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Biotechnological interventions and sustainable practices in augmenting *Solanum lycopersicum* productivity

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Abstract

A review of *Solanum lycopersicum*, or the tomato, highlights its significance in agriculture, nutrition, and research. As a member of the Solanaceae family, tomatoes display a range of morphological diversity, characterized by compound leaves, yellow flowers, and fleshy berries of various sizes and colors. They can grow as compact determinate varieties or sprawling indeterminate types, with morphological features such as anisocytic stomata and collateral vasculature. Optimal cultivation requires specific techniques, considering soil preparation, climate, and integrated farming practices. Modern methods like hydroponics could further boost productivity, but variations in adoption rates point to a need for better farmer education. This review covers taxonomy, morphology, cultivation practices, nutrition, and advancements in genomics and breeding. Tomato peels and seeds could serve as potential sources for new therapies because they are rich in phytonutrients and exhibit antibacterial and antioxidant properties. The study's findings suggest that green tomatoes might be a promising option for developing herbal medications with beneficial health effects, as different parts of the tomato contain varying levels of nutritional value and antibacterial activity. The economic importance of tomatoes drives research in breeding and genomics to improve this crop in the face of challenges like food security and climate change. Although regulatory issues remain, genetic engineering has led to transgenic varieties with enhanced nutritional content, shelf life, and pest resistance. Emphasizing sustainable practices, precision agriculture, and disease resistance, research is also focused on breeding drought- and heat-resilient varieties. Innovations in harvesting, packaging, and ethylene biosynthesis are leading to improved quality alongside traditional breeding methods. Scientists are discovering that the phytochemical constituents in tomatoes may hold exciting potential as alternative therapeutic agents for combating endometrial cancer. This finding suggests that something as simple as a tomato could play a significant role in cancer treatment, opening new avenues for hope and innovation in oncology.

Keywords: *Solanum lycopersicum*, biotechnology, nutritional value, tomato, *Solanaceae* family

Introduction

A thorough review of *Solanum lycopersicum*, commonly known as the tomato, highlights its significant role in agriculture, nutrition, and scientific research. The Solanaceae family, which also includes other economically significant crops like potatoes and eggplants, includes *Solanum lycopersicum*. Compound leaves, yellow flowers, and fleshy berries (fruits) that differ in size, shape, and color depending on the cultivar are the plant's defining features. There is a great deal of morphological diversity and taxonomic complexity in the genus *Solanum*, which includes tomatoes (*S. lycopersicum*). Within the Solanaceae, pollen morphology varies; *S. lycopersicum* produces tricolporate pollen (Ashfaq *et al.*, 2020) ^[1]. Anisocytic stomata and bicollateral vasculature are features of *S. lycopersicum*, an annual herb with compound leaves, yellow flowers, and red berries (Wahua *et al.*, 2020) ^[42]. Concerns regarding genetic contamination are raised by the coexistence of introduced *S. lycopersicum* and *S. pimpinellifolium* with *cheesmaniae* and *S. Galapagos* (Darwin *et al.*, 2003) ^[41]. Usually growing as vines or bushes, tomato plants can range in height from compact determinate varieties to indeterminate types that can grow to several meters. The leaves are pinnately compound, with

five to nine serrated leaflets arranged alternately on the stem. Small, yellow, and usually self-pollinating, the flowers grow in clusters known as racemes. Traditional subgeneric classifications are questioned when phylogenetic analysis using *ndhF* sequences shows that *S. lycopersicum* is nested within the *Solanum* clade. The study proposes several evolutionary origins for important morphological features in *Solanum*, such as stellate hairs and spines (Bohs & Olmstead, 1997) ^[4]. Growing tomatoes (*Solanum lycopersicum*) calls for particular methods in order to achieve the best possible yield and quality. According to Miftahurohmat *et al.* (2023) ^[22], production of tomatoes is greatly impacted by land preparation methods such as minimum, maximum, and no tillage. Around all over the globe, tomatoes are grown in a variety of climates, ranging from temperate to tropical. They need regular moisture, enough sunlight, and soil that drains properly. Quality and productivity can be enhanced by protected cultivation in polyhouses (Sharma & Singh, 2020) ^[32]. With daily light durations of 8-16 hours, temperatures between 10-35°C, relative humidity between 30 and 90%, and CO₂ concentrations between 200 and 1500 µmol mol⁻¹, tomatoes thrive in controlled conditions (Schwarz *et al.*, 2014) ^[36].

Precision farming, hydroponics, and greenhouse production are examples of contemporary cultivation methods that have greatly expanded growing seasons and raised yields. The ideal pH range for soil preparation is between 6.0 and 6.8. Crop rotation is frequently used to preserve soil fertility and stop soil-borne illnesses. Although 58% of farmers apply recommended fertilizer doses and 65% use recommended seed varieties, adoption of recommended practices varies among farmers (Sharma & Ladher, 2013) ^[37]. The need for integrated extension strategies to raise vegetable cultivators' knowledge and awareness is highlighted by the fact that most farmers only partially utilize suggested cultivation practices (Sharma & Ladher, 2013) ^[37]. These results highlight how crucial appropriate growing methods are to the successful production of tomatoes. For indeterminate varieties, trellising or staking is frequently used to promote plant growth and make harvesting easier. Traditional surface irrigation and more effective drip systems are two types of irrigation techniques. Mulching is frequently used in conjunction with irrigation to retain soil moisture and inhibit the growth of weeds. This review will discuss the plant's taxonomy, morphology, cultivation practices, nutritional value, and recent advancements in genomics and breeding.

Nutritional value and antimicrobial property

The tomato, or *Solanum lycopersicum*, is a nutrient-dense fruit that is consumed all over the world. According to Parmar *et al.* (2021) ^[13, 25], it contains a variety of vitamins (A, B, C, E, and K), minerals (potassium, magnesium, calcium, and iron), and phytochemicals (carotenoids, polyphenols, and flavonoids). Lycopene, a carotenoid with potential health benefits such as lowering the risk of cardiovascular disease, preventing cancer, and improving skin protection from UV rays, is especially abundant in tomatoes (Dawid, 2016) ^[14]. Above all, tomatoes are a great source of lycopene, a potent antioxidant linked to a lower risk of cardiovascular disease and some types of cancer. Additional healthy substances like beta-carotene, vitamin E, and flavonoids are included in tomatoes' nutritional profile. The fruit's bioactive compounds are responsible for its 48-118 µmol TEAC/100 g antioxidant activity (Parmar *et al.*, 2021) ^[25]. According to research, tomatoes' nutritional value can be improved by pyramiding quantitative trait loci, which raises the amounts of phenolics, ascorbic acid, and total antioxidant activity (Rigano *et al.*, 2014) ^[29]. Consuming tomatoes may have chemo-preventive effects, boost the immune system, and help prevent chronic diseases (Parmar *et al.*, 2021; Raja, 2016) ^[25, 31]. Because of these qualities, tomatoes are a useful functional food that may be used to create industrial goods and medications (Raja, 2016) ^[31]. The cultivar, growing environment, and harvest ripeness can all affect the concentration of these nutrients. Lycopene's bioavailability can be increased by cooking tomatoes, which makes processed tomato products like pastes and sauces an excellent source of this antioxidant.

The antioxidant activity of tomato extracts is higher in ripe seeds compared to raw seeds, and ripe tomatoes contain more vitamin B1 than raw tomatoes. Tomato extracts exhibit greater antibacterial effectiveness against *E. coli* bacteria. extracts from green tomato peels and pulp have a higher protein content than those from red tomatoes. Ripe aqueous pulp extracts and raw aqueous peel extracts contain

more carbohydrates than ripe peel extracts. ripe tomatoes not only have higher vitamin B1 levels but also demonstrate stronger antioxidant activity in their seeds compared to raw tomatoes. Additionally, raw aqueous peel extracts have more carbohydrates than ripe peel extracts, while ripe aqueous pulp extracts have a higher carbohydrate content than raw aqueous pulp extracts. Lastly, glutamic acid is the most prevalent amino acid found in tomatoes. (Majumder A. *et al.* 2023) ^[40].

Genomics and Breeding

The tomato "*Solanum lycopersicum*" is a model species in genomics analysis due to its small genome size and many resources available (Barone *et al.* 2009) ^[6]. The evolution of tomato breeding techniques has recently been impacted by genomic advances. As a result of the Tomato Genome Sequence being released in 2012, it was possible to locate the genes responsible for major traits such as fruit size and shape and disease resistance. By allowing the identification and breeding of resistance genes and improving the fruit quality, increased tomato milled area and production concerning the amount of work has increased (Barone *et al.*, 2009) ^[6]. Population genetics research has also contributed to understanding the structure of genetic variation, origin and domestication, and the improvement of indifferent stress tolerance of tomatoes (Sauvage *et al.*, 2020) ^[35]. With the emergence of genome sequences and SNP markers gene mapping of different traits and genome wide association studies were easily accepted (Sauvage *et al.* 2020) ^[35]. The development of detailed molecular maps and markers has been achieved through efforts in structural genomics (Barone *et al.*, 2008; Foolad, 2007) ^[7, 16]. Even though the usage of marker-assisted selection has been slow in tomato breeding due to the low polymorphism and the cost involved, efforts made in sequencing, EST databases, and microarray technology should accelerate marker development and usefulness to breeding programs (Foolad, 2007) ^[16]. This information has hastened the development of new cultivars with enhanced characteristics through conventional breeding as well as through genetic engineering approaches (Rauf *et al.*, 2024) ^[21]. In tomato breeding, marker-assisted selection has become a valuable asset that enables breeders to select positive traits more efficiently. Researchers are exploring the use of techniques such as CRISPR-Cas9 gene editing to achieve specific gene modifications that may help enhance the nutrition content of tomatoes, increase their shelf life, or make them more resilient to stress. CRISPR-Cas9 is particularly effective when used for tomato (*Solanum lycopersicum*) genome editing. Using this system, first-generation transgenic tomato plants have been produced, which successfully incorporated targeted mutations (Brooks *et al.*, 2014). CSCRIPT-cas9 has also been used to change characteristics in tomatoes including but not limited to changes in the ripening of fruit by targeting the RIN gene (Ito *et al.*, 2015) ^[18] as well as an increase in the production of lycopene. By altering the SIDMR6-1 gene, the technology has also been used to provide broad-spectrum disease resistance, increasing resistance to pathogens like *Phytophthora capsici* and *Pseudomonas syringae* (Thomazella *et al.*, 2016) ^[27]. These investigations show that CRISPR-Cas9 is a precise and effective technique for enhancing tomato

characteristics, with benefits such as high efficiency and infrequent off-target mutations, as well as the steady transfer of desired traits to future generations (Li *et al.*, 2018) ^[20].

Gene from phytochemical constituents found in tomatoes, could serve as alternative therapeutic agents for treating disease

The potential of some tomato-derived compounds as natural therapeutic agents is highlighted by the fact that they exhibit binding energies that are on par with or even better than those of lenvatinib mesylate. The PTEN tumor suppressor protein showed strong binding energies with nine tomato phytochemicals. Interestingly, a few of these substances displayed binding energies that were on par with or less than those of lenvatinib mesylate, the control medication. The substances Kombetin, Cryptochrome, Phytosterols, and Solanacol showed lower binding energies than the widely available endometrial cancer medication Lenvatinib mesylate, according to molecular docking data. It is crucial to remember that prescription drugs for endometrial cancer, such as Keytruda and Lenvatinib mesylate, can have serious side effects that could be dangerous and have major repercussions if taken for an extended period. Future studies aiming at creating safe derivatives from the naturally existing phytochemical elements in tomatoes may be facilitated by this initial evaluation. These compounds may replace pharmaceuticals that are currently on the market, lowering side effects and potentially improving endometrial cancer treatment options. (Bhattacharya, M.2024) ^[9].

Disease resistance

Due to serious production constraints, the breeding program focused on developing several disease-resistant cultivars and F1 hybrids (Sadashiva *et al.*, 2017) ^[38]. Host-pathogen interactions for some diseases-late blight, early blight, fusarium wilt, verticillium wilt, and tomato mosaic virus-have become quite easy to study and transfer resistance genes due to genomic approaches. To reduce losses caused by pests and diseases, integrated pest management strategies incorporating biological control techniques, cultural practices, and resistant varieties have been formulated (Panthee & Chen, 2010) ^[28]. Modern techniques, such as high-throughput DNA sequencing and extensive accumulation of expression data, make it possible to create disease-resistant varieties (Ercolano *et al.*, 2012) ^[15]. The wild relatives of cultivated tomatoes have also been sources for improving quality characteristics and resistance to abiotic factors which they can be employed in breeding (Sadashiva *et al.*, 2017) ^[38].

Climate change

The cultivation of tomatoes (*Solanum lycopersicum*) faces significant challenges due to climate change as it results in adverse effects such as increased temperature, alteration in precipitation regimes, and higher CO₂ concentration levels (Biratu, 2018) ^[8]. Justifiably, these changes can impact food security and crop productivity. However, there are potential ways to cope with them such as optimal scheduling of planting and growing seasons, developing crops that are resilient to climate change, and improving farm management practices (Biratu, 2018; Schafleitner, 2016) ^[8, 33]. In addition, the spread of insect pests including

Neoleucinodes elegantalis, may be influenced by climate change which would affect the risk scenarios in tomato-growing areas (da Silva *et al.*, 2017) ^[12]. Since some tomato cultivars manage to tolerate water stress with little or no significant reduction in yield, developing drought-resistant tomato varieties makes sense for sustainable climate-smart agriculture (Nahar & Ullah, 2022) ^[23]. Water stress can also lead to enhanced organic solute and acid accumulation resulting in improved fruit quality indicating a possible adaptive response to climatic stress (Nahar & Ullah, 2022) ^[23].

Post-harvest technology

Tomatoes are required by *Solanum lycopersicum* to undergo post-harvest technology preservation as a means to retain quality and extend shelf life. These treatments include chlorinated water, ozone, temperature control, ultrasounds, UV-C radiation, modified atmosphere packaging, edible coatings, and 1-methylcyclopropene (Pinheiro *et al.*, 2013) ^[26]. However, post-harvest losses are still a problem in Africa, both in the issues connected with on-farm factors which include poor harvesting and packing to off-farm factors which include poor transportation and lack of storage facilities (Arah, 2015; Arah *et al.*, 2015) ^[2, 3]. Such losses can easily reduce the profitability of tomato production despite its nutritional value and economic benefits. Low-cost intermediate technologies are helpful for the improvement of these challenges (Arah *et al.*, 2015) ^[3]. Good handling practices, such as harvesting, precooling, washing, sorting, packaging, and storage, are critical elements in ensuring tomatoes remain good and minimize losses (Dawad & Karki, 2022) ^[11]. Improvement in these areas will be vital in ensuring improvement in food security and profitability of production in tomatoes in the African continent.

Biotechnology and genetic engineering

Biotechnology and genetic engineering have significantly advanced tomato (*Solanum lycopersicum*) research and improvement. These techniques have been used to enhance drought tolerance, a major challenge in tomato production (Taheri *et al.*, 2022; Krishna *et al.*, 2022) ^[39, 19]. Transgenic approaches and genome editing, particularly CRISPR-Cas9, have enabled the introduction of drought-resistant genes and modification of existing ones (Krishna *et al.*, 2022) ^[19]. Additionally, "omics" technologies have facilitated the identification of drought-responsive genes (Taheri *et al.*, 2022) ^[39]. Genetic engineering has also been employed to increase salinity tolerance in tomatoes through the introduction of the AtOPR1 gene (Nagar, 2013) ^[24]. Furthermore, biotechnology has been utilized to improve resistance to various environmental stresses and enhance fruit quality (Gerszberg *et al.*, 2015) ^[17]. These advancements in genetic engineering and biotechnology have opened up new possibilities for tomato improvement, addressing both biotic and abiotic stresses while enhancing nutritional content and overall crop performance.

Sustainable production

Production of tomatoes (*Solanum lycopersicum*) sustainably is hampered by issues like soil salinity and water scarcity. Although more research is required to determine the ideal

dosages, bio-nano fertilizers containing copper and selenium can encourage tomato growth in saline irrigation conditions (Saffan *et al.*, 2022) ^[34]. Compared to unamended soil, organic amendments such as vermicompost can increase tomato growth; however, varying dosages may not significantly impact development (Barbosa *et al.*, 2021) ^[5]. Certified seeds and traditional agrochemicals are the main methods used in Nicaraguan tomato production systems to control pests, with whiteflies (*Bemisia tabaci*) being a significant issue (Castillo Martínez *et al.*, 2019) ^[10]. With little fertilizer, traditional production systems, like those in Tehuantepec-Juchitán, Mexico, preserve the diversity of native tomatoes. These systems mainly serve local markets and help preserve tomato genetic resources. They are usually run by older farmers who cultivate small plots (Ríos-Orsorio *et al.*, 2014) ^[30].

Conclusion

The economic importance and improvement potential of *Solanum lycopersicum*, or tomatoes, remains a significant area of research. Ongoing studies in breeding, genomics, and cultivation techniques aim to enhance this adaptable crop, addressing global challenges like food security and climate change. Advances in genetic engineering have produced transgenic tomato varieties with improved nutritional content, shelf life, and pest resistance, despite regulatory challenges. Research is also focusing on sustainable agriculture through organic production, reduced pesticide use, and beneficial microorganisms to enhance growth and stress tolerance. Precision agriculture techniques are being employed to optimize resource use. Tomatoes are susceptible to viruses, bacteria, and fungi, prompting research on breeding disease-resistant cultivars for issues like Fusarium wilt and Tomato mosaic virus. Integrated pest management combines resistant varieties with cultural practices and biological methods. Ongoing studies on the plant's immune system aim to create more resilient varieties. Additionally, with rising global temperatures and erratic weather, there is a focus on developing tomato varieties resilient to abiotic stresses such as drought and heat, crucial for food security amid climate change. Research is identifying QTLs linked to stress tolerance and exploring wild tomato relatives for genetic resources to improve cultivated varieties. Efforts to improve harvested tomato quality include modified atmosphere packaging and genetic modifications to slow ripening. Advances in ethylene biosynthesis have yielded "long shelf-life" varieties. Overall, combining modern biotechnology with traditional breeding may produce nutrient-dense, resilient tomato varieties crucial for global food systems.

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