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Advancing Tomato Bioactives: Approaches to Enhance Antioxidant Efficacy and Functional Food Development

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ABSTRACT

Tomato by-products are rich in key bioactive constituents, including lycopene, polyphenols, carotenoids, dietary fibers, and essential fatty acids, which significantly contribute to nutritional and functional quality. Various approaches such as green extraction technologies, fermentation, encapsulation, and elicitation have been shown to improve the stability, bioavailability, and efficacy of these compounds. These advancements support their incorporation into diverse food systems, improving product quality, shelf life, and consumer acceptance. The valorization of tomato processing residues presents a sustainable and innovative pathway aligned with circular economy principles. The development of closed-loop bioactive systems enables the conversion of waste streams into high-value functional ingredients, supporting zero-waste biorefineries. Although challenges such as scalability and economic feasibility remain, this approach holds significant promise for advancing next-generation functional foods and promoting human health. This review aims to explore the potential of tomato processing by-products—such as pomace, peels, and seeds—as valuable sources of bioactive compounds with strong antioxidant properties. It highlights the transition from conventional waste management to value-added utilization, focusing on strategies to enhance the antioxidant activity of these compounds and their application in developing functional tomato-based foods.

Keywords- Tomato, Nutritional profile, Functional food, Bio-fortification, Health benefits, Antioxidant activity

1. Introduction

The tomato, or *Lycopersicon esculentum*, is the second most widely grown crop in the world and is therefore very important. Known for their many health benefits, including lowering the risk of chronic diseases, tomatoes are an essential part of the Mediterranean diet [1-3]. An estimated 186 million tonnes of fresh tomatoes were produced worldwide in 2020, underscoring both their enormous consumption and agricultural importance [4]. Tomatoes are attractive ingredients for the development of functional foods because of their rich antioxidant composition, which is largely responsible for their health-promoting qualities [1]. According to research, the antioxidant chemicals in tomatoes may help lower the incidence of chronic diseases, especially by improving cardiovascular health and lowering the risk of some cancers, primarily prostate cancer [5-8]. In preventive nutrition, functional meals made from tomatoes are especially interesting because diet-related diseases like diabetes and obesity are becoming more common.

Global consumption of tomatoes is on the rise, and they are widely consumed both fresh and processed, notably in ketchup, puree, and other value-added products. Furthermore, recent research has looked into the possibility of using tomato seeds and other by-products to produce high-value oils that are high in antioxidants and unsaturated fatty acids [9,10]. The food industry is increasingly using these by-products, which are impacted by cultivar and growth conditions, to improve the antioxidant profile of different products.

According to Collins et al., [11] tomatoes are a great source of bioactive components such as flavonoids, phenolic compounds, ascorbic acid, tocopherols, carotenoids (lycopene and β-carotene), and ascorbic acid. These chemicals all have potent antioxidative qualities, can help ameliorate many diseases, especially chronic diseases. A lower risk of cancer, cardiovascular diseases (CVDs), and neurological disorders has been associated with the high antioxidant content of tomatoes and their derivatives [11-13]. Antioxidants have a role in chelating metal ions, lowering hydroperoxides, inhibiting cellular proliferation and damage, inhibiting apoptosis as well as working in concert with other reducing substances in addition to their capacity to neutralise free radicals, modulation of enzymatic activities, cytokine expression and signal transduction pathways. Additionally, numerous body processes such as the control of metabolic pathways, the development of vital organs, the preservation of physiological processes, the control of blood pressure, pH, fluid balance, nerve transmission, muscular contraction, and energy production depend on minerals, which are inorganic solids that exist naturally. Several minerals, like Ca, K, Na, P, Mg, S and Cl are referred to as significant elements since they are extremely necessary. Other trace elements include Fe, I, Zn, F, Cu,Mn, Co, Cr, Ni, Mo and Se. These elements are needed in relatively lesser levels (< 50 mg/day). In terms of nutrition and involvement in antioxidant activities, tomatoes are a good provider of several elements and minerals [14]. These primary antioxidants (carotenoids, vitamins and polyphenols) and micronutrients found in tomatoes, help to protect cell membranes and other medicinal qualities by lowering oxidative stress and lipid peroxidation [15,16]. Nevertheless, there is a shortage of current, comprehensive knowledge on the nutritional makeup of tomatoes and how they are enhanced, which is crucial for their antioxidant properties and health advantages. Thus, in this review, we look at how tomatoes are nutrient-dense, how to increase bioactive substances (such ascorbic acid, lycopene, and total phenolics), and how to treat foods to increase their antioxidant activity and micronutrients. We also go over the health advantages of these bioactive substances and how they contribute to general wellbeing.

2. Chronological overview

Tomato is believed to have originated from wild, small green-fruited species native to the Andean foothills [17]. Around 700 AD, a yellow-fruited form resembling present-day tomatoes in size was cultivated in Central America, while its domestication is considered to have begun in Mexico. Following colonization, tomato seeds were dispersed across different parts of the world, leading to the widespread adoption of monoculture systems [17]. After Mexico gained independence, advancements in transportation infrastructure and land reforms significantly enhanced tomato production [18].

Historical evidence suggests that tomatoes were introduced into Europe by 1544, although they were initially perceived as toxic. Over the following two centuries, their acceptance gradually increased, leading to their incorporation into European diets. The Green Revolution further accelerated global tomato production through improved irrigation techniques and the use of agrochemicals. The modern tomato has evolved substantially due to advancements in horticultural practices. In the 1990s, developments in biotechnology and genetic engineering facilitated the production of tomato varieties with improved color, flavor, shelf life, and nutritional quality [18]. A range of techniques has since been employed to enhance fruit characteristics such as size, appearance, and overall quality. In recent years, crop improvement strategies have shifted toward enhancing nutritional benefits and increasing resistance to diseases [19].

3. Tomato as a rich source of antioxidants

Tomatoes have emerged as one of the most widely consumed vegetables globally, distinguished by their rich profile of natural antioxidants essential for human nutrition. These fruits are characterized by an impressive array of bioactive compounds, including carotenoids (primarily lycopene and β-carotene), vitamins (C and E), minerals and various phenolic compounds (particularly flavonoids), all of which contribute significantly to human health and disease prevention. Among dietary sources of antioxidants, tomatoes and their processed products stand out as exceptional providers of α-tocopherol and several carotenoids, including β-carotene, phytoene, and phytofluene. Notably, tomatoes represent the primary dietary source of lycopene, which has been identified as the most potent antioxidant among carotenoids in in vitro studies. Extending beyond the fruit itself, tomato processing by-products have also been recognized as valuable sources of phytochemicals, containing significant levels of carotenoids, polyphenols, vitamins (ascorbic acid, tocopherols, and provitamin A), glycoalkaloids (tomatine), and essential minerals (K, Mn, Ca, Cu, and Zn) [17]. This comprehensive nutritional profile emphasizes the value of utilizing both tomato fruits and their processing residues in promoting human health.

