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Trends and developments in vegetable research In India — a review

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ABSTRACT

Vegetables are an integral component of horticulture sector, praying a pivotal role in the tapestry of Indian agriculture. Their substantial contributions extend to enhancing global food security and nutritional well-being. During 2021-22, India produced 204.84 million tonnes of vegetables, covering the area of 11.35 million hectares, with a fresh vegetable export value worth 865.24 USD millions. The AICRP on Vegetable Crops has forged a national network to test vegetable technologies in India. In the past five decades, 587 vegetable varieties, 442 production technologies, and 42 protection technologies have been developed through AICRP. The use of molecular markers has been proven promising in several vegetable crops, however only limited example of improvements are available from India. Through genetic engineering several biotic and abiotic stress resistant lines are developed. The genome editing has opened a new avenue in development of improved lines, however it is just gaining momentum in vegetable research in India.

Key words: Vegetables, Genome editing, Vegetable export, Breeding, Biotechnological approach, Biofortification

Vegetables play a crucial role in promoting human nutrition by serving as invaluable sources of essential nutrients, dietary fiber, vitamins, minerals, plant-based proteins, and antioxidants. Additionally, the presence of phytochemicals in vegetables has been scientifically linked to a reduction in the risk of non-communicable diseases (NCDs). These include some of the most prevalent and serious health concerns, such as certain forms of cancer, diabetes, gastric ulcers, stroke, and heart diseases (Dias, 2013). India has embraced a remarkable diversity in its vegetable consumption, with a repertoire that encompasses over 97 species of higher plants and among these, nearly 60 being cultivated on a commercial scale (Behera *et al.*, 2021). Further. These vegetable crops span an impressive spectrum of 20 distinct plant families, with notable representatives from families such as Cucurbitaceae, Fabaceae, Brassicaceae, and Solanaceae, which together account for a rich tapestry of flavours, textures, and nutritional profiles.

The world's total vegetables production was estimated to be 1,154 million tonnes in 2021, China being at top position with a production of 600 million tonnes that accounts for 52.18% of the world. The top 5 countries (China, India, the United States of America, Turkey and Vietnam) account for 70.36% of total world's production (Statista, 2023). During 2021-22, India produced 204.84 million tonnes of vegetables covering the area of 11.35 million hectares, with average productivity of 18.05t/ha compared to area (2.84 million ha), production (16.5 million tonnes) and productivity (5.8 t/ha) of vegetables in 1950-51. Since 1951, there has been enhancement in area (4.0 fold), productivity (3.1 fold), production (12.41 fold) and per-capita availability (3.3 fold). Presently, India is the largest producer of ginger (2.23 mt) and okra (6.47 mt) in the world, while ranking second in the production of potatoes (54.23 mt), dry onions (26.64 mt)), cauliflowers and broccoli (9.25 mt), brinjal (12.87mt), and cabbage (9.56 mt) (FAO, 2020). The fresh vegetable export value was reported to be worth of 865.24 USD millions (APEDA, 2023).

In India, systematic vegetable improvement work was initiated in the 1960's. This transformative effort gained momentum through the establishment of several national research institutes and the implementation of All India Coordinated Research Project (AICRP) focusing on vegetables. These strategic initiatives have not only propelled significant advancements in vegetable production and productivity but have also positioned India as the second-largest global producer in this domain. As on date, a total of 553 vegetable varieties in 30 vegetables have been in public domain for cultivation in different agro climatic zones of India

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(Behera *et al.*, 2021). Vegetable breeding presents a distinct level of complexity and challenge when compared to grain crops, where the grain itself is the primary product. In the realm of vegetables, various plant components like leaves, stems, roots, flowers, and fruits are consumed. The region-specific demand for attributes such as colour, shape, nutrition, taste, and the optimal harvest stage, along with the need to address quality concerns, ensure a consistent year-round supply, and manage other intricate considerations, represents the requirement for a comprehensive and specialized approach to achieve the desired outcomes in crop improvement.

Vegetables, production and quality are significantly impacted by a multitude of pathogens and insects. The consequences of excessive pesticide and fungicide use, coupled with the presence of microbial contaminants, colorants, and heavy metals, pose notable environmental and health hazards. Among these concerns, the presence of pesticide residues emerges as a paramount food safety issue. Alarmingly, India contributes to 25% of global pesticide poisoning cases, and between 50-60% of vegetables harbour pesticide residues (Dhaliwal *et al.*, 2015). Further, vegetable crops are particularly sensitive to environmental extremes particularly elevated temperatures and inadequate soil moisture stand out as primary contributors to diminished yields in tropical regions, and these challenges are anticipated to intensify with the progression of climate change. To combat these problems a due focus is given on the resistance breeding for various biotic and abiotic stresses in each vegetable crop. A diverse array of vegetable crop varieties with increased productivity and other desirable attributes has already been attained through the implementation of conventional breeding techniques. However, this traditional approach to genetic enhancement is characterized by a gradual pace, involving numerous generations for genome refinement in an uncontrolled manner. Alongside conventional breeding, recently innovative genetic engineering techniques, including recombinant DNA technology, RNA interference (RNAi), and CRISPR-Cas9, has notably contributed to the genesis of novel crop varieties. This review provides an overview of the current state of vegetable cultivation, prevalent breeding techniques, focal traits of interest, utilization of wild genetic resources for biotic and abiotic stress resilience, as well as modern breeding methodologies encompassing biotechnological assisted strategies, gene editing, and the potential integration of artificial intelligence and machine learning techniques to advance and enhance vegetable production in India.

Network approach of research

The All India Coordinated Research Project (AICRP) on Vegetable Crops began during the IVth five-year plan in 1970-71, establishing a national network for testing vegetable technologies from diverse research institutions and state agricultural universities. Presently, the AICRP Vegetable Crops is a network of 36 regular and 18 voluntary centres and 26 co-operating centres, located in different agro climatic zones of the country with its headquarters at Indian Institute of Vegetable Research (IIVR) in Varanasi. The main function of AICRP-VC is to provide a national level platform for multi-location testing of the vegetable technologies developed by various research institutes and state agricultural universities to identify region specific recommendations. Over the period of last five decades, a total of 587 vegetable varieties in 28

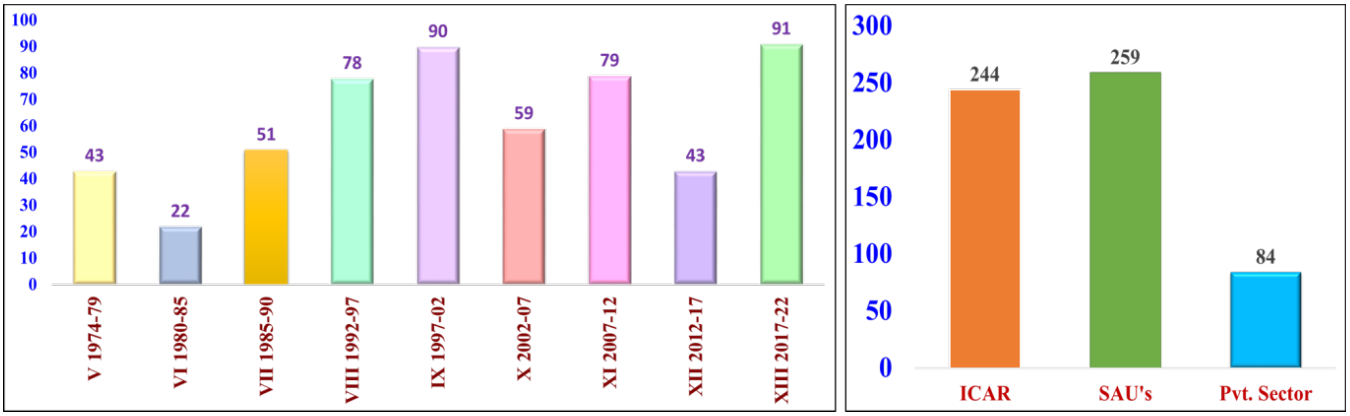

Fig. 1: Plan-wise varieties/hybrids developed and number of varieties/hybrids contributed by different sectors, identified through AICRP (VC) in last five decades

