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REVIEW ARTICLE

Vegetable Breeding: Status and Strategies

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Abstract

Vegetable crops are a crucial component of the global food supply chain, with a vast range of variety, flavor profiles, and nutritional value, making them a staple meal of many cultures globally. India is the second-largest producer of vegetables in the world, commercially growing over 60 different types of vegetables for fresh consumption. Breeding vegetables is a challenging and complex process due to location-specific demand for color, shape, nutrition, taste, harvest stage of product, quality issues, and demand for year-round supply of fresh product. A combination of specialized knowledge, use of cutting-edge technology, availability of genetic resources and sufficient capital to effectively utilize these resources is a prerequisite for more innovative breeding. The present review summarizes the status of vegetable cultivation, common breeding methods, targeted traits, wild genetic resources, the modern breeding approaches, use of intelligence and machine learning approaches for improvement in vegetable crops for yield, quality, adaptability, safe product and consumers' expectation.

Keywords: Vegetable, Breeding, Genomics, Resistance, Biotic, Abiotic, Quality.

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Introduction

The term 'vegetable' refers to the edible parts of the plants which are usually their leaves, roots, fruits, or seeds and can be consumed either cooked or raw. Vegetables are a vital element of a human healthy diet since they provide essential nutrients including vitamins (C, A, B_1, B_6, B_9 and E), minerals (iron, zinc, selenium, iodine, and potassium), dietary fiber and phytochemicals (Silva-Dias, 2010). Dietary fiber-rich vegetables improve digestion, while also lowering the risk of obesity, diabetes, high cholesterol and heart disease (Behera *et al.*, 2021). According to Rimm (1996), eating more vegetables lowers the risk of death by 20%, cardiovascular disease by 30% and cancer by 15%. A world vegetable survey showed that around 392 vegetable crops are cultivated worldwide, representing 70 families and 225 genera (Kays and Silva-Dias, 1995). Over 97 species of higher plants are being cultivated and consumed as vegetables in India (Nayar *et al.*, 2003) and with close to 60 being grown commercially for fresh consumption (Kochhar, 1998). These crops belong to 20 different families such as Cucurbitaceae (25 crops), Fabaceae (16 crops), Brassicaceae (12 crops) and Solanaceae (6 crops). The world's total vegetable production is estimated to be 1,155 mt in 2021, with China being at top position with a production of 600 mt which 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 (https://www.statista.com). As far as India is concerned, it is the largest producer of ginger (2.23 mt) and okra (6.47 mt) in the world, while ranking 2nd in potato (54.23 mt), dry onion (26.64 mt)), cauliflower and broccoli (9.25 mt), brinjal (12.87 mt) and cabbage (9.56 mt) (FAO, 2021).

Vegetable breeding is more complex and challenging compared with grain crops where grain is the primary product, however in vegetables different plant parts are of economic importance such as leaves, stems, roots, flowers, and fruits. Moreover, the location-specific demand for color, shape, nutrition, taste, product maturity stage, quality issues, year-round supply and many more makes breeding for specific traits more complex. The vegetable is a broad segmented area of research, for example, in Brinjal, there are more than 42 types of segments based on the morphological character of the fruit is present (Ghuge and Mirza, 2021). With its prime goal to improve the quality and quantity of total production, vegetable breeding is the process of developing new varieties of vegetables that have improved traits of economic importance, namely increased yield, disease and insect-pest resistance, and improved nutritional content. Moreover, consumers' demand for safe and healthy food, urbanization and the emergence of supermarket chains are all driving changes worldwide. These modifications have increased the diversity and availability of vegetables as well as improved production and delivery systems. In addition, there is a growing demand for veggies that are easier to transport and have longer shelf-life.

Conventional Breeding Methods and Targeted Traits

The process of vegetable breeding began to evolve in the 18th century with the work of plant breeders such as Gregor

Table 1: Common breeding methods and targeted traits in some of the vegetable crops

