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Lycopene in tomatoes: genetic regulation, agronomic practices, and environmental influence

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ABSTRACT

Lycopene is one of the key carotenoids in tomatoes (*Lycopersicon esculentum* Mill.). It is known for its strong antioxidant activity and its role in preventing cardiovascular diseases, cancer, and other chronic conditions. A complex interplay of genetic factors, agronomic practices, and environmental conditions determines its accumulation in tomato fruits.

Breeding for high-lycopene tomato varieties is actively advancing through traditional breeding methods and modern molecular markers, which facilitate the identification of promising genotypes and accelerate the breeding process.

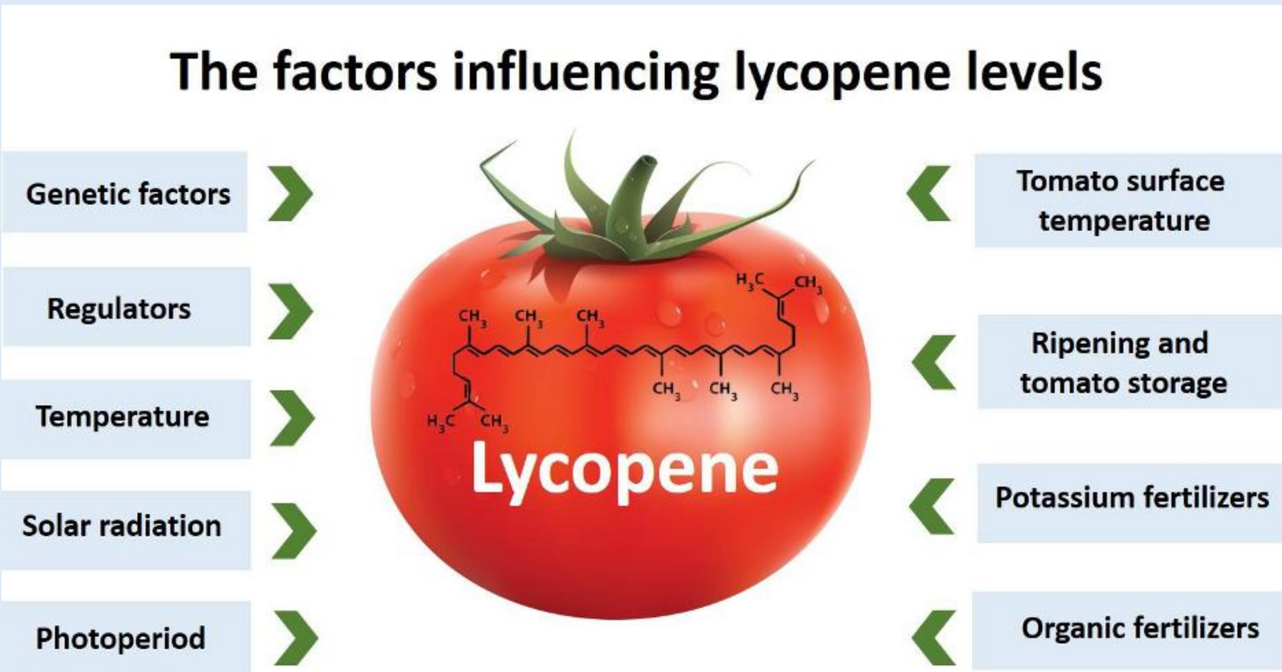
Beyond genetic traits, external factors significantly impact lycopene synthesis. Temperature regimes, solar radiation levels, photoperiod, and temperature fluctuations on the fruit surface can all influence its accumulation. Agronomic practices, such as growth regulators, organic amendments, and potassium fertilizers, also contribute to increased lycopene content. Potassium enhances carbon transport into the fruits, while organic fertilizers stimulate the enzymatic activity of the carotenoid biosynthesis pathway. Growth regulators can activate gene expression related to lycopene accumulation, offering opportunities for targeted control of its levels.

This review uniquely integrates insights from molecular genetics, environmental factors, and agronomic strategies to comprehensively understand lycopene biosynthesis in tomatoes. Systematically connecting molecular mechanisms with practical cultivation approaches addresses a significant gap in the existing literature.

Additionally, the ripening stage and storage conditions further affect lycopene content. Thus, an integrated approach- combining molecular marker-assisted breeding, optimized agronomic techniques, and environmental factor management- can significantly enhance lycopene concentration in tomatoes, improving their nutritional value and functional properties.

The findings presented offer actionable guidance for future breeding programs and cultivation practices to produce functionally enriched tomato varieties for the health-oriented food market.

Keywords: lycopene, tomato, genetic factors, environmental factors, potassium fertilizers, organic fertilizers



INTRODUCTION

In recent years, there has been a growing interest in studying bioactive compounds in agricultural crops, as they play a crucial role in determining their nutritional value and functional properties [1-2]. Research on these compounds' content and accumulation dynamics in various crops provides insight into mechanisms for enhancing their nutritional quality and cultivation efficiency [3-9].

