

ADVANCED BREEDING HORIZONS FOR QUALITY AND NUTRITIONAL ENHANCEMENT IN SOLANACEOUS VEGETABLES: A COMPREHENSIVE REVIEW

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ABSTRACT

Solanaceous vegetables, including tomato (*Solanum lycopersicum* L.), brinjal (*Solanum melongena* L.), chilli and pepper (*Capsicum spp.*) and potato (*Solanum tuberosum* L.), constitute some of the most important vegetable crops worldwide owing to their nutritional, economic and health-promoting value. Traditionally, breeding programmes have focused primarily on increasing yield; however, growing consumer awareness regarding nutrition, taste, processing quality and health benefits has shifted breeding objectives toward quality improvement. Quality in vegetables encompasses a wide range of attributes, including morphological, organoleptic, nutritional, processing and storage characteristics. Important quality traits in solanaceous vegetables include fruit colour, firmness, total soluble solids, vitamin C, carotenoids, capsaicin, anthocyanins, protein content, shelf life and processing suitability. The genetic control of these traits is often complex, involving oligogenic, polygenic and maternal inheritance. Consequently, diverse breeding strategies have been employed to enhance quality attributes. Conventional approaches such as selection, hybridization, interspecific hybridization and mutation breeding have contributed significantly to the development of quality-improved cultivars. In addition, modern biotechnological tools including marker-assisted selection, QTL mapping, genomic selection, genetic engineering and genome editing have accelerated the identification, transfer, and manipulation of genes governing quality traits. The development of transgenic crops and the advent of CRISPR/Cas-based genome editing technologies have opened new avenues for precise quality enhancement. Despite significant progress, challenges such as negative associations between yield and quality, environmental influences and low heritability of certain traits continue to hinder breeding efforts. Integration of conventional and molecular breeding approaches offers immense potential for developing nutritionally superior, consumer-preferred, and climate-resilient solanaceous vegetable cultivars capable of meeting future food and nutritional security demands.

KEYWORDS: Solanaceous vegetables; Quality improvement; Tomato; Brinjal; Chilli; Potato; Nutritional quality; Marker-assisted selection; Genetic engineering; Genome editing; CRISPR/Cas9; Hybridization; Mutation breeding; Lycopene; Capsaicin.

INTRODUCTION

The family Solanaceae represents one of the most economically important groups of vegetable crops and comprises nearly 85 genera and over 2,500 species distributed worldwide. It includes both tuberiferous crops such as potato (*Solanum tuberosum* L.) and non-tuberiferous crops such as tomato (*Solanum lycopersicum* L.), brinjal (*Solanum melongena* L.), chilli and sweet pepper (*Capsicum spp.*). Solanaceous vegetables contribute significantly to human nutrition owing to their richness in vitamins, minerals, dietary fiber, antioxidants, and several bioactive compounds. These crops are important sources of vitamin C, provitamin A carotenoids, phenolics, flavonoids, and other nutraceutical compounds that promote human health and help prevent chronic diseases. According to Kalloo (1993), solanaceous vegetables have gained immense importance not only because of their economic value but also due to their nutritional and medicinal significance. Similarly, Prohens et al. (2019) reported that the increasing consumer demand for nutritious and health-promoting foods has further enhanced the importance of quality improvement in solanaceous crops.

Traditionally, vegetable breeding programmes concentrated primarily on increasing yield and developing resistance against pests, diseases, and environmental stresses. However, modern consumers increasingly demand vegetables with superior appearance, enhanced flavour, better texture, improved nutritional composition, and longer shelf life. Consequently, quality improvement has become one of the major objectives of vegetable breeding programmes. Kader (2008) emphasized that quality attributes strongly influence consumer preference, market acceptance, processing suitability, and export potential. Therefore, breeding for quality has become an indispensable component of modern crop improvement programmes.

Quality in solanaceous vegetables is a complex and multidimensional trait encompassing physical, sensory, nutritional, biochemical, functional, and post-harvest attributes. Physical characteristics such as fruit size, shape, colour, uniformity, firmness, and freedom from defects are important determinants of market value. Sensory characteristics, including flavour, aroma, sweetness, acidity, texture, and pungency, are particularly important for consumer acceptance. Nutritional quality is largely determined by the concentration and composition of vitamins, minerals, carotenoids, phenolic compounds, flavonoids, anthocyanins, and other health-promoting phytochemicals. In addition, post-harvest quality traits such as firmness, resistance to physiological deterioration, delayed ripening, reduced moisture loss, and extended shelf life are essential for minimizing losses during storage, transportation, and marketing. Thus, quality improvement requires the simultaneous consideration of multiple traits rather than the improvement of a single characteristic.

Among solanaceous vegetables, tomato, brinjal, chilli, sweet pepper, and potato exhibit substantial genetic variation for economically important quality attributes. Tomato provides an important source of lycopene, β -carotene, vitamin C, flavonoids, and other antioxidant compounds, while brinjal is characterized by considerable variation in fruit colour, phenolic content, anthocyanins, texture, and fruit shape. Chilli and sweet pepper possess diverse pungency levels, colours, carotenoid profiles, vitamin C contents, and flavour characteristics. Potato quality is determined by traits such as dry matter, starch content, reducing sugars, processing quality, texture, and nutritional composition. The wide diversity present within these crops provides valuable opportunities for developing cultivars combining high productivity with improved nutritional, sensory, processing, and storage qualities.

The genetic improvement of quality traits is, however, challenging because many quality attributes are quantitative in inheritance and strongly influenced by genotype $\times$ environment interactions. Traits such as soluble solids, vitamin content, antioxidant activity, fruit firmness, sugar–acid balance, and phytochemical accumulation are often controlled by several genes and are affected by environmental conditions, crop management, developmental stage, and post-harvest handling. In addition, improvement of one quality component may sometimes be associated with undesirable changes in other agronomic or quality characteristics. For example, selection for increased fruit size or yield may affect flavour, firmness, or nutritional composition. Therefore, effective breeding strategies require the identification and utilization of genetic variation, understanding of trait inheritance, and simultaneous selection for multiple desirable attributes.

Conventional breeding approaches, including introduction, selection, hybridization, pedigree breeding, backcrossing, heterosis breeding, mutation breeding, and wide hybridization, have contributed substantially to the development of improved solanaceous cultivars. These approaches have enabled breeders to combine desirable agronomic performance with improved fruit quality, nutritional value, processing characteristics, and resistance to biotic and abiotic stresses. The utilization of wild relatives and landraces has further expanded the genetic base available for quality improvement. Interspecific hybridization has been particularly useful for transferring novel alleles for nutritional, processing, and post-harvest traits from related wild species into cultivated backgrounds.