3.1 Carotenoids

Carotenoids are a broad class of fat-soluble natural pigments that give many fruits and vegetables their characteristic yellow, orange, and red color and exhibit strong antioxidant activity. They can be broadly classified into two types: carotenoids, which have linear hydrocarbons without oxygen, such as lycopene and β-carotene, deliver an orange color, and xanthophylls, which have oxygen atoms, offer a yellow color [18]. Carotenoids are produced during the ripening process of tomato fruit, with lycopene being the main pigment, making up to 80–90% of all carotenoids [19]. Additionally, fruits are rich in pro-vitamin A and β-carotene molecules, which are bioavailable in natural form and act as antioxidants. This antioxidant ability is especially crucial for human health since it aids in the body's defence against dangerous free radicals. According to Yamagata et al., [20], the various isomers of β-carotene, all trans and 9-cis β-carotene, all efficiently quench singlet oxygen, hence lowering oxidative stress and neuronal damage. However, in the presence of light, heat, metals, or pro-oxidants, carotenoids are isomerised from their trans-form to cis-form, which results in a loss of colour and pro-vitamin activity. Because it directly affects the nutritional content and aesthetic appeal of meals containing these substances, this conversion is important. Although β-carotene is frequently the most well-known carotenoid, other carotenoids, such as lutein and zeaxanthin, which are known to support eye health and telomere maintenance in older adults, can be found in lesser concentrations but still offer significant health advantages [21]. Although they target different body systems, these substances function through comparable antioxidant pathways. It's interesting to note that zeaxanthin has higher protective benefits against oxidative stress in the brain because of its extra conjugated double bond, which improves its antioxidant efficacy [22]. Despite having identical general capabilities, some carotenoids may offer better neuroprotection than others due to this structural advantage.

As the main carotenoid in tomato, lycopene, an acyclic carotene that has 11 conjugated double bonds, predominantly in the trans form, is isomerized in blood plasma and is better absorbed. Lycopene is an important precursor for compounds such as β-carotene and xanthophylls as one of the key terminal intermediates in carotenoid biosynthesis and ranges from around 3.1-7.7 mg/100g fresh weight in ripe tomatoes [13]. Lycopene has been extensively investigated in the management of several diseases including obesity, type 2 diabetes, cancer, and neurodegenerative diseases [23,24]. Particularly, lycopene is the most efficient carotenoid at scavenging singlet oxygen and reactive oxygen species.

3.2 Phenolic Compounds

Phenolic compounds are characterized by an aromatic ring consisting of one or more hydroxyl substituents, having antioxidant activities found at lower levels in tomatoes than carotenoids. These molecules show structural diversity characterized by simple low-molecular-weight phenolic compounds to complex high-molecular-weight polymeric structures. There are two classes of compounds; flavonoids and non-flavonoids. The flavonoids encompass subclasses such as flavanones, flavonols, flavones, flavan-3-ols, anthocyanins, and chalcones while non-flavonoids include stilbenes, phenolic acids (hydroxybenzoic acids and hydroxycinnamic acids), tannins, neolignans, and coumarins. The primary phenolic compounds found in peel, pomace, and seeds of tomato are flavonols and phenolic acids, with quercetin, naringenin, and rutin being the predominant molecules [25]. However, Tomato peels contain a significantly higher level of phenolic compounds (33.5 mg TAE/100 g dried peel) in comparison with the seeds and pulp; flavonols (83%) and flavone in tomatoes are present in the peels [26].

3.3 Flavonoids

Among flavonols, quercetin stands out as a key compound, with concentrations varying between 0.7 and 4.4 mg 100 g^{-1} fresh weight across different tomato varieties. Its glycosylated form, rutin, can accumulate up to 4.5 mg 100 g^{-1} [27]. The accumulation pattern of flavonoids in tomatoes demonstrates notable tissue specificity and developmental regulation. For instance, the predominant non-flavonoids polyphenol Naringenin chalcone accumulates up to 18.2 mg 100 g^{-1} fresh weight in the overripe fruit peels [27,28] coinciding with carotenoid synthesis and chlorophyll degradation, while its related flavanone, naringenin, occurs at lower levels of up to 1.3 mg 100 g^{-1} fresh weight [29].This distinct distribution pattern explains why tomato processing by-products, particularly peel-rich waste streams, represent valuable sources of both polyphenols and carotenoids, suggesting their potential application as functional ingredients in novel food formulations. In addition to being used as a functional food, tomatoes have antioxidant potential because of phenolic compounds, which have drawn a lot of interest because they can reduce the risk of a number of chronic illnesses, including cancer, diabetes, heart disease, neurological conditions, cataracts, and certain cognitive function disorders [30].

3.4 Vitamins

Additionally, it is essential to make sure that vitamin levels are thoroughly examined in order to maintain a standard. Keeping up a diet is crucial since deficiencies or excesses of specific vitamins can impact normal cell growth processes, resulting in health problems. In many parts of the world, tomatoes are used in many different types of food and are a great source of important vitamins, including C, B complex, A, E, and K [14]. Of these, vitamin C is the most plentiful in tomatoes. Vitamins C (Ascorbic acid), exerting a crucial role in the detoxification of reactive oxygen species generated following exposure to biotic stress factors. Ascorbic acid is abundant in many fruits and is the most common in the majority of them, when compared with the presence of vitamin E (α-tocoferol). Therefore, it is believed that ascorbic acid contributes much to the antioxidant activity of fruit extracts. Tomato contain a considerable content of ascorbic acid varies significantly (10-40 mg/100g fresh weight) depending on variety, maturity stage, and growing conditions. In this way, fruits and vegetables go through changes from the moment of being harvested. One of the most reactive substances in the world, ascorbic acid is very sensitive to storage and handling conditions. Studies generally show that low temperatures and gentle treatment enhance vitamin retention. It should be highlighted, therefore, that a variety of interrelated factors influence ascorbic acid retention [31]. Additionally, vitamin E, often known as tocopherol, are found in tomatoes and have qualities that can help prevent cancer and other ailments. Folate is one of the forms of vitamin B complexes that is present in tomatoes. It's important to note that since the body can readily excrete these vitamins, consuming too much water vitamin B does not cause toxicity. These vital nutrients are involved in processes including blood cell and enzyme synthesis and nervous system upkeep. It's important to note that since the body can readily excrete these vitamins, consuming too much water vitamin B does not cause toxicity. These vital nutrients are involved in processes including blood cell and enzyme synthesis and nervous system upkeep.

4. Extraction method

In order to reduce the number of by-products and increase the economic feasibility of processes by creating ingredients with added value, agro-industrial by-products are valuable sources of functional food components with commercial appeal. Supercritical carbon dioxide (SC-CO2) technology was explored for this purpose in order to add value to tomato (cultivar 'Admiro' F1) by-products, which include peel, seeds, and a little amount of pulp. The antioxidant impact of the extract in cell culture was examined, and the extraction parameters of high-value components (oleoresin with 60% cis-lycopene isomers content) were optimized. Total lycopene and its various isomers (15-cis-lycopene, 13-cis-lycopene, 9-cis-lycopene, 7-cis-lycopene, trans-lycopene, and 5-cis-lycopene) were measured in the extract that was obtained under ideal conditions (52°C temperature, 55 MPa pressure, and 180 minutes extraction time). The antioxidant effect of the extracts was assessed by measuring the production of reactive oxygen species (ROS) by murine macrophage J774 cell culture. According to the results, tomato by-products (peel, seeds, and a tiny quantity of pulp) can be extracted using SC-CO2 to produce cis-lycopene isomers (the extract's total cis-lycopene isomer content was 60%). These oleoresins have prospective uses in the food and pharmaceutical industries [32].