Tomatoes (*Lycopersicon esculentum* Mill.*)* are a valuable source of essential nutrients, including vitamins (C, E, B), microelements, and antioxidants, among which carotenoids are particularly significant [10]. Lycopene, a red pigment, is the predominant carotenoid in tomato fruits, accounting for up to 98% of the total carotenoid content [11].

Lycopene was first isolated in 1910, and its molecular structure was determined in 1930. It belongs to the polyene isoprenoid class of terpenes, specifically tetraterpenes. Structurally, lycopene is a tetraterpene composed of eight isoprene units, with a molecular formula containing 40 carbon atoms. Lycopene molecules exhibit symmetry and consist of two C20 subunits with a hexagonal structure. A characteristic feature of lycopene is its geometric isomerism. It contains 13 double bonds and has an extended linear structure, distinguishing it from other carotenoids [12-13]. The 2D molecular structure of lycopene is presented below (Figure 1):

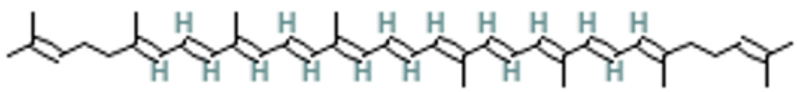


Figure 1. The lycopene molecule [14]

One of the critical stages in tomato cell metabolism is lycopene biosynthesis. Lycopene is a key carotenoid precursor for other carotenoids and significantly influences fruit pigmentation. Its biosynthesis proceeds through a series of desaturation and isomerization reactions, forming its characteristic structure with conjugated double bonds responsible for its red coloration and light absorption properties [15].

Within the plant pigment complex, lycopene and chlorophyll regulates photosynthesis by preventing singlet oxygen-induced damage to photosynthetic membranes. Its primary function is to protect cellular biomembranes from the harmful effects of solar radiation, ionizing radiation, and oxidative stress caused by free radicals [16].

In the human body, lycopene is a potent carotenoid antioxidant that reduces oxidative stress, lowers the risk of atherosclerosis, protects DNA, and prevents oncogenesis [17]. Its antioxidant activity significantly surpasses β-carotene and vitamin E, while remaining safe even at high doses. Exposure to high temperatures does not degrade lycopene; on the contrary, it enhances its bioavailability. The highest concentrations of lycopene are found in tomato paste (up to 1500 mg/kg), dried tomatoes (up to 460 mg/kg), and tomato sauce (up to 135 mg/kg) [16, 18].

The unique ability of lycopene to effectively neutralize reactive oxygen species makes it a key component in the prevention of diseases associated with oxidative stress [19-21]. Despite lacking provitamin A activity, its effectiveness in scavenging singlet oxygen is nearly twice that of β-carotene [22-23]. Furthermore, lycopene exhibits pronounced anticancer properties through its antioxidant action, stimulation of detoxifying enzymes, activation of apoptosis, and inhibition of cell proliferation [24-27]. Studies have shown that lycopene possesses antioxidant and anti-inflammatory properties [28].

Considering the role of lycopene, its significance in the prevention of various diseases can be highlighted (Table 1).

Table 1. The Impact of Lycopene on the Prevention of Various Diseases.

Prevention of diseases	Description of the effects of lycopene	References
Prostate Cancer	Lycopene helps reduce the risk of prostate cancer by inhibiting tumor growth, promoting apoptosis, and reducing oxidative stress	[24-25, 29-33]
Lung Cancer	Lycopene lowers lung cancer risk through antioxidant effects, preventing DNA damage and reducing tumor cell proliferation.	[32-33]
Breast Cancer	Lycopene inhibits breast cancer cell proliferation, induces apoptosis, and modulates estrogen receptor signaling.	[34-35]
Cardiovascular Diseases	Lycopene reduces oxidative stress, lowers cholesterol, improves endothelial function, and prevents atherosclerosis.	[17, 36-38]
Neurodegenerative Diseases	Lycopene protects neural cells from oxidative damage, reduces amyloid-beta accumulation, and supports brain health.	[39-41]
Inflammatory Processes	Lycopene reduces inflammation by inhibiting cytokine production and inflammatory enzymes, preventing chronic diseases.	[28, 42-44]
Obesity	Lycopene aids in reducing fat accumulation, improving insulin sensitivity, and lowering inflammation linked to obesity.	[28, 43, 45-46,]
Diabetes	Lycopene enhances insulin sensitivity, reduces oxidative stress, and improves glucose metabolism in diabetes.	[28, 45, 47-48]
Immunostimulatory Effects	Lycopene boosts immune cell activity and enhances the body's defense against infections and diseases.	[49-50]
Cellular Aging (in vivo and in vitro)	Lycopene slows cellular aging by reducing oxidative stress, promoting DNA repair, and improving cell viability.	[51]
Photodamage/Photoaging of Skin	Lycopene protects skin from UV-induced damage, reducing wrinkles and improving elasticity and hydration.	[52]

Lycopene cannot be synthesized in the human body and is obtained solely through food. Lycopene consumption varies by country, which is attributed to differences in diet and the traditions of consuming tomatoes and tomato-based products (Table 2).