Crop	*Common breeding methods*	*Biotic and abiotic stress resistance*	*Yield, fruit quality and other traits*
Tomato	Hybrid breeding, Introduction, Pure line selection, Pedigree method, Bulk method, Single seed descent, Backcrossing	*Biotic: Fusarium* wilt, *Verticillium* wilt, late blight, early blight, Septoria leaf spot, anthracnose, bacterial wilt, bacterial canker, tomato yellow leaf curl virus, root knot nematode (RKN), fruit borer, white fly *Abiotic:* Heat, drought, cold/ chilling, salt, herbicide	Earliness, yield, indeterminate cultivars for greenhouse production *Fresh tomato:* Large round fruit with good firmness, shelf life, uniform fruit size, shape, and free from external blemishes *Processing tomato:* Dark red, pH < 4.4, high TSS (4.5-7) and high alcohol insoluble solids (AIS)
Brinjal	Hybrid breeding, Introduction, Pure line selection, Pedigree method, Bulk method, Single seed descent, Backcrossing	*Biotic:* Bacterial wilt, phomopsis blight, little leaf, RKN, shoot and fruit borer, jassids and epilachna beetle *Abiotic:* Heat	High yield, earliness, fruit shape, size, color, low solanine content Upright plant free from lodging, less deeded, soft flesh
Chilli and Bell pepper	Hybrid breeding, Introduction, Pure line selection, Pedigree method, Back cross method	*Biotic:* Fruit rot, Cercospora leaf spot, powdery mildew, bacterial leaf spot, Phytophthora root rot, RKN, TMV, thripts, mites, aphid, fruit borer *Abiotic:* Heat, drought, salinity	*Bell pepper*: Oblate or round fruit, pleasing flavour, high sugar/acid ratio, high pigment content and vitamin C *Chilli:* High yield, earliness, long fruit, high capsaicin, high oleoresins
Okra	Hybrid breeding, Mass selection, Pedigree method, Mutation	*Biotic:* YVMV, fusarium wilt, Cercospora leaf spot, fruit rot, fruit and shoot borer, jassids and white fly *Abiotic:* Low temperature, salinity	Dark green, tender, thin, medium long, free from trichomes, smooth, 4-5 ridges fruits; early, prolonged harvest, short internode, optimum seed setting ability
Vegetable pea	Pure line selection, Pedigree method, Bulk method, Introduction, Single seed descent, Back cross method, Mutation breeding	*Biotic:* Downy mildew, powdery mildew, rust, wilt, leaf miner, aphids, pod-borer and pea stem fly *Abiotic:* Frost	Log attractive green pod with more seeds/pod; sweet, high shelling percentage, suitability to freezing and canning
French bean	Introduction, Pure line selection, Pedigree method, Single plant selection	*Biotic:* Bean common mosaic virus, bean yellow mosaic virus, curly top, halo blight, common blight, bacterial wilt, brown spot, root rot, white mold, anthracnose, angular leaf spot, rust, powdery mildew, pod borer, pea stem fly. *Abiotic:* Drought, heat, cold	Non-stringy, tender, fleshy, free from inter-locular spaces and long pod; slow seed development, early, photo-insensitivity, Wider adaptability
Cowpea	Pedigree method, Pure line selection; Back cross method, Mutation breeding	*Biotic:* Anthracnose, Cercospora leaf spot, powdery mildew, Fusarium wilt, Ascochyta blight, bacterial blight, bacterial postules, cow pea yellow mosaic virus, hairy caterpillar, leaf hopper, aphids, thrips, pod borer, pod sucking insects *Abiotic:* Drought, heat, cold	Early, erect and determinate plant type for vegetable and seed type cultivar; spreading plant for fodder type; photo-insensitive, short tender pods for whole pod processing, long tender and stringless pod for fresh consumption

Cauliflower	Hybrid breeding, Population improvement, Backcross method, DH	*Biotic:* Black rot, sclerotinia rot, alternaria blight, Erwinia rot *Abiotic:* Heat tolerance	Non-ricy, compact and bract free protected curd with retentive white color; better seeding ability; robust CMS lines, DH inbreds
Cabbage	Hybrid breeding, Population improvement, Backcross method, DH	*Biotic:* Black rot, cabbage yellow, cabbage butter fly, aphids and diamond back moth *Abiotic:* High temperature	Longer field staying capacity; narrow, short and soft core; compact and round head, short stem, robust CMS lines, DH inbreds
Radish	Hybrid breeding, Population improvement, Backcross method, DH	*Biotic:* Alternaria blight, white rust, radish mosaic virus, flea beetle, painted bug, aphids *Abiotic:* Heat, drought, rain	Early, wide adaptability, smooth root, delayed pithiness and bolting, pungency as per consumers choice
Carrot	Hybrid breeding, Population improvement, Backcross method, DH	*Biotic:* Alternaria blight, Cercospora leaf spot *Abiotic:*	Dark root color; blunt, smooth and scar-free root; uniform root shape and size; narrow, short and self-colored core; high sugar and dry matter content; delayed-bolting; Early
Turnip	Hybrid breeding, Population improvement, Backcross method, DH	*Biotic:* Club root, powdery mildew, turnip mosaic virus, white rust, phyllody, cabbage root fly, and turnip root fly	Early, uniform root color, smooth root, delayed-bolting, uniform root shape and size, high dry matter
Garden beet	Hybrid breeding, Introduction, Mass selection	*Biotic:* Downy mildew, powdery mildew	Early, uniform root color, smooth root, delayed-bolting, uniform root shape and size, monogerm seed
Onion	Population improvement, Hybrid breeding, Backcross method	*Biotic:* Purple blotch, basal root, stem psyllium blight, bacterial storage rot, thrips *Abiotic:* Drought, heat, salinity	Longer dormancy and storage life, thin necked bulb, uniform bulb color, size and shape, high TSS, pungent, wider adaptability
Cucumber	Hybrid breeding, Population improvement, Backcross method	*Biotic:* Powdery mildew, downy mildew, anthracnose, cucumber mosaic virus and fruit fly *Abiotic:* drought, cold, salinity	Early, high female to male sex ratio, attractive and smooth fruit surface, long and cylindrical fruit shape, free from bitterness, crook neck and carpel separation, less and soft seeded
Muskmelon	Controlled inbreeding, Pedigree method, Backcross method, Hybrid breeding	*Biotic:* Powdery mildew, downy mildew, virus, red pumpkin beetle, fruit fly and aphids *Abiotic:* drought, cold, salinity	Attractive round/spherical fruit shape, thick flesh with attractive color, small seed cavity, sweet, juicy, musky flavorsome fruits, high TSS (> 10%), tough netted fruit skin
Watermelon	Pedigree method, Backcross method, Hybrid breeding	*Biotic:* Virus, Fusarium wilt, anthracnose, powdery mildew, cucumber aphid, fruit fly, cucumber beetle, red pumpkin beetle *Abiotic:* drought, cold, salinity	Earliness, pistillate flowers at lower node number Tough-skinned fruits for longer distance transport, TSS (> 10%) Fruits with smaller and fewer seeds with attractive deep red flesh Firm flesh, intermediate fruit shape between typical long and round, high yield
Squash and pumpkin	Inbreeding, Hybrid breeding	*Biotic:* Powdery mildew, viruses and red pumpkin beetle *Abiotic:* drought, cold, salinity	High fruit yield, early, first pistillate flower at early node number, high female to male ratio Yellow and mottled skin of fruit, non-ridge fruit surface, thick fruit flesh and small seed cavity Round/oblong/flat round fruit shape, orange flesh color, rich in beta-carotene
Bottle gourd	Inbreeding, Hybrid breeding	*Biotic:* Powdery mildew, red pumpkin beetle and fruit fly *Abiotic:* drought, cold, salinity	High yield, greater fruit number, fruit weight Earliness, pistillate flower at early nod enumber, high female to male ratio Round, long and club shaped fruit, sparse hairs persisting on skin Non-fibrous flesh at edible stage, non-bitter fruit, attractive green fruit