A sizable tomato processing company gathered tomato pomace, a by-product produced during tomato processing. The by-product had a high moisture content (66.58 g.100 g−1 wet basis) and was primarily composed of tomato skin (61.5%). Dietary fiber was the most abundant nutrient, followed by proteins and fat (50.74, 20.91, and 14.14 g, 100 g−1 d.w., respectively). According to the TEAC experiment, the pomace has a strong in vitro antioxidation capacity (224.81 μmol Trolox equivalent 100g−1 d.w.). The significant amount of lycopene that remains in the by-product after processing (446.9 μg. g−1 d.w.) is mostly to blame for this. This is mostly because to the significant quantity of lycopene that is still present in the by-product following processing (446.9 μg. g−1 d.w). By using the skin fraction as the source material instead of the total pomace, the waste was separated into skin and seed fractions by sedimentation, increasing the lycopene yield by 55%. This by-product has a lot of promise for utilization as a source of very nutritious nutrients, including lycopene and dietary fiber [17].

The first method used by some researchers to extract bioactive compounds was ultrasound-assisted extraction (UAE) for carotenoid extraction, followed by spray-drying technology for encapsulating the enriched carotenoid extract and analyzing its powder qualities. The second one assessed the possibility of using tomato peel that contains total dietary fiber (TDF) in place of wheat and fat in four different cookie recipes. Physicochemical, textural, sensory, and theoretical proximate studies were used to evaluate each formulation. The findings showed that a solvent ratio of 80:20 ethyl acetate to ethanol and a 2.5% w/v solvent biomass ratio were used for UAE optimization. 89.08% of the total carotenoid content was recovered. On a dry basis, the TDF content was 49.46 (3.91) g/100 g. The drying yield was 67.3% (0.5) and the encapsulation efficiencies were 58.1% (0.8) for encapsulation. The means for the 30% fat replacement cookie and the control cookie did not differ significantly, according to sensory analysis. Additionally, customers were most likely to buy these 30% fat replacement cookies. Through the development of new functional food products with a high carotenes and dietary fiber content, this study offered a solution for the industrial waste of tomato peels, improving the nutritional and health benefits for consumers [33].

5. Approaches to improve antioxidant activity and micronutrients

Some following approaches are involved to create tomato cultivars with improved nutritional profiles, specifically, higher levels of antioxidants. The cost-effective strategy for enhancing nutrient contents in edible crops through seed priming techniques, soil amendments, and foliar sprays [34]. Traditional breeding and modern biotechnological approaches have been also extensively utilized to enhance the levels of bioactive compounds in tomatoes.

5.1 Hydroponics

Tomatoes are a vital vegetable and a major dietary source of carotenoids, which confer nutritional and sensory value. They are also enriched with a wide range of phytochemicals, including lycopene, flavonoids, carotenoids and carotenoid-derived volatile compounds, which highly contributed to the beloved flavor and the health-promoting attributes of tomato products [35]. Hydroponic cultivation systems have proven to exceed traditional soil-based agriculture and enhance the nutritive quality of tomatoes. This is especially important, because fruits and vegetables are not good sources of some vital micronutrients needed to support a human nutrition. For example, when iodine was provided to the roots of hydroponically grown plants, it was absorbed more efficiently. Iodized salts (potassium iodide, KI or KIO_3) positively influenced the iodine content in tomato fruits and did not negatively affect the growth or development of plants in hydroponic systems. The amount of iodine in the fruits varied considerably from several milligrams per kilogram of fresh weight to 10 mg per kilogram of fresh weight, which is a quite enough for biofortification programs. Because the recommended daily dietary intake of iodine for adults is 150 micrograms, hydroponically grown tomatoes could be a unique food to improve human nutrition [36,37]. A alternative way was used to increase the iodine content and yield of tomato, Smoleń et al., [38] evaluated the influence of salicylic acid (SA) with iodine salts (KI or KIO_3). Fruits of plants treated with KI contained significantly more iodine. SA contributed to a 157% and 37% increase in iodine accumulation in fruits – for KIO3 + SA and KI + SA, respectively. Treatment with KIO3 was the best for nutritional value of tomato fruits (Fig. 1).

Selenium (Se), an essential trace element crucial for antioxidant activity in higher plants, accumulates at low concentrations in species like *Solanum lycopersicum*, necessitating supplementation through biofortification programs. Studies have explored various selenium delivery methods, including irrigation with sodium selenite (Na2SeO3) at concentrations ranging from 0-5 mg L^{-1}, which enhanced both selenium and macronutrient accumulation across plant tissues while improving tomato productivity [39]. Comparative analyses of enrichment strategies revealed that while sodium selenate (Na2SeO4) application in hydroponic systems resulted in higher selenium accumulation compared to selenium nanoparticles (SeNPs), the latter demonstrated superior characteristics for organic incorporation and environmental safety. Alternative approaches, such as passive immersion of harvested fruits, have emerged as promising biofortification strategies that minimize environmental impact [40].

5.2 Foliar treatment

A thorough salicylic acid treatment approach that included both pre- and post-harvest treatments was investigated. Three weeks prior to harvest, foliar treatments at different concentrations (4+1, 4+2, and 4+4 mM) were applied. The post-harvest treatment involved immersing the fruits in a salicylic acid solution for five minutes. After 40 days of storage, fruits receiving the dual treatment showed noticeably higher retention of ascorbic acid content, measured by titrimetric measurement and expressed as mg/100g fresh weight, than untreated controls [41]. Beyond ascorbic acid preservation, treatment with 1mM salicylic acid enhanced both antioxidant activity and pigment concentrations. Comparative studies revealed that propolis foliar application exhibited superior efficacy in elevating antioxidant enzyme levels compared to salicylic acid treatments [42]. Furthermore, salicylic acid demonstrated multifaceted benefits, including enhanced stress tolerance through antioxidant system fortification, improved photosynthetic efficiency, and increased fruit productivity [43] (Fig. 1).

Iron biofortification strategies have demonstrated remarkable success through diverse application methods, including nutrient solution enhancement, foliar application, and seed priming. In particular, studies have revealed optimal iron supplementation protocols, where the combination of 2 mmol Fe L^{-1} in nutrient solution with foliar sprays at 500 μmol Fe L^{-1} yielded the most significant increases in fruit iron concentration. While this supplementation led to enhanced fruit dry matter content, showing an increase of up to 10.21%, it conversely resulted in a reduction of fruit fresh weight by up to 11.06%. Notably, the elevated iron concentrations not only improved iron content but also synergistically enhanced the accumulation of other essential minerals, including potassium, magnesium, sodium, and zinc. Furthermore, these treatments positively influenced fruit quality parameters, resulting in increased titratable acidity and soluble solids content. These comprehensive improvements in both nutritional and quality attributes demonstrate that iron biofortification of cherry tomatoes represents an effective strategy for addressing iron deficiency while maintaining superior product quality [44]. Moreover, agronomic biofortification has emerged as a promising strategy to combat global iron deficiency, prompting researchers to investigate optimal iron supplementation protocols in tomatoes. Studies have systematically evaluated various iron application methods and their effects on both fruit iron enrichment and overall plant performance. Foliar application at 6 mM Fe concentration has proven particularly effective, achieving significant increases in fruit iron content (30.07-34.1 mg kg^{-1}) while enhancing crop productivity [34]. Additionally, seed priming with iron sulfate at 10 mg L^{-1} has demonstrated notable success, doubling fruit iron content (2.04-2.37 fold increase compared to control) while simultaneously improving plant growth parameters. These comprehensive studies, examining multiple metrics including growth, yield, and quality attributes, have established effective iron supplementation strategies that optimize both nutritional enhancement and agricultural productivity [45] (Fig. 1).