Table 2. Average daily lycopene consumption in different countries

Country	Average daily lycopene consumption	References
USA	6.6-10.5 mg/day for men, 5.7-10.4 mg/day for women	[53]
UK	1.1 mg/day	[53]
Spain	1.6 mg/day	[53]
Australia	3.8 mg/day	[53]
France	4.8 mg/day	[53]
Italy	7.4 mg/day	[53]
Netherlands	4.9 mg/day	[53]
Belgium	4.1 mg/day	[54]
South Korea	1.9 mg/day	[55]

According to studies, the daily preventive dose of lycopene ranges from 6 to 15 mg daily, equivalent to approximately 2–3 servings of fresh tomatoes or one serving of tomato juice. The data presented highlights the role of knowledge on lycopene accumulation and the impact of various factors on its biosynthesis in developing diets and daily intake recommendations for individuals with health issues.

Tomato varieties with high lycopene content have been developed in various parts of the world to meet growing nutritional and functional food demands. At the Scientific Centre of Vegetable and Industrial Crops in Armenia, several local high-lycopene varieties have also been developed, including “Lusarpi” F1, “Syune” F1, “Noy,” “Norq,” “Anahit 351” and others [56–58]. These varieties are actively used for fresh consumption and producing various tomato-based products, such as juices, sauces, pastes, and salads. Tomato processing enterprises supply the local market and exports, contributing to the country's development of the food industry.

Optimizing lycopene content in fruits is key to improving their nutritional value and commercial appeal. The lycopene content in tomato fruits can vary significantly depending on numerous factors. Among these, the genetic predisposition of the variety, agronomic practices, various fertilizers, and environmental factors play a crucial role. A comprehensive study of these factors is essential for enhancing the biological value of tomatoes and their application in the food industry.

Despite extensive research on lycopene biosynthesis and accumulation, the interplay between genetic factors, agronomic practices, and environmental conditions remains insufficiently explored in a holistic framework. This review integrates recent genetic and agronomic advancements to provide a more comprehensive understanding. This review article presents current data on the factors influencing lycopene content in tomatoes, focusing on genetic traits and breeding, agronomic practices, fertilizer application, and environmental conditions. The uniqueness of this approach lies in the interdisciplinary analysis, integrating data from genetics, agrochemistry, and ecology, which will enable a more in-depth understanding of the mechanisms regulating lycopene content in tomato fruits.

Influence of Genetic Factors on Lycopene Levels in Tomatoes: 1.1. Lycopene Biosynthesis and Genetic Regulation: Lycopene biosynthesis begins with the formation of 15-cis-phytoene, the first colorless carotenoid, resulting from the condensation of two molecules of geranylgeranyl pyrophosphate (GGPP). This reaction is catalyzed by the enzyme phytoene synthase (PSY) [59]. PSY1 is exclusively expressed in fruits [60].

The subsequent conversion of phytoene to all-trans-lycopene proceeds through desaturation and isomerization steps. In plants, desaturation is carried out by two key enzymes: phytoene desaturase (PDS) and ζ-carotene desaturase (ZDS). Intermediate products such as Phytofluene, Neurosporene, and Prolycopene (Tetra-cis-lycopene) undergo either light-dependent or enzymatic isomerization involving ζ-carotene isomerase (Z-ISO) and carotenoid cis-trans isomerase (CRTISO). These isomerization reactions are essential for forming biologically active all-trans-lycopene, which is required for downstream processes, including cyclization [59-60]. The number of conjugated double bonds increases throughout these steps, determining the pigment's coloration (Figure 2).