Bitter gourd	Inbreeding, Pureline selection, Hybrid breeding	*Biotic:* Red pumpkin beetle and fruit fly *Abiotic:* drought, cold, salinity	Early fruiting, high female:male ratio, whitish green to glossy green fruit color Less ridge fruit surface, thick fruits for stuffing, fruit size (small: 7.5-10 cm, medium: 10-15 cm, long: 15-20 cm, xtra long: 20-40 cm) Immature seeds for longer period during green edible stage, high-yield
Ridge gourd and Sponge gourd	Inbreeding, Pureline selection, Hybrid breeding	*Biotic:* Powdery mildew, downy mildew, fruit fly, beetle *Abiotic:* drought, cold, salinity	Earliness, high female to male sex ratio, uniform thick cylindrical fruits free from bitterness Tender, non-fibrous fruits for a longer time, high fruit yield (number and weight)
Potato	Clonal selection	*Biotic:* Late blight, potato viruses (PVX, PVY, PLRV etc.), common scab, wart, nematode, bacterial wilt, storage rot, aphids, white fly, potato tuber moth *Abiotic:* Heat, drought, salinity, cold	High tuber yield, earliness, photoperiod insensitive, better-keeping quality Quality tubers: round, smooth skin, medium size, shallow eyes, free from greening, high vitamin C), high dry matter for processing purposes (French fries, chips etc), low sugar

Table 2: Status of cultivated and wild germplasm of vegetable crops at ICAR-NBPGR (Pandey *et al.*, 2019)

Vegetables	*Approx. of germplasm holding*
Solanaceous vegetables	14646
Cucurbitaceous vegetables	16750
Leguminous vegetables	5435
Okra	4235
Brassica and Cole crops	1776
Bulbous vegetables	4769
Root vegetables	8298
Leafy vegetables	2084

Mendel who developed the basic principles of inheritance and genetic variation. The early plant breeding efforts were focused on improving crop yield. During the 20th century, vegetable breeding advanced significantly with the introduction of new technologies such as hybridization, backcross breeding, heterosis breeding, mutation breeding and genetic engineering. However, conventional breeding has now been assisted by genetic and molecular techniques to develop improved varieties with traits of specialty, quality and tolerance. The common breeding goals for all vegetable crops are higher yield, earliness, wider adaptability, tolerance to stresses and better quality (Behera *et al.*, 2023). To date, a total of 553 vegetable varieties in 30 vegetable crops have been recommended through AICRP-VC for cultivation in India for various agro-climatic zones, including 329 OP varieties, 168 hybrids and 56 resistant to different biotic and abiotic stresses (Behera *et al.*, 2021). The common breeding methods for targeted traits in major vegetable crops are summarized (Table 1).

Genetic Resources: The Current Status

Genetic diversity is a fundamental requirement for successful plant breeding programs, as it provides the necessary variation upon which selection can be based. The genetic diversity of vegetable cultivars, however, has decreased significantly over the past seven decades due to various factors, including the influence of commercial markets and societal forces. The decline in genetic diversity is primarily attributed to breeding techniques that favor uniformity, leading to the widespread cultivation of improved and hybrid vegetable cultivars with limited genetic diversity. Moreover, the professionalization of the industry and commercial market demands have contributed to a reduction in the number of farmers storing seeds, creating a new threat to genetic diversity conservation efforts. ICAR-NBPGR is the national nodal agency for crop genetic resource conservation, including vegetable crops followed by various breeding organizations. About 58000 accessions of vegetable crops have been conserved with ICAR-NBPGR national gene bank (NBPGR Annual Report, 2021; Table 2). More than 75% of this diversity is of exotic origin. Additionally, ICAR-IIHR and ICAR-IIVR hold around 9000 and 6500 germplasm, respectively of various vegetable crops under active collection (Behera *et al.*, 2021). India is also fortunate to hold genetic diversity for some unique traits in vegetable crops that are found nowhere in the world as stated by Tiwari *et al.* (2023). Furthermore, it is important to determine how well novel variations can be used to aid in the development of new varieties capable of responding to new environmental challenges (Devi *et al.*, 2023).