5.3 Biostimulants

Tomatoes are recognized for their significant antioxidant properties, particularly in preventing cardiovascular diseases. Recent studies have explored various bio-fertilization strategies to enhance these beneficial compounds. Bio-fertilizers, comprising quality components such as cow dung, poultry litter, household waste, and sugar mill press mud, have demonstrated significant potential in improving antioxidant content. Research has shown that different bio-fertilizer treatments yield varying results: 100% bio-fertilizer application maximizes ascorbic acid content, while a combination of 75% bio-fertilizer with 25% nitrogen enhances beta-carotene levels. Interestingly, recommended doses of NPK have been found to optimize lycopene content [46].

In the realm of microbial bio-fertilizers, biofilm-producing bacteria (BPB) isolated from tomato rhizosphere have shown remarkable potential. Various species of *Pseudomonas, Bacillus, and Enterobacter* have demonstrated significant improvements in multiple plant parameters. Specifically, inoculation with selected bacterial strains has led to substantial increases in biomass production (4.3–20.7% in roots, 6.0–41.7% in shoots), yield (4.4–69.1%), and quality parameters including total soluble solids (11.2–33.5%), lycopene (28.5–142.8%), β-carotene (27.2–363.6%), phenolics (6.3–52%), flavonoids (10.4–69.2%), and antioxidant capacity (13.3–66.6%) compared to controls [47] (Fig. 1).

The implementation of Effective Microorganisms (EM) technology represents another innovative approach in eco-friendly crop enhancement. Studies comparing EM with traditional methods across different tomato varieties (Brandywine, Corbarino Giallo, S. Marzano Cirio 3, and S. Marzano Antico) have revealed significant improvements in both productivity and nutritional quality. The San Marzano Antico and Brandywine varieties, in particular, showed enhanced antioxidant activity and altered polyphenol and carotenoid profiles in response to EM treatment [48].

Additionally, marine bio-resources have emerged as promising biostimulants. The green seaweed *Ulva flexuosa* has demonstrated significant potential in enhancing cherry tomato production. Extract applications resulted in impressive improvements across various parameters, including total soluble solids (93%), phenol content (92%), lycopene (12%), ascorbic acid (86.8%), and overall fruit yield (97%) [49] (Fig. 1).To enhance the antioxidant enzymes which cope up with the stresses and required for sustainable growth of plant seedlings, the allicin containing garlic aqueous extract act as a biostimulant [50]. These findings highlight the potential of biostimulant as an effective bio-fertilizer for sustainable agricultural practices aimed at meeting increasing food demands.

6. Impact of processing

Processed fruits and vegetables have been long considered to have lower nutritional value than their fresh commodities due to the loss of vitamin C during processing. Here it is shown that thermal processing elevated total antioxidant activity and bioaccessible lycopene content in tomatoes and produced no significant changes in the total phenolics and total flavonoids content, although loss of vitamin C was observed. The *trans*-lycopene content (5.45 mg of *trans*-lycopene/g) and the total antioxidant activity significantly had increased while the vitamin C content significantly dropped when heated at 88 °C at different time intervals [51]. To prevent vitamin C content, freezing drier method was used to enhance antioxidant activity with increased GSH, cysteine, total phenolic compound and CUPRAC values. . Hence by keeping tomatoes in cool environment can significantly increase antioxidants levels in fruit [52] (Fig. 1).

7. Impact of Harvest maturity

For experimental investigation, mature green tomatoes of consistent size and quality were gathered, cleaned, and dried. Recent investigations into pre-harvest treatments have demonstrated promising results for enhancing post-harvest quality of tomato fruits through the application of organic acids. A comprehensive study evaluated the combined effects of humic acid (HA), fulvic acid (FA), and salicylic acid (SA) on tomato fruit quality parameters during storage. The study revealed significant improvements in physicochemical properties across all treatments compared to untreated controls. Notably, the combination of HA and FA proved superior in maintaining fruit firmness compared to HA-SA treatments. The most effective treatment (40 mL L^{-1} HA plus 2 g L^{-1} FA) resulted in substantial enhancements in key quality parameters, including a 10% increase in carotenoid content and a remarkable 92% improvement in total soluble solids. This treatment also demonstrated optimal results for reducing sugars, ascorbic acid, and pectin content at the conclusion of the storage period. Furthermore, the pre-harvest treatments positively influenced antioxidant enzyme activities, specifically α-amylase, catalase (CAT), and peroxidase (POX), during storage. These findings collectively demonstrate that the synergistic application of HA and FA as pre-harvest treatments effectively preserves post-harvest quality and extends the shelf life of tomato fruits under controlled storage conditions (12°C, 95% relative humidity) [53]. Meanwhile, harvesting at the proper stage of maturity and appropriate postharvest handlings including chemical regulation, optimum storage conditions, and processing methods during postharvest period can also maximize carotenoid retention [35].

8. Genetical and biotechnological approaches

The metabolic engineering in plants involved various biochemical and genetic modification techniques to enhance the expression of several phytonutrients, enzymes and genes in tomato fruit. Genetic modification has further advanced selenium biofortification through the overexpression of selenocysteine methyltransferase (SMT) in tomato plants, enabling the conversion of inorganic selenium to methylselenocysteine (MeSeCys). This transformation has proven particularly effective with selenite supplementation, though selenate treatment yielded higher overall MeSeCys accumulation due to enhanced root-to-shoot translocation. Notably, the stability of MeSeCys during processing suggests its potential for developing functional food products [54].

Ascorbic acid (Vitamin-C) is a vital dietary phytonutrient required to perform major metabolic processes in human body. To enhance the ascorbic acid production in tomato, scientists overexpressed the genes associated with ascorbate recycling enzymes DHAR and MDHAR [55]. The green and ripened fruit of resulting transgenic lines showed 1.6-fold increase in ascorbic acid levels thus enhancing its nutritional value. β-carotene and lycopene are well known for being beneficial for human health. When a carotenoid (crtl) gene of bacterial origin was transformed in tomato, an increase of 3-fold (45%) of β-carotene level was observed in transgenic line [56]. Folate is a vital nutrient and its deficiency in humans can cause many neurological and physical defects and diseases. In biological system the folate is synthesized from pteridine and p-amino-benzoate (PABA). Plant scientists managed to increase the level of folate in tomato fruit by 25 folds by overexpressing the amino-deoxychorismate-synthase which is 1st enzyme of PABA pathway [57]. Beta-carotene is also a precursor for Vitamin-A, and a powerful antioxidant. Other studies involving antioxidant enhancements showed that when a *Vitis vinifera* L. stilbene synthase (StSy) gene was overexpressed in tomato plant, the transgenic plants relatively accumulated more transresveratrol, resulting in much higher contents of glutathione and ascorbate which are vital soluble antioxidants involved in crucial metabolic activities in humans [58]. In the effort to improve the dietary value of tomato fruit scientist have utilized unique techniques like RNA interference (RNAi). Attempts were made to suppress an endogenous photo-morphogenesis gene (DET-1) in tomato fruit with the help of RNAi technology. Resulting transgenic plant indeed contained degraded DET-1 expression while consequently an impressive increase in both flavonoid and β-carotenoid contents was observed thus improving the nutritional value of genetically modified tomato [59]. Transgenic tomato lines (*BcZAT12*-transformed) demonstrated distinct phenotypic and biochemical characteristics compared to their non-transgenic counterparts. Morphologically, these lines produced smaller fruits with enhanced red coloration and exhibited accelerated ripening patterns. Biochemical analysis revealed significant alterations in primary and secondary metabolites: elevated levels of total soluble solids and sugars were accompanied by increased concentrations of bioactive compounds, including phenolics, flavonoids, lycopene, and β-carotene, while vitamin C content remained comparable. Notably, the enhanced accumulation of these bioactive compounds translated into superior antioxidant capacity in transgenic fruits, suggesting their potential as nutritionally enhanced products suitable for human consumption [60].