Recent advances in quantitative genetics, genomics, molecular marker technology, and high-throughput phenotyping have substantially increased the efficiency of quality-oriented breeding. Quantitative trait locus (QTL) mapping has enabled the identification of genomic regions associated with important quality attributes, while molecular markers linked to favourable alleles facilitate their selection at early stages of plant development. Marker-assisted selection (MAS) and marker-assisted backcross breeding (MABB) have therefore become useful approaches for incorporating specific quality traits into elite genetic backgrounds. In addition, genomic selection provides an opportunity to predict breeding values for complex traits controlled by many genes, thereby accelerating the selection process.

The increasing availability of reference genomes, transcriptomic information, metabolomic profiles, and genome-wide molecular markers has further enhanced understanding of the genetic and biochemical basis of vegetable quality. Candidate genes involved in pigment biosynthesis, carotenoid accumulation, sugar metabolism, cell-wall modification, flavour formation, capsaicinoid biosynthesis, starch metabolism, and other quality-related pathways have been identified in different solanaceous crops. Functional genomics and gene-expression studies have provided insights into the molecular mechanisms regulating these traits, creating opportunities for more precise manipulation of quality characteristics.

Modern breeding has also expanded beyond conventional selection and marker-assisted approaches through the application of genome editing, transgenic approaches, speed breeding, and genomic-assisted selection. Genome-editing technologies, particularly CRISPR/Cas-based systems, offer opportunities to modify specific genes associated with fruit ripening, nutritional composition, plant architecture, metabolite accumulation, and post-harvest characteristics. Such approaches can complement conventional breeding by enabling targeted modification of specific traits while reducing the need for extensive linkage drag. Nevertheless, regulatory requirements, biosafety considerations, consumer acceptance, and the complexity of quality traits remain important considerations in the deployment of advanced breeding technologies.

Another important dimension of quality improvement is the development of cultivars suited to processing, value addition, and changing consumer preferences. The requirements of fresh-market vegetables differ considerably from those of processing industries. For example, processing tomato requires appropriate soluble solids, colour, firmness, viscosity, and suitable processing characteristics, whereas fresh-market tomato may require attractive appearance, balanced flavour, firmness, and extended shelf life. Similarly, potato breeding requires attention to cooking quality, starch properties, reducing sugars, and acrylamide-related processing characteristics. Chilli and sweet pepper breeding increasingly emphasizes colour, pungency, carotenoid composition, vitamin content, and suitability for fresh and processed products.

Climate change and the intensification of production systems have further complicated quality improvement. High temperature, drought, salinity, irregular rainfall, and other environmental stresses can alter fruit development and the

accumulation of nutritional and bioactive compounds. Therefore, future breeding programmes need to integrate quality improvement with tolerance to abiotic stresses and stable yield performance. Developing cultivars that maintain nutritional and sensory quality under variable environmental conditions will be particularly important for sustainable vegetable production.

In this context, an integrated understanding of conventional breeding, genetic resources, inheritance of quality traits, QTL mapping, molecular markers, marker-assisted breeding, genomic selection, functional genomics, and genome editing is essential for accelerating the development of quality-enhanced solanaceous vegetables. A comprehensive assessment of these approaches can help identify the progress achieved, major limitations, emerging technologies, and future opportunities for improving nutritional, sensory, processing, and post-harvest quality. Therefore, the present review focuses on the breeding strategies employed for quality improvement in major solanaceous vegetable crops, with particular emphasis on conventional and molecular breeding approaches, important quality traits, genetic and genomic resources, target genes and QTLs, and emerging technologies for developing nutritionally superior, consumer-preferred, and value-added cultivars.

Concept of Quality and Quality Traits

Quality can be defined as the degree of excellence or suitability of a product for its intended use. In vegetable crops, quality refers to a combination of attributes that determine the acceptability of produce by consumers, processors, traders and growers. According to Ryder (1998), vegetable quality encompasses visual appearance, texture, flavour, nutritional value, shelf life and processing characteristics. Since different stakeholders may have different expectations, the concept of quality varies depending on the end use of the crop.

A trait that contributes to any aspect of produce quality is termed a quality trait. Such traits may be controlled by one or several genes and are often influenced by environmental conditions. Quality traits determine the market value and consumer acceptance of vegetables and therefore serve as important targets in crop improvement programmes. Kader (2008) reported that quality traits have become increasingly important because of growing consumer awareness regarding nutrition, food safety and health benefits.

Classification of Quality Traits

Quality traits in vegetables can be broadly classified into five major groups: morphological traits, organoleptic traits, nutritional traits, undesirable traits, and other post-harvest-related traits. This classification helps breeders identify specific targets for quality improvement and develop cultivars suited to different market requirements.

Morphological Traits

Morphological traits refer to the visible external characteristics of vegetable produce. These include fruit shape, size, colour, surface texture, firmness, and pericarp thickness. Such traits largely determine the visual appeal and marketability of vegetables. Consumers often make purchasing decisions based on appearance, making morphological traits crucial quality parameters. In tomato and brinjal, fruit shape and colour are among the most important selection criteria influencing consumer preference. Kalloo (1993) reported that attractive fruit appearance significantly enhances market acceptance and commercial value.

Organoleptic Traits

Organoleptic traits are sensory characteristics perceived by consumers through taste, smell, touch, and sight. These include flavour, aroma, sweetness, acidity, pungency, and texture. Such traits directly influence consumer satisfaction and repeat purchases. In tomato, flavour is determined by the interaction of sugars, organic acids, and volatile compounds, whereas pungency in chilli is primarily governed by capsaicin content. Baldwin et al. (2000) highlighted that flavour-related traits are among the most important determinants of consumer acceptance in fresh vegetables.

Nutritional Traits (Nutraceutical Traits)

Nutritional quality refers to the concentration of essential nutrients and health-promoting compounds present in vegetables. Important nutritional traits include vitamin C, β -carotene, lycopene, capsanthin, proteins, minerals, antioxidants, and total soluble solids (TSS). These compounds contribute significantly to human nutrition and disease prevention. Rao and Rao (2007) reported that carotenoids such as lycopene and β -carotene possess strong antioxidant properties and reduce the risk of several chronic diseases. Consequently, breeding programmes increasingly focus on enhancing the nutraceutical value of solanaceous vegetables.

Undesirable Traits

Undesirable traits are characteristics that negatively affect consumer acceptance, processing suitability, or food safety. Examples include excessive glycoalkaloid content in potato, browning, seediness, fruit cracking, bitterness, and excessive pungency. These traits reduce product quality and market value. In potato, high solanine concentration is considered undesirable because of its toxic effects on human health. Therefore, breeders aim to minimize such undesirable traits while maintaining yield and other desirable characteristics.

Other Quality Traits

Other quality traits include characteristics related to storage, transportation, processing, and cooking performance. These traits comprise keeping quality, shelf life, cooking quality, transportability, and processing suitability. Such attributes are increasingly important because of the expansion of food processing industries and long-distance transportation

systems. According to Kader (2008), improved post-harvest quality contributes significantly to reducing losses and increasing profitability across the supply chain.

