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REVIEW ARTICLE

Breeding vegetable crops for higher yield, superior quality, climate resilience and export competitiveness

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Abstract

Vegetable crops are essential for food, nutritional and livelihood security, providing affordable sources of vitamins, minerals and nutraceuticals, while generating employment and supporting farm diversification and rural development. Increasing population, urbanization, income, demographic changes and declining arable land are expected to intensify the demand for vegetables. India, therefore, needs to increase annual vegetable production substantially to meet future demand. According to the second advance estimates for 2025–26, vegetable production is expected to reach about 221.0 mt from 11.879 mha. Meeting future demand requires sustained genetic improvement for higher productivity, superior quality, wider adaptability, climate resilience, pest and disease resistance, resource-use efficiency, extended shelf-life, processing suitability and export quality. The development and utilization of robust genetic emasculation technologies and doubled-haploid lines should be prioritized to accelerate parental-line development, harness heterosis and reduce the cost of hybrid seed production. Development of climate-resilient cultivars with wider adaptability is essential for ensuring year-round availability of fresh vegetables under changing environmental conditions and dietary patterns. To lessen import dependence and promote exports, special emphasis is required on processing/nutraceutical traits in tomato, chilli, potato, carrot, onion, bitter gourd, pea and beans, as well as export-oriented traits in onion, potato, pea, chilli, gherkin, okra, garlic, cabbage, cauliflower and baby/sweet corn. The limitation of land resources can be partly addressed by breeding vegetable crops with indeterminate growth habits that efficiently utilize the vertical space of protected structures, thereby enabling prolonged harvesting of quality produce and higher productivity per unit area. Furthermore, grafting and rootstock breeding are emerging as important approaches for coping with extreme biotic, climatic and edaphic stresses, particularly in solanaceous and cucurbitaceous crops. Overall, addressing crop-, region- and industry-specific priorities will require integrated breeding strategies combining classical and cutting-edge technologies, speed-breeding facilities and precise phenotyping to develop high-yielding, quality-oriented, climate-resilient and market-specific vegetable cultivars that meet the future needs of consumers, growers, processors and exporters.

Keywords: Vegetable, Advanced breeding technology, Male sterility, Specialty traits, Stress tolerance.

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Introduction

Vegetable crops are generally herbaceous plants whose edible parts such as roots, stems, leaves, flowers, fruits or seeds, are consumed as food. Plant domestication and early agriculture began during the Neolithic period (10,000–7,000 BC), after which different vegetable crops were domesticated independently in different regions. About 400 vegetable crops are cultivated worldwide, representing 70 families and 225 genera (Kays & Dias, 1995), and 97 species of higher plants are cultivated and consumed as vegetables in India (Nayar et al., 2003). Globally, vegetable crops are consumed either cooked or raw and are increasingly recognized as essential components of food, nutrition and livelihood security. They are affordable sources of vitamins, minerals, dietary fibre and nutraceuticals essential for maintaining good health. Vegetable cultivation also plays an important role in farm and food-system diversification and provides opportunities for enhancing farm income, generating employment, and reducing rural poverty. In India, rapid population growth, increasing urbanization, rising per capita income, declining availability of arable land and demographic changes are creating new challenges for agricultural production, including vegetable production. Over the past few decades, the availability of vegetables has increased manifold (35 kg in the 1950–227 kg per capita per year in the 2020s) because of multiple transformations in the Indian dietary pattern, including increased consumption, greater dietary diversification, growing emphasis on nutrition, and a gradual shift towards higher-value and superior-quality vegetables (Pingali & Khwaja, 2004). In response to increasing demand for vegetables driven by changing dietary patterns among the Indian population, vegetable production has increased substantially over the past several decades. According to the Second Advance Estimates for 2025–26, vegetable production is expected to be about 221.0 million tonnes from 11.879 million ha (Anonymous, 2026). Despite this remarkable growth, continued increases in population, consumption and demand for quality vegetables necessitate sustained improvement in productivity, resource-use efficiency and quality.

Vegetable crops are generally high-value, input-intensive and highly sensitive to various abiotic and biotic stresses. Climate change is expected to increase the instability of vegetable production, particularly in regions already experiencing high temperature and water stress. At the same time, the availability of cultivable land and good-quality water is becoming increasingly constrained. Thus, further expansion of vegetable production through increasing cultivated area alone is neither economically nor environmentally sustainable. Quality has also emerged as an increasingly important objective of vegetable breeding. Consumers and processors are demanding vegetables with improved appearance, uniformity, texture, color, flavor, freshness, extended shelf life, nutritional value and health-promoting compounds. The challenge for breeders is to develop cultivars in which high yield, stress tolerance and desirable quality are combined without compromising consumer acceptability or economic returns.