Recent advances in tomato breeding and genetic engineering have focused on enhancing carotenoid content through various strategies. Traditional breeding approaches have successfully developed cultivars with enhanced β-carotene content through the incorporation of Beta (B) gene and its modifier Beta-modifier (moB). Notable examples include Caro Red and Caro Rich fresh market, and Caro beta for processing, achieving β-carotene levels up to 5 mg 100 g^{-1} fresh weight—approximately ten times higher than standard red cultivars. By examining the transcript-level changes in carotenoid biosynthesis genes and their possible relationship to variations in carotenoid content, the bottlenecks in carotenoid biosynthesis have been investigated. Transcripts of genes encoding ζ-carotene desaturase (SlZDS), carotene isomerase (SlCrtISO), phytoene synthase (SlPSY), phytoene desaturase (SlPDS), geranylgeranyl pyrophosphate synthase (SlGGPPS), and 1-deoxy-D-xylulose 5-phosphate synthase (SlDXS) are up-regulated during tomato fruit ripening, which aids in the production of lycopene. Biotechnological approaches have demonstrated significant progress in carotenoid enhancement. Transplastomic tomatoes engineered with the lycopene B-cyclase (LCYB) gene from daffodil showed remarkable metabolic modifications, resulting in up to 77% yield increase, induced considerable metabolic modifications in carotenoid (50% β-carotene), apo-carotenoid and improved vitamin A content [61]. During fruit maturity, beta-carotenoid accumulation not only decide the level of antioxidant levels but also its colors and shelf life. Usually, in common red tomatoes, overexpression of LCY-B and the chromoplast specific CYC-B enzymes are present [62]. Molecular studies have established a significant correlation between CYCB gene expression and fruit color phenotype development. Notably, plant-based gene expression showed superior lycopene synthesis compared to bacterial origins, achieving a 50% increase in total beta-carotenoid content in transplastomic tomatoes. Even more impressive results have been obtained to achieve lycopene content through the utilization of specific mutations. The old gold (og) and old gold crimson (ogc) mutants, which inhibit β-carotene synthesis through lycopene cyclization, have achieved up to 30% higher lycopene content and lower lower β-carotene accumulations [63]. In fact, better results have been obtained with cultivars carrying both crimson and high pigment genes (*hp-1* or *hp-2* alleles), as increments in the lycopene content up to 3- to 4-fold of common cultivars has been obtained [64]. Further investigations revealed that a single nucleotide polymorphism in the Stay-Green (SGR) gene sequence impairs chlorophyll degradation, resulting in the retention of brown pigmentation in specific tomato genotypes. Through strategic hybridization of orange-fruited KNY2 and brown-fruited KNB1 genotypes, researchers generated F2 progeny exhibiting a novel orange-brown phenotype. Biochemical analysis of these F2 fruits demonstrated elevated levels of both β-carotene and chlorophyll compared to their parental lines. These findings have provided valuable insights for breeding programs aimed at developing tomato cultivars with enhanced nutritional profiles, particularly increased β-carotene and antioxidant content, while maintaining specific color characteristics.

According to recent transcriptome study, the pathway is regulated by new transcription factors [65]. There is a correlation between the expression of genes involved in the flavonoid biosynthesis pathway and at least 20 transcription factors. Naturally, this set includes SlMYB12. LIM, which is strongly associated with the expression of genes involved in the production of flavonoids and ascorbic acid, as well as other MYB and bHLH genes, are more examples.

9. Bioavailability for absorption

In pharmacology, the term "bioavailability" was first used to describe the "rate and extent to which a drug reaches its site of action." The portion of an eaten nutrient or chemical that enters the systemic circulation and the precise locations where it can exert its biological activity seem to be the most appropriate definition of bioavailability, despite the fact that there have been various other definitions put forth [66].

In addition to examining the antioxidant capacity, it's critical to assess the bioavailability of health-related compounds found in tomato products. This will yield important information for clarifying the compounds' actual biological significance in relation to human health and nutrition. From this vantage point, this review looks at the results of studies on how food processing affects the bioavailability of antioxidants found in tomatoes, such as lycopene, carotenoids, and phenolic compounds [67].

For lycopene to have any health benefits, it must enter the bloodstream and go to its site of action. As a result, lycopene content by itself does not fully represent nutritional value. As is well known, vitamin bioavailability can be measured to determine nutritional value. The literature also contains conflicting findings about how heat affects lycopene bioavailability and bioaccessibility. For example, heating cherry tomatoes at 100°C for 15 minutes had no effect on the plasma's lycopene content [68]. Similarly, the bioaccessibility of lycopene was not affected by boiling, grilling, microwave heating, or steaming tomatoes [69].

Although carotene is found in tomatoes in smaller amounts than lycopene, it still has certain health advantages that lycopene does not, such as provitamin A activity. Furthermore, research shows that carotene has a greater relative bioavailability in the tomato matrix than lycopene [70]. Pectin makes up around one-third of the tomato cell wall. Pectin has a significant effect on tomato products' textural qualities, but it has also been demonstrated to decrease the bioavailability of lycopene and carotene, among other carotenoids [71].

Cooking cherry tomatoes at 100°C for 15 minutes dramatically raised the plasma contents of naringenin and chlorogenic acid in the study by [68]. Research on the impact of tomato processing on antioxidant activity is also limited, despite some research examining the bioavailability of tomatoes and tomato-derived products. The durability of commercial tomato juice antioxidants after in vitro digestion was assessed by Wooton-Beard et al., [72]. After in vitro digestion, the examined juices' overall antioxidant capacity was either unchanged or increased. Comparing fresh and cooked tomatoes did not significantly change the antioxidant capacity of human plasma. While the effect of additional heat treatment was not significant, homogenization greatly increased the antioxidant activity in plasma [73].

Furthermore, compared to fresh tomatoes, the dialyzed fraction's antioxidant activity in the small intestine was noticeably reduced in canned and sun-dried tomatoes [74].

10. Innovative functional foods

Because of the delicious flavour, diverse forms and colours, antioxidant qualities, and chemoprotective and cardioprotective benefits, tomatoes are highly valued and consumed. About 85 percent of dietary lycopene, a healthy antioxidant, is found in tomatoes or tomato-derived products, with the remaining portion coming from watermelon, guava, and pawpaw. Juice, ketchup, soup, and pasta and pizza sauces are among the tomato products that are significant dietary sources of lycopene. However, there are significant amounts of wet solid byproducts produced during the manufacturing of these tomato-based food products, which raises concerns regarding waste management and possible recycling prospects.