Importance of Breeding for Quality Improvement

Quality improvement has become a major objective in modern vegetable breeding because it directly influences consumer satisfaction, market demand, nutritional security, and industrial utilization. Breeding for quality helps farmers obtain premium prices for their produce and increases competitiveness in domestic and export markets. Improved quality vegetables often command higher market value, thereby enhancing farm profitability. Kalloo (1993) emphasized that quality breeding not only benefits consumers through superior produce but also improves economic returns to growers.

The growing awareness of nutrition and health has further increased the importance of quality breeding. Nutrient-rich vegetables contribute to food and nutritional security by supplying essential vitamins, minerals, and antioxidants required for healthy living. Dias (2012) reported that consumption of nutrient-dense vegetables plays a vital role in reducing micronutrient deficiencies and improving public health.

Breeding for quality also supports the processing industry by developing cultivars with higher TSS, improved colour, enhanced pigment content, and better processing characteristics. Such cultivars are preferred for the manufacture of sauces, purees, dehydrated products, and processed foods. Thus, quality improvement has become an essential strategy for meeting the demands of producers, processors, retailers, and consumers.

Quality Traits of Major Solanaceous Vegetables

The quality attributes targeted in breeding programmes differ among solanaceous crops depending on their end use. In tomato, important quality traits include total soluble solids, lycopene content, vitamin C content, fruit firmness, acidity, colour, and shelf life. In brinjal, breeders focus on fruit colour, glossiness, texture, low seed content, and phenolic composition. Chilli quality is determined by capsaicin content, capsanthin concentration, oleoresin content, colour value, and vitamin C. Sweet pepper breeding programmes emphasize sweetness, carotenoid concentration, vitamin C content, fruit firmness, and storage quality. In potato, important quality traits include dry matter content, starch content, reducing sugars, processing quality, cooking quality, and low glycoalkaloid concentration. According to Bradshaw and Ramsay (2009), these crop-specific quality attributes are essential for satisfying consumer and industrial requirements.

Genetics of Quality Traits

Quality traits are important breeding targets in solanaceous vegetables because they directly influence consumer preference, nutritional value, processing quality, and marketability. The inheritance of quality traits is often complex and may be controlled by one or a few major genes, several minor genes, cytoplasmic factors, or maternal effects. Understanding the genetic basis of quality traits is essential for selecting suitable breeding methods and developing improved cultivars. According to Allard (1999), the inheritance pattern of a trait determines the efficiency of selection and the breeding strategy to be adopted. In solanaceous vegetables, quality traits such as fruit colour, capsaicin content, lycopene concentration, vitamin content, total soluble solids, and anthocyanin pigmentation are governed by different genetic mechanisms. Therefore, knowledge of gene action and inheritance patterns provides the foundation for quality improvement programmes.

Oligogenic Inheritance

Oligogenic inheritance refers to the control of a trait by one or a few major genes having distinct phenotypic effects. Such traits generally exhibit discontinuous variation and are relatively easy to transfer through breeding. Several quality traits in solanaceous vegetables are controlled by major genes. Fruit colour in tomato, anthocyanin pigmentation in brinjal, and capsaicin production in chilli are examples of traits influenced by a small number of genes. Tanksley (2004) reported that major genes controlling carotenoid biosynthesis and fruit pigmentation have been extensively utilized in tomato improvement programmes. Oligogenic traits are generally amenable to simple selection procedures because the desired phenotype can be identified easily in segregating populations.

Polygenic Inheritance

Many economically important quality traits are quantitatively inherited and controlled by numerous genes with small additive effects. Such traits exhibit continuous variation and are greatly influenced by environmental conditions. Total soluble solids, vitamin C content, fruit firmness, carotenoid concentration, dry matter content, and flavour components are examples of polygenic traits in solanaceous vegetables. Polygenic inheritance makes selection more challenging because phenotypic expression depends on both genetic and environmental factors. Falconer and Mackay (1996) emphasized that quantitative traits require large populations and repeated evaluations across environments for effective genetic improvement. Modern breeding tools such as QTL mapping and genomic selection have greatly facilitated the improvement of polygenic quality traits.

Maternal Effects

Maternal effects occur when the phenotype of the offspring is influenced by the genotype or environment of the maternal parent. In vegetable crops, maternal effects may influence seed quality, fruit characteristics, nutrient accumulation, and certain biochemical traits. Reciprocal crosses are often used to determine the magnitude of maternal influence on trait inheritance. According to Singh (2015), maternal effects should be carefully considered while planning hybridization programmes because the direction of crossing may significantly influence the expression of quality attributes.

Inheritance Pattern of Quality Attributes

The inheritance of quality attributes in solanaceous vegetable crops is complex and varies considerably among traits, crops and parental combinations. Quality traits such as total soluble solids (TSS), titratable acidity, ascorbic acid, dry matter, carotenoids, lycopene, reducing sugars, capsaicin, oleoresin, fruit colour and starch content are governed by both additive and non-additive gene actions. The relative contribution of these gene effects determines the effectiveness of different breeding strategies for improving nutritional, biochemical and processing-quality characteristics. Additive gene action is particularly useful for selection and fixation of desirable alleles, whereas dominance and epistatic interactions contribute substantially to heterosis and hybrid performance. In tomato, several quality traits, including TSS, ascorbic acid, lycopene and reducing sugars, have been reported to exhibit varying degrees of additive, dominance and epistatic effects. Similarly, capsaicin and oleoresin content in chilli may show predominantly additive inheritance in certain crosses, while dominance, over-dominance and epistatic interactions have also been reported. In brinjal, fruit colour and anthocyanin pigmentation are influenced by additive, dominance and epistatic effects depending on the genetic background. Potato quality traits such as dry matter, reducing sugars, specific gravity and starch content likewise exhibit differences in the relative importance of additive and non-additive gene action. Table 1 summarizes the reported inheritance patterns and gene action governing major quality attributes in important solanaceous vegetable crops.