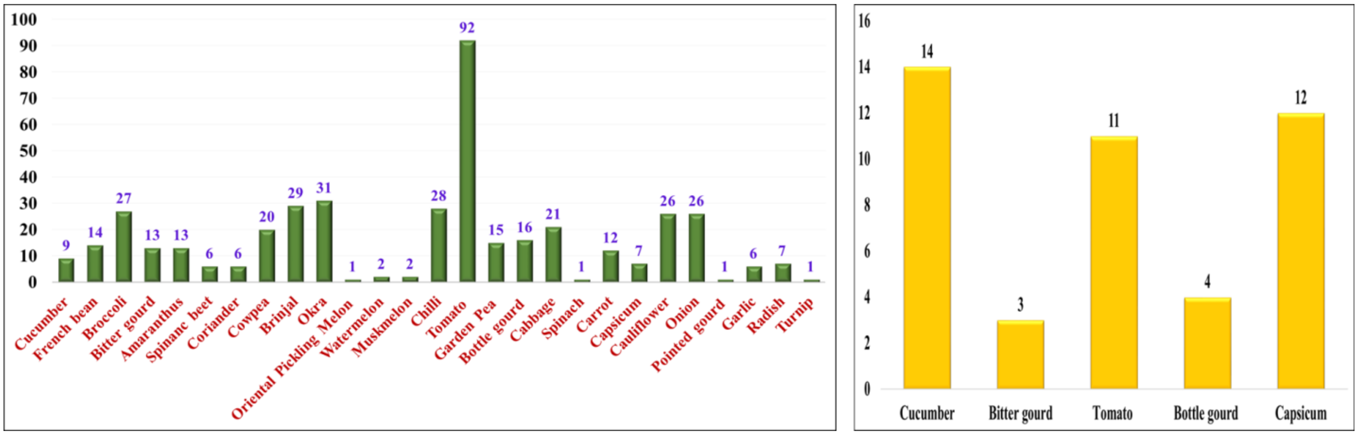

Fig. 2: Crop-wise production and protection technologies developed through AICRP (VC) during last five decades

vegetable crops have been recommended for cultivation in various agroclimatic zones of the country (Fig. 1). This includes 309 O.P. varieties, 163 hybrids and 54 O.P./ hybrids resistant to different biotic and abiotic stresses. During 2009 – 2019, a total of 126 varieties including 66 OPV, 50 F_1 hybrids and 10 resistant varieties have been identified and recommended by the AICRP (VC) in 24 vegetables.

Likewise, the centre has successfully developed 432 production technologies covering 27 distinct vegetables, complemented by an additional 46 protection technologies in 5 vegetables (Fig 2). It is worth noting that when it comes to protection technologies, cucumber takes the lead, closely followed by bitter gourd, tomato, bottle gourd, and capsicum.

Traditional breeding approaches and targeted traits

The traditional breeding methods, encompass prominent approaches such as introduction, pure line selection, pedigree method, bulk method, single seed descent, back cross method, heterosis, and mutation. As emphasized by Behera *et al.* (2023), the significant breeding objectives in various vegetables crops includes focus on high yields (Pandey *et al.* 2008), consumer liking, multiple diseases resistance, pest tolerance, processing quality and high Nutraceutical value (Pandey *et al.*, 2010). Singh *et al.* (2009) listed the available resistant cultivars, genotypes or wild species in various vegetables crops for various biotic stresses. The comprehensive listing of cultivars and hybrids developed to confer resistance against a myriad of biotic stresses across diverse vegetable crops is outside the purview of this review article. However, some of the most popular achievements have been mentioned with few examples as in case of brinjal (Pusa Vaibhav, resistant to *Fusarium* wilt, virus complex and little leaf under field condition; Arka Keshav: resistant to bacterial wilt); pea (Matar Ageta-7, resistant to rust & powdery mildew diseases; Kashi Samridhi: powdery mildew resistance), Okra (Kashi Chaman, resistant to YVMV & OLECV) etc. Similarly, due focus has been directed towards abiotic stresses and specific growth conditions. Some of landmarks varieties developed by the leading institutes across nation are summarized in table 1.

The significance of bioactive-rich and edible colour varieties cannot be ignored as they play a pivotal role in promoting both human health and culinary diversity. As stated in beginning, bioactive compounds, such as antioxidants, vitamins, and phytochemicals, present in these varieties offer a multitude health benefits, including bolstering the immune system, reducing the risk of chronic diseases, and supporting overall well-being. Moreover, the vibrant and diverse array of colours in these varieties not only enhances the visual appeal of dishes but also signifies the presence of different nutrients and phytochemicals. This is particularly important in a country like India, where traditional cuisine is deeply rooted and where the cultural significance of food is closely intertwined with its nutritional value. Table 2 listed out some of these varieties developed to cater to Indian consumers' preferences and nutritional needs.

Further, hybrid seed development stands as a pivotal factor in propelling the expansion of vegetable production on a global scale. This progress has been propelled by the strategic implementation of self-incompatibility (SI)

Table 1: Varieties for special growth conditions in some of crops

Crop	Special growth trait	Cultivars	Institute
Brinjal	Summer and autumn cultivation	Punjab Chamkila	PAU, Ludhiana
Brinjal	Summer and autumn cultivation	Pusa Purple Cluster	ICAR-IARI, New Delhi
Cabbage	Tolerance to high temperature	Green Express, Green Boy, KK Cross,	-
Cabbage	Tolerance to high temperature	Pusa Ageti	ICAR-IARI, New Delhi
Cabbage	Tolerance to high temperature (36°C)	Bajrang (F1 hybrid)	Bejo Sheetal Seeds Pvt. Ltd., Jalna
Cauliflower	Tolerant to heat	Garima	Golden Seeds
Chilli	Tolerant to moisture stress	Arka Lohit	IIHR, Bangalore
Chilli	Tolerant to salinity	Aparna (CA-1068)	APAU (Lam)
Cowpeas	Tolerant to heat and drought	Arka Garima	ICAR-IIHR, Bangalore
Cowpeas	Wider adaptability	Kashi Kanchan, Kashi Nidhi	ICAR-IIVR, Varanasi
Garlic	Tolerant against soil salinity	HG-6	CCSHAU, Hissar
Onion	Kharif season	Arka Kalyan,	ICAR-IIHR, Bangalore
Onion	Kharif season	N53, Agrifound Dark Red, Baswant 780	-
Pea	Wider adaptability	Kashi Udai, Kashi Nandini	ICAR-IIVR, Varanasi
Peas	High Temperature	Arka Tapas	ICAR-IIHR, Bangalore
Pointed gourd	Tolerant to moisture stress	Swarna Alaukik	CHES, Ranchi
Potato	Tolerant to frost	Kufri Navtal, Kufri Sheetman	ICAR- CPRI, Kufri, Shimla
Potato	High temperature tolerant	Kufri Surya	ICAR- CPRI, Kufri, Shimla
Radish	Year round cultivation	Pusa Chetki, Pusa Desi	ICAR-IARI, New Delhi
Radish	High temperature tolerant (up to 40°C)	Kashi Mooli-40	ICAR-IIVR, Varanasi
Tomato	High Temperature	Kashi Tapas, Kashi Adhbhut	ICAR-IIVR, Varanasi
Tomato	High Temperature	Pusa Hybrid 1 (28°C night temp)	ICAR-IARI, New Delhi
Tomato	Low temperature	Ostenkinskiz, Cold Set	-
Tomato	Low temperature	Pusa Sheetal (8°C)	ICAR-IARI, New Delhi
Tomato	Fruit set at low temperature	Hissar Arun	HAU, Hissar
Tomato	Tolerant to moisture stress	Arka Vikas	ICAR-IIHR, Bangalore
Watermelon	Resistant to drought	Sugar Baby	ICAR- IARI, New Delhi