10.1 Lycopene-Enriched Beverages

Industries are harnessing the health benefits of lycopene by adding purified extracts to a variety of food products. These include foods like yoghurts, baked goods, and drinks like juices and smoothies that are advertised as having higher antioxidant content. The main market for these items is health-conscious people looking for easy ways to get more lycopene without necessarily eating whole tomatoes (Fig.2). One important development in this area is the conversion of tomato juice into functional beverages. To improve the nutritional profile and health advantages of tomato-based beverages, a number of strategies have been explored. Because lycopene and good bacteria work together to promote health, probiotic enrichment—especially with Lactobacillus strains—has drawn a lot of attention. For instance, after 21 days of refrigeration, a functional tomato beverage enhanced with *Lactobacillus rhamnosus* by Domínguez-Díaz et al., [75] showed both stability and possible therapeutic benefit, with viable probiotic counts of 10^8 CFU/mL. In this changing industry, fermented tomato beverages are another creative strategy. In addition to increasing shelf life, which is advantageous for commercial purposes, lactic acid fermentation also produces bioactive peptides that may have further health advantages and improves the bioavailability of phenolic chemicals. Moreover, fresh tomato lycopene is mostly present in the isomeric trans form.To boost lycopene's bioavailability, tomato juices should be thermally processed to promote isomerisation to cis isomers. Beyond preventing cancer, several components of tomatoes, such as ascorbic acid and phenolic compounds, offer preventative advantages. According to Kim et al., [76] tomato juice fermented with *Lactobacillus plantarum* showed a 45% increase in antioxidant capacity when compared to unfermented juice, indicating that fermentation can greatly enhance tomato products' health-promoting qualities. The creation of these functional tomato drinks is in line with consumers' increasing desire for foods that offer advantages over simple nourishment. While preserving or improving the beneficial qualities of lycopene and other tomato phytochemicals, this movement also offers food scientists the chance to solve issues with taste, texture, and shelf stability.

10.2 Functional Tomato-Based Foods

Innovative functional tomato-based foods that still appeal to consumers and offer unique health benefits include fortified tomato sauces, pastes, and powders. The functional potential of tomato products has been greatly increased through enrichment with plant proteins, dietary fibre, and omega-3 fatty acids (Fig.2). A tomato sauce enhanced with microencapsulated fish oil was created by Domínguez-Díaz et al., [77]. It contains 250 mg of EPA+DHA per serving and effectively covers up fishy smells, making it more consumer-friendly while still providing vital fatty acids. Impressive bioactive qualities are displayed by these novel sauces, such as increased antioxidant activity, total flavonoid content (TFC), total phenolic content (TPC), and overall antioxidant values. Graff et al., [5] highlighted the potential therapeutic uses of tomato sauce and lycopene by demonstrating a positive correlation between their consumption and a decrease in prostate cancer. According to these results, eating novel tomato sauces may help immune system function, avoid inflammatory disorders, and enhance human health, especially in relation to liver and cholesterol profiles. According to research by Rahman et al., [78], tomato pulp-enriched sauces had higher concentrations of phenolics, flavonoids, vitamin C, and β-carotene. Their research revealed that products made with 25–50% pumpkin pulp and 50–75% tomato pulp had higher sensory appeal, demonstrating that functional advancements can be made without compromising consumer approval. The consumption of tomatoes and tomato sauces, particularly those enhanced with refined olive oil, may control the lipid profile and soluble inflammatory biomarkers linked to the development and progression of atherosclerosis, according to Valderas-Martinez et al., [79].

Another important category of processed tomato products with practical uses is tomato paste. After the skin and seeds are removed, tomato pulp is concentrated to produce a dispersion of solid particles (pulp) in an aqueous medium (serum) that contains at least 24% (w/w) of natural soluble solids (NTSS). The final nutritional profile may be impacted by heat-treatment and pulping/finishing procedures used in the manufacturing process. It was shown by Pellegrini et al., [80] that consuming tomato purée over a period of days can significantly raise blood levels of β-carotene and lycopene. Prior to consuming tomato purée, the plasma concentrations of β-carotene and total lycopene were 0.24 μmol/L and 0.13 μmol/L, respectively. Both concentrations dramatically increased to 0.57 μmol/L for total lycopene and 0.31 μmol/L for β-carotene following tomato purée administration. Tomato paste is a concentrated source of lycopene, with about 16 mg/100g of this healthy substance.

10.3 Tomato By-products

The significant waste streams produced by the processing industry were underutilised until recently. Because they contain vital levels of organic acids, carbohydrates, antioxidants, fibres, vitamins, proteins, and oils that are important to the proper operation of the human body, numerous research have looked into the repurposing of these by-products. Peels, seeds, and little amounts of pulp are the primary by-products of tomato processing (Table 1). About 10% of the fruit and 60% of the total trash produced during processing come from the seeds alone. Because tomatoes include a variety of phytochemicals and bioactive substances that may withstand industrial processes and persist in the waste materials, these by-products are very important(Fig.2). Carotenoids, polyphenols, vitamins, proteins, and high-quality fatty acids are among the bioactive substances present in tomato by-products, per studies by Szabo et al., [81,82] and Popescu et al., [83]. Carotenoids are the primary substances found in by-products of the tomato industry, and they can be effectively incorporated into a variety of functional food products. According to Szabo et al., [84,85] these substances improve food's sensory qualities while also extending its shelf life and raising the amount of bioactive ingredients in finished goods. Additionally, they may be used as natural food colouring, meeting customer desire for clean-label products devoid of artificial ingredients. These carotenoids have various activities such as anti-inflammatory and antioxidant qualities, which are crucial for human health. Additionally, tomato by-products have antibacterial properties, which makes them appropriate for use in cooking or in food compositions.

Numerous research have examined the difficulties of incorporating these chemicals into food products, especially their hydrophobic character, which restricts their bioavailability and water solubility. To get around these restrictions, a recent study combined several vegetable oils with tomato by-products. These extracts had intriguing rheological effects, increasing the viscosity of flaxseed oil while decreasing that of hempseed and grapeseed oils. This variance in viscosity can be explained by the enrichment's enhanced thermal motion of the oil molecules and, in certain situations, its lower intermolecular resilience. These fortified oils can be readily included into functional foods and serve as an effective carotenoid extract delivery mechanism [84]. Innovation in tomato product development goes a long way towards using what were once thought of as waste by products. Its remarkable nutritional profile, which includes a high protein and fibre content, has made tomato seed powder—which was previously thrown away during processing—a desirable functional element. Fortifying baked goods and other food products that might use more nutritional richness is a great use for this composition. By successfully integrating tomato seed powder into bread recipes, researches showed useful applications. In comparison to control bread samples, their study reported a noteworthy 40% increase in protein content and a 65% increase in dietary fibre. These findings not only highlight the possibility of repurposing processing waste into meals with higher nutritional value, but they also tackle the twin problems of lowering food waste and raising the nutritional value of common foods.

CONCLUSION AND FUTURE PERSPECTIVES

Tomato by-products, including pomace, peels, and seeds, represent valuable and sustainable sources of bioactive compounds with significant antioxidant potential. Rich in lycopene, polyphenols, carotenoids, dietary fibers, and essential fatty acids, these residues offer immense opportunities for the development of innovative, health-promoting functional foods. Their utilization not only enhances antioxidant capacity but also contributes to improved nutritional quality and shelf life of food products. Various approaches, such as advanced extraction techniques, fermentation, encapsulation, and incorporation into diverse food matrices, have demonstrated effectiveness in improving the stability, bioavailability, and functional performance of these bioactives. The successful application of tomato-derived compounds in bakery, dairy, meat, and snack products further highlights their potential as natural alternatives to synthetic additives, aligning with the growing demand for clean-label and functional foods.