Table1. Inheritance pattern of important quality attributes in solanaceous vegetables

Quality attribute	Reported gene action / inheritance pattern	Crop	Reference
Total soluble solids (TSS)	Non-additive; dominance and epistatic effects important	Tomato	Bhatt et al. (2001); Singh et al. (2021)
Titratable acidity	Non-additive; additive $\times$ additive and dominance-related effects reported	Tomato	Chauhan et al. (2019); Kaur et al. (2022)
Ascorbic acid	Additive and non-additive effects; dominance and epistasis also reported	Tomato	Bhatt et al. (2001); Chauhan et al. (2019)
Dry matter content	Predominantly non-additive/over-dominance reported in some studies	Tomato	El-Shazly et al.
Lycopene	Additive and non-additive effects; dominance and epistasis reported	Tomato	Chauhan et al. (2019); Kaur et al. (2022)
Carotenoids / β -carotene	Predominantly dominance/over-dominance in some genetic backgrounds	Tomato	Singh et al. (2021)
Reducing sugars	Non-additive; dominance and epistatic effects important	Tomato	Kaur et al. (2022)
Capsaicin content	Predominantly additive in some crosses; epistasis and over-dominance also reported	Chilli	Zewdie & Bosland (2000); Asha et al. (2019)
Oleoresin content	Predominantly additive	Chilli	Asha et al. (2019)
Anthocyanin pigmentation / fruit colour	Dominance and epistatic effects reported	Brinjal	Sidhu et al. (2022)
Fruit colour	Additive, dominance and epistatic effects depending on cross	Brinjal	Sidhu et al. (2022)
Dry matter content	Predominantly additive; both additive and non-additive effects have been reported	Potato	Manivel et al. (2010); Namugga et al. (2020)
Reducing sugars	Predominantly non-additive; both additive and non-additive effects reported	Potato	Namugga et al. (2020)
Specific gravity	Predominantly additive in recent genetic analyses	Potato	Genetic control studies of tetraploid potato (2025)
Starch content	Additive and non-additive effects reported	Potato	Genetic studies of potato processing quality
Chip colour	Influenced by genetic control of reducing sugars and dry matter	Potato	Manivel et al. (2010); Paul et al. (2025)

Shankar et al. (2013) reported the predominance of non-additive gene action for TSS, acidity, and ascorbic acid content in tomato, suggesting the usefulness of heterosis breeding for quality improvement. Similarly, Hazra et al. (2012) observed the importance of dominant and over-dominant gene action in determining carotenoid and nutritional quality traits in tomato. In chilli, additive gene action has been reported for capsaicin and vitamin content, indicating that pedigree selection and recurrent selection can be effectively utilized for quality enhancement (Zewdie and Bosland, 2000).

Sources of Quality Traits

The success of a quality breeding programme depends largely on the availability of suitable genetic variability. Sources of quality traits may be obtained from cultivated varieties, germplasm collections, wild relatives, induced mutants, and transgenic materials. Cultivated varieties often possess desirable agronomic characteristics and acceptable quality levels, whereas germplasm accessions and wild species serve as reservoirs of novel genes for quality improvement. Mutants and transgenic lines provide additional opportunities for introducing unique quality attributes not readily available in cultivated gene pools.

Wild relatives have played a major role in improving nutritional quality in solanaceous vegetables. For example, wild tomato species such as *Solanum pimpinellifolium* and *Solanum habrochaites* have been used as sources of high lycopene content, disease resistance, and improved flavour. Similarly, wild *Capsicum* species have contributed genes for enhanced capsaicin content and fruit colour. According to Prohens et al. (2017), wild germplasm remains an invaluable resource for broadening the genetic base of cultivated vegetables and improving quality traits.

Breeding Approaches for Quality Improvement in Solanaceous Vegetables

Quality improvement in solanaceous vegetables has been achieved through both conventional and modern breeding approaches. The choice of breeding method depends on the nature of inheritance of the target trait, availability of genetic variability, breeding objectives, and resources available. Conventional breeding methods such as selection, hybridization, interspecific hybridization, and mutation breeding have played a pivotal role in improving fruit colour, nutritional composition, flavour, processing quality, shelf life, and nutraceutical content. In recent years, molecular breeding and genetic engineering have accelerated the development of quality-enhanced cultivars.

Selection

Selection is the simplest and oldest breeding method used for quality improvement. It involves identifying superior plants from genetically variable populations and advancing them through successive generations. Selection is particularly effective for traits governed predominantly by additive gene action. According to Allard (1999), selection in random mating populations increases the frequency of favourable alleles but does not completely eliminate undesirable alleles. However, when combined with selfing and progeny testing, selection can efficiently fix desirable quality traits.

In solanaceous vegetables, selection has been extensively used for improving fruit colour, total soluble solids, vitamin C content, pungency, dry matter content, and processing quality. Traditional landraces and germplasm collections have served as valuable sources of variation for quality improvement. Several tomato cultivars with high TSS and processing quality have been developed through recurrent selection programmes. Similarly, selection has been used to develop chilli varieties with enhanced capsaicin content and improved colour value.

For example, the tomato variety Pusa Ruby was selected for attractive red fruit colour and good processing quality, whereas Arka Vikas possesses desirable TSS and adaptability. In chilli, varieties such as Pusa Jwala and Kashi Anmol were selected for superior pungency and quality attributes (Singh, 2015).

Hybridization

Hybridization is an important breeding method for combining desirable quality traits from genetically diverse parents. It exploits heterosis and recombination to develop superior solanaceous vegetable genotypes with improved nutritional, biochemical and sensory quality. Non-additive gene action reported for several quality traits makes heterosis breeding particularly useful in tomato, chilli and brinjal. Shankar et al. (2013) reported significant heterosis for TSS, acidity and ascorbic acid content in tomato hybrids. Hybridization has also contributed to improvement in fruit firmness, lycopene, colour, flavour and shelf life. Selected examples of solanaceous cultivars and hybrids with improved quality attributes are presented in Table 2.

Table 2. Selected solanaceous vegetable cultivars/hybrids with improved quality attributes

Crop	Hybrid/Variety	Quality trait improved / important quality characteristics	Reference
Tomato	Arka Rakshak	Fruit firmness, lycopene content and marketable shelf life	Dheemanth et al. (2020)
Tomato	Pusa Hybrid-2	Total soluble solids (TSS), acidity and fruit quality	Sivakumar et al. (2002)
Chilli	Arka Meghana	Fruit colour, pungency and fresh/dry fruit quality	ICAR-IIHR (2026)
Brinjal	Arka Navneet	Attractive deep-purple fruit colour, soft flesh, fewer seeds and good cooking quality	KAU Agri Infotech Portal (2026)
Sweet	Bharat	Fruit quality and nutritional	ICAR-IIHR varietal

pepper		characteristics	information
Potato	Kufri Chipsona-1	High dry matter, low reducing sugars, acceptable chip colour and processing quality	Marwaha et al. (2010); Paul et al. (2021)
Potato	Kufri Chipsona-3	High dry matter, low reducing sugars and light-coloured chips	Marwaha et al. (2010); Paul et al. (2021)
Potato	Kufri Frysona	High dry matter, low reducing sugars, excellent French-fry colour, crispness and processing quality	Singh et al. (2010); Paul et al. (2021)
Potato	Kufri Himsona	High dry matter and low reducing sugar content, suitable for processing	Paul et al. (2021)
Tomato	Arka Vishesh	High lycopene, TSS, firmness and processing quality	ICAR-IIHR (2024)
Tomato	Arka Apeksha	High lycopene, TSS, firmness and processing quality	ICAR-IIHR (2024)