Plant breeding is the deliberate genetic improvement of plants to develop desirable traits of economic importance that ultimately contribute to higher yield and productivity, greater tolerance to biotic and abiotic stresses, wider adaptability, and enhanced quality and market acceptability. Advances in bhasing, genomics, molecular breeding, speed breeding, doubled haploid technology, genetic emasculation techniques, genomic selection and gene editing have created new opportunities to accelerate genetic improvement in vegetable crops. Integration of these approaches with conventional breeding, germplasm characterization, high-throughput phenotyping and precise evaluation under target environments can facilitate the development of superior cultivars with multiple desirable attributes. The future of vegetable improvement will consequently depend on a multidisciplinary breeding strategy that combines productivity, quality, climate resilience, resource-use efficiency and market requirements. The limitation of arable land can be partly addressed by breeding vegetable crops with indeterminate growth habits suited to utilizing the vertical space of protected structures, thereby enabling prolonged harvesting, higher productivity per unit area and more efficient use of limited land resources (Shekhar et al., 2026; Premalakshmi et al., 2025). Protected cultivation can be an effective strategy to attract youth towards agriculture because it transforms farming into a technology-driven, commercially viable and skill-oriented enterprise. Furthermore, grafting and rootstock breeding are emerging as important approaches for coping with extreme biotic, climatic and edaphic stresses, particularly in solanaceous and cucurbitaceous crops. The development and selection of robust rootstocks can impart tolerance to drought, salinity, waterlogging, nutrient imbalance and soil-borne pathogens, while sustaining plant growth, yield and quality under challenging production environments (Venema et al., 2011).

To meet future demand, breeding programmes need to focus on desirable and specialty traits in various vegetable crops, such as tomato (processing quality, tomato leaf curl virus resistance, tolerance to extreme temperatures and cherry type), brinjal (fruit and shoot borer, little leaf, bacterial wilt, preferred fruit shape and size), chilli (thrips, viruses and bacterial wilt), bell pepper (thermo-insensitivity and high-temperature tolerance), cauliflower (compactness, self-blanching, high-temperature tolerance, earliness, diamondback moth and white-rot tolerance), cabbage (diamondback moth tolerance, tropical adaptation and compactness), broccoli (high-temperature tolerance, compactness, delayed bud opening. Extended shelf-life, and black-rot resistance), tropical carrot (smoothness, cylindrical shape, color intensity and self-colored core), radish (high-temperature and high-humidity tolerance and desirable leaf shape), okra (yellow vein mosaic virus resistance, okra enation leaf curl virus resistance, shorter internodes and cytoplasmic genic male sterility), pea (sweetness, earliness, powdery mildew resistance and cluster bearing), cowpea (golden cowpea mosaic virus resistance, fleshiness and non-stringiness), French bean (non-stringiness, delayed seed development, fleshiness, high-temperature tolerance and sclerotinia rot tolerance), onion (longer storability, photo-thermo-insensitivity and wider adaptability), cucumber (gynoecism, non-bitterness, desirable fruit shape and reduced carpel separation), watermelon (tough and thin skin, higher TSS, smaller fruits, fewer seeds and flesh firmness), bottle gourd (all-weather suitability, juiciness and delayed seed development), bitter gourd (glossy fruits, reduced ridge prominence, appropriate bitterness, fruit-fly and virus resistance), and potato (photoperiod insensitivity, better storability, shallow eyes, high dry matter, and blight & virus tolerance) (Karmakar et al., 2026; Garcia-Oliveira et al., 2025; Singh et al., 2025; Tiwari et al., 2024; Behera et al., 2023; Kalia et al., 2023; Singh et al., 2009). As with breeding for higher yield and quality, it is essential across vegetable crops to develop cultivars with wider adaptability to extend the cultivation window and availability of fresh produce. Furthermore, cultivars of tomato, capsicum, gherkin, cucumber, yard long bean and muskmelon should be developed specifically for protected structures to harvest more produce from less land. Intensive breeding efforts targeting specialty traits for processing and nutraceutical industries in tomato, chilli, potato, carrot, onion, pea, beans and leafy vegetables, along with export-oriented traits in onion, pea, chilli, gherkin, okra, baby/sweet corn and brinjal, are essential for enhancing the international presence, market competitiveness and export potential of Indian-bred vegetable varieties, as reported in detail by Prasad et al. (2026).

Against this backdrop, breeding vegetable crops for higher yield, superior quality, climate resilience and export competitiveness has become a strategic necessity. Developing high-yielding cultivars with enhanced nutritional and processing quality, greater consumer acceptance, wider adaptability to diverse and extreme growing conditions, resistance to multiple pests and diseases, efficient response under low-input conditions, extended shelf-life and suitability for processing, nutraceutical applications and export markets is a challenging and complex task. This challenge is further intensified by region- and ethnicity-specific preferences for a diverse range of vegetables and the growing demand for year-round availability of fresh produce. Therefore, the development of improved cultivars with stable performance across environments, enhanced nutritional value, resistance to biotic and abiotic stresses, extended shelf-life and market-specific quality will be central to meeting the future needs of consumers, farmers, processors and exporters.

Breeding for Yield and Climate Resilience

With continuous population growth, limited opportunities for expansion of cultivated land, increasing climatic uncertainties and rising year-round demand for fresh vegetables, the need to enhance vegetable productivity has become increasingly urgent. In this context, plant breeding assumes greater strategic importance in developing high-yielding, adaptable and stable vegetable cultivars capable of sustaining production under diverse and changing environmental conditions. Moreover, climate change, which is likely to lead to increased temperatures and uncertain rainfall, is expected to have a particularly negative effect on crop productivity. Vegetable breeding is inherently more complex than field-crop breeding because the economic product varies widely among crops and may comprise different plant organs, including leaves, stems, roots, flowers, bulbs, tubers and fruits. Consequently, breeding objectives and selection criteria differ considerably across vegetable crops, requiring simultaneous consideration of yield, quality, maturity, nutritional value, appearance and consumer preferences.