Table 2: Varieties rich in bioactive and edible colour in India

Crop	Variety	Pigment
Amaranthus	Pusa Lal Chaulai	Anthocyanin
Basella	Kashi Poi-3	Betalain
Bitter gourd	Pusa Aushadi	Beta carotene
Bitter gourd	Pusa Vishesh	Ca & Fe
Bitter gourd	Pusa Hybrid -2	Ca & Fe
Carrot	Pusa Ashita	Anthocyanin
Carrot	Kashi Krishna	Anthocyanin
Carrot	Pusa Rudhira, Pusa Vrishti	Lycopene
Carrot	Pusa Yamdagini, Pusa Nayanjyoti	Carotene
Paprika	KTPL-19	Capsanthin
Pumpkin	Arka Chandan	Carotene
Purple headed Broccoli	Palam Vichitra	Anthocyanin
Radish	Pusa Jamuni, Kashi Lohit	Anthocyanin
Radish	Pusa Gulabi	Lycopene
Red cabbage	Red Acre	Anthocyanin
Tomato	Pusa Uphar, Pusa Rohini, Pusa Hybrid 2, Pusa Red Plum	Vitamin C & Lycopene

and male sterility (MS) mechanisms in the production of hybrid seeds for various vegetable crops, each with distinct advantages and drawbacks. The utilization of the SI system, primarily found in Brassica species like broccoli, cauliflower, and cabbage, has demonstrated its commercial viability, albeit with certain limitations. In contrast, the male sterility system has found its application across a wider spectrum of vegetables. This innovative approach has not only contributed to enhancing crop yields and quality but has also provided an avenue to target other specific traits to meet the demands of an ever-evolving agricultural landscape. Table 3, describes some of the example in which these mechanisms have been exploited for hybrid development in vegetable crops.

Biotechnological approaches for vegetable improvement

Numerous varieties have been developed through conventional breeding in vegetable crops in India, as discussed in the previous sections. The breeding through conventional breeding is random and it takes several generations, long time and financial resources to develop the desired combination of traits. The success of conventional breeding depends on the available variation and is associated with two major problems, i.e., linkage drag and the distant hybridization barrier. There are different biotechnological tools for vegetable improvement such as genome editing using marker-assisted selection (MAS), CRISPR/Cas9, RNA interference (RNAi), genetic engineering etc.

Marker-assisted Selection

The integration of molecular markers into traditional breeding methods has ushered in a transformative approach known as marker-assisted selection (MAS). Through the utilization of molecular markers, significant breakthroughs have been achieved in identifying key QTLs/genes associated with critical horticultural, quality, and processing traits. Over the course of time, this treasure trove of discovered QTLs/gene has been utilized by researchers and breeders for development of new cultivars and improved lines. By leveraging the intricate markers information, a new era of precision and efficiency has emerged in vegetable breeding, ultimately leading to more resilient, high-yielding, and desirable varieties (Pandey *et al.*, 2021). The term 'marker assisted selection' was first used by Bechmann and Soller (1986) but it gained popularity in reference to mapping and tagging genes with the help of molecular markers (Xu and Crouch, 2008). The first report of application of MAS in plant breeding was for soybean cyst nematode (*Heterodera glycines* Ichinohe) (Concibido *et al.*, 1996). Application of MAS in vegetable crops are still limited in India. Few studies related to MAS application in vegetable crops in India has been presented in Table 4. The use of marker assisted breeding to improve varieties of vegetable crops is necessary because it requires less time and efficient. With the help of marker assisted selection, plant breeder can identify the plants possessing gene of interest at seedling stage, it speeds up the whole process by reducing the load of the population carried to next generation and also reduce the burden of making unnecessary crosses in marker assisted backcross breeding (MABB), marker assisted recurrent selection (MARS) and pyramiding of genes. The MABB is most widely utilized for transfer of oligogenes into the background of a desirable recurrent background, it involves three basic steps; foreground selection, recombinant selection and background selection (Sagar *et al.* 2020)

Table 3: Harnessing genetic mechanisms to develop hybrids in select vegetable crops

Crop	Vegetable crop	Variety
Cabbage	KGMR-1(Pusa cabbage hybrid 1), KTCBH 51, KTCBH 81	Self-incompatibility
Cabbage	KCH-5, Hybrid 991-5, Hybrid 854-6	Cytoplasmic male sterility
Carrot	Pusa Nayanjyoti, Pusa Vasudha	Cytoplasmic male sterility
Cauliflower	Pusa Hybrid-2, Pusa Kartik Sankar	Self-incompatibility
Cauliflower	Hybrid 8401 ×31022	Cytoplasmic male sterility
Chilli	Arka Sweta, Arka Meghna, Arka Harita, Arka Khyati,Kashi Surkh, CH-1, CH-3	Cyto genic male Sterility and Genetic male sterility
Cucumber	Solan Khira Hybrid-1, Solan Khira Hybrid-2	Gynoecious based F_1 hybrids
Onion	Arka Kirthiman, Arka Lalima	Cytoplasmic male sterility

Table 4: Vegetable crops improved through marker assisted selection in India

Crop	Gene introgressed	References
Tomato	*Ty-2* and *Ty-3* for tomato leaf curl disease	Prasanna *et al.* 2015
Onion	Transfer male sterility to other onion lines or genotypes	Saini *et al.* 2015
Cauliflower	Downey mildew resistant gene *Ppa3* and black rot resistant gene *Xca1bo*	Saha *et al.* 2021
Bell pepper	Genetic male sterility gene *ms10* from hot pepper to heat tolerant bell pepper	Rani *et al.* 2021
Tomato	Gene pyramiding of *Ty-1, Ty-2, Ty-3* for tomato leaf curl resistance genes; *Ph-2* and *Ph-3* for late blight resistance genes; *Mi-1.2* for root not nematodes resistance	Kumar *et al.* 2019
Soybean	Kunitz trypsin inhibitor free soybean	Kumar *et al.* 2020
Tomato	Gene pyramiding of *ToLCV* gene for enhanced tomato leaf curl virus disease resistance	Kumar *et al.* 2014
Cauliflower	Introgression of *Or* gene for enhancing β-carotene content in cauliflower	Kalia *et al.* 2018
Tomato	*Ty-1/Ty-3, Ty-2, ty-5 and ty-6*	Prabhandakavi *et al.* 2021
Tomato	Stacking of *Ty*3, *Mi*1.2 and *Ph*3	Maurya *et al.* 2023
Tomato	Marker assisted selection for *Mi 1.2* gene and *Ph2* and *Ph3*.	Kaur *et al.* 2023

Genomes sequencing of vegetable crops

The era of plant genome sequencing started with the sequencing of model plant *Arabidopsis thaliana* genome in 2000 by using Sanger sequencing method (first generation sequencing). The second generation sequencing era started with the discovery of sequencing-by-synthesis technology in 2005 developed by 454 Life Sciences. The third generation sequencing also known as next generation sequencing (NGS) became popular among the researchers because it reduced the cost of sequencing, time saving, and high accuracy. The first sequenced vegetable crop plant was soybean (*Glycine max* L. Merr.) (Shultz *et al.*, 2006), belonging to Fabaceae family, having small genome size of 1.1-1.15 Gb. After soybean, cucumber (*Cucumis sativus*) genome has been sequenced by Huang *et al.* (2009) with the genome size 367 Mb. The size of genomes of various vegetable crops varies greatly. The Faba bean (*Vicia faba*) is possessing the largest genome of 13 Gb (Carrillo-Perdomo et al., 2020) among the sequenced vegetable crop while silver seed squash (*Cucurbita argyrosperma*) having 238 Mb (Barrera-Redondo J *et al.*, 2019).