Interspecific Hybridization

Interspecific hybridization involves crossing different species belonging to the same genus. Wild relatives are rich reservoirs of genes controlling nutritional quality, flavour compounds, pigments, antioxidants, and disease resistance. Tomato breeders have extensively utilized wild species such as *Solanum pimpinellifolium*, *S. cheesmaniae*, *S. habrochaites* and *S. pennellii* for improving quality traits. High β -carotene content was successfully transferred through crosses involving *Lycopersicon hirsutum* and cultivated tomato. Similarly, genes for increased lycopene concentration and enhanced antioxidant activity have been introgressed from wild tomato species (Rick, 1974). In chilli, the interspecific cross *Capsicum annum* $\times$ *Capsicum chinense* produced progenies with higher capsaicin content (0.92%), oleoresin content (34.4%), and colour value (58.62%) than cultivated parents (Zewdie and Bosland, 2000). Brinjal improvement programmes have utilized wild species such as *Solanum incanum*, *S. aethiopicum*, and *S. macrocarpon* as sources of anthocyanins, phenolics, and antioxidants (Prohens et al., 2017).

Table 3. Important quality traits contributed through interspecific hybridization in solanaceous vegetables

Crop	Wild species	Quality trait	Breeding significance	Reference
Tomato	<i>Solanum habrochaites</i>	β -carotene, carotenoids, antioxidant compounds and flavour-related traits	Provides useful allelic variation for fruit nutritional quality and flavour-related metabolites	Gürbüz Çolak et al. (2020); Causse et al. (2023)
Tomato	<i>Solanum pennellii</i>	Total soluble solids (TSS), sugars and fruit flavour	Important source of alleles for improving soluble solids and fruit metabolic composition	Eshed & Zamir (1995); Causse et al. (2023)
Tomato	<i>Solanum pimpinellifolium</i>	Lycopene, vitamin C, phenolics and antioxidant capacity	Widely used wild donor for improving nutritional and antioxidant quality	Gürbüz Çolak et al. (2020)
Tomato	<i>Solanum chmielewskii</i>	High soluble-solids content and fruit quality	Useful source for increasing TSS and improving processing characteristics	Causse et al. (2023)
Chilli	<i>Capsicum chinense</i>	Capsaicin, total capsaicinoids and oleoresin	Introgression can enhance pungency and oleoresin-related quality	Asha et al. (2019); Tripodi et al. (2016)
Chilli	<i>Capsicum frutescens</i>	Pungency and fruit colour	Provides allelic variation for capsaicinoid accumulation and fruit pigmentation	Tripodi et al. (2016); Ha et al. (2021)
Chilli	<i>Capsicum baccatum</i>	Carotenoids, fruit colour and antioxidant compounds	Useful genetic resource for broadening nutritional and pigment diversity	Ha et al. (2021)
Brinjal	<i>Solanum incanum</i>	Phenolics, anthocyanins and antioxidant-related traits	Wild relative provides genetic diversity for fruit biochemical quality and stress-associated traits	Gramazio et al. (2016); Barchi et al. (2019)
Brinjal	<i>Solanum aethiopicum</i>	Phenolics, antioxidant capacity and fruit	Important source of diversity for nutritional and functional quality	Barchi et al. (2019); Dabbou et al. (2023)

		biochemical composition		
Brinjal	<i>Solanum macrocarpon</i>	Phenolic compounds and antioxidant potential	Can contribute novel alleles for nutritional quality improvement	Dabbou et al. (2023)
Potato	<i>Solanum chacoense</i>	Dry matter, starch and processing-related traits	Important wild source for improving tuber quality and processing characteristics	Bradshaw et al. (2008); Jansky et al. (2016)
Potato	<i>Solanum commersonii</i>	Cold-induced sweetening and processing quality	Provides alleles associated with adaptation to cold storage and reduced sugar accumulation	Li et al. (2018); Jansky et al. (2016)
Potato	<i>Solanum berthaultii</i>	Dry matter, tuber quality and processing-related traits	Broadens the genetic base for tuber quality and other agronomic traits	Jansky et al. (2016)

Mutation Breeding

Mutation breeding creates new genetic variability through spontaneous or induced mutations and is particularly useful when desirable variation is absent in available germplasm. Physical mutagens such as gamma rays and X-rays and chemical mutagens such as EMS and sodium azide have been used to generate useful mutants. In solanaceous vegetables, mutation breeding has contributed to improvement of fruit colour, carotenoids, nutritional quality, shelf life and processing quality. In tomato, mutant genes such as high pigment (hp), old gold crimson (ogc), Beta (B) and crimson (og) have been associated with increased lycopene and β -carotene accumulation. Combinations of hp and Beta genes have further enhanced antioxidant and carotenoid concentrations in tomato fruits (Hazra et al., 2012). Important mutant genes/loci and mutant-derived varieties used for quality improvement are summarized in Tables 4 and 5, respectively.

Table 4. Important mutant genes/loci used in quality improvement of tomato

Mutant gene/locus	Crop	Trait improved	Major quality effect	Reference
hp-1 (high pigment-1)	Tomato	Lycopene, carotenoids and antioxidants	Enhances fruit pigmentation and increases carotenoid accumulation, particularly lycopene	Azari et al. (2010); Bovy et al. (2002)
hp-2 (high pigment-2)	Tomato	Lycopene, β -carotene and antioxidant content	Increases carotenoid accumulation and intensifies fruit colour	Bino et al. (2005); Azari et al. (2010)
og (old-gold)	Tomato	Carotenoid composition and fruit colour	Alters carotenoid biosynthesis, resulting in orange/golden fruit pigmentation	Isaacson et al. (2002)
og ^c (old-gold crimson)	Tomato	Lycopene and deep-red fruit colour	Increases lycopene accumulation and produces intense crimson-red fruit colour	Liu et al. (2003); Bovy et al. (2002)
B (Beta)	Tomato	β -carotene content	Increases β -carotene accumulation by increasing lycopene β -cyclase activity	Ronen et al. (2000)
B-2	Tomato	β -carotene and provitamin-A content	Enhances conversion of lycopene toward β -carotene	Ronen et al. (2000); Stanley & Ginzberg (2011)
rin (ripening inhibitor)	Tomato	Shelf life and firmness	Delays ripening, softening and colour development, thereby extending postharvest life	Giovannoni (2007); Qin et al. (2012)
nor (non-ripening)	Tomato	Shelf life and firmness	Strongly delays ripening and reduces softening, extending fruit storage life	Giovannoni (2007); Vrebalov et al. (2002)
Nr (Never-ripe)	Tomato	Ripening and shelf life	Reduces ethylene responsiveness and delays ripening and softening	Lanahan et al. (1994); Giovannoni (2007)
Cnr (colourless non-)	Tomato	Fruit colour and ripening	Produces abnormal ripening and reduced pigmentation, with prolonged firmness	Manning et al. (2006); Giovannoni (2007)

ripening)				
alc (alcobaca)	Tomato	Shelf life and firmness	Delays fruit softening and extends postharvest storage life while allowing relatively normal colour development	Al-Hamad et al. (2020)
Nr/rin combination	Tomato	Extended shelf life	Combines reduced ethylene responsiveness with delayed ripening and softening	Giovannoni (2007)