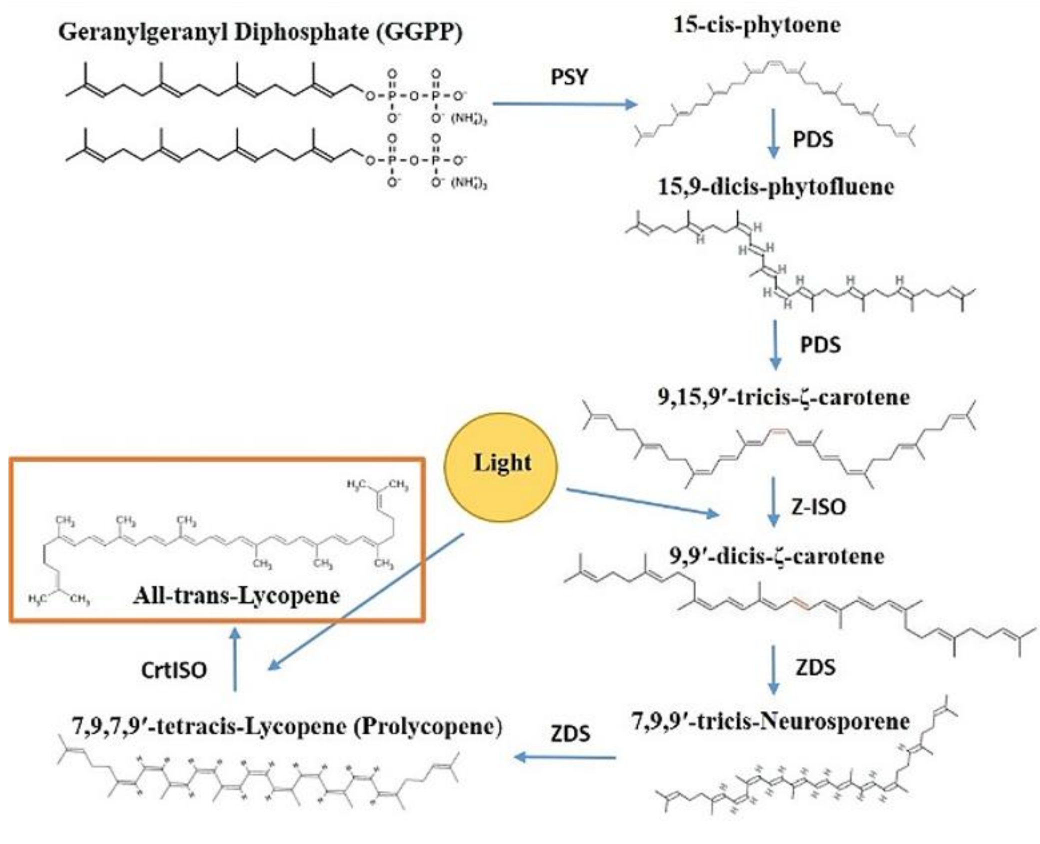


Figure 2. Scheme of all-trans-lycopene biosynthesis in plants

At the molecular level, lycopene biosynthesis is regulated by a set of structural genes, including:

PSY1 (Phytoene synthase 1) catalyzes the first and rate-limiting step in the carotenoid biosynthetic pathway by producing phytoene. The regulation of the PSY gene occurs at multiple levels — epigenetic, transcriptional, post-transcriptional, and post-translational — in response to various factors [61]. A mutant with a loss of PSY1 function produces yellow fruits due to the disruption of carotenoid biosynthesis [62].

PDS (Phytoene desaturase) catalyzes the removal of hydrogen atoms, forming the first double bonds in the molecule. When the PDS gene was silenced in tomato, the fruits exhibited a pale-yellow coloration, which was associated with reduced expression not only of PDS itself but also of other key genes in the carotenoid pathway: ZDS, CrtISO, and CrtR-b2. Additionally, the expression of ripening-related genes such as RIN, TAGL1, PE, LOX, FUL1/FUL2, and ethylene biosynthesis and response genes (ACO1, ACO3, E4, E8) also decreased [63].

The ZDS (ζ-carotene desaturase) gene encodes the enzyme ζ-carotene desaturase, which catalyzes the subsequent desaturation steps of ζ-carotene, first into neurosporene and then into prolycopene (tetra-cis-lycopene). This is a key stage following the action of the PDS enzyme in the lycopene biosynthetic pathway. Disruptions in ZDS function lead to intermediate compounds such as ζ-carotene accumulation, highlighting its critical role in maintaining a proper carotenoid biosynthesis flow [64].

CRTISO (Carotenoid isomerase) – completes the process by converting prolycopene into all-trans-lycopene. The loss of CRTISO gene function in tomato fruits leads to the accumulation of the cis-form of lycopene (prolycopene) instead of the normal trans-lycopene, highlighting the important role of CRTISO in lycopene biosynthesis [65].

Lycopene biosynthesis represents a complex, multistep pathway under tight biochemical and genetic control, and is highly responsive to environmental cues.

Varietal characteristics of lycopene accumulation: The lycopene content in tomato fruits is determined by genetic characteristics and varies depending on the genotype [57, 66-67], ranging from 4.9 to 12.7 mg per 100 g of fresh weight or from 3.5 to 6.9 mg per 100 g of fresh weight depending on measurement conditions [68]. It has been shown that pink-fruited varieties contain significantly higher levels of lycopene than red-fruited varieties [69]. In the study by Ayuso-Yuste et al. (2022), it was noted that the lycopene level increases as the fruit ripens in all traditional/local varieties, reaching 132.64 mg/kg of raw mass. Moreover, traditional varieties contained more lycopene than commercial varieties during the last two stages of ripening [70]. Additionally, Kang (2022) emphasized the key role of the genotypic characteristics of tomato varieties in lycopene accumulation [71].