Wild relatives for genetic improvement

Vegetable wild relatives are the wild, progenitors and closely related species have played a crucial role in providing beneficial traits for vegetable improvement in terms of ideotype, agronomic, nutritional and stresses (Sharma *et al.*, 2023). Among the different vegetable crops, potato (*Solanum tuberosum*) stands out as particularly vulnerable to biotic and abiotic stresses due to its genetic uniformity. Late blight is a devastating disease caused by the *Phytophthora infestans* that affects potato production globally. The impact of this disease is exemplified by the Irish potato famine in the mid-nineteenth century. Over the years, efforts have been made to develop resistant potato cultivars successfully through the introgression of resistance genes from wild and cultivated species such as *S. demissum*, S. *stoloniferum*, S. *tuberosum* ssp. *andigena*, and *S. phureja*. Additionally, diploid wild potato species like *Solanum pinnatisectum*, *S. etuberosum*, *S. cardiphyllum*, *S. acaule*, *S. brachistotrichum*, *S. jamesii*, *S. polyadenium* and *S. stoloniferum* possess many novel genes for late blight resistance, virus resistance, high dry matter content, etc. Tomato breeding programs have also utilized wild tomato species to develop cultivars with improved traits. More than 40 resistance genes have been derived from species such as *S. peruviannum*, *Solanum pennellii* var. *pennellii, S. cheesmanii* and *S. pimpinellifolium*. These species have been used to improve many desirable traits namely soluble solid content, fruit color, and adaptation to harvesting, resulting in the development of improved tomato cultivars (Rick and Chetelat, 1995). In case of brinjal (*Solanum melongena)*, a wild relative *Solanum viarum* is highly resistant to shoot and fruit borer (Pugalendhi *et al*., 2010), and wild Andaman species *S. torvum* exhibit recessive gene action for resistance to bacterial wilt (Bainsla *et al*., 2016). Certain wild species of okra *A. manihot*, *A. tuberculatus* and *A. moschatus* are reported to have resistance genes for yellow vein mosaic disease (YVMD), shoot and fruit borer, and leaf hopper, respectively (Rana *et al*., 1991). Further *A. caillei*, *A. manihot*, *A. moschatus* are resistant to YVMD, while *A. caillei*, *A. manihot*, *A.*

Table 3: Vegetable wild relatives for biotic and abiotic stresses

Crop	*Wild species*	*Trait*	*Reference*
Tomato	*Solanum pimpinellifolium L.*	Fusarium wilt, late blight, early blight, Bacterial wilt, Bacterial spot, Gray leaf spot, leaf mould, TSWV bacterial speck and bacterial canker	Khazaei and Madduri *et al.* (2022)
	S. habrochaites S. Knapp and D. M. Spooner	Late blight, Leaf mold, TYLCV, ToMV, Powdery mildew, Bacterial canker, gray mould	
	S. peruvianum L.	TYLCV, TSWV, Root-knot Nematodes, ToMV, Verticillium wilt, Fusarium crown	
	S. chilense (Dunal) Reiche	TYLCV, TSWV, Bacterial canker, powdery mildew, gray mould	
	S. pennellii Correll	Fusarium wilt, alternaria stem canker, Bacterial spot, wild range of insects	
	S. galapagense S. C. Darwin and Peralta	whitefly	
Brinjal	*Solanum torvum*	Root-knot nematodes, bacterial and *Verticillium* wilt	Syfert *et al.* (2016)
	S. violaceum Ortega	Fusarium wilt	Rao and Kumar (1980); Syfert *et al.* (2016)
	S. *sisymbriifolium* Lam	Verticillium wilt, Bacterial wilt, fruit and shoot borers, root-knot nematodes, spider mite	Syfert *et al.* (2016)
	S. incanum L.	Fusarium wilts	Rao and Kumar (1980)
Cucumber	*Cucumis hystrix, C. metuliferous*	Gummy stem blight, Downy mildew, Cucumber mosaic Virus, Zucchini yellow mosaic virus and Papaya ringspot virus watermelon strain *Meloidogyne* sp.	Chen *et al.* (2008)
Cucurbita spp	*Cucurbita argyrosperma* C. Huber subsp. *sororia* (L. H. Bailey) L. Merrick and D. M. Bates	Resistant to BYMV and TmRSV	Khoury *et al.* (2019)
	C. cordata S. Watson	Drought-tolerant; resistant CMV, TRSV, BYMV	Khoury *et al.* (2019)
	C. digitata A. Gray	Drought-tolerant; resistant to CMV, TmRSV	
	C. ecuadorensis H. C. Cutler and Whitaker	Resistant to papaya ringspot virus, WMV, powdery mildew, downy mildew	
	C. foetidissima Kunth	Drought-tolerant; resistant to CMV, TRSV, BYMB, WMV, and squash vine borer	
	C. *lundelliana* L. H. Bailey	Resistant to SqLCV, CMV, powdery mildew; used as a genetic bridge for breeding noninterfertile species	
	C. okeechobeensis (Small) L. H. Bailey subsp. *martinezii* (L. H. Bailey) T. C. Andres and Nabhan ex T. W. Walters and D. S. Decker	Resistant to CMV, BYMV, TRSV, bacterial leaf spot, powdery mildew, downy mildew	