As per available data, 45 vegetable crops have been sequenced till date (Chen *et al.*, 2019) and these sequenced genomes help researchers to better understand the domestication process. To procure the data of sequenced genomes, several databases have been developed, among them few are freely accessible while other requires user registration and a login to access the data (Chen *et al.*, 2019). The Sol Genomics Network (SGN), a database of Solanaceous crops; the Cucurbit Genomics Database (CuGenDB), provide genome sequences of Cucurbitaceous crop and the Brassica Database (BARD) provide information of Brassica species. Plant genome sequencing accelerates the genomic-assisted breeding by providing a reference genome for sequence analysis. Further, this can facilities marker assisted breeding, genomic selection and epigenetic approach to improve the various traits of vegetable crops. As India is the origin of several crops, the sequencing of several indigenous, underutilized vegetables are still awaited.

Genome editing in vegetable crops

The optimal production and productivity of vegetable crops hinge upon their ability to withstand a variety of challenges, encompassing both biotic and abiotic stresses. This underlines the critical importance of developing vegetable varieties that are either resilient or tolerant to these adversities. Beyond mere yield, aspects such as flavour, nutritional value, and post-harvest shelf life also stand as crucial attributes warranting improvement within vegetable crops. In the era of genomic advancements, the revolutionary CRISPR/Cas9 tool emerges as a pivotal instrument, enabling precision modification of genetic material at specifically designated loci. Stemming from the adaptive immune system of bacteria, this mechanism induces double-stranded breaks via endonucleases guided by single-guide RNAs. Its resounding success traverses various domains including field crops, horticultural crops, and model plants. An illustrative instance is the development of a drought-tolerant soybean variant featuring elevated oil content in 2017 through CRISPR/Cas9 technology (Waltz, 2018), garnering FDA approval for market distribution in the United States. It is noteworthy that CRISPR-edited crops traverse distinct regulatory mechanism compared to transgenic GM crops. Recently, government of India has notified detailed guidelines for the generation and testing of SDN1 and SDN2 opening the avenues of opportunity for cultivation of genome edited products.

Table 5: List of sequenced genomes of major vegetables crops

Common name	Species	Family	References	Estimated genome size
Sugar beet	*Beta vulgaris*	Amaranthaceae	Arumuganathan and Earle (1991)	758 Mb
Soybean	*Glycine max*	Fabaceae	Shultz *et al.* (2006)	1.1–1.15 Gb
Cucumber	*Cucumis sativus*	Cucurbitaceae	Huang *et al.* (2009)	367Mb
Musk melon	*Cucumis melo*	Cucurbitaceae	Gonzalez *et al.*, (2010)	450 Mb
Potato	*Solanum tuberosum*	Solanaceae	The potato genome sequencing consortium (2011)	844 Mb
Chinese cabbage	*Brassica rapa*	Brassicaceae	Wang *et al.* (2011)	485 Mb
Tomato	*Solanum lycopersicum*	Solanaceae	The tomato genome consortium (2012)	900 Mb
Water melon	*Citrullus lanatus*	Cucurbitaceae	Guo *et al.* (2013)	425 Mb
Cabbage	*Brassica oleracea*	Brassicaceae	Liu *et al.* (2014)	630 Mb
Common bean	*Phaseolus vulgaris*	Fabaceae	Schmutz *et al.* (2014)	587 Mb
Eggplant	*Solanum melongena*	Solanaceae	Hirakawa *et al.* (2014)	1126 Mb
Moringa	*Moringa oleifera*	Moringaceae	Tian *et al.* (2015)	315 Mb
Pumpkin	*Cucurbita moschata*	Cucurbitaceae	Zhang *et al.* (2015)	271.4 Mb
Radish	*Raphanus sativus*	Brassicaceae	Mitsui *et al.* (2015)	383Mb
Adzuki bean	*Vigna angularis*	Fabaceae	Kang *et al.* (2015)	538 Mb
Carrot	*Daucus carota*	Apiaceae	Iorizzo *et al.* (2016)	473 Mb
Brown mustard	*Brassica juncea*	Brassicaceae	Yang *et al.* (2016)	316.1 Mb
Berry-like pepper	*Capsicum baccatum*	Solanaceae	Kim *et al.* (2017)	3.9 GB
Bonnet pepper	*Capsicum chinense*	Solanaceae	Kim *et al.* (2017)	3.2 GB
Bitter melon	*Momordica charantia*	Cucurbitaceae	Urasaki *et al.* (2017)	339 Mb
Bottle gourd	*Lagenaria siceraria*	Cucurbitaceae	Wu S *et al.* (2017)	313.4 Mb
Lettuce	*Lactuca sativa*	Asteraceae	Kozik *et al.* (2017)	2.5 GB
Garden asparagus	*Asparagus officinalis*	Asparagaceae	Harkess *et al.* (2017)	~1.3 Gb
Spinach	*Spinacia oleracea*	Amaranthaceae	Xu *et al.* (2017)	989 Mb
White Guinea yam	*Dioscorea rotundata*	Dioscoreaceae	Tamiru *et al.* (2017)	594 Mb
Winter squash	*Cucurbita maxima*	Cucurbitaceae	Sun H *et al.* (2017)	372.0 Mb
Spanish pepper	*Capsicum annuum*	Solanaceae	Hulse-Kemp *et al.* (2018)	~3.5 GB
Summer squash	*Cucurbita pepo*	Cucurbitaceae	Montero-Pau J *et al.* (2018)	263 Mb
Silver-seed gourd	*Cucurbita argyrosperma*	Cucurbitaceae	Barrera-Redondo J *et al.* (2019)	238 Mb
Fava bean	*Vicia faba*	Fabaceae	Carrillo-Perdomo *et al.* (2020)	~ 13 GB
Snake gourd	*Trichosanthes anguina*	Cucurbitaceae	Ma *et al.* (2020)	919.8 Mb
Chayote	*Sechium edule*	Cucurbitaceae	Fu *et al.* (2021)	606.42 Mb
Ash gourd	*Benincasa hispida*	Cucurbitaceae	Xie *et al.* (2019)	913 Mb

The genomes of several important vegetables have been edited by using CRISPR/Cas9 technology in various countries. CRISPR/Cas9 technology was first time utilized in tomato in 2014. The gene *ARONAUTE7 (SlAGO7)* was targeted which is involved in leaf development (Brooks *et al.*, 2014). The scope broadened to encompass traits like root growth, fruit maturation, anthocyanin synthesis, parthenocarpy, and fruit pigmentation. These achievements were attained through precision targeting of genes such as SHORT-ROOT (*SHR*) (Ron et al., 2014), ripening inhibitor (*RIN*) (Ali *et al.*, 2015), Anthocyanin 1 (*ANT1*) (Cermak *et al.*, 2015), SIAGAMOUS-LIKE 6 (Klap *et al.*, 2017), and PHYTOENE SYNTHASE (*PSY*1) (Hayut *et al.*, 2017) in the tomato genome. Meanwhile, CRISPR/Cas9 efforts also bolstered starch quality in potatoes by modifying the granule-bound starch synthase (GBSS) gene (Andersson *et al.*, 2017). In the dynamic landscape of agricultural innovation, India has emerged as a prominent player in the application of CRISPR/Cas9 technology, where substantial research endeavours are currently underway to harness the potential of genome editing across diverse vegetable crops such as tomato, potato, onion, cucumber, and chili pepper, much of this work remains in progress. In line with this trajectory, Indian Council of Agricultural Research, New Delhi is proactively establishing centre of excellence for genome editing of various crops including vegetable crops, where major challenges hampering the production and processing of will be addressed.

The successful example of genome editing is available in tomato, chilli and onion. In tomato, the cv. Arka Vikas was improved for resistance against RNA viruses through genome editing of eukaryotic translation initiation factor (*eIF*) gene family, including *eIF4E* and its paralogue *eIF(iso)4E* (Santosh, 2020). The *Capsicum annuum* (cv.) Arka Lohit was successfully improved against the anthracnose disease caused by *Colletotrichum truncatum*. The target was achieved by altering *CaERF*28 through CRISPR/Cas9-mediated genome editing. The developed mutants demonstrated enhanced resistance to anthracnose compared to wild type as demonstrated by reduced spore count and fungal growth as well as induced expression of defense-related genes (Mishra *et al.*, 2021). In onion, where phytoene desaturase (*AcPDS*) gene was edited in the cultivar Bhima Super, and albino mutants were identified in the subsequent generations. This is the first time a CRISPR/Cas9-mediated genome editing protocol has been successfully established in onion, with the *AcPDS* gene serving as an example (Mainkar *et al.* 2023). These landmark accomplishments not only showcases the tangible progress made in genome editing but also underscores the potential for similar advancements across a spectrum of vegetable crops, with far-reaching implications for agriculture and sustainability.

Genetic engineering

In recent years, remarkable progress has been made in improving the introgression of quality traits, cultivating resistant cultivars, and synthesising industrial proteins in vegetable crops. New research highlights the viability of incorporating novel agronomic traits into these crops. This integration has been accomplished through the skilled application of genetic engineering techniques, allowing for the cultivation of vegetables with desired phenotypic characteristics derived from wild species gene reservoirs. Simultaneously, genetic engineering has demonstrated its effectiveness in reducing the expression of genes responsible for the production of naturally occurring toxic compounds that endanger human health when consumed.

Genetic manipulation, for example, has facilitated the incorporation of genes responsible for bolstering defence responses against plant-pathogen, as well as the activation of mechanisms to combat a variety of stressors such as heat, cold, drought, salinity, and low oxygen levels. These trailblazing achievements demonstrate the successful application of genetic engineering in reshaping the genetic landscape of vegetables, resulting in crops that are not only more resilient and adaptable, but also safer and more nutritious for human consumption.

Several successful genetic engineering applications has been recorded in the horticultural crops including vegetables. The first ever commercialized transgenic has been recorded in vegetable crop tomato for enhanced shelf-life trait ‘Flavr-Savr’ in USA in 1994. The major traits introduced through transgenics include insect-pest resistant (*Bt*. Toxin gene), virus resistance, male sterility, drought tolerance, etc. In India several examples are available where genetic engineering has been used for the improvement of vegetable crops. In potato the high nutritive value was achieved through expressing *AmA1* seed albumin gene derived from *Amaranthus hypochondriacus* in the potato tubers. The derived tubers were rich in the sulphur-containing amino acids such as methionine and cystine and essential amino acids lysine and tyrosine (Chakraborty *et al.*, 2000). Transgenic potato with enhanced vitamin E (α-tocopherol) was developed by over expressing *homogentisate-phytyltransferase* (*At-HPT*) and γ-tocopherol-*methyltransferase* (*At-γ-TMT*) genes isolated from *Arabidopsis* in potato, which was shown to combat with degenerative health problems, abating cancer risk and coronary heart diseases in humans (Upadhyaya *et al.*, 2020). In carrots the transgenic plants overexpressing glycine betaine and betaine aldehyde dehydrogenase (BADH) in their plastids exhibited high tolerance to salinity (Kumar *et al.*, 2004). In tomato the cultivar H-86 was transformed with *BcZAT*12 and the resulting plants were found to be tolerant to the heat stress through lowering the free radical formation, improved electrolyte leakae, relative water and chlorophyll content. Also, higher anti-oxidant activity related enzymes such as superoxide dismutase, catalase, ascorbate peroxidase and glutathione reductase were observed when exposed to HS (Shah *et al.*, 2013). In tomato cv. Pusa Ruby, the boiling stable protein (*bspA*) gene from *Populus tremula* was over expressed to achieve moisture deficit tolerance. The boiling stable proteins plays role in desiccation tolerance by protecting the proteins in membrane and cytosols. The transgenic plants were having improved desiccation tolerance over the non-transgenic plants (Roy *et al.*, 2006). The tomatoes are sensitive to chilling stress (0-12 °C), severely affecting growth and reproduction. In tomato, transgenic plants overexpressing *AtDREB1A* was found to show less sensitivity to the chilling stress. The cold stress induces ROS production, which is regulated by enhanced production of anti-oxidant enzymes (CAT), superoxide dismutase (SOD), and ascorbate, high relative water content, less electrolyte leakage and improved accumulation of proline and soluble sugars in transgenic plants (Karkute *et al.*, 2019).

Generally vegetable crops lack resistance against the insect-pest, which is controlled through the application of chemical. Attempts have been made to utilize the *Bt* (*Cry*) gene isolated from a soil bacteria Bacillus thuringiensis for controlling the lepidopteran insects in number of crops. The *Bt*-cotton cultivation in India has been remarkably successful. Insect resistance was firstly reported in tomato using *Bt*. gene in 1987. Transgenic *Bt* tomato plants exhibited resistance against *Spodoptera litura* and *Heliothis virescens* (Fischhoff *et al.*, 1987). Brinjal (*Solanum melongena*) cv. Pusa Purple Long was transformed with cry1Ab gene coding for an insecticidal crystal protein (ICP). The transgenic brinjal plants displayed significant differences in the insect mortality in fruit bioassays. Very high level of ICP in these plants are responsible for complete protection against the *Leucinodes orbonalis* (Kumar *et al.*, 1998). The Cauliflower var. Pusa Snowball K-1 was transformed with a synthetic cryIA(b) showed effective resistance against infestation by diamondback moth (*Plutella xylostella*) larvae during insect bioassays (Chakrabarty *et al.* 2002). Paul *et al.* (2005) developed transgenic cabbage (*Brassica oleracea* var. capitata) line DTC 507 with a synthetic fusion gene of *B. thuringiensis* encoding a translational fusion product of *cry1B* and *cry1Ab* δ-endotoxins to confer resistant against diamondback moth (Plutella xylostella). In okra *(Abelmoschus esculentus) Cry1Ac* has been successfully transformed for incorporating resistance against the fruit and shoot borer (*Earias vittella*) of okra. The transgenic plants showed 100% larval mortality (Narendran *et al.*, 2013).

Crops can now be genetically engineered to resist disease. Numerous genes, including chitinase, glucanase, osmotin, defensin, etc. are being inserted into different horticultural crops all over the world to confer resistance against bacterial and fungal diseases. According to Ceasar and Ignacimuthu (2012), a number of glycolytic enzymes, such as chitinase, glucanase, PR proteins, etc., are encoded by genes inside plant cells and have the ability to degrade cell walls. This property makes them attractive for use in the development of transgenic plants that incorporate resistance to fungal pathogens. The use of systemic acquired resistance (SAR)-related genes is one of the various approaches used in genetic engineering for disease resistance that is of utmost significance. According to Ryals *et al.* (1996), SAR is long-lasting and frequently accompanied by local and systemic accumulation of salicylic acid (SA) and induced expression of numerous genes, including pathogenesis-related (PR) genes. Girhepuje and Shinde (2011) created transgenic tomato plants overexpressing *chi*194, a wheat chitinase gene, under maize ubiquitin 1 promoter. Transgenic tomato lines with higher chitinase activity were highly resistant to Fusarium wilt caused by *Fusarium oxysporum f. sp. Lycopersici*.

Polyamines like putrescine, spermidine, and spermine help with biotic and abiotic stress tolerance. Hazarika and Rajam, (2011) transformed a human S-adenosyl methionine decarboxylase (*samdc*) gene to tomato cv. Pusa Ruby to biosynthesize spermidine and spermine. Transgenic tomato plants produced more polyamines and were more resistant to *Fusarium oxysporum* and *Alternaria solani*, which cause wilt and early blight respectively. Transgenic lines also showed better tolerance to high temperature, drought, salinity, and chilling stress.

A bacterial mannitol-1-phosphate dehydrogenase (*mtl*D) gene driven by the constitutive cauliflower mosaic virus (CaMV) 35S promoter was transferred into tomato plants to improve abiotic stress tolerance (Khare *et al*. 2010). Transgenic lines tolerate abiotic stresses better than non-transformed plants in drought and salinity tests. Gangadhar *et al*. (2016) used *Agrobacterium tumefaciens* to transform a potato-derived gene *StnsLTP*1 into potato (*Solanum tuberosum* cv. Desiree) to make it tolerant to abiotic stresses. Transgenic potato lines reduced membrane lipid peroxidation activity and H_2O_2 content under stress, enhancing cell membrane integrity. Transgenic potato plants also had increased antioxidant enzyme activity, ascorbate accumulation, and stress-related gene upregulation, including *StAPX*, *StCAT*, *StSOD*, etc.

Subramanyam *et al*. (2011) could successfully improve the tolerance of chilli pepper (*Capsicum annum* L. cv. Aiswarya 2103) plants by the ectopic expression of tobacco osmotin gene via *Agrobacterium tumefaciens*-mediated gene transfer technique. T_2 generation of transgenic pepper plants revealed enhanced levels of chlorophyll, proline, glycine betaine, ascorbate peroxidase (APX), superoxide dismutase (SOD), glutathione reductase (GR) and relative water content (RWC) in biochemical analysis and survived in salinity level up to 300 mM NaCl concentration. Kaur *et al*. (2010) inserted a fruit-specific expansion gene, *LeEXP*1, into tomato cv. Pusa Uphar. The force required to rupture the fruit pericarp was higher in *LeEXP*1-overexpressed plants than in non-transgenic plants, and fruits were redder at different ripening stages.

Tomato Cv. H-88 was transformed with genes *AtDREB1* and BcZAT12 to generate double transgenics tomato plants. The developed transgenics showed improved tolerance against drought stress. Double transgenic plants showed increased activity of antioxidant enzymes, like catalase (CAT), superoxide dismutase (SOD), glutathione reductase (GR), ascorbate peroxidase (APX), dehydroascorbate reductase (DHAR), mono dehydroascorbate reductase (MDHAR) and guaiacol peroxidase (POD), and accumulation of non-enzymatic antioxidants like ascorbic acid, glutathione as compared to non-transgenic and single transgenic (Krishna *et al*., 2021).

Bio-fortification in vegetables

Vitamins and micronutrients are vital element for human growth and development and deficiency of these components can cause “hidden hunger.” Conventional way to deal with the problem of hidden hunger are supplementation or food fortification, but these methods have shortcoming of significant recurring cost and less extent of reach to rural areas. Vegetables are the cheapest and most readily available source of energy and nutrition. Vegetables, except for a few starchy ones, are rich in micronutrients compared to staple foods such as cereals (Singh *et al*., 2022). The vegetables are inherently rich in minerals, antioxidants, and vitamins. These crops offer a wide range of variability in terms of the number of choices of crops to be grown across the seasons. Leafy vegetables are found to be one of the richest sources of iron and calcium. Coloured vegetables offer a wide choice to consumers along with anthocyanins, betalains and β-carotene. Demand for the natural products has led to the emergence of the science of biofortification by various means *i.e.* metabolic engineering (transgenic), agronomical biofortification, and genetic biofortification. Biofortification is the process of adding nutritional value to the crop. Biofortification is an economical and sustainable mode to improve the intake of vitamin and *mineral*, as micronutrients are breed into the crops.

Broccoli, spinach, carrot, squash, sweet potato, and pumpkin are rich in provitamin A carotenoids. Low levels of β-carotene were found in commonly grown cauliflower. A new orange cauliflower variety with 8-20 ppm β-carotene was developed through pure line selection (Kalia *et al*., 2018). The Pusa Rudhira carrot variety contains β-carotene at 7.60 mg/100 g, β-carotene at 4.92 mg/100 g, and lycopene at 6.70 mg/100 g root. The pure line selection method was used to breed the sweet potato variety Bhu Sona. This variety has higher β-carotene (14 mg/100 g) content than other potato cultivars (Yadava *et al*. 2017). The 10-14 mg/100 FW carotene Sree Kanaka sweet potato was also released for cultivation. Another sweet potato Sree Vardhini rich with carotene (1200 IU carotene/100g). Sree Bhadra sweet potatoes have 972 IU/100g carotene and pink skin and flesh. Sree Rathna sweet potatoes, with purple skin and orange flesh, are now ready for cultivation. This variety contains 3500 IU/100g of carotene.

Table 6: Bio-fortified vegetable crops in India

Crop	Varieties	Characters	Year
Sweet potato	Sree Kanaka	Dark orange flesh colour, high beta carotene (ß-carotene 9-10 mg/100 g FW) content as compared to 2.0-3.0 mg/100 g β- carotene in popular varieties.	2017
	Bhu Sona	High β-carotene (14.0 mg/100 g) content	2017
	Bhu Krishna	High anthocyanin (90.0 mg/100g) content in comparison to popular varieties which have negligible anthocyanin content	2017
Potato	Kufri Neelkanth	Rich in anthocyanin (1.0 ppm) in comparison to negligible content in popular varieties	2020
	Kufri Manik	Rich in anthocyanin (0.68 ppm) in comparison to negligible content in popular varieties	2020
Okra	Kashi Lalima	Rich in anthocyanin and phenolics.	2019
Greater Yam	Sree Neelima	Rich in anthocyanin (50.0 mg/100g), crude protein (15.4 %) and zinc (49.8 ppm) in comparison to negligible anthocyanin, 2.7 % crude protein and 22-32 ppm zinc in popular varieties	2020
	Da 340	Rich in anthocyanin (141.4 mg/100g), iron (136.2 ppm) and calcium (1890 ppm) in comparison to negligible anthocyanin, 70-120 ppm iron and 800-1200 ppm calcium in popular varieties	2020
Carrot	Pusa Rudhira	Has higher level of Carotenoid (7.14mg) and Phenol (45.15mg)/ 100g	2008
	Pusa Asita	Rich source of anthocyanin.	2008
	Kashi Krishna	A black carrot variety is rich source of anthocyanin (285 mg/100 g FW carrot), 737 phenolics, and antioxidants.	2019
Radish	Pusa Gulabi	First Pink fleshed variety High in total caroteniods, anthocyanin and ascorbic acid content.	2013
	Pusa Jamuni	first purple fleshed nutritionally rich variety high in anthocyanin & ascorbic acid content.	2012
	Kashi Lohit	Red colour root and rich source of 740 antioxidants specially anthocyanin 80–100% higher than white radish	2019
Cauliflower	Pusa Beta Kesari 1	Contains high β-carotene (8.0-10.0 ppm) in comparison to negligible β-carotene content in popular varieties	2015
Cabbage	Kinner Red	Anthocyanin rich cultivar	2016
Brinjal	Pusa Safed Baigan 1	It has high total phenol content (31.21 mg GAE/100G) with high antioxidant activity.	2018
Soybean	NRC – 127	Free from Kuntiz Trypsin Inhibitor (30-40 mg/g of seed meal in popular varieties)	2018
	NRC – 132	Free from Lipooxigenase -2	2021
	NRC – 147	High Oleic acid (42%) as compare to popular cultivars (25%).	2021
Cowpea	Pant Lobia-1	high iron and zinc fortified variety 82 ppm Fe and 40ppm Zn	2008
	Pant Lobia-2	high iron and zinc fortified variety 100 ppm Fe and 37ppm Zn	2010
Poi/ Indian Spinach	Kashi Poi -3	excellent source of Carotenoids 635.9mg/100g FW with lower oxalate content (522.3 mg/100g FW)	2019
French bean	Kashi Baingani	Purple-coloured 750 French bean variety has high antioxidants and rich in anthocyanin	2020
Amaranth	Pusa Lal Chaulai	Red pigmented cultivar developed at IARI, yield 45-49 t/ha in 4 harvests	1991

Several anthocyanin rich varieties have been developed in vegetable crops. Anthocyanin rich Bhu Krishna sweet potatoes rich in anthocyanin (90 mg/100 g) has been released (Yadava *et al*. 2017). Kufri Neelkanth, the first purple-colored indigenous speciality potato variety, rich in antioxidants (anthocyanins > 100μg/100 g and carotenoids ~ 200μg/100 g). Anthocyanin rich black carrot variety Kashi Krishna (285 mg/100 g FW carrot) and Pusa Asita 520mg/100g has been released (Singh *et al*. 2019). Kashi Lohit, a red-root radish variety with 80-100% more anthocyanin than white radish, Pusa Jamuni and Pusa Gulabi are other radish varieties with anthocyanin and antioxidants (Singh *et al*. 2019). Kashi Lalima, a red/purple okra (*Abelmoschus esculentus* L.), has a high anthocyanin content (*Karmakar et al*., 2022). French bean variety Kashi Baingani rich in antioxidants and anthocyanin recommended for cultivation.

Indian spinach (*Basella alba* L.) and amaranth (*Amaranthus tricolour* L.) have high betalain content in leaves, stems, and fruits (Sagar *et al*., 2022). These two vegetables dominate national kitchen gardens. Many Amaranth varieties (Sagar *et al*., 2021a) have been released, but few are available in Indian spinach (Sagar *et al*., 2021b). Biofortified varieties of few vegetables crops has been developed in India are given in Table 5.

Pests and disease management

Cultivation of vegetable crops are suffered by several biotic stresses such as insect pests, pathogens and nematodes. It is highly essential to minimize the impact of pests and diseases in vegetable crops in order to obtain the economic yield by the resource poor farmers. In vegetables, insect pests and diseases cause huge loss as reflected in the table 6. If we could alleviate the losses due to plant diseases, we would be able to produce roughly 20% more food enough to feed predicted world population 9.1 billion by 2050 (Maxmen, 2013). In recent past, several insect pests and diseases are emerging into a major threat for the vegetable production system which were not previously reported in India. For example, tomato pin worm (*Tuta absoluta*) is one of the global destructive invasive pests of tomato with a potential to cause 100% yield loss was first time documented during 2014 in Maharashtra. From then, it has spread to different parts of the country including hilly regions (Sharma and Gavkare, 2017). Likewise, poleroviruses and criniviruses causing yellowing disease in cucurbits becomes a major constraint for its cultivation since 2018 (Nagendran *et al*., 2023; Krishnan *et al*., 2022; Kumari *et al*., 2021).

For the management of these biotic stresses, farmers are relying on the chemical pesticides and fungicides. Ill effects of chemical insecticides are well known and therefore, researches are focusing on the management options with reduced application of chemicals in the vegetable crops. Crop protection measures include integrating different components of cultural, host plant resistance, chemical and biological measures. Several studies successfully demonstrated the integrated pest management (IPM) and Integrated disease management (IDM) modules for the management of pest and diseases of vegetable crops, respectively (Table 7). Integrated management of pests and diseases is a systematic approach for the control that syndicates biological, cultural, and other alternatives to chemicals with the sensible use of pesticides. The main aim of IPM is to maintain pest and disease levels below economic threshold levels through minimizing the use of chemical pesticides which pose harmful effects on human health and environment. IPM is a constantly evolving and dynamic system in which all the suitable control strategies are combined into a holistic management module along with the forecasting information for the use of farmer (Kumar *et al*., 2022).

Activities of cultural practices includes deep summer ploughing, use of resistant cultivars, adjustment in the time of planting or sowing, intercropping with barrier crops, use of trap crops, mulching with black silver polythene sheet, etc. Similarly, the mechanical activities such as hand picking of larvae, installation of suction traps, light traps, yellow sticky and pheromone traps, trenching the field, proper disposal of infected plant parts, etc. In the management of insect pests, biocontrol agents such as predators, parasitoids, bacterial bioagents, fungal bioagents (including entomopathogenic fungus), viral bioagents and nematode bioagents (entomopathogenic nematodes) (Kumar *et al*., 2022) were explored (Table 8).

Pathogens of vegetable crops including fungus, bacteria and viruses were demonstrated to be effectively managed by several biocontrol agents either through direct action (antibiosis) or indirect action (induced systemic resistance and growth promotion). Elanchezhiyan *et al*. (2018) and Manikandan *et al*. (2010) have efficiently demonstrated the management of Fusarium wilt in tomato caused by the *Fusarium oxysporum* f. sp. *lycospersici* using the *Bacillus amyloliquefaciens* (FZB 24) and *Pseudomonas fluorescens* (PF1). Both the bioagents showed the growth promotional activity, increased activity of resistance mechanism in tomato crop ultimately resulted in the enhanced yield with reduced disease incidence. Severity of bud necrosis disease caused by the tospoviruses in tomato and watermelon has been found to be reduced upon treatment with the bioagents such as *Pseudomonas fluorescens* (Thiribhuvanamala *et al.*, 2013; Kandan *et al.*, 2005; Priyanka *et al.*, 2019). Culture filtrate of *Ganoderma lucidum* reduced the lesion numbers and inhibited the virus population build-up in tomato (Sangeetha *et al.*, 2020). With the help of *Trichoderma* isolates (Nagendran *et al.*, 2016) has managed the wilt disease incidence in the chilli crop. Soil borne bacterial pathogen *Ralstonia solanacearum* causing wilt disease in brinjal crop has been suppressed by the *Bacillus* strains-based consortia upon applied with FYM in field conditions and enhanced yield (Sakthivel *et al.*, 2023). Similarly, several other works have demonstrated the management of diseases in vegetable crops through biological means.

Due to the instant result and easy availability of chemical pesticides, farmers prefer to use the chemicals for the pest and diseases management in

Table 7: Yield loss in vegetable crops due to different pests and diseases

Crop	Pest/disease	Yield loss (%)	References
Tomato	Fruit borer (*Helicoverpa armigera*)	24-65	Rai *et al.* (2014)
Chilli	Thrips (*Scirtothrips dorsalis*)	12-90	
Chilli	Mites (*Polyphagotarsonemus latus*)	34	
Brinjal	Fruit and shoot borer (*Leucinodes orbonalis*)	11-93	
Okra	Fruit borer (*H. armigera*)	22	
Okra	Leafhopper (*Amrasca biguttula biguttula*)	54-66	
Okra	Whitefly (*Bemisia tabaci*)	54	
Okra	Shoot and fruit borer (*Earias vittella*)	23-54	
Cabbage	Diamond back moth (*Plutella xylostella*)	17-99	
Cabbage	Caterpillar (*Pieris brassicae*)	69	
Cabbage	Leaf webber (*Crocidolomia binotalis*)	28-51	
Cabbage	Cabbage borer (*Hellula undalis*)	30-58	
Bitter gourd	Fruit fly (*Bactrocera cucurbitae*)	60-80	
Cucumber	Fruit fly (*Bactrocera cucurbitae*)	20-39	
Tomato	Root knot nematode (*Meloidogyne incognita*)	27.21	Gowda *et al.* (2019)
Brinjal	Root knot nematode (*Meloidogyne incognita*)	16.67	
Chilli	Root knot nematode (*M. incognita*)	12.85	
Okra	Root knot nematode (*M. incognita*)	14.10	
Cucurbits	Root knot nematode (*M. incognita*)	18.20	
Carrot	Root knot nematode (*M. incognita*)	10	
Tomato	Early blight (*Alternaria solani*)	36-47.9	Saha and Das, (2012)
Tomato	Septoria leaf spot (*Septoria lycopersici)*	50	Ferrandino and Elmer (1992)
Tomato	Fusarial wilt (*Fusarium oxysporum* f.sp. *lycopersici*)	60-70	Ravindra *et al.* (2015)
Tomato	Late blight (*Phytophthora infestans*)	12.84 - 79.47	Sandeep Kumar *et al.* (2022)
Brinjal	*Phomopsis vexans*	50	Rohini *et al.* (2023)
Chilli	Fusarium wilt	30-40	Wani and Najar (2012)
Cucurbits	Powdery mildew	50-70	Sitterly (1972)
Cowpea	Cercospora leaf spot	36 – 42	Schneider *et al.* (1976)
Tomato	Bacterial wilt	10.8 – 92.62	Ramkishun, (1987; Mishra *et al.* (1995)
Brinjal	Bacerial wilt	11.67 - 96.67	Bainsla *et al.* (2016)

Table 7 continued

Crop	Pest/disease	Yield loss (%)	References
Tomato	Leaf curl virus (Begomovirus)	>70	Nagendran *et al.* (2017a)
Chilli	Leaf curl virus (Begomovirus)	>80	
Okra	yellow vein mosaic (Begomovirus)	>50-9	
Okra	Enation leaf curl (Begomovirus)	30-100	
Tomato	Bud necrosis (Groundnut bud necrosis virus)	80-100	
Watermelon	Bud necrosis (Watermelon bud necrosis virus)	60-100	
Cucurbits	Green mottle mosaic (Cucumber green mottle mosaic virus)	10-15	
Watermelon	Green mottle mosaic (Tobamovirus)	11.4-47.6	
Cucurbits	Yellow mosaic virus (Potyvirus)	upto 95	
Cowpea	Mosaic (Cucumovirus)	14	
Tomato	Mosaic (Cucumovirus)	25	
Chayote	Mosaic (Tomato leaf curl New Delhi virus)	>60	Nagendran *et al.* (2017b)

Reference: Nagendran *et al.*, (2017b)

Table 8: Management modules developed against the pests and diseases of vegetables in India

Crop	Method	Target pests/ Diseases	References
Bitter gourd	Integrated	Fruit flies, cucumber moth, whiteflies and downy mildew	Halder *et al.* (2018)
Bottle gourd	Integrated	Fruit flies, plume moth, mirid bug, whiteflies and downy mildew	Halder et al. (2020)
Brinjal	Integrated	Shoot and fruit borer, whiteflies, hoppers, Phomopsis blight, Sclerotinia white rot and little leaf	Halder *et al.* (2022)
Bitter gourd	Integrated	downy mildew and mosaic disease	Nagendran *et al.* 2020a
Chilli	Integrated	Leaf curl disease	Nagendran *et al.* (2020b)
Tomato	Integrated	Fruit borer, leaf miner, leaf curl virus	Gajanana *et al.* (2006)
Watermelon	Integrated	Bud necrosis disease	Priyanka *et al.* (2019)
Cabbage	Integrated	Aphid and Diamond back moth	Tulsi *et al.* 2017
Okra	Integrated	Aphids, whiteflies, leafhoppers, leaf miners, nematodes, fruit borer, yellow vein mosaic virus and powdery mildew	Mohankumar *et al.* (2016)
Cucumber	Integrated	Nematode, mite, damping off, fusarial wilt	Sabir *et al.* (2011)
Chilli	Integrated	*Spodoptera litura* and die back	Reddy *et al.* (2011)

Table 9: List of bioagents used in the management of insect pest

Nature of bioagents	Bioagent	Target pests
Predators	Lady bird beetle (*Rodolia cardinalis* and *Coccinella* sp.)	Aphids, mealybugs and spider mites
Predators	Syrphid fly larvae	Aphids and mealybugs
Predators	Green lacewing larvae (*Chrysoperla carnea*)	Aphids, spider mites, thrips, leafhopper nymphs, and small caterpillar larvae
Predators	Damsel bug	Aphids, leafhoppers, mites and caterpillars
Predators (Bugs)	*Orius maxidentex* and *O. tantillus*	Thrips
Predators (mites)	*Amblyseius cucumeris, A. swirski* and *Stratiolaelaps scimitus*	Thrips
Parasitoids	*Trichogramma* wasp (Egg parasitoids)	Cutworms, corn borers, corn earworms, armyworms, codling moths, and cabbage moths

Table 9 continued

Nature of bioagents	Bioagent	Target pests
Parasitoids	*T. brasilensis*	Fruit borer
Parasitoids	*Cotesia plutellae, C. glomeratus*	Diamond back moth
Parasitoids	*C. plutellae*	*H. armigera*
Parasitoids	*Campoletus chloridae*	*H. armigera*
Parasitoids	*Telenomus remus*	*Spodoptera litura*
Parasitoids	*Phryxe vulgaris*	Caterpillars in cabbage and cauliflower
Parasitoids	*Ceranisus* sp. and *Thripobius* sp	Thrips
Entomopathogenic nematodes (EPN)	*Steinernema feltiae*	Thrips
Entomopathogenic fungi (EPF)	*Metarhizium anisopliae* and	Thrips, whitefly, Earias sp. brinjal fruit and shoot borer
Entomopathogenic fungi (EPF)	*Beauveria bassiana*	Thrips, whitefly, *Earias* sp., brinjal fruit and shoot borer
Entomopathogenic fungi (EPF)	*Nomuraea relyie*	*Earias* sp., brinjal fruit and shoot borer
Bacterial bioagent	*B. thuringienesis*	*L. orbonalis*, *Earias* sp., *Helicoverpa*, tomato fruit borer, diamond back moth
Viral bioagent	HNPV	Tomato fruit borer
Viral bioagent	SNPV	Tobacco caterpillar

vegetable crops. Nearly, 13-14% of the total pesticides are consumed in the vegetable crops against the 2.6% of cropped area of vegetables in India (Kumar *et al.*, 2022). Since, indiscriminate use of chemical is not desirable in vegetable crops, IPM strategy will help to attain the goal of safe vegetable cultivation and consumption.

Conclusion

Vegetable crop improvement through plant breeding is critical for sustainable production of vegetable crops that contribute to healthful diets and enhanced quality of life for people around the world. Integrated management of pests and disease is a strategy, based on a systems approach that looks at the whole ecosystem and therefore, implementing management programme, growers should select ways to reduce overall pest and pesticide load and ensure that the management options are compatible with their other crop management strategies. Policymakers and investors have to turn their attention to enhanced funding for the vegetable sector, allowing farmers to compete with their products on a world market. Only then will the silent vegetable revolution currently underway benefiting poor farmers, consumers and industries.

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