Breeding and Genetic Mutations: Traditional breeding of tomato varieties with high lycopene content presents a complex challenge due to the insufficient understanding of the molecular mechanisms regulating the accumulation of this carotenoid. With the development of molecular genetics and biotechnology, it has become possible to carry out such work in a more targeted manner. Several important genes in tomatoes have been mapped and cloned, and databases of sequenced whole-genome sequences have been created, opening the possibility for developing convenient and straightforward molecular markers [72]. Genome editing technology allows for the targeted modification of key genes that affect fruit quality, which can be effectively applied in breeding programs. This is especially relevant for breeding traits manifest in later stages of vegetative development, such as lycopene content in mature fruits [73].

A network of genes that coordinate precursor formation and conversion tightly regulates lycopene biosynthesis in tomatoes. Among the critical enzymes involved are PSY, ZDS, and CrtISO, all regulated during fruit development [64]. Duduit (2022) analyzed 42 high-lycopene tomato (HLY) varieties from different world regions to study these mechanisms. A comparative analysis using HPLC revealed that the lycopene level in HLY varieties significantly varied compared to control varieties, including the wild species Solanum pimpinellifolium, "Moneymaker," and NC 1Y. The expression of 25 genes involved in carotenoid biosynthesis was studied using real-time quantitative PCR. The results showed that genes such as GGPPS1, GGPPS2, GGPPS3, TPT1, SSU II, PSY2, ZDS, CrtISO, and CrtISO-L1 exhibited higher expression during the pink and red ripening stages in HLY varieties compared to control varieties. Meanwhile, genes responsible for the further conversion of lycopene (β-LCY2 and ε-LCY) demonstrated low activity, contributing to lycopene accumulation [74].

The characteristic red pigmentation of ripe fruits results from carotenoid synthesis, specifically lycopene and β-carotene, responsible for the color change of fruits from green to red. Lycopene synthesis in plants is regulated by several genes encoding key enzymes in biosynthetic pathways, such as lycopene-β- and lycopene-ε-cyclases, which play a central role in the conversion of lycopene into β- and α-carotenoids. Manipulating the expression of these genes, such as overexpression or suppression, is an effective method for increasing lycopene content in fruits. It is important to note that the genetic regulation of lycopene is also closely associated with plant adaptation to external conditions, such as stress factors [75].

Modern molecular breeding techniques, such as TILLING (Targeting Induced Local Lesions IN Genomes) and CRISPR/Cas9 (Clustered Regularly Interspaced Short Palindromic Repeats/CRISPR-associated proteins 9), offer new opportunities for creating tomato varieties with improved lycopene content. These approaches can enhance fruit quality and increase plant resistance to various stresses. Li et al. (2018) used CRISPR/Cas9 for targeted editing of five genes involved in carotenoid metabolism. This enabled the simultaneous stimulation of lycopene biosynthesis and inhibition of its conversion into β- and α-carotene. Genetic modification, performed using Agrobacterium tumefaciens, resulted in a 5.1-fold increase in lycopene content in the fruits. The resulting homozygous mutations were stably inherited in subsequent generations [75]. In 2021, Japan became the first country to release a tomato created using CRISPR technology on the market [76].

Genetic modification, including CRISPR/Cas9 technologies, offers new opportunities for precise gene editing related to the synthesis and degradation of carotenoids. For example, enhancing the expression of PSY or suppressing genes responsible for converting lycopene into other carotenoids can significantly increase the content of fruits [77].

Research conducted by Petrozza and colleagues (2023) demonstrated that modifying the enzyme lycopene-β-cyclase using the TILLING technology effectively increases lycopene levels in tomatoes. The novel allelic variant TILLING SlLCY-E has become a valuable genetic resource, capable of enriching fruits with lycopene and enhancing plant resistance to drought, which opens new prospects for developing varieties with improved traits [78].

The Del mutation, as shown in the studies by Ronen (1999), regulates lycopene accumulation in fruits by altering the expression of genes involved in carotenoid biosynthesis. During the fruit development phase, the mRNA levels of enzymes such as PSY and PDS, which participate in lycopene synthesis, increase, while the expression of genes responsible for converting lycopene into other carotenoids decreases. Specifically, the Del mutation in the tomato mutant Delta changes fruit color from red to orange due to the accumulation of beta-carotene instead of lycopene. The CrtL-e gene, which encodes lycopene epsilon-cyclase, is located on chromosome 12 and converts lycopene into delta-carotene. In plants with the Delta mutation, the transcript level of this gene increases 30 times during the ripening process [79].

Furthermore, mutations that slow down the degradation of lycopene, such as old-gold (og), old-gold crimson (og^c), and the chemically induced mutation A949G, are found in tomatoes with a determinate growth type, which limits the vegetative development of the plants. These tomatoes also carry a mutant allele in the SELF-PRUNING (SP) gene, which regulates plant growth [80]. Varieties containing the Crimson (og) gene had higher lycopene content (5086–5786 μg/100 g fresh weight) compared to varieties without this gene (2622–4318 μg/100 g) [81]. However, modern tomato hybrids predominantly exhibit an indeterminate growth type. Since the SP and CYC-B genes, which influence lycopene levels, are in close genetic linkage, their separation using traditional breeding methods is challenging. This complicates the development of varieties with high lycopene content while maintaining an indeterminate growth type [82].