	C. okeechobeensis (Small) L. H. Bailey subsp. *okeechobeensis*	Resistant to CMV, BYMV, TRSV, bacterial leaf spot, powdery mildew, downy mildew	
	C. palmata S. Watson	Drought-tolerant; resistant to CMV, TRSV, BYMV, TmRSV	
	C. pedatifolia L. H. Bailey	Drought-tolerant; disease resistance unstudied; potential as bridge species between xerophytic and mesophytic species	
	C. radicans Naudin	Drought-tolerant; resistant to CMV, TmRSV; BYMV; production of potato-sized tubers	
	C. x scabridifolia L. H. Bailey	Drought-tolerant	
Peas	*Pisum fulvum*	Rust, virus, powdery mildew resistance and Drought tolerance	Aryamanesh *et al.* (2012); Pratap *et al.* (2021)
	P. elatius	Pulse beetle tolerance	
Bean	*Phaseolus acutifolius*	Drought-tolerant and subzero temperatures tolerance	Pratap *et al.* (2021)
Cowpea	*Vigna unguiculata* group *sesquipedalis*	Heat and salinity	Pratap *et al.* (2021)
	V. heterophylla, *V. kirkii*, *V. exilis, V. trilobata,* and *V. riukiensis*	drought tolerance	Kapazoglou *et al.* (2023)
	V. minima and *V. indica*	tolerant to acidic and limestone type of soils	Tomooka *et al.* (2011)
	V. luteola, V. marina, V. nakashimae, V. vexillata var. macrosperma, V. riukiuensis, and *V. trilobata*	Salinity tolerance	Kapazoglou *et al.* (2023)
	V. vexillata	Water-logging-tolerant	Yoshida *et al.* (2020)
	Wild cowpea relative – line TVNu 1158	Aphid	Pratap *et al.* (2021)
Onion	*Allium galanthum, Allium altaicum, Allium pskemense*	Anthracnose	Galván *et al.* (1997); Malik *et al.* (2021)
	Allium fistulosum Allium schoenoprasum Allium pskemense Allium roylei Allium galanthum	Fusarium basal rot	Galván *et al.* (2008); Malik *et al.* (2021)
	Allium schoenoprasum Allium roylei	Purple blotch resistance	Nanda *et al.* (2016); Malik *et al.* (2021)

TYLCV: Tomato yellow leaf curl virus; CMV: Cucumber mosaic virus; ToMV: tomato mosaic virus; TSWV: Tomato spotted wilt virus; BYMV: Bean Yellow Mosaic Virus; TmRSV: Tomato ringspot virus; TRSV: Tobacco ring spot virus; WMV: Watermelon mosaic virus; and SqLCV: Chinese squash leaf curl virus

Table 4: Male sterility system in vegetable crops and its use for hybrid development in India

Crop	*Male sterility system*		*Development of MS lines and hybrids in India*
	Type, gene and inheritance	*Source and Reference*	
Chilli and Capsicum	GMS (ms)	Martin and Crawford (1951) in *C. frutescens*; California Wonder by Shifriss and Rylsky (1972)	CH-1 and CH-3 (Hundal and Khurana 1993)
	CGMS (S-cytoplasm, ms)	P.I. 164835 by Peterson (1958); *C. frutescens* by Csillery (1983)	Kashi Surkh, Kashi Early, Kashi Tej and Kashi Ratna (Kumar *et al.*, 2007, Kumar *et al.*, 2016); Arka Meghana, Arka Sweta, Arka Harita, Arka Khyati (Prasanth and Kumary, 2014); GAVCH-1
	GEMS, GMS (ms)	Dong *et al.* (2023)	
Tomato	GMS (ms)	Rick (1945)	
	GMS (ps)	Czech cv. Vrbicanske Nizke by Tronickova (1962)	Pusa Divya
	GMS (sl)	Sawhney (1974)	
	CGMS (S-cytoplasm)	*L. peruvianum, + L. pennellii* by Petrova *et al.* (1999)	
	GEMS, GMS (ms)	CRISPR/Cas9-based GMS (Du *et al.* 2020)	