Looking ahead, future research should focus on optimizing sustainable and cost-effective technologies to maximize the recovery and functionality of these compounds. However, the next frontier lies beyond conventional extraction. Future research should move beyond extraction toward ‘bioactive engineering,’ where fermentation, elicitation, and nano-delivery systems are combined to actively enhance antioxidant pathways at the molecular level. This emerging approach could enable the design of next-generation functional foods with enhanced and targeted health benefits.In addition, expanding the application of tomato-derived bioactives into nutraceuticals, cosmeceuticals, and biodegradable materials, along with the integration of advanced tools such as metabolomics, transcriptomics, and artificial intelligence, can further optimize their functionality and application. A shift from linear utilization to ‘closed-loop bioactive systems’ could transform tomato processing industries into zero-waste, high-value biorefineries, thereby supporting circular economy principles and sustainable development. Despite these advancements, challenges such as high processing costs, scalability, and seasonal variability of raw materials remain key limitations. Addressing these issues will require collaborative efforts among researchers, industry stakeholders, and policymakers to develop economically viable and scalable solutions.

In conclusion, enhancing the antioxidant activity of bioactive compounds derived from tomato by-products and incorporating them into functional foods represents a promising strategy for sustainable food innovation. This approach not only supports waste valorization but also contributes to improved human health and environmental sustainability, paving the way for a more resilient and future-ready food system.

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REFERENCES

1. Cámara M, Fernández-Ruiz V, Sánchez-Mata MC, Cámara RM, Domínguez L, Sesso HD. Scientific evidence of the beneficial effects of tomato products on cardiovascular disease and platelet aggregation. Front Nutr. 2022; 9:849841.
2. Kumar A, Kumar V, Gull A, Nayik GA. Tomato (Solanum Lycopersicon). InAntioxidants in vegetables and nuts-Properties and health benefits 2020; 191-207. Singapore: Springer Singapore.
3. Pinela J, Oliveira MB, Ferreira IC. Bioactive compounds of tomatoes as health promoters. In Natural bioactive compounds from fruits and vegetables as health promoters: Part II 2016; 48-91. Bentham Science Publishers.
4. FAOSTAT. Faostat statistical database. Food and Agriculture Organization of the 740 United Nations, 2022.
5. Graff RE, Pettersson A, Lis RT, Ahearn TU, Markt SC, Wilson KM, Rider JR, Fiorentino M, Finn S, Kenfield SA, Loda M. Dietary lycopene intake and risk of prostate cancer defined by ERG protein expression. Am J Clin Nutr. 2016; 103(3):851-60.
6. Gann PH, Ma J, Giovannucci E, Willett W, Sacks FM, Hennekens CH, Stampfer MJ. Lower prostate cancer risk in men with elevated plasma lycopene levels: results of a prospective analysis. Cancer Res. 1999; 59(6):1225-30.
7. Giovannucci E, Rimm EB, Liu Y, Stampfer MJ, Willett WC. A Prospective Study of Tomato Products, Lycopene, and. JNCI. 2002; 94(5):391.
8. Xu X, Li J, Wang X, Wang S, Meng S, Zhu Y, Liang Z, Zheng X, Xie L. Tomato consumption and prostate cancer risk: a systematic review and meta-analysis. Sci Rep. 2016; 6(1):37091.
9. Giuffrè AM, Capocasale M. Policosanol in tomato (Solanum lycopersicum L.) seed oil: The effect of cultivar. J Oleo Sci. 2015; 64(6):625-31.
10. Giuffrè AM, Capocasale M. Sterol composition of tomato (Solanum lycopersicum L.) seed oil: The effect of cultivar. Int Food Res J. 2016; 23(1):116.
11. Collins EJ, Bowyer C, Tsouza A, Chopra M. Tomatoes: An extensive review of the associated health impacts of tomatoes and factors that can affect their cultivation. Biology. 2022; 11(2):239.
12. Cheng HM, Koutsidis G, Lodge JK, Ashor AW, Siervo M, Lara J. Lycopene and tomato and risk of cardiovascular diseases: A systematic review and meta-analysis of epidemiological evidence. Crit Rev Food Sci Nutr. 2019; 59(1):141-58.
13. Li N, Wu X, Zhuang W, Xia L, Chen Y, Wu C, Rao Z, Du L, Zhao R, Yi M, Wan Q. Tomato and lycopene and multiple health outcomes: Umbrella review. Food Chem. 2021; 343:128396.
14. Ahmed MJ, Iya IR, Dogara MF. Proximate, mineral and vitamin content of flesh, blanched and dried tomatoes (Lycopersicon esculentum). Asian F Sci J. 2020; 18(4):11-8.
15. Sofy AR, Dawoud RA, Sofy MR, Mohamed HI, Hmed AA, El-Dougdoug NK. Improving regulation of enzymatic and non-enzymatic antioxidants and stress-related gene stimulation in Cucumber mosaic

cucumovirus-infected cucumber plants treated with glycine betaine, chitosan and combination. Molecules. 2020; 25(10):2341.

16. Kelebek H, Selli S, Kadiroglu P, Kola O, Kesen S, Uçar B, Çetiner B. Bioactive compounds and antioxidant potential in tomato pastes as affected by hot and cold break process. Food Chem. 2017; 220:31–41.
17. Silva YPA, Borba BC, Pereira VA, Reis MG, Caliari M, Brooks MSL, Ferreira TA. Characterization of tomato processing by-product for use as a potential functional food ingredient: nutritional composition, antioxidant activity and bioactive compounds. Int J Food Sci Nutr. 2019; 70(2):150–160.
18. Szabó K, Teleky B, Ranga F, Roman I, Khaoula H, Boudaya E, et al. Carotenoid recovery from tomato processing by-products through green chemistry. Molecules. 2022; 27:3771.
19. Pecker I, Chamovitz D, Linden H, Sandmann G, Hirschberg J. A single polypeptide catalyzing the conversion of phytoene to zeta-carotene is transcriptionally regulated during tomato fruit ripening. Proc Natl Acad Sci U S A. 1992; 89(11):4962–6.
20. Yamagata K, Nakayama C, Suzuki K. Dietary β-carotene regulates interleukin-1β-induced expression of apolipoprotein E in astrocytes isolated from stroke-prone spontaneously hypertensive rats. Neurochem Int. 2013; 62(1):43–9.
21. Sen A, Marsche G, Freudenberger P, Schallert M, Toeglhofer AM, Nagl C. Association between higher plasma lutein, zeaxanthin, and vitamin C concentrations and longer telomere length: results of the Austrian Stroke Prevention Study. J Am Geriatr Soc. 2014; 62(2):222–9.
22. Deshpande J, Shankaranarayanan J. Neuroprotective effect of carotenoids in brain. Google Patents. 2014; 6-12.
23. Wang J, Li L, Wang Z, Cui Y, Tan X, Yuan T. Supplementation of lycopene attenuates lipopolysaccharide-induced amyloidogenesis and cognitive impairments via mediating neuroinflammation and oxidative stress. J Nutr Biochem. 2018; 56:16–25.
24. Clinton SK. Lycopene: chemistry, biology, and implications for human health and disease. Nutr Rev. 1998;56:35–51.Shahidi F, Varatharajan V, Oh WY, Peng H. Phenolic compounds in agri-food by-products, their bioavailability and health effects. J Food Bioact. 2019; 5(1):57–119.
25. Sarkar A, Kaul P. Evaluation of tomato processing by-products: a comparative study in a pilot scale setup. J Food Process Eng. 2014; 37:299–307.
26. Slimestad R, Fossen T, Verheul MJ. The flavonoids of tomatoes. J Agric Food Chem. 2008; 56(7):2436–41.
27. Muir SR, Collins GJ, Robinson S, Hughes S, Bovy A, Ric De Vos CH, et al. Overexpression of petunia chalcone isomerase in tomato results in fruit containing increased levels of flavonols. Nat Biotechnol. 2007; 19:470–4.
28. Martinez-Valverde I, Periago MJ, Provan G, Chesson A. Phenolic compounds, lycopene and antioxidant activity in commercial varieties of tomato (*Lycopersicum esculentum*). J Sci Food Agric. 2002; 82(3):323–30.
29. Testai L, Calderone V. Nutraceutical value of citrus flavanones and their implications in cardiovascular disease. Nutrients. 2017, 9:502.
30. Zhang L. Vitamin C in tomatoes: from biosynthesis to human nutrition. Trends Food Sci Technol. 2023; 131:123–35.
31. Urbonaviciene D, Bobinaite R, Trumbeckaite S, Raudone L, Janulis V, Bobinas C, et al. Agro-industrial tomato by-products and extraction of functional food ingredients. Zemdirbyste. 2018;105(1):139–46.
32. Lopez Bermudez YN, Aldana Heredia JF, Sanchez-Camargo ADP, Hernandez-Carrion M. Valorization strategies for a by-product of organic tomato processing as potential ingredient in functional food formulations. Front Food Sci Technol. 2022; 2:1–14.
33. Ikram NA, Abdalla MA, Muhling KH. Developing iron and iodine enrichment in tomato fruits to meet human nutritional needs. Plants. 2024; 13(23):3438.
34. Meng F, Li Y, Li S, Chen H, Shao Z, Jian Y, et al. Carotenoid biofortification in tomato products along whole agro-food chain from field to fork. Trends Food Sci Technol. 2022, 124:296–308.
35. Landini M, Gonzali S, Perata P. Iodine biofortification in tomato. J Plant Nutr Soil Sci. 2011,174(3):480–6.

36. Kiferle C, Gonzali S, Holwerda HT, Ibaceta RR, Perata P. Tomato fruits: a good target for iodine biofortification. Front Plant Sci. 2013;4:205.
37. Smolen S, Wierzbińska J, Sady W, Kołton A, Wiszniewska A, Liszka-Skoczylas M. Iodine biofortification with additional application of salicylic acid affects yield and selected parameters of chemical composition of tomato fruits (*Solanum lycopersicum* L.). Sci Hortic. 2015;188:89–96.
38. Rahim FP, Rocio CG, Adalberto BM, Lidia Rosaura SC, Maginot NH. Agronomic biofortification with selenium in tomato crops (*Solanum lycopersicon* L. Mill). Agriculture. 2020;10(10):486.
39. Shiriaev A, Pezzarossa B, Rosellini I, Malorgio F, Lampis S, Ippolito A, et al. Efficacy and comparison of different strategies for selenium biofortification of tomatoes. Horticulturae. 2022;8(9):800.
40. Mandal D, Pautu L, Hazarika T, Nautiyal BP, Shukla AC. Effect of salicylic acid on physico-chemical attributes and shelf life of tomato fruits at refrigerated storage. Int J Bio-Resour Stress Manag. 2016;7:1272–8.
41. El-Hady NA, ElSayed AI, El-Saadany SS, Deligios PA, Ledda L. Exogenous application of foliar salicylic acid and propolis enhances antioxidant defenses and growth parameters in tomato plants. Plants. 2021;10(1):74.
42. Aires ES, Ferraz AK, Carvalho BL, Teixeira FP, Rodrigues JD, Ono EO. Foliar application of salicylic acid intensifies antioxidant system and photosynthetic efficiency in tomato plants. Bragantia. 2022;81:e20210320.
43. Buturi CV, Coelho SR, Cannata C, Basile F, Giuffrida F, Leonardi C, et al. Iron biofortification of greenhouse cherry tomatoes grown in a soilless system. Horticulturae. 2022;8(10):858.
44. Ikram NA, Ghaffar A, Khan AA, Nawaz F, Hussain A. Optimizing iron seed priming for enhanced yield and biofortification of tomato. J Plant Nutr. 2023;46(12):2796–810.
45. Borguini RG, Bastos DHM, Moita-Neto JM, Capasso FS, Torres EAFS. Antioxidant potential of tomatoes cultivated in organic and conventional systems. Braz Arch Biol Technol. 2013;56(4):521–9.
46. Haque MM, Khatun M, Mosharaf MK, Rahman A, Haque MA, Nahar K. Biofilm producing probiotic bacteria enhance productivity and bioactive compounds in tomato. Biocatal Agric Biotechnol. 2023;50:102673.
47. Tommonaro G, Abbamondi GR, Nicolaus B, Poli A, D'Angelo C, Iodice C, et al. Productivity and nutritional trait improvements of different tomatoes cultivated with effective microorganisms technology. Agriculture. 2021;11(2):112.
48. Chanthini KM, Stanley-Raja V, Thanigaivel A, Karthi S, Palanikani R, Shyam Sundar N, et al. Sustainable agronomic strategies for enhancing the yield and nutritional quality of wild tomato, *Solanum lycopersicum* var. *cerasiforme* Mill. Agronomy. 2019;9(6):311.
49. Dewanto V, Wu X, Adom KK, Liu RH. Thermal processing enhances the nutritional value of tomatoes by increasing total antioxidant activity. J Agric Food Chem. 2002;50(10):3010–4.
50. Nkolisa N, Magwaza LS, Workneh TS, Chimphango A, Sithole NJ. Postharvest quality and bioactive properties of tomatoes (*Solanum lycopersicum*) stored in a low-cost and energy-free evaporative cooling system. Heliyon. 2019;5(8):e02266.
51. Al-Saif AM, Ahmed ME, Taha MA, Sharma A, El-Sheshtawy AN, Abouelsaad IA, et al. Preharvest applications improve the postharvest storage and quality of tomato fruits by enhancing the nutritional value and antioxidant system. Horticulturae. 2024;10(12):1248.
52. Brummell DA, Watson LM, Pathirana R, Joyce NI, West PJ, Hunter DA, et al. Biofortification of tomato (*Solanum lycopersicum*) fruit with the anticancer compound methylselenocysteine using a selenocysteine methyltransferase from a selenium hyperaccumulator. J Agric Food Chem. 2011;59(20):10987–94.
53. Haroldsen VM, Chi-Ham CL, Kulkarni S, Lorence A, Bennett AB. Constitutively expressed DHAR and MDHAR influence fruit, but not foliar ascorbate levels in tomato. Plant Physiol Biochem. 2011;49(10):1244–9.
54. Romer S, Fraser PD, Kiano JW, Shipton CA, Misawa N. Elevation of the provitamin A content of transgenic tomato plants. Nat Biotechnol. 2000;18(6):666–669.
55. Diaz de la Garza RI, Gregory JF 3rd, Hanson AD. Folate biofortification of tomato fruit. Proc Natl Acad Sci U S A. 2007;104(10):4218–22.
56. Giovinazzo G, D'Amico L, Paradiso A, Bollini R, Sparvoli F. Antioxidant metabolite profiles in tomato fruit constitutively expressing the grapevine stilbene synthase gene. Plant Biotechnol J. 2005;3(1):57–69.

57. Nonaka S, Arai C, Takayama M, Matsukura C, Ezura H. Efficient increase of γ-aminobutyric acid (GABA) content in tomato fruits by targeted mutagenesis. Sci Rep. 2017;7(1):665.
58. Shah K, Singