emerged as an important tool for overcoming limitations of conventional breeding, limited genetic variability and interspecific incompatibility. Since the introduction of biotech crops in 1996, the global area has expanded and reached 209.8 million hectares in 2024, with major contributors including the USA, Brazil, Argentina, India and Canada. In India, cultivation is predominantly limited to Bt cotton, which remains the only genetically modified crop commercially approved in the country[57]. Due to its resistance to fruit and shoot borer, Bt Brinjal (*Cry1Ac*) was commercialized in Bangladesh[58]. The USA produced Purple Tomato™, which has been commercialized due to its high anthocyanin concentration[59]. One of the successful examples of commercialization is Innate® potatoes that were marketed in the USA and Canada for their minimal acrylamide production and less bruising[60]. The applications of GE are presented in Table 6.

C. Molecular Markers

Molecular markers are DNA fragments that are linked to a particular place in a genome. They are applied in studies of evolution and phylogeny, the development of genetic maps, DNA profiling, Marker-Assisted Selection (MAS), heterotic breeding and gene tagging/ mapping[4].

- *Quantitative Trait Loci (QTL) Mapping*: QTL investigations are used to recognize the number of genes influencing quantitative traits such

Table 5. Application of synthetic seed production of vegetable crops

Crops	Explants	Encapsulation material	Results	References
Cauliflower	Graded and fractionated curd	4% sodium alginate and 100 mM $CaCl_2$	High germination rate	52
Cucumber	Encapsulated shoot tips	Sodium alginate + $CaCl_2$	Plantlet regeneration and genetic stability	53
Tomato	Apical meristem	Hollow/ solid alginate beads	Storage up to 90 days at a temperature of 4 ± 1°C; germination declined over time	54
Broccoli	Shoots and somatic embryos	Calcium alginate with BAP and NAA	Storage up to 28 days and germination rate increased after storage	55
Garlic	Shoot tips or clove segments	Sodium alginate encapsulated beads	Germination rate varies from 65-80% with storage up to 80-90 days at a temperature of 4 ± 1°C	56

Table 6. Applications of GE in vegetable crops

Crop	Purpose/modified trait	Technology/gene used	References
Tomato	Enhanced shelf life	Antisense RNA technology targeting polygalacturonase	61
Tomato (Purple Tomato)	High anthocyanin content	*Del* and *Ros1* genes from Snapdragon	59
Tomato	Improved floral and fruit traits	CRISPR-Cas9 genome editing	62
Tomato	Resistance to Fusarium wilt	*chi194* wheat chitinase gene	63
Potato	Enhanced vitamin E (α-tocopherol)	*At-HPT* and *At-γ-TMT* genes from Arabidopsis thaliana	64
Potato	Resistance to Colorado potato beetle	*Cry 3A* gene	65
Brinjal (Bt Brinjal)	Resistance against ***Leucinodes orbonalis***	*cry1Ac* gene	66
Brinjal	Salinity tolerance	Antioxidant and flavonoid pathway enhancement	67
Chinese Cabbage	Drought and salinity tolerance	Expressing late embryogenesis abundant *LEA* gene	68
Brinjal	Salinity stress resistance	Biochemical and ionic regulation studies	69
Okra	Resistance against ***Earias vittella***	*Cry1Ac* gene	70

as yield, disease resistance and nutritional quality, *etc*. Several genes and QTLs can be integrated into one genotype through the gene pyramiding approach[71]. For instance, SSR and SNP markers have been linked to the firmness, colour and soluble solid content of the tomato fruit[72].

- *Marker Assisted Selection (MAS)*: By utilizing marker-assisted selection, plant breeders are able to identify selected plants with favored genes during the seedling phase. This accelerates the entire process by lowering the number of plants that advance to the next generation and diminishes the effort needed for unnecessary crosses in Marker-Assisted Backcross Breeding (MABB), MARS and gene pyramiding[73]. Some important events of MAS are illustrated in Table 7. The garden pea powdery mildew-resistant *er2* gene was introgressed from donor parent 'JI2480', which was linked to the SCAR marker "ScX171400"[74]. The er-2 gene-linked SCAR marker "ScX171400" and SSR marker "AD141" showed the possibility of "er-2" gene in mutant L-40-1014, while SSR markers "PSMPSAD60 d" and "PSMPA5 c" linked to the er-1 gene indicated the presence of the "er1" gene in mutant L-0.3-139 [75].

Table 7. Application of MAS in vegetable crops

Crop	Gene introgressed	Recipient cultivar	References
Tomato	Gene pyramiding of *Ty-1*, *Ty-2*, *Ty-3* (ToLCV resistance), *Ph-2* and *Ph-3* (late blight resistance) and *Mi-1.2* (root knot nematode resistance)	Advanced tomato lines derived from 'Punjab Chhuhara'	76
Tomato	*Ty-3* and combinations involving *Ty-2*, *ty-5* and *ty-6* for (ToLCNDV)	Lines in Pusa Rohini, Pusa Ruby, Pusa Sadabahar and Pusa Sheetal cultivars	77
Onion	Transfer male sterility to other onion lines or genotypes	VL Piaz-3, VL Piaz-67 and KR1 populations	78
Pea	*er2* gene for powdery mildew resistance from donor parent 'JI2480'	Powdery mildew resistant pea lines	74
Cauliflower	Downey mildew resistance gene *Ppa3* and black rot resistance gene *Xca1bo*	Improved early cultivar 'Pusa Meghna'	79
Cauliflower	Introgression of *Or* gene for enhancing β-carotene content	Biofortified cultivar 'Pusa KesariVitA-1' derived from improved 'Pusa Sharad' and parental lines of 'Pusa Hybrid-2'	80
Cauliflower	Introgression of *Pr* gene for enhancing anthocyanin content	Lines in 'Pusa Ashwini' and 'Pusa Kartiki' cultivars	81
Bell pepper	Genetic male sterility gene *ms10* from hot pepper cultivar 'MS-12'	Heat-tolerant bell pepper lines	82

D. Genome editing/(CRISPR-Cas9)

It is a revolutionary genome editing technology that enables precise and predictable modifications at specially designated loci[83]. In the field of vegetables, these methods are being utilized to create non-transgenic varieties that possess enhanced stress resistance, longer shelf life or altered metabolic characteristics without the incorporation of foreign DNA[84]. On September 15, 2021, Japan commercialized a noteworthy product from genome editing that is a Gamma-Aminobutyric Acid (GABA) tomato that is designed to help with relaxation and may assist in lowering blood pressure[85]. On March 30, 2022, gene-edited plants falling under the category of Site-Directed Nuclease-1 (SDN-1) and SDN-2, free from exogenous introduced DNA, are exempted from GMOs regulation in India. The application of CRISPR/Cas9 has been successfully applied in several vegetable crops such as tomato, potato, cucumber, brinjal and chilli to improve disease resistance, reduce post-harvest losses and enhance the quality traits. For example, editing of *MLO* genes has conferred resistance against powdery mildew in tomato and chilli, while the targeted mutagenesis of *PPO* genes in brinjal reduced enzymatic browning. Similarly, modification of *eIF4E* genes in tomato and cucumber has resulted in resistance against viral diseases. The application of genome editing that improved the specific trait with target gen are presented in Table 8.

Table 8. Application of genome editing in vegetable crops

Crop	Target gene	Improved Trait/purpose	References
Tomato	*ARGONAUTE7 (SIAGO7)*	Leaf development (Needle-like/ wiry leaves)	86
Tomato (Arka Vikas)	*eIF4E* and *eIF(iso)4E*	Resistance against RNA virus	87
Brinjal (Pusa Purple Long)	*SmelPPO*	Reduced enzymatic browning	88
Chilli (Arka Lohit)	*CaERF28*	Anthracnose (*Colletotrichum truncatum)* resistant	89
Chilli (Pusa Jwala)	*CaMLO2*	Powdery mildew resistance	90
Onion (Bhima Super)	*AcPDS*	Albino mutants	91
Potato (Kufri Chipsona -1)	*PDS (Phytoene Desaturase)*	Albino mutants	92
Potato (Kufri Jyoti)	*ALS1*	Herbicide tolerance	93
Cucumber (Chinese Long)	*eIF4E*	Resistance against viral diseases	94
Watermelon (Sugar Baby)	*ClPDS*	Albino phenotype for gene function analysis	95

FUTURE PROSPECTS OF BIOTECHNOLOGY

The future of vegetable biotechnology depends on its capacity to combine scientific discoveries with modern technologies as well as conventional wisdom to produce solutions that can improve food production's sustainability, adaptability and accessibility for future generations. Modern biotechnology supports entire industries and influences policy frameworks, going far beyond laboratory research.

(i) *Nanobiotechnology*: This novel technology emphasizes the generation of nanoparticles with efficiency in pest control and delivery of nutrients. It assists in encouraging sustainable agricultural practices by reducing waste and enhancing the efficacy of agrochemicals with minimal environmental impact[96]. In regard to diagnosis and treatment, some viruses such as the Tomato spotted wilt virus have been detected with the use of gold nanoparticles combined with certain antibodies[97].

(ii) *Precision Agriculture (PA)*: Site-specific crop management is an innovative farming method that makes use of technologies such as genomics, sensor technology, geospatial mapping and data analytics to maximize productivity while minimizing environmental impact and maximizing resource utilisation[98]. Additionally, PA's integration of AI (Artificial Intelligence) and big data facilitates data-driven decision-making, which improves farming practices.

(iii) *Synthetic and System Biology*: With reliable plant molecular engineering, synthetic biology and system biology open up exciting chances to develop

sustainable vegetable varieties that are rich in nutrients and can withstand stress. This is done by blending techniques like computer modelling and omics data integration[99]. These systems can be utilized to create plants with highly specific traits such as self-fertilizing and self-pruning, *etc*.

CONCLUSION

Biotechnology has emerged as a vital approach for the sustainable improvement of vegetable crops for the enhancement of yield, nutritional quality, shelf life and tolerance to biotic and abiotic stresses. Emerging technologies such as CRISPR/Cas-mediated genome editing, omics-based approaches and bioinformatics play a significant role in the development of climate-resilient, resource-efficient and disease-resistant vegetable cultivars. However, the successful application of these technologies requires stringent biosafety assessments, ethical considerations and well-defined regulatory frameworks. Despite challenges related to biosafety, high development costs and public acceptance, biotechnology plays a crucial role in ensuring sustainability, environmental protection and global food and nutritional security in the future. Biotechnology should be integrated with conventional breeding to ensure precision, speed and efficiency of vegetable improvement programmes for sustainable agriculture.

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AUTHORS CONTRIBUTION

A: Literature integration and wrote the original manuscript; AS: Conceptualized the idea, methodology, provided resources, reviewed and edited the manuscript; DRC: Structural framework and strategic insights; SR: Literature review and structural framework. S: Literature screening and compilation of tables; R: Bibliographic searches and construction of data tables. AT: compilation of tabular information; KS: structural formatting ST: Final tables.