Brinjal	GMS (ms)	Jasmin (1954)	
	CGMS (S-cytoplasm)	*S. gilo* by Fang *et al.* (1985); *S. violaceum* by Isshiki and Kawajiri (2002); *S. virginianum* by Khan and Isshiki (2008); *S. kurzii* by Khan and Isshiki (2009); and *S. aethiopicum* by Khan and Isshiki (2010)	MS lines from *S. aethiopicum* × *S. melongena* cv. Punjab Barsati (Garcha and Dhatt, 2017)
Muskmelon	GMS (ms)	Bohn and Whitaker (1949)	Punjab Hybrid, Punjab Anmol and MH-27 (Nandpuri *et al.*, 1982)
Watermelon	GMS (ms)	Irradiated population of cv. Sugar Baby (Watts, 1962)	
Cucumber	GMS (ms)	Han *et al.* (2018)	
Carrot	Petaloid-CMS (Sp-Cytoplasm)	North American wild carrot Munger in 1953	CMS lines (Kalia *et al.*, 2019; Singh and Karmakar 2021)
			Pusa Nayanjyoti, Pusa Vasuda and VRCARH-3 (VRCAR-214×VRCAR-85)
	Brown anther-CMS (Sa-Cytoplasm)	Tendersweet (Welch and Grimball 1947); Thompson (1961)	
	GUM-CMS in wild relative *D. carota* subsp. *gummifer*, MAR-CMS in wild relative *D. carota* subsp. *maritimus* and GAD-CMS in wild relative *D. carota* subsp. *gadecaei* by Nothnagel *et al.* (2000)		
Onion	CGMS (S-Cytoplasm)	cv. Italian Red 13–53 by Jones (1936); and cv. N-2-4-1 by Patil *et al.* (1973)	Arka Kirtiman and Arka Lalima (Veere Gowda *et al.*, 1998); Hybrid-63 and Hybrid-35; DOGR Hy-4 and DOGR Hy-7 (Gupta and Singh, 2016)
	CGMS (T-Cytoplasm)	cv. Jaunepaille des Vertus by Berninger (1965)	
	CMS (S-Cytoplasm)	cv. Nasik White Globe in 1987 (Pathak, 1994)	
Beet root	CGMS (S-Cytoplasm, xxzz)	Owen cytoplasm from cv. US1 by Owen (1945)	
		I-12 CMS from wild beets by Mikami *et al.* (1985)	
		BMC-CMS cytoplasm from wild beet *Beta maritime* by Mann *et al.* (1989)	
Spinach beet	CGMS	MS in OP population of cv. VRPLK-31 by Singh and Bhuvaneswari (2022)	
Radish	CMS (S-Cytoplasm)	Ogura CMS in a Japanese radish by Ogura (1968)	CMS lines and hybrid Kashi Rituraj (Singh *et al.* 2018, Singh and Singh 2020)
		77-01A CMS by He *et al.* (1981)	
		Kosena CMS by Ikegaya (1986)	
		NWB CMS by Nahm *et al.* (2005)	
		805A CMS by Wang *et al.* (2012)	
	GMS	DCGMS by Lee *et al.* (2008)	
Cole crops (*Brassica oleracea*)	CMS	Source of CMS: *Raphanus sativus*, *B. nigra*, *B. napus*, *B. juncea*, *B. tournefortii*. *Erucastrum canariense* and *Diplotaxis muralis*	
Broccoli	CMS (Ogura)	From radish by Bannerot *et al.* (1974); McCollum (1981)	CMS lines (Sharma and Kumar, 2002)
	GMS (ms)	Cole (1959)	
	GMS (Ms)	Han *et al.* (2019)	
Cabbage	CMS (Ogura)	From radish by Bannerot *et al.* (1977)	CMS lines (Parkash *et al.*, 2015)
			Pusa Hybrid-81, KtCBH-822, Pusa Red Cabbage Hybrid-1

	CMS	From *B. nigra* by Pearson (1972)	
		From *B. napus* by Chiang and Crete (1987)	
	GMS (ms)	Nieuwhof (1961), Sampson (1966)	
	GMS (Ms)	Fang *et al.* (1997)	
Cauliflower	CMS (Ogura)	From broccoli by Hoser-Krauze (1987)	CMS lines (Sharma *et al.*, 2004, Verma and Kalia 2011, Dey *et al.*, 2011, Singh *et al.*, 2022, Singh and Karmakar, 2022)
			Pusa Snowball Hybrid-1, Pusa Snowball Hybrid-2, Pusa Hybrid-301, Pusa Hybrid-3, Pusa Hybrid-102
	GMS (ms)	Nieuwhof (1961)	
	GMS (Ms)	Ruffio-Chable *et al.* (1993)	
Okra	GMS (ms)	Thombre and Deshmukh (2006)	MS lines (Thombre and Deshmukh, 2006; Pitchaimuthu *et al.*, 2012)
			Arka Nikita

moschatus and *A. tuberculatus* are resistant to shoot and fruit borer and leaf hopper (Gangopadhyay *et al.*, 2017). Among different species of cucurbits, wild *Cucumis figarei* has been found to possess absolute resistance to cucumber green mottle mosaic virus (CGMMV), Fusarium wilt, and high-level resistance to downy mildew (Pan *et al.*, 1996). Additionally, *C. figarei*, *C. myriocarpus*, *C. africanus*, *C. meeusii*, *C. ficifolius* and *C. zeyheri* have also been reported to be resistant to CGMMV virus (Rajamony *et al.*, 1990). Furthermore, the wild species *C. hardwickii* has been observed to exhibit high-level resistance to powdery and downy mildew diseases (Pitchaimuthu *et al.*, 2012), making it a potential source for increased yield in pickling cucumbers (Horst *et al.*, 1978). The identification and incorporation of such resistance traits from wild cucurbit species into commercial cultivars through conventional breeding or genetic engineering approaches could provide an effective and sustainable means of controlling diseases and enhancing crop yield in cucurbit production. Table 3 summarizes wild relatives for biotic and abiotic stresses in some of the important vegetable crops.

Hybrid Seed: A Driving Force in Vegetable Production

Hybrid seed development has played a crucial role in the growth of vegetable production around the world. Self-incompatibility (SI) and male sterility (MS) mechanisms have been broadly utilized in hybrid seed production of various vegetable crops with certain advantages and disadvantages. While SI system is commercially limited to Brassica species such as broccoli, cauliflower, and cabbage, MS system has been utilized in number of vegetables. Further, genetically engineered male sterility (GEMS) has been created in various crops through various biotechnological tools such as CRISPAR/Cas9 and transgenic. The male sterility system in vegetable crops and its use for the development of MS lines and hybrids in India has been summarized (Table 4).