Table 5. Released mutant-derived varieties

Variety	Crop	Improved quality trait	Reference
Arka Ahuti	Tomato	Thick flesh, high TSS (5.2–5.25%), uniform ripening and suitability for processing/puree	ICAR-IIHR (2024)
Arka Ashish	Tomato	Excellent fruit colour, lycopene (10 mg/100 g), TSS (4.8%) and suitability for ketchup, juice and puree	ICAR-IIHR (2024)
Punjab Lal	Chilli	Dark-red colour, high pungency, capsaicin (~0.96%), oleoresin and suitability for powder production	Thakur et al. (1987); PAU (2026)
Pusa Sadabahar	Chilli	Dark-red fruit colour, high pungency and good green/dry fruit quality	IARI (2014)

Non-Conventional Breeding Approaches for Quality Improvement

Marker-Assisted Selection (MAS)

Marker-assisted selection (MAS) is a molecular breeding technique that utilizes DNA markers closely linked to genes or quantitative trait loci (QTLs) controlling desirable traits. Unlike conventional selection, which depends on phenotypic expression, MAS allows breeders to identify plants carrying favourable alleles at an early growth stage. This approach is particularly useful for quality traits that are difficult, expensive, or time-consuming to evaluate through conventional methods. Molecular markers such as RFLP, RAPD, AFLP, SSR, and SNP markers have greatly improved the efficiency and accuracy of breeding programmes by facilitating indirect selection of superior genotypes.

In solanaceous vegetables, MAS has been successfully employed for improving fruit quality attributes including lycopene content, β -carotene concentration, vitamin C content, fruit firmness, shelf life, capsaicin content, and anthocyanin pigmentation. In tomato, markers linked to high pigment (hp), Beta (B), and old gold crimson (ogc) genes have enabled breeders to develop nutritionally enhanced cultivars. Similarly, markers associated with pungency and colour value have been used in chilli improvement programmes. Compared with conventional breeding, MAS reduces breeding cycles, minimizes environmental influences on selection, and accelerates the development of superior cultivars possessing multiple quality traits simultaneously (Collard & Mackill, 2008). Figure 1 illustrates the major steps involved in marker-assisted selection for improving tomato quality traits.

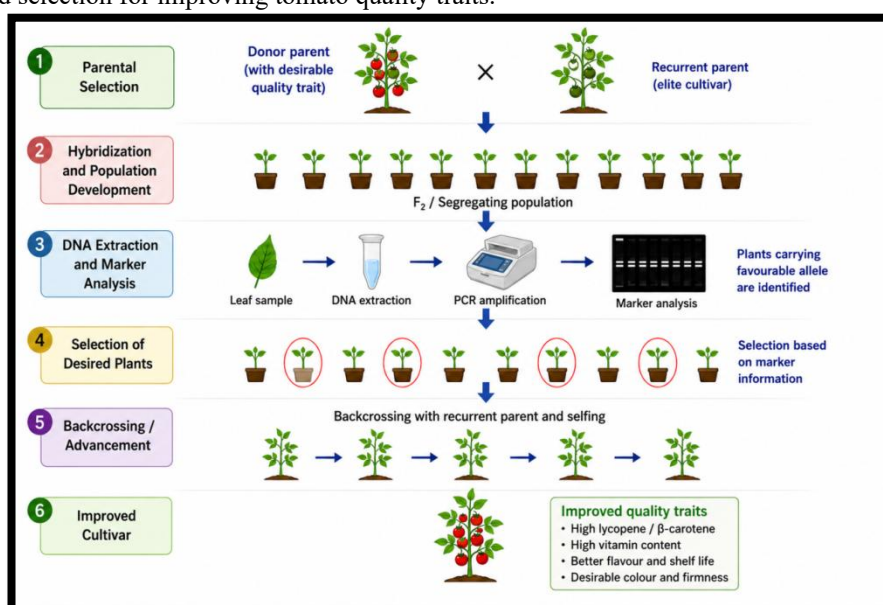


Figure 1. Marker-Assisted Selection (MAS) for tomato quality improvement

Quantitative Trait Loci (QTL) Mapping

Most economically important quality traits in vegetable crops are quantitative in nature and controlled by multiple genes. Quantitative trait loci (QTL) mapping is a molecular approach used to identify genomic regions associated with

the expression of complex traits. QTL analysis helps breeders understand the genetic architecture of quality traits and provides valuable information for marker-assisted breeding programmes. Identification of major QTLs enables precise transfer of favourable alleles into elite cultivars. Several QTLs associated with fruit quality have been identified in tomato, chilli, brinjal, and potato. In tomato, QTLs controlling total soluble solids, fruit firmness, carotenoid accumulation, lycopene concentration, flavour compounds, and shelf life have been extensively characterized. The identification of these genomic regions has facilitated the development of superior cultivars with enhanced nutritional and processing quality. Tanksley (2004) reported that wild tomato species possess numerous favourable QTLs that can significantly improve fruit quality in cultivated tomato through introgression breeding. Figure 2 illustrates the major steps involved in QTL mapping for tomato quality traits.

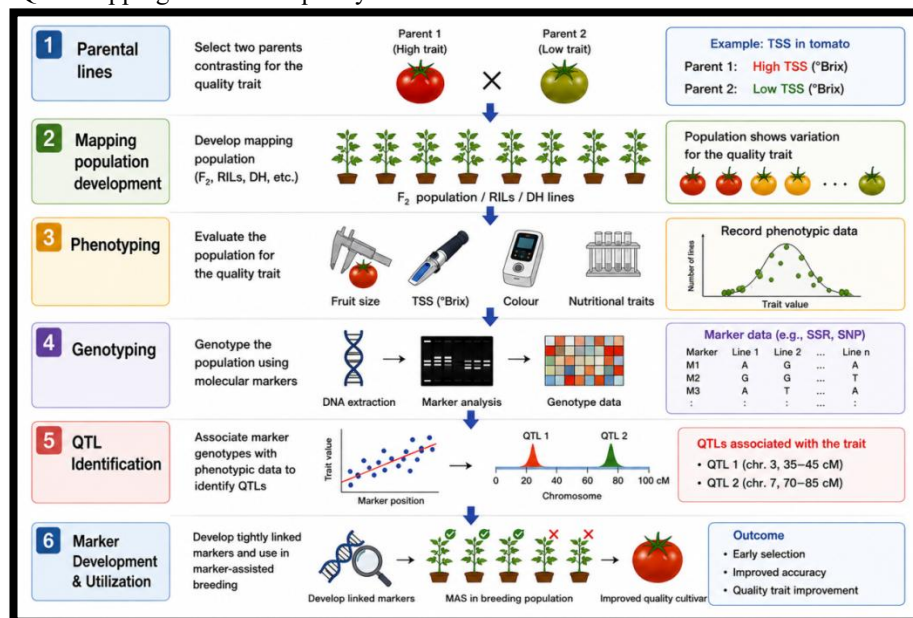


Figure 2. Steps involved in QTL mapping in tomato

Marker-Assisted Backcross Breeding (MABB)