Location-specific demands for color, shape, nutrition, taste, maturity stage, quality, year-round supply and other attributes make breeding for specific traits particularly complex; for example, substantial market segmentation of about 15 to 40 types has been reported for brinjal, pepper and tomato (Ambali et al., 2025; Ghuge & Mirza, 2021). Thermo-tolerance, photo-insensitivity and tolerance to water stress are key traits that can help minimize the negative effects of climatic variability, ultimately contributing to wider adaptation, an extended growing period and longer availability of fresh vegetables. The pollination behavior, trait heritability, gene action, the number of genes controlling target traits, heterosis and genotype × environment interactions determine the most appropriate breeding method. Hybridization and heterosis breeding have achieved substantial success in vegetable crops, particularly where genetic emasculation mechanisms facilitate economical hybrid-seed production. Hybrids are a major driving force in the seed industry and vegetable production. Heterosis refers to the phenomenon in which offspring from crosses between genetically divergent parents exhibit superior performance for one or more traits compared with their parents. It has contributed substantially to the development of high-yielding, early-maturing and uniform cultivars combining several important economic traits. Different mechanisms, including manual emasculation, self-incompatibility (SI), genetic male sterility (GMS), cytoplasmic male sterility (CMS), cytoplasmic-genic male sterility (CGMS) and gynoecism, have been utilized to harness heterosis and facilitate commercial hybrid seed production in various vegetable crops (Červenski et al., 2026; Singh et al., 2025; Behera et al., 2023; Farinati et al., 2023; Singh et al., 2023; Singh & Karmakar, 2023; Karmakar et al., 2022; Singh et al., 2016; Dhall, 2010; Table 1). The development and utilization of robust genetic emasculation techniques, particularly male sterility and gynoecism, together with doubled-haploid lines, especially in cross-pollinated crops, should be prioritized to harness heterosis and produce hybrid seed more economically.

In cucurbitaceous crops, manipulation of sex expression is an important breeding strategy for increasing the frequency of fruit-bearing nodes, thereby enhancing fruit number and yield. Breeding for a low male:female flower ratio (<10:1) is desirable in monoecious cucurbits such as

Table 1: Various mechanisms of commercial hybrid development in vegetable crops

Crop & emasculation	*Hybrid mechanism*	*Utilization in India*
Male sterility		
Chilli and capsicum	GMS (ms)	PAU
	CGMS (S-cytoplasm, ms)	IIVR, IIHR, PAU, PSC
Tomato	GMS (ms)	
	GMS (ps)	IARI
	GMS (sl)	
Brinjal	GMS (ms)	
	CGMS (S-cytoplasm)	PAU, PSC
Muskmelon	GMS (ms)	PAU, PSC
Watermelon	GMS (ms)	
Cucumber	GMS (ms)	
Carrot	Petaloid-CMS (Sp-Cytoplasm)	IIVR, IARI, PSC
	Brown anther-CMS (Sa-Cytoplasm)	
Onion	CGMS (S-Cytoplasm)	IIHR, DOGR, IARI, PSC
	CGMS (T-Cytoplasm)	
	CMS (S-Cytoplasm)	
Beetroot	CGMS (S-Cytoplasm, xxzz)	
Ridge gourd	CGMS	KAU, IIHR
Spinach beet	CGMS	IIVR, PSC
Radish	CMS (S-Cytoplasm)	IIVR, PSC
	GMS (ms)	
Cauliflower,	CMS (Ogura)	IARI, IIVR, PSC
	GMS (ms)	
Cabbage, broccoli	CMS (Ogura)	IARI, PSC
	GMS (ms)	
Okra	GMS (ms)	IIHR, IIVR, PSC
Indian bean	GMS (ms)	PSC
Yard long bean	GMS (ms)	PSC
Sex form		
Cucumber	Gynoecism	IARI, IIVR, GBPUAT, PSC
Bitter gourd	Gynoecism	IARI, IIVR, PSC
Manual emasculation and flower pinching		
Tomato	Hand emasculation	All organizations, PSC
Brinjal	Hand emasculation	All organizations, PSC
Okra	Hand emasculation	All organizations, PSC
Cucurbits	Pinching of male flowers or removal of male plants	All organizations, PSC
Self-incompatibility (SI)		
Cole crops	Sporophytic SI	IARI, PSC

Cont...

PSC: Private Sector Companies

cucumber, muskmelon, watermelon, pumpkin, summer squash, bottle gourd, bitter gourd, sponge gourd and ridge gourd. High-frequency femaleness and subgynoecy (predominance of female flowers) are particularly useful in cucumber, summer squash, bitter gourd and watermelon, whereas andromonoecy (male and bisexual flowers) is the predominant and commercially important sex form in muskmelon. Gynoecy, characterized by exclusively pistillate flowers, is especially valuable in cucumber and bitter gourd and has also being exploited in muskmelon, watermelon and ridge gourd for hybrid breeding. Furthermore, gynomonoecy (female and bisexual flowers) represent additional sex-expression types that can be exploited, particularly in cucumber and muskmelon. Thus, selection for increased femaleness, reduced male:female flower ratio, gynoecy/subgynoecy and appropriate sex-expression types provides considerable scope for increasing female flower frequency, fruit-bearing nodes, hybrid seed production efficiency and ultimately productivity in cucurbitaceous vegetables.

Furthermore, thermo-tolerance (high and low temperature), photo-insensitivity (neutral-day response) and tolerance to water stress (waterlogging and drought) are key traits that can minimize the negative effects of climatic variability, ultimately contributing to wider adaptation, an extended growing period and longer availability of fresh vegetables, including off-season production. Vegetable crops possess substantial genetic variability within and among gene pools that can be utilized to develop cultivars and lines with thermo-tolerance, photo-insensitivity and tolerance to water stress, thereby improving adaptation to abiotic stresses and extending the production period. To meet future requirements, vegetable breeding in India should accelerate and focus on traits of importance such as high-temperature and cold tolerance in tomato; frost and high-temperature tolerance in brinjal; high-temperature tolerance in bell pepper; high-temperature tolerance under humid and dry conditions in cauliflower and radish; high-temperature tolerance in cabbage, broccoli and carrot; low temperature tolerance in okra; high-temperature tolerance in pea; low-temperature tolerance and photo-insensitivity in cowpea; low/high-temperature tolerance and photo-insensitivity in French bean and hyacinth bean; photo-thermo-insensitivity and high-humidity tolerance in onion; all-weather suitability in bottle gourd; wider adaptation in bitter gourd, cucumber, *Luffa*, watermelon and muskmelon; wide adaptation with high-temperature and high-humidity tolerance in spinach beet; and photoperiod insensitivity in potato and amaranth. Grafting has emerged as an important technique for improving productivity, resilience and adaptability, particularly in solanaceous and cucurbitaceous vegetables such as tomato, brinjal, chilli, watermelon, cucumber, muskmelon and other cucurbits (Kumar et al., 2025; Bahadur & Kumar, 2024; Schwarz et al., 2010; Davis et al., 2008).

From a breeding perspective, the development of indeterminate cultivars with strong stems, short internodes, appropriate leaf architecture, sustained flowering, high fruit-setting ability and a prolonged reproductive phase can substantially enhance productivity per unit area. Continued production of new leaves and reproductive nodes enables plants to maintain fruit production over an extended period, thereby increasing cumulative yield and allowing multiple or staggered harvests from the same planting. This is particularly valuable for high-value vegetables grown under protected conditions, where the objective is not merely early yield but also sustained production of marketable, high-quality produce over a longer crop cycle. Recent research on indeterminate tomato genotypes under protected conditions has demonstrated significant genetic variability for yield and associated quality traits, highlighting opportunities for selection of superior genotypes specifically adapted to protected environments (Shekhar et al., 2026). Furthermore, research on indeterminate tomato grown under protected conditions has shown that stem training and canopy management influence plant growth, fruit number, fruit mass and fruit quality, indicating that plant architecture is an important component of productivity optimization in protected environments (Mngoma et al., 2022). The integration of indeterminate growth, compact and manageable canopy architecture, prolonged fruiting, high harvest index and efficient use of vertical growing space can therefore contribute to greater productivity per unit land area, prolonged availability of quality produce and improved economic returns. These plant ideotypes are particularly relevant in the context of shrinking agricultural land, increasing urbanization and the need for sustainable intensification of vegetable production. Thus, developing vegetable cultivars specifically adapted to protected cultivation, rather than simply transferring open-field cultivars into protected structures, represents an important breeding strategy for maximizing the productive potential of limited land resources. Several public-sector organizations, particularly ICAR institutes and State Agricultural Universities (SAUs), have developed varieties and hybrids suitable for protected cultivation such as Pusa Rakshit, Arka Meghali, Arka Saurav, Pant Polyhouse Bred Tomato-2, Pant Polyhouse Bred Tomato Hybrid-1, Punjab Gaurav, Punjab Sartaj, Punjab Swarna, Punjab Red Cherry, Punjab Sona Cherry and Punjab Kesar Cherry in tomato; Pusa Parthenocarpic Cucumber-6, Pusa Pickling Cucumber-8, Pusa Parthenocarpic Cucumber-3, Pant Parthenocarpic Cucumber-2 and Him Palam Khira-1 in cucumber; Arka Basant, Arka Gaurav and PSM-1 in capsicum; and the triploid seedless watermelon Arka Madhura.

Consumer- and Market-Driven Vegetable Breeding

Vegetable breeding must be responsive to the diverse and evolving requirements of growers, consumers, exporters and processing industries. For growers, the major breeding objectives include high and stable yield, resistance to pests and diseases, uniformity, and tolerance to abiotic stresses. In contrast, consumers, exporters and industries demand cultivars with superior quality, attractive appearance (color, shape and size), desirable taste and flavour, extended shelf-life, nutritional value, and suitability for processing and transportation.

Nowadays, in vegetable crops, overall quality is often as important as, or more important than, yield because market acceptance strongly influences the price received by growers. To meet the demands of markets, consumers and exporters, vegetable breeding needs to focus on economically important traits (Table 2). Breeding of export-oriented vegetables such as onion, potato, pea, chilli, cucumber/gherkin, okra, garlic, cabbage, cauliflower and baby/sweet corn is required to enhance the international presence of Indian-bred varieties. Intensive breeding programmes are also needed for specialty traits to meet the requirements of processing and nutraceutical industries, including tomato (lycopene and processing quality), chilli (pungency, color and oleoresin), capsicum (capsanthin, carotenoids and capsaicinoids), potato (chips, fries and starch), sweet potato (anthocyanins, β-carotene, dry matter and starch), orange and baby carrot (β-carotene and canning quality), black carrot (anthocyanins and natural colorants), beetroot (betalains and colorants), onion (flakes and powder), pea (freezing and canning quality), French bean (canning quality), cauliflower and cabbage (glucosinolates, carotenoids and anthocyanins), broccoli (glucosinolates and sulforaphane), and leafy vegetables (dehydrated powders for dietary and food fortification).

Further, intensive breeding programmes targeting specialty traits are needed to meet the diverse requirements of processing, nutraceutical and functional-food industries. Such breeding efforts should focus not only on yield but also on specific biochemical, nutritional, processing and functional attributes. For instance, tomato can be improved for lycopene content, firmness and suitability for paste, puree and juice processing; chilli and capsicum for pungency, color, carotenoids, capsaicinoids and oleoresin; potato for low

Table 2: Desired traits of economic importance in various vegetable crops to meet the demand of market, consumers and exporters

Vegetable crop	*Important trait*
Tomato	Better shelf-life, attractive appearance, medium-sized round fruits, thick skin, red color and cherry type
Potato	Earliness, better storability, shallow eyes and high dry matter
Brinjal	Fewer seeds, shiny fruits, and desirable fruit shape and size
Chilli	Medium to high pungency, medium-sized and straight fruits
Bell pepper	Bell-shaped and colored fruits
Okra	Dark green, thin, medium-long pods, reduced trichome density, short internodes, easy harvesting and delayed seed development
Cucumber	Attractive, long cylindrical, firm and crisp fruits; free from bitterness; high frequency of female flowers; soft seeds; reduced crook neck and no carpel separation
Bitter gourd	High frequency of female flowers, glossy fruits, reduced ridge prominence and appropriate bitterness
Muskmelon	Round/spherical fruit shape, thick flesh with attractive color, small seed cavity, sweet and musky fruits, and tough netted skin
Watermelon	Tough skin, firm flesh, higher TSS, smaller & less seeded fruits
Bottle gourd	High frequency of female flowers, juicy fruits, free from bitterness and delayed seed development
Pumpkin	Earliness, high frequency of female flowers, yellow and mottled skin, non-ribbed surface, thick flesh, small seed cavity and dark-orange flesh
Sponge gourd	Earliness, high frequency of female flowers, delayed seed development, and cylindrical fruits free from bitterness
Vegetable pea	Dark-green longer pods, sweetness, high shelling percentage, earliness and cluster-bearing habit
Cowpea	Erect plant type, fleshiness, delayed seed development, free from inter-locular spaces and non-stringiness
French bean	Non-stringiness, delayed seed development, freedom from inter-locular spaces, fleshiness and straight pods
Cauliflower	Self-blanching leaves, compact and non-ricy curd and earliness
Cabbage	Compact, round heads with a narrow, short and soft core and delayed bursting
Turnip	Uniform root shape, color and size, smooth roots, delayed bolting and high dry matter
Carrot	Blunt, smooth and scar-free roots, delayed bolting, dark color and self-colored small core
Radish	Entire/sinuate leaf margin, less-tapered smooth roots, mild to high pungency, delayed pithiness and delayed bolting
Beetroot	Monogerm seed, earliness, uniform root color, shape and size, smooth roots and longer storability
Onion	Medium to high pungency, longer dormancy and storability, thin neck, high TSS, uniform bulb color and shape and free from doubling
Spinach beet	Delayed bolting, dark green leaf, higher regeneration ability, high dry matter and multigerm seed

Cont...

reducing sugars, dry matter and processing quality for chips, fries and starch; orange and baby carrot for β-carotene, root shape and suitability for canning and processing; black and purple carrot for anthocyanins and natural colorants; radish for red and purple pigmentation; beetroot for betalains and natural colorant production; onion for dry matter, pungency and suitability for flakes, powder and dehydration; pea for freezing, canning and processing quality; and French bean for tenderness, pod quality and canning suitability. Similarly, broccoli and cauliflower can be targeted for enhanced glucosinolates, sulforaphane, carotenoids and other health-promoting phytochemicals, while sweet potato can be bred for elevated anthocyanins, carotenoids, dry matter and starch for functional foods and industrial processing. Leafy vegetables offer opportunities for improvement in iron, folate, carotenoids, lutein, dry matter, antioxidants and other micronutrients, with potential applications in dehydrated powders, dietary supplements and food fortification. Thus, breeding for specialty biochemical and processing traits can facilitate the development of value-added vegetable cultivars tailored to the specific needs of food-processing, nutraceutical, pharmaceutical and functional-food industries (Zhang et al., 2025; Sagar et al., 2025; Liu et al., 2022; Koley et al., 2020; Behera & Singh, 2019; Singh et al., 2018; Singh et al., 2017).

Breeding for Safe Vegetable Products

The application of pesticides at different stages of crop growth has become common practice in agriculture to minimize crop losses caused by various biotic stresses, including insect pests, diseases and weeds. However, indiscriminate and repeated use of pesticides may result in the accumulation of pesticide residues in vegetables, raising concerns regarding food safety and consumer health. In addition, urban and industrial effluents constitute important sources of potentially toxic heavy metals, including Cr, Cu, Pb, Cd, Hg, Ni and Zn, which can accumulate in agricultural soils and subsequently be taken up by vegetable crops.

Studies conducted in India have reported elevated concentrations of heavy metals in vegetables grown in urban and industrially contaminated environments, with some edible portions exceeding permissible safety limits (Sharma et al., 2009; Sharma et al., 2011). The increasing occurrence of pesticide and heavy-metal residues in vegetables, particularly in developing countries, is therefore a major concern for consumers and food-safety regulators. Small- and medium-scale growers may also face challenges in adhering to prescribed residue limits because of inadequate awareness, inappropriate pesticide application and limited access to residue-monitoring facilities. In India, a survey of pesticide residues in vegetable crops collected at farm gates and markets during 1999–2003, involving 3,043 samples, reported pesticide residues in approximately two-thirds of the samples, with 9% containing residues above the maximum residue limits (Choudhary & Gaur, 2009). More recently, long-term monitoring of 966 vegetable samples from India detected residues of 36 pesticides among 155 compounds investigated, although the dietary risk assessment indicated that the detected residues did not pose a significant chronic dietary risk to consumers (Sharma et al., 2022). Variations in heavy-metal accumulation among crop species, including vegetables, highlight the importance of screening and selecting crops and cultivars with lower concentrations of contaminants in edible parts (Gupta et al., 2019). Overall, based on metal-accumulating properties, Arthur et al. (2005) categorized plants as low accumulators (pea, soybean), moderate accumulators (garlic chives, cucumber, pumpkin, Luffa, bitter gourd, carrot, capsicum), and high accumulators (turnip, radish, brinjal, tomato, amaranth, spinach and lettuce). Generally, leafy vegetables tend to absorb and accumulate higher quantities of heavy metals than fruit or root vegetables (Gupta et al., 2019). Moreover, heterosis breeding has been reported as a potential approach for developing high-yielding tomato hybrids with reduced accumulation of heavy metals such as cadmium and lead (Kilchevsky et al., 1999).

The breeding of improved vegetable cultivars possessing resistance or tolerance to insect pests and diseases can substantially reduce crop losses, pesticide dependence and the associated risk of pesticide residues, thereby contributing to safer and more sustainable vegetable production. Host-plant resistance is an important component of integrated pest management (IPM), as resistant cultivars can reduce pest establishment and disease development while lowering the need for pesticide application. In addition to improving production efficiency and reducing the cost of crop protection, resistant cultivars can contribute to the production of safer vegetables and enhance their market acceptability, including for residue-sensitive and export markets. Consequently, increasing emphasis is being placed on the identification and utilization of genetically diverse sources of resistance and their incorporation into high-yielding, quality-oriented cultivars. For the development of resistant cultivars and pre-breeding materials, sources of resistance constitute the foundation of resistance-breeding programmes. Valuable resistance to insect pests and diseases has been identified in cultivated varieties, indigenous cultivars, landraces, farmer selections, wild and semi-wild relatives and allied species of several vegetable crops (Swarnapriya, 2021; Singh et al., 2009). The identification, characterization and transfer of such resistance through collaborative efforts involving vegetable breeders, plant pathologists and entomologists have consequently become integral components of pre-breeding and cultivar development. The major biotic stresses of vegetable crops receiving attention in resistance breeding are summarized in Table 3.

The development of vegetable cultivars with multiple biotic-stress tolerance has emerged as an important breeding strategy for achieving stable productivity and reducing dependence on chemical pesticides under increasingly complex pest and disease pressures. Public-sector breeding programmes in India have developed several vegetable varieties, hybrids and breeding lines possessing resistance or tolerance to multiple diseases and or insect pests (Table 4). Furthermore, rootstock breeding and grafting, particularly in solanaceous and cucurbitaceous crops, are important approaches for coping with soil-borne diseases and nematodes.

Advanced Breeding Tools in Vegetable Crops

Vegetables are essential components of a balanced and nutritious diet, and their consumption is increasing with growing awareness of health benefits, improved economic status and dietary diversification. Their productivity is constrained by major biotic stresses such as pathogens, insects, nematodes and weeds, as well as abiotic stresses including drought, waterlogging, temperature extremes and salinity. Plant breeding provides an effective approach for developing cultivars combining host-plant resistance, stress adaptation, high yield and market-preferred quality. Recent advances in genetic engineering, marker-assisted breeding, genomic selection, genomics and phenomics have enabled more precise and efficient genetic improvement. Linkage mapping and genome-wide association studies facilitate the identification of genes and QTLs governing important traits, while dense molecular markers and high-throughput phenotyping enable the dissection of complex trait variation and prediction of breeding values. Genomic selection can further accelerate breeding by predicting breeding values from genome-wide marker data, thereby reducing dependence on costly phenotyping (Dias & Ortiz, 2019; Crossa et al., 2017). Genetic engineering has provided opportunities to introduce traits unavailable in conventional breeding populations, particularly resistance to pests and pathogens, with potential benefits for reducing pesticide

Table 3: Major biotic stresses of vegetable crops

Vegetable crop	*Major biotic stress*
Tomato	Tomato leaf curl virus (ToLCV), late blight, early blight, Fusarium wilt, bacterial wilt, buck eye rot, root-knot nematode (RKN), fruit borer and whitefly
Potato	Late blight, early blight, potato viruses, common scab, wart, nematode, bacterial wilt, aphids, whitefly and potato tuber moth
Brinjal	Fruit and shoot borer (FSB), little leaf, bacterial wilt, phomopsis blight and RKN
Chilli & bell pepper	Thrips, mite, aphid, whitefly, chilli leaf curl virus (ChiLCV), pepper leaf curl virus, bacterial wilt and anthracnose
Okra	Yellow vein mosaic virus (YVMV), okra enation leaf curl virus (OELCV), fruit and shoot borer, jassids and whitefly
Cucumber	Downy mildew, powdery mildew, cucumber mosaic virus, gummy stem blight, bacterial wilt, RKN and spider mite
Bitter gourd	Downy mildew, powdery mildew, angular leaf spot, cucumber mosaic virus, fruit fly, red pumpkin beetle
Muskmelon	Downy mildew, powdery mildew, cucumber green mottle mosaic virus, whitefly and fruit fly
Watermelon	Fusarium wilt, anthracnose, powdery mildew, watermelon mosaic virus and red pumpkin beetle
Bottle gourd	Powdery mildew, red pumpkin beetle, watermelon mosaic virus, cucumber mosaic virus and squash mosaic virus
Pumpkin/ Squash	Powdery mildew, zucchini mosaic virus, watermelon mosaic virus, cucumber mosaic virus and squash mosaic virus
Sponge gourd	Mosaic virus, downy mildew, gummy stem blight
Vegetable pea	Fusarium wilt, powdery mildew, downy mildew, leaf miner, aphids, pod borer and pea stem fly
Cowpea	Anthracnose, Cercospora leaf spot, powdery mildew, bacterial blight, golden cowpea mosaic virus, pod borer
French bean	Bean common mosaic virus, bean yellow mosaic virus, white mold, angular leaf spot and powdery mildew
Cauliflower	Black rot, Sclerotinia rot, Alternaria blight, diamondback moth, Spodoptera
Cabbage	Black leg, club root, cabbage yellows, cabbage butterfly, diamondback moth
Carrot	Scab, Alternaria blight and Cercospora leaf spot
Radish	Alternaria blight, radish mosaic virus, flea beetle, painted bug and aphids
Onion	Purple blotch, Stemphylium blight, bacterial storage rot and thrips
Spinach beet	Cercospora leaf spot

Table 4: Multiple biotic stress tolerant/resistant varieties and hybrids

Crop	*Variety/hybrid*	*Multiple disease/pest trait*
Tomato	Arka Abhed (F_1)	ToLCV, bacterial wilt, early blight and late blight
	Arka Rakshak (F_1)	ToLCV, bacterial wilt and early blight
	Arka Samrat (F_1)	
	Arka Apeksha (F_1)	
	Arka Vishesh (F_1)	
	BCTH-4 (F_1)	ToLCV and early blight
Brinjal	Kashi Manohar (F_1)	Phomopsis blight and Fusarium wilt
	Kashi Vijay	
	Kashi Utsav (F_1)	Little leaf and Phomopsis blight
	Kashi Modak	Fruit and shoot borer and Phomopsis blight
Chilli	CH-27 (F_1)	Leaf curl virus, fruit rot and root-knot nematode, thrips and mites
	Arka Meghana (F_1)	Powdery mildew and virus tolerance
	Arka Harita (F_1)	
	Kashi Garima (F_1)	ChiLCV, thrips and mites tolerance
	Kashi Abha	Anthracnose, ChiLCV, thrips and mite tolerance
Okra	Kashi Prakram	YVMV and OELCV
	Kashi Sahishnu	
	Kashi Chaman	
	Kashi Utkarsh	
Garden pea	Kashi Trishakti	Powdery mildew, rust and downy mildew
	Arka Kirthiman (F_1)	Purple blotch, basal rot and thrips tolerance
	Arka Lalima (F_1)	
	Arka Laliman	
Watermelon	Arka Manik	Downy mildew, powdery mildew and anthracnose resistance
	Arka Muthu	
	Arka Shyama	

use, residues and production costs. More recently, CRISPR/Cas9-based gene editing has emerged as a precise tool for modifying target genes governing traits such as stress tolerance, disease resistance, fruit ripening and nutritional quality in tomato, brinjal, potato, carrot, watermelon, pumpkin, lettuce and cole crops (Kim et al., 2021; Devi et al., 2022). Speed breeding, molecular-assisted selection and genome-enabled breeding are further accelerating the development of improved vegetable cultivars by enabling rapid generation advancement, early selection of desirable alleles and precise incorporation of target traits. These

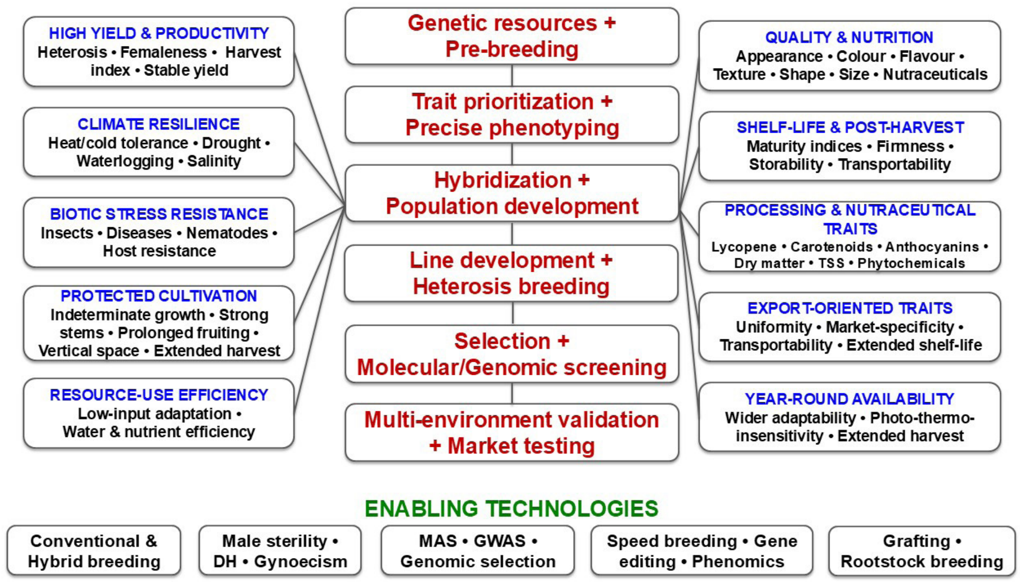

Figure 1: Integrated vegetable breeding approaches for enhanced productivity, resilience, quality and marketability

approaches help shorten breeding cycles, improve selection efficiency and facilitate the development of cultivars with enhanced yield, quality, nutritional value and resistance to biotic and abiotic stresses (Watson et al., 2018). Overall, Figure 1 illustrates the integration of genetic resources, breeding methodologies and enabling technologies to address diverse biotic and abiotic stresses sustainably while meeting the evolving demands and future needs of vegetable production and consumption.

Conclusion

In conclusion, breeding for high yield, superior quality, wider adaptability, protected cultivation, multiple biotic- and abiotic-stress tolerance, and specialty traits for processing and export markets is essential to meet future demands and enhance the global presence of Indian vegetable cultivars. Grafting and rootstock breeding are emerging as important approaches for overcoming biotic, climatic and edaphic stresses, particularly in solanaceous and cucurbitaceous crops. Speed breeding, molecular-assisted selection and genome-enabled technologies can further accelerate cultivar development with greater precision. Integrating conventional breeding with modern technologies will facilitate the development of high-yielding, quality-oriented cultivars suited to advanced production systems and improved post-harvest handling and processing, thereby meeting the needs of consumers, growers, processors and exporters.

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सारांश

सब्जियाँ खाद्य, पोषण और आजीविका सुरक्षा के लिए अत्यंत महत्वपूर्ण हैं। ये विटामिन, खनिज एवं न्यूट्रास्यूटिकल्स के किफायती स्रोत उपलब्ध कराने के साथ-साथ रोजगार सृजन, कृषि विविधीकरण और ग्रामीण विकास में भी महत्वपूर्ण योगदान देती हैं। बढ़ती जनसंख्या, शहरीकरण, आय में वृद्धि, जनसांख्यिकीय परिवर्तन तथा कृषि योग्य भूमि में कमी से भविष्य में सब्जियों की मांग और अधिक बढ़ने की संभावना है। अतः भविष्य की मांग को पूरा करने के लिए भारत को वार्षिक सब्जी उत्पादन में पर्याप्त वृद्धि करने की आवश्यकता है। वर्ष 2025–26 के द्वितीय अग्रिम अनुमानों के अनुसार, 11.879 मिलियन हेक्टेयर क्षेत्र से सब्जियों का उत्पादन लगभग 221.0 मिलियन टन है। भविष्य की मांग को पूरा करने के लिए अधिक उत्पादकता, बेहतर गुणवत्ता, व्यापक अनुकूलनशीलता, जलवायु-सहनशील, कीट एवं रोग प्रतिरोधकता, संसाधन-उपयोग दक्षता, विस्तारित भंडारण अवधि, प्रसंस्करण उपयुक्तता तथा निर्यात गुणवत्ता के लिए निरंतर आनुवंशिक सुधार की आवश्यकता है। नर-बंध्य तकनीकों तथा द्विगुणित हैप्लॉइड के विकास और उपयोग को प्राथमिकता दी जानी चाहिए, ताकि जनक-वंशावली के विकास में तेजी लाई जा सके, संकर किस्मों के विकास किया जा सके तथा संकर बीज उत्पादन की लागत कम की जा सके। बदलती पर्यावरणीय परिस्थितियों और आहार संबंधी प्राथमिकताओं के बीच वर्षभर ताजी सब्जियों की उपलब्धता सुनिश्चित करने के लिए व्यापक अनुकूलनशीलता वाली जलवायु-सहनशील किस्मों का विकास आवश्यक है। आयात पर निर्भरता कम करने और निर्यात को बढ़ावा देने के लिए टमाटर, मिर्च, आलू, गाजर, प्याज, करेला, मटर और फलियों में प्रसंस्करण एवं न्यूट्रास्यूटिकल गुणों तथा प्याज, आलू, मटर, मिर्च, घेरकिन, भिंडी, लहसुन, पत्तागोभी, फूलगोभी और बेबी कॉर्न में निर्यात-उन्मुख गुणों पर विशेष बल देने की आवश्यकता है। भूमि संसाधनों की सीमित उपलब्धता को कुछ हद तक ऐसी सब्जी फसलों के प्रजनन द्वारा दूर किया जा सकता है जिनमें अनिश्चित वृद्धि प्रकृति हो और जो संरक्षित संरचनाओं में अधिक उत्पादन दे सके। इससे गुणवत्तापूर्ण उत्पादन की अवधि बढ़ाने तथा प्रति इकाई क्षेत्र उत्पादकता बढ़ाने में सहायता मिलेगी। इसके अतिरिक्त, विशेष रूप से सोलेनेसी तथा कुकर्बिटेसी फसलों में अत्यधिक जैविक, जलवायवीय एवं मृदा-संबंधी समस्याओं से निपटने के लिए ग्राफ्टिंग तथा रूटस्टॉक प्रजनन महत्वपूर्ण उभरती रणनीति है। समग्र रूप में, उपभोक्ता और उद्योग-विशिष्ट प्राथमिकताओं के लिए परंपरागत एवं अत्याधुनिक प्रजनन तकनीकों, स्पीड ब्रीडिंग सुविधाओं तथा सटीक फीनोटाइपिंग को एकीकृत करने की आवश्यकता होगी, ताकि अधिक उपज देने वाली, गुणवत्तापरक, जलवायु-सहनशील और बाजार-विशिष्ट सब्जी किस्मों का विकास किया जा सके तथा उपभोक्ताओं, उत्पादकों, प्रसंस्करण उद्योग और निर्यातकों की भविष्य की आवश्यकताओं को पूरा किया जा सके।