Table 5: Sequenced Genome of Vegetable Crops

Crop	*Estimated genome size*	*References*
Cucumber	367.0	Huang *et al.* (2009)
Musk melon	450.0	Gonzalez *et al.* (2010)
Potato	844.0	The potato genome sequencing consortium (2011)
Chinese cabbage	529.0	The *Brassica rapa* genome Sequencing project consortium (2011)
Tomato	900.0	The tomato genome consortium (2012)
Water melon	425.0	Guo *et al.* (2013)
Brinjal	1126.0	Hirakawa *et al.* (2014)
French bean	587.0	Schmutz *et al.* (2014)
Chilli	3480.0	Kim *et al.* (2014)
Cabbage	630.0	Liu *et al.* (2014)
Pumpkin	271.4	Zhang *et al.* (2015)
Carrot	473.0	Iorizzo *et al.* (2016)
Peas	4450.0	Kreplak *et al.* (2019)

Advancements in Vegetable Breeding Technology

Our ability to understand and regulate genetic diversity in crop plants has undergone a radical transformation since the early 1980s due to technological advancements. Techniques such as genetic engineering, marker-assisted breeding and genomic selection have been developed for precise manipulation of plant genetics. Several plant genomes have been sequenced and assembled as a result of the advent of high-throughput sequencing tools and analytical techniques (Table 5). The development of dense and ultra-dense molecular linkage maps, the detection of structural variants, and the application of molecular markers are the major outcomes (Simko *et al.*, 2021). In order to identify the chromosomal locations of genes and QTLs responsible for plant phenotypes which are essential for crop development, linkage mapping and genome-wide association mapping studies have been extremely helpful.

Biotechnological-assisted breeding

Several studies highlight the use of various biotechnological approaches including marker-assisted selection (Singh *et al.*, 2020; Simko *et al.*, 2021; Shweta and Sood, 2021), marker assisted backcrossing (Phan and Sim, 2017), somaclonal variation and tissue culture (Pradhan *et al.*, 2021), etc. for the vegetable improvement. For nearly two decades, linkage analysis has been extensively conducted to identify QTL of various economic traits using segregating populations derived from biparental crosses F_2, backcross (BC), doubled haploid (DH) and recombinant inbred line (RIL) populations. Several QTLs has been mapped in various crops for many economic traits (Shweta and Sood, 2021). Recently, predictive breeding *via* genomic selection (GS) has become an essential tool in crop improvement. GS refers to selecting individuals' performance within a population based on genomic estimated breeding values (GEBV). The decreasing cost of DNA sequencing renders GS affordable and powerful by providing high-density markers across the genome. GS has been shown to be more efficient over traditional MAS when dealing with small-effect QTL.

Gene editing

CRISPR/Cas9 technology is a powerful tool that allows for precise and efficient manipulation of the genome. This technology has the potential to speed up the breeding process, increase precision, and reduce the need for chemical and radiation-based mutation breeding. Recent reviews by Kim *et al.* (2021) and Devi *et al.* (2022) has summarized the gene-edited vegetables like tomato, brinjal, potato, carrot, watermelon, pumpkin, lettuce, Chinese cabbage, chicory, cabbage and Chinese kale for heat and drought tolerance, salt tolerance, powdery mildew, ripening, lycopene content, etc.

High-throughput plant phenotyping (HTTP)

Genomics has had a significant impact on vegetable breeding. With the cost of genome sequencing decreasing drastically, scientists have been able to sequence a large number of genotypes for allele mining and association mapping. However, a bottleneck still exists in linking physiological and phenotype data to the sequenced genome data (Ilakiya *et al.*, 2020). Advancements in technology have allowed for the rapid and accurate measurement of a wide range of plant traits, such as yield, disease resistance, and nutritional content. The high throughput plant phenotyping platforms would help the vegetable breeder in saving their time, as conventional phenotyping is a time-consuming process. Many studies have been devoted for HTTPs in various vegetable crops such as tomato (Szuvandzsiev *et al.*, 2014); Bean (Rodriguez-Moreno *et al.*, 2008); Cabbage (Chiu *et al.*, 2015); Watermelon (Tamburini *et al.*, 2017); Spinach (Zhu *et al.*, 2019), etc. Various software has been used to analyse the root (KineRoot, PlaRoM, EZ-Rhizo), shoot (Traitmill, Leafanalyser, Lamina) and seed parameters (ImageJ, SmartGrain) etc.

Artificial intelligence (AI) and Machine learning (ML)

Cutting-edge technologies for crop genome sequencing and phenotyping combined with advances in computer science are currently fuelling a revolution in vegetable science (Sharma *et al.*, 2021). AI also called machine intelligence is a domain in computer science that instructs machines on how to replicate human physical actions and react like humans. Advancements in AI and ML can be used to predict the performance of the plants and can be used to analyze data from high-throughput phenotyping, genotyping and sequencing which leads to better selection of plants with desirable traits. AI is currently being used for vegetable grading and sorting through color and shape (Farooq and Gill, 2022). Similarly, ML has been widely used to decipher the relationship between DNA sequences and observed phenotypes in both conventional and in vitro plant breeding research. ML is currently in use for the assessment of seed quality, disease detection and control, prediction of climatic variations, crop monitoring and yield prediction (Sharma *et al.*, 2021).

Speed breeding

Breeding crops in a conventional way demands considerable time of usually 8 to 10 years, space, and inputs for selection after initial crosses are performed with parental genotypes. Speed breeding is likely to reduce this time

Table 6: Techniques for rapid generation advancement in some of the vegetables

Crop	*Technique*	*DTF*	*Generation/year*	*Selection method*	*Reference*
Amaranth	Photoperiod and temperature	28	6	SSD	Stetter *et al.* (2016)
Faba bean	Plant hormones, photoperiod, light intensity and immature seed	29-32	7	SPD	Mobini *et al.* (2015); Mobini *et al.* (2020)
Peas	Plant hormones, photoperiod and immature seed germination	33	5	-	Ribalta *et al.* (2019)
	hydroponic system, with a 22-h photoperiod supplied by fluorescent T5 tubes, a temperature of 20 ± 2 C	46-57	5	-	Cazzola *et al.* (2020)
Peppers	Modification in light intensities, photoperiods, and red-to-far-red ratios	39	4	-	Liu *et al.* (2022)

Abbreviations: DTF: days to flower; SPD: single pod descent; SSD: single seed descent through manipulation of environmental conditions such as photoperiod, temperature, moisture, plant nutrition, hormone and tissue culture etc. under which crop genotypes are grown aiming to accelerate flowering and seed set, to advance to the next breeding generation as quickly as possible (Table 6).

Major challenges and Strategies for improvement

Need for Germplasm creation and conservation

The vegetable crops are facing a major challenge of genetic erosions as much area is under hybrid cultivation with a narrow genetic base as a result of increasing globalization in the seed sector. Many of the traditional landraces local varieties are now not available. Vegetable breeding must create new cultivars that not only yield more and are of better quality but also use energy, water, fertilizers, agrochemicals, and fertilizers more effectively. Germplasm development is the associated area that can be undertaken through creation of MAGIC population, use of wild relatives, genetic transformation and gene pyramiding, etc.

Nutrition and shelf-life

Breeding vegetables with improved nutritional quality is an important area of research, with a focus on increasing the content of vitamins, minerals, and antioxidants along with the extended shelf life. To ensure crop diversification and nutritional security, it is essential to focus on underutilized vegetables alongside improving the yield and quality of commonly grown vegetables.

Resistance to biotic and biotic stresses

Because of globalization and environmental changes, the threat of invasive plant pests and pathogens is a significant and growing problem. The adoption of very input-intensive high-yielding varieties/hybrids has allowed farmers to produce more crops in less time, yet also reduced crop diversity. Many exotic and invasive insect pests have invaded in India recently *viz*., the South American pinworm (*Tuta absoluta*), and Solenopsis mealybug (*Phenacoccus solenopsis*) are few such insects (Halder and Rai, 2021). Similarly, there are various reports of new diseases affecting vegetable crops. Climate change had increased the frequency of extreme weather events, and breeding vegetables with improved tolerance to abiotic stresses such as drought, heat, and salinity is becoming increasingly important.

Emerging new areas

In the recent past, demand has been raised for cultivars suitable for organic farming, natural framing, microgreens, vertical gardening, urban rooftop gardening, year-round supply, export, etc. Similarly, urban consumers and supermarkets are looking for unique and engaging eating experiences, and they are willing to pay more for produce that meets their expectations. Innovations like baby carrot, yellow and orange capsicum and chili, cherry and pear tomatoes, non-bitter cucumbers, mild-tasting brinjal, seedless watermelons, and lettuces with different colors, textures, and flavors for baby leaf and pre-cut salads have been developed to meet the evolving preferences of metros (Silva-Dias *et al*., 2014).

Conclusions

Conventional breeding has been instrumental in improving the production of vegetable crops. However, recent biotechnological advancements such as marker-assisted selection, gene editing, high-throughput plant phenotyping, and the application of artificial intelligence, machine learning, and synthetic biology offer numerous benefits and have the potential to reduce the breeding cycle period. In addition to these advancements, it is essential to prioritize the creation and conservation of germplasm, improve nutritional quality and shelf-life, develop cultivars that are resistant to biotic and abiotic stresses, and create varieties that are suitable for emerging areas. Adequate funding for vegetable research is crucial to achieve the goals. Overall, a combination of conventional and advanced breeding techniques along with a strong research focus on important areas will be necessary to meet the increasing demand for vegetables and to address challenges of climate change, food and nutritional security, and demands for specialty produce.

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सारांश

सब्जी फसलें वैश्विक खाद्य आपूर्ति श्रृंखला का महत्वपूर्ण हिस्सा हैं । जैव विविधता, स्वाद और पोषण मूल्यों के कारण, यह विश्व स्तर मुख्य भोजन आहार है । भारत दुनिया में सब्जियों का दूसरा सबसे बड़ा उत्पादक है, जो व्यावसायिक रूप से ताजा खपत के लिए 60 से अधिक विभिन्न प्रकार की सब्जियां उगाता है। रंग, आकार, पोषण, स्वाद, उत्पाद की कटाई/तुड़ाई का समय, गुणवत्ता, ताजा उत्पाद की साल भर आपूर्ति एवं स्थान-विशिष्ट मांग के कारण सब्जियों की अच्छी किस्म का विकास एक चुनौतीपूर्ण और जटिल प्रक्रिया है। अधिक उन्नत किस्म के विकास के लिए विशेष ज्ञान, अत्याधुनिक तकनीक का उपयोग, आनुवंशिक संसाधनों की उपलब्धता और इन संसाधनों का प्रभावी ढंग से उपयोग करने के लिए पर्याप्त पूंजी का होना अनिवार्य है । वर्तमान पाठ में सब्जी की खेती की स्थिति, सामान्य प्रजनन विधियों, लक्षित लक्षण, जंगली आनुवंशिक संसाधन, आधुनिक प्रजनन दृष्टिकोण, उपज, गुणवत्ता, अनुकूलन क्षमता, सुरक्षित उत्पाद तथा सब्जी फसलों में और अधिक सुधार लाने के लिए आर्टिफिशियल इंटेलिजेंस और मशीन लर्निंग के प्रयोग पर समीक्षा की गई है ।