According to Romdhane et al. (2023), homozygosity for the hp-2dg gene in tomato varieties significantly increases the content of lycopene, β-carotene, phenols, flavonoids, and vitamin C. Such varieties exhibit improved functional properties, including high antioxidant activity, and maintain good agronomic characteristics even under organic cultivation conditions [83].

Particular attention should be given to transgenic tomatoes. For example, a null mutation in the lycopene β-cyclase 2 gene (LCY-B2) increases the lycopene content in fruits by 5%. It promotes the formation of dark red fruits, indicating high potential for developing tomatoes with improved characteristics [75, 79].

The influence of environmental factors on lycopene content in tomatoes.

Temperature: The biosynthesis of lycopene in tomatoes is sensitive to temperature fluctuations, as confirmed by several studies [84]. According to Dumas et al. (2003), temperatures below 12 °C significantly suppress lycopene biosynthesis, while temperatures above 32 °C completely halt the process [67]. One of the reasons for this is the deactivation of the enzyme phytoene synthase (PSY), a key component in the carotenoid biosynthesis pathway. PSY catalyzes the first committed step in the carotenoid pathway and is considered the primary rate-limiting enzyme in carotenogenesis. Its activity is tightly regulated by various regulators and factors, allowing the plant to modulate carotenoid biosynthesis in response to both environmental and developmental signals. At high temperatures (>32 °C), PSY activity decreases sharply, leading to the cessation of lycopene synthesis [61]. The highest levels of lycopene are observed when moderate to high daytime temperatures (20–30°C) are combined with cool night conditions [67]. Research by Choi and Park (2023) demonstrated that tomatoes ripening at a daytime temperature of 30°C and a nighttime temperature of 20°C, along with a light intensity of 400 $\mu mol \cdot m^{-2} \cdot s^{-1}$, contain the maximum amount of lycopene. These findings highlight the importance of controlling the temperature regime during the fruit ripening stage to achieve optimal product quality [85].

In general, field-grown tomatoes contain more lycopene than greenhouse-grown ones. A study by Ilić (2014) involving 39 tomato genotypes showed that the lycopene content in greenhouse varieties ranged from 0.6 to 6.4 mg/100 g, while in field-grown tomatoes, it reached 11.7 mg/100 g [86]. However, data from Joseph O. Kuti (2005) demonstrate that cluster and round tomatoes grown in greenhouses contained more lycopene (30.3 mg/kg) compared to field-grown ones (25.2 mg/kg). In contrast, cherry tomatoes exhibited the opposite trend (91.9 mg/kg in the field vs. 56.1 mg/kg in greenhouses). This confirms that lycopene content is influenced not only by growing conditions but also by the genetic characteristics of the varieties [87].

While temperature directly affects enzyme activity in lycopene biosynthesis, light intensity and photo period further influence pigment accumulation by modulating chloroplast metabolism.

Solar Radiation, Photoperiod, and Fruit Surface Temperature: Light positively affects lycopene synthesis in tomatoes, with the key factor being the intensity of solar radiation. A study by Jarquín-Enríquez (2013) showed that increasing the photoperiod promotes an increase in lycopene content, especially under high light intensity, when the fruit color index (a*/b*) reaches 1.22 [88]. Moreover, light exposure, especially in the red/far-red spectrum, upregulates the expression of the Carotenoid isomerase (CrtISO) gene, which plays a crucial role in lycopene biosynthesis [64]. Light can also restore lycopene synthesis when Z-ISO (ζ-carotene isomerase) is suppressed [64]. However, it is essential to note that excessive solar radiation may negatively affect the lycopene content in the fruit [67].

In the research by Helyes et al. (2003), a significant difference was found in lycopene content between tomatoes grown in open field conditions (49.15 mg/kg ± 1.19) and those grown in greenhouses (66.03 mg/kg ± 2.02). Additionally, a negative correlation (R^2 = 0.95) was established between fruit surface temperature and lycopene levels, highlighting the importance of surface temperature in determining lycopene content. The higher the fruit surface temperature, the lower the lycopene content, especially under intense sunlight. This study confirms that the fruit surface temperature is a more accurate indicator of lycopene content than air temperature, particularly when the fruit is exposed to direct sunlight. In open field conditions, tomatoes are subjected to higher daytime temperatures and more intense sunlight, which can lead to reduced lycopene content. The lycopene content in greenhouse-grown tomatoes was 40% higher than in field-grown tomatoes [89].

Later, in the study by Helyes et al. (2007), a relationship was established between solar radiation, fruit surface temperature, and lycopene content in indeterminate-type tomatoes (*Lycopersicon esculentum* Mill.) grown in the field on a trellis system. The results showed that the positive correlation between solar radiation and surface temperature was significantly stronger on non-shaded fruits ($R^2 = 0.87$) than on shaded fruits ($R^2 = 0.79$). This indicates increased solar radiation and fruit surface temperature may reduce lycopene content. A strong negative correlation ($R^2 = 0.95$) was found between surface temperature and lycopene content, confirming the loss of nutritional qualities in non-shaded fruits as temperature rises. These data emphasize the importance of controlling temperature and light conditions to maintain high lycopene content in tomatoes [90].

Fruit Ripening and Storage: Ripening conditions play a crucial role in determining the lycopene content in tomatoes. Studies have shown that fruits ripening at low temperatures (15 ^{o}C) or on the vine contain significantly more lycopene than fruits stored at 30 ^{o}C. This is confirmed by data from analyzing the hue index (a*) using the CIELab system, where fruits ripening on the cluster or at low temperatures show higher values [91]. Other studies have also highlighted the importance of storage temperature: ripening increases lycopene content if the temperature is maintained within the range of 8±2 ^{o}C, and packaging helps to preserve lycopene levels when proper storage conditions are maintained [92].

The Role of Regulators in Lycopene Accumulation

Ethylene: Ethylene (ET) is a plant hormone that plays a crucial role in fruit ripening. It coordinates the ripening process through a transcriptional network, interacting with developmental factors and epigenetic regulation, which affects gene expression during ripening [93]. Shen (2024) highlighted the SlFSR (Fruit Shelf-life Regulator) gene's role in regulating ethylene biosynthesis and lycopene content. One of the effects of ET is the degradation of chlorophyll, which contributes to the color change of fruits from green to red. This process is also accompanied by increased lycopene concentration [94]. Ethylene accelerates ripening and influences changes in texture, taste, aroma, and post-harvest shelf life of fruits [95].

In addition to ET, another important hormonal regulator involved in lycopene biosynthesis is Jasmonic acid (JA), which has been increasingly studied for its distinct and complementary effects.

Jasmonic Acid: While ethylene has long been recognized as a key ripening regulator, recent studies have emphasized the influence of JA on lycopene accumulation. Experiments with mutants, such as spr2 and def1 (deficient in JA levels), and the transgenic line 35S::ProSystem (with enhanced JA activity), demonstrated that lycopene levels and the expression of its biosynthetic genes were significantly reduced in mutants. In contrast, they increased in plants with enhanced jasmonic acid signaling. Treatment of fruits with methyl jasmonate (MeJA) revealed a dose-dependent effect, with the optimal concentration (0.5 μM) restoring lycopene content in spr2 and def1 mutants. Interestingly, JA can act independently of ethylene. In the Never Ripe (Nr) mutant, which is insensitive to ethylene, the application of MeJA still promoted lycopene accumulation and the activation of associated genes. This suggests an alternative, ethylene-independent mechanism for regulating lycopene biosynthesis under the influence of jasmonic acid [96].

These results highlight the importance of JA as an additional regulator of carotenoid metabolism in tomato fruits, opening up new possibilities for managing product quality through hormonal regulation.

Together, ethylene and JA represent two distinct yet complementary hormonal pathways that modulate lycopene biosynthesis in tomatoes. Ethylene primarily drives the classical ripening cascade, while jasmonic acid can activate lycopene accumulation through both ethylene-dependent and -independent mechanisms. Understanding the interplay between these hormones provides valuable insight into optimizing fruit quality through integrated hormonal regulation strategies.

Effect of Potassium Fertilizers: Various studies confirm that increasing potassium fertilizer doses positively affect lycopene content in tomato fruits [97-98].

Research by Shanshan Li (2006) on greenhouse-grown tomato plants demonstrated that potassium concentration directly influences the biosynthesis of phytoene and phytofluene, colorless precursors of lycopene, and the expression of carotenoid biosynthesis genes. Increasing the potassium concentration to 10 meq/L was associated with enhanced expression of the phytoene synthase and carotenoid isomerase genes, which led to increased lycopene content [99].

Regarding carbohydrate metabolism, potassium modulates the enzymes pyruvate kinase and phosphofructokinase. It affects the formation of acetyl-CoA, which is involved in the production of isopentenyl diphosphate, the first precursor of carotenoids [100].

Effect of Potassium Doses: According to Serio et al. (2007), lycopene content in tomatoes increased linearly with higher potassium concentration in the nutrient solution, especially in genotypes with high pigment content [101]. Similar conclusions were made by Khan & Bakhsh (2012), who showed that the application of K_2O at a dose of up to 375 kg/ha increased lycopene content by 52.54%, but further increasing the dose to 450 kg/ha decreased its level. This is explained by the sensitivity of the lycopene biosynthesis process to potassium concentration in the cytoplasm of cells [102].

Studies by Taber et al. (2008) found that excessive potassium reduces lycopene levels, highlighting the need for balanced fertilizer use. A proper combination of nitrogen and potassium can enhance lycopene concentration and tomato quality [97].

Potassium and Ripening Stages: Kaori et al. (2024) found that a high potassium concentration (24 mM) increases lycopene content during the early stages of ripening and maintains its high levels until full ripening. These results emphasize the importance of managing potassium levels to produce fruits with enhanced nutraceutical value [103].

Similarly, Taber et al. (2008) observed that when potassium concentration increased from 5 to 13 mmol/m^3 during the reproductive stage, lycopene concentration increased by 39%, 49%, and 51% in the fruits of the first, third, and fifth clusters, respectively. The increased lycopene concentration was linked to the increased potassium supply to the tomato harvest [97].

Ecological and Physiological Interactions: Studies by Shabani Sangtarashani et al. (2013) show that under salinity conditions, an optimal potassium concentration (7 mM) helps improve fruit quality and enhance their antioxidant potential [98]. San Martín-Hernández et al. (2021) also noted the positive effect of potassium on the content of sugars, vitamin C, proteins, and carotenoids, including lycopene [104].

Recent advancements in precision agriculture have enabled targeted potassium delivery based on real-time plant nutrient sensing, allowing optimized lycopene enrichment with reduced environmental impact [105].

Impact of Balanced Nutrition and Organic Fertilizers: Balanced mineral and organic nutrition play a critical role in modulating lycopene biosynthesis in tomato fruits by influencing key physiological and metabolic pathways.

Mineral nutrition significantly influences the lycopene content in tomato fruits, as nitrogen, phosphorus, and potassium fertilizers directly or indirectly regulate fruit coloration by affecting pigment synthesis. Studies have shown that balanced fertilization significantly increases the lycopene content. In particular, Li et al. (2024) reported a 58.02% increase in lycopene concentration compared to the control, while reducing the fertilizer dose by 10% led to a decrease in lycopene levels [106].

Moreover, organic fertilizers also play a key role in enhancing the lycopene content and improving the overall quality of tomato fruits [107]. According to Gao (2023), when the organic matter content in the soil exceeds 20 $g \cdot kg^{-1}$ and the total nitrogen content exceeds 1 $g \cdot kg^{-1}$, the lycopene concentration in the fruits increased by 23.95%. These data highlight the importance of an optimal balance of soil components, which promotes the intensity of fruit coloration and their nutritional value. This indicates that nutrient form and soil composition are crucial factors in optimizing fruit quality and nutritional value [108].

In addition, using fulvic acid-based preparations can significantly increase the lycopene content in tomato fruits. Fulvic acids, as part of humic substances, improve the absorption of nutrients by the plant, which positively affects the biosynthesis of carotenoids, including lycopene. Research confirms that treating tomatoes with fulvic acid increases the lycopene concentration, making the fruits more valuable in terms of antioxidant activity and nutraceutical significance. Numerous scientific studies have noted the effectiveness of fulvic-humic fertilizers in increasing lycopene content [57, 109-110].

In summary, an integrated approach involving balanced mineral fertilization and organic soil amendments, including fulvic acids, synergizes lycopene accumulation. This reinforces the importance of optimizing nutritional strategies for producing high-quality, functionally enriched tomatoes.

CONCLUSIONS

Lycopene is one of the most important carotenoids in tomatoes, responsible for their antioxidant properties and health-promoting effects. It plays a significant role in neutralizing reactive oxygen species, activating detoxification enzymes, inducing apoptosis, and inhibiting abnormal cell proliferation. These biological activities contribute to the prevention of chronic diseases such as cancer and cardiovascular disorders, making lycopene a key compound in developing functional foods.

Its accumulation in tomato fruits depends on various factors, including genetic characteristics, agronomic practices, and environmental conditions. Breeding tomato varieties rich in lycopene, especially with molecular markers and modern genomic tools, makes it possible to develop products with higher nutritional and biological value. Additionally, optimized agronomic practices- such as potassium fertilizers, growth regulators, temperature and light control, and post-harvest management- play a significant role in maintaining and enhancing lycopene levels.

This review presents a novel, integrated approach combining the latest molecular genetics achievements with practical agronomy. Unlike previous reviews that mainly focused on genetic or agronomic aspects, this paper emphasizes the importance of their synergy. It offers a more holistic view of strategies to enhance lycopene accumulation in tomatoes. This comprehensive approach improves tomatoes' commercial and nutritional qualities and contributes to expanding their application in the development of functional foods and preventive nutrition.

List of Abbreviations: GGPP- Geranylgeranyl pyrophosphate; PSY- Phytoene synthase; PDS -Phytoene desaturase; ZDS- ζ-carotene desaturase; Z-ISO -ζ-carotene isomerase; CRTISO- Carotenoid isomerase; CRISPR/Cas9- Clustered Regularly Interspaced Short Palindromic Repeats/CRISPR-associated protein 9; TILLING- Targeting Induced Local Lesions in Genomes;

HLY- High-lycopene; HPLC- High-performance liquid chromatography; JA- Jasmonic acid; ET- Ethylene

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