Marker-assisted backcross breeding (MABB) integrates molecular marker technology with conventional backcross breeding to transfer specific genes or QTLs into elite cultivars. This approach enables rapid introgression of desirable quality traits while minimizing linkage drag. MABB is particularly useful when a quality trait is controlled by one or a few major genes and the objective is to improve an established cultivar without altering its overall genetic background. In solanaceous vegetables, MABB has been extensively utilized to transfer genes controlling high lycopene content, β -carotene accumulation, disease resistance, and fruit quality characteristics. Molecular markers facilitate foreground selection for the target gene and background selection for rapid recovery of the recurrent parent genome. As a result, breeding efficiency is considerably increased and the time required for cultivar development is substantially reduced. MABB is now considered one of the most effective approaches for quality improvement in tomato and pepper breeding programmes.

Genomic Selection

Genomic selection is an advanced breeding strategy that utilizes genome-wide molecular markers to predict the breeding value of individuals. Unlike MAS, which focuses on a limited number of markers linked to major genes, genomic selection simultaneously evaluates thousands of markers distributed throughout the genome. This approach is particularly valuable for improving complex traits controlled by numerous genes with small individual effects. Quality traits such as flavour, nutritional composition, antioxidant activity, shelf life, and processing quality are often governed by polygenic inheritance. Genomic selection enables breeders to predict the performance of breeding lines without extensive phenotypic evaluation, thereby accelerating genetic gain. The integration of high-throughput genotyping technologies with statistical prediction models has made genomic selection an increasingly important tool in modern vegetable breeding programmes. Meuwissen et al. (2001) highlighted the potential of genomic selection for improving quantitatively inherited traits in crop plants.

Genetic Engineering for Quality Improvement

Genetic engineering is the direct manipulation or alteration of genes to create desirable characteristics in an organism. Unlike conventional breeding methods, which depend on sexual hybridization and recombination, genetic engineering allows the precise introduction, modification, or silencing of specific genes associated with quality traits. A plant in which a foreign gene has been introduced through recombinant DNA technology is known as a transgenic plant. Genetic engineering has emerged as a powerful tool for improving nutritional quality, shelf life, flavour, texture, processing quality, and resistance to biotic and abiotic stresses in vegetable crops (Datta et al., 2000).

The application of genetic engineering in solanaceous vegetables has enabled breeders to overcome barriers associated with conventional breeding, such as incompatibility between species, linkage drag, and long breeding cycles. Through

genetic transformation, genes from unrelated organisms can be introduced into crop plants to enhance quality characteristics. The development of transgenic crops has opened new opportunities for improving nutritional composition and post-harvest quality while maintaining high productivity (James, 2017). One of the earliest and most successful examples of genetic engineering for quality improvement was the development of the Flavr Savr tomato, in which the expression of the polygalacturonase (PG) gene was suppressed. Polygalacturonase is responsible for cell wall degradation during fruit ripening. Reduced expression of this enzyme delayed fruit softening and extended shelf life without significantly affecting fruit quality. This achievement demonstrated the potential of genetic engineering in improving post-harvest quality traits in vegetable crops (Kramer & Redenbaugh, 1994).

Genetic engineering has also been used to enhance nutritional quality. Datta et al. (2000) developed transgenic potato plants expressing a seed albumin gene from *Amaranthus hypochondriacus*, resulting in increased protein content and improved nutritional value. Such approaches provide opportunities to address nutritional deficiencies and improve food security through biofortification. Recent advances in molecular biology and genome editing technologies such as CRISPR/Cas9 have further enhanced the efficiency of genetic engineering. These technologies allow precise modifications in genes controlling carotenoid biosynthesis, vitamin accumulation, starch metabolism, fruit colour, flavour, and antioxidant content. Consequently, genetic engineering has become an important component of modern vegetable quality improvement programmes.

Target Genes for Quality Improvement in Solanaceous Vegetables

Several genes have been identified and functionally characterized as important regulators of quality-related traits in solanaceous vegetable crops. Genetic engineering and genome-editing approaches targeting these genes have been used to improve fruit nutritional quality, antioxidant content, flavour, pigment accumulation, shelf life, texture, and other desirable quality attributes. Important target genes include those involved in carotenoid and anthocyanin biosynthesis, capsaicinoid accumulation, cell-wall modification, fruit ripening, and metabolic pathways. Manipulation of these genes provides opportunities for the development of vegetable cultivars with enhanced nutritional value and improved postharvest quality. Table 6 summarizes important target genes that have been utilized or proposed for quality improvement in major solanaceous vegetables, along with their desired effects and target crops.

Table 6. Important target genes used for quality improvement in solanaceous vegetables

S. No.	Target gene	Desired effect	Crop	Reference
1	Polygalacturonase (PG)	Reduced pectin degradation, delayed fruit softening and increased shelf life	Tomato	Smith et al. (1988); Giovannoni (2001)
2	Seed albumin gene (AmA1)	Increased protein content and improved nutritional quality	Potato	Chakraborty et al. (2000); Ghosh et al. (2001)
3	Granule-bound starch synthase (GBSS)	Modification of amylose/starch composition and improvement of processing quality	Potato	Kumar et al. (2004); Tuncel & Okita (2013)
4	Phytoene synthase (PSY1)	Increased carotenoid and provitamin-A accumulation	Tomato	Fray et al. (1995); Fraser et al. (2007)
5	Phytoene desaturase (PDS) / carotenoid pathway genes	Modification of carotenoid biosynthesis and fruit pigmentation	Tomato	Li et al. (2018); Zaidi et al. (2020)
6	PUN1 (Pun1)	Increased pungency through capsaicinoid biosynthesis	Chilli	Stewart et al. (2005); Tripodi et al. (2010)
7	Capsaicinoid biosynthetic genes (AT3, BCAT, KasI, C4H, COMT)	Enhanced capsaicin and total capsaicinoid accumulation	Chilli	Aza-González et al. (2011); Arce-Rodríguez & Ochoa-Alejo (2019)
8	Anthocyanin regulatory genes (SmMYB1, SmTTG1)	Enhanced anthocyanin accumulation, fruit pigmentation and antioxidant potential	Brinjal	Zhang et al. (2014); Barchi et al. (2019)
9	Anthocyanin biosynthetic gene (SmANS)	Increased anthocyanin biosynthesis and purple fruit pigmentation	Brinjal	Zhang et al. (2014); Colanero et al. (2024)
10	Polyphenol oxidase (PPO)	Reduced enzymatic browning and improved processing quality	Potato	Rommens et al. (2006); Clasen et al. (2016)
11	Asparagine synthetase (Asn1)	Reduced free asparagine and potentially lower acrylamide formation during processing	Potato	Rommens et al. (2008); Richael et al. (2016)
12	Vacuolar invertase (VInv / StVInv)	Reduced reducing sugars and cold-induced sweetening; improved chip colour	Potato	Bhaskar et al. (2010); Paul et al. (2025)
13	UDP-glucose	Reduced cold-induced sweetening	Potato	Paul et al. (2025)

	pyrophosphorylase (StUGPase)	and improved processing quality		
14	Glutamate decarboxylase (SIGAD2/SIGAD3)	Increased γ -aminobutyric acid (GABA) concentration	Tomato	Nonaka et al. (2017); Li et al. (2018)
15	LCY-B1 / LCY-B2 (lycopene β -cyclase)	Modification of lycopene-to- β -carotene conversion and enhancement of provitamin-A carotenoids	Tomato	Ronen et al. (2000); D'Ambrosio et al. (2011)

Kramer and Redenbaugh (1994) reported that suppression of the polygalacturonase gene successfully delayed fruit ripening in tomato, thereby improving shelf life and reducing post-harvest losses. Similarly, Datta et al. (2000) demonstrated that the expression of the AmA1 seed albumin gene significantly increased protein content and improved the nutritional quality of potato tubers. Advances in genomics have enabled the identification of several additional genes involved in carotenoid biosynthesis, capsaicinoid synthesis, anthocyanin accumulation, and starch metabolism, thereby facilitating targeted improvement of quality traits.

Genome Editing (CRISPR/Cas9)

Genome editing is the latest advancement in plant breeding and enables precise modification of target genes without introducing foreign DNA. Among the available genome-editing tools, CRISPR/Cas9 has emerged as the most versatile and efficient technology due to its simplicity, accuracy, and cost-effectiveness. CRISPR technology utilizes a guide RNA to direct the Cas9 nuclease to a specific genomic location where targeted modifications can be introduced. In solanaceous vegetables, CRISPR/Cas9 has been employed to modify genes controlling fruit ripening, carotenoid biosynthesis, shelf life, flavour, disease resistance, and nutritional quality. Gene editing offers several advantages over traditional transgenic approaches because it enables precise modifications without affecting other genomic regions. Recent studies have demonstrated successful editing of genes associated with lycopene accumulation, fruit firmness, and antioxidant content in tomato. Consequently, CRISPR technology is expected to play a major role in future quality improvement programmes aimed at developing nutrient-rich and consumer-preferred vegetable cultivars (Zsögön et al., 2018).

Advantages of Quality Trait Improvement

Improvement of quality traits in vegetable crops provides numerous benefits to producers, processors, and consumers. Enhanced quality increases consumer acceptance by improving appearance, flavour, texture, nutritional value, and overall eating quality. Quality improvement also contributes to food and nutritional security through the development of vegetables rich in vitamins, minerals, antioxidants, and other health-promoting compounds. High-quality produce generally fetches premium prices in the market, thereby increasing farmers' income and profitability. Improved quality traits such as higher total soluble solids, better colour retention, enhanced firmness, and increased shelf life make vegetables more suitable for processing and value addition. Furthermore, quality breeding helps meet the requirements of export markets, where strict standards regarding appearance, nutritional content, and post-harvest quality are imposed. Therefore, improvement of quality traits enhances market competitiveness and contributes to sustainable vegetable production (Kalloo, 1993; Dias, 2012).

Limitations in Improvement of Quality Traits

Despite its importance, the improvement of quality traits faces several challenges. Most quality traits are quantitatively inherited and controlled by many genes, making their improvement more complex than simply inherited traits. Breeding for quality generally requires a longer period because accurate evaluation of quality attributes often involves biochemical and laboratory analyses. Many quality traits are strongly influenced by environmental factors such as temperature, soil fertility, irrigation, and crop management practices, resulting in low heritability and inconsistent expression across environments. Another major limitation is the existence of negative associations between yield and quality traits. Improvement in nutritional quality, flavour, or dry matter content may sometimes lead to reduced yield potential. In addition, quality assessment is often expensive, time-consuming, and requires specialized equipment and trained personnel. Consumer preferences also vary across regions and markets, making it difficult to develop cultivars that satisfy all quality requirements simultaneously. Therefore, breeders must carefully balance quality improvement with yield, adaptability, and economic viability (Falconer & Mackay, 1996; Singh, 2015).

CONCLUSION

Quality improvement has become one of the foremost objectives in modern breeding programmes of solanaceous vegetables due to increasing consumer demand for nutritious, safe, and value-added food products. Quality traits such as fruit colour, flavour, texture, nutritional composition, shelf life, processing suitability, and bioactive compounds significantly influence consumer preference and market value. The inheritance of these traits ranges from simple monogenic control to complex polygenic systems, necessitating the use of diverse breeding strategies for their effective improvement.

Conventional breeding methods, including selection, hybridization, interspecific hybridization, and mutation breeding, have played a crucial role in enhancing quality traits and continue to remain important components of crop improvement programmes. However, the emergence of molecular breeding and biotechnology has greatly accelerated the pace and

precision of quality improvement. Marker-assisted selection, QTL mapping, genomic selection, genetic engineering, and genome editing technologies provide powerful tools for identifying and manipulating genes responsible for desirable quality characteristics. Successful examples such as high-lycopene tomato, high-capsaicin chilli, anthocyanin-rich brinjal, and protein-enriched potato demonstrate the immense potential of these approaches.

Nevertheless, breeders continue to face challenges such as negative correlations between yield and quality, genotype $\times$ environment interactions, low heritability of certain traits, and regulatory concerns associated with transgenic crops. Future breeding efforts should focus on integrating conventional and advanced molecular approaches to simultaneously improve yield, quality, and stress tolerance. The application of next-generation genomic tools and precision breeding technologies will play a pivotal role in developing superior solanaceous vegetable cultivars that contribute to sustainable agriculture, enhanced nutritional security, and improved human health.

Statements and Declarations

Funding

The authors received no financial support for the research, authorship and/ or publication of this article.

Acknowledgement

We hereby acknowledge that all authors actively contributed to the overall execution of this research. Every author participated equally in the articles analysis, data analysis and language analysis. All authors have responsibility for the published work.

Consent for publication

All authors consent the publication of the current article.

Competing interests

The authors declare no competing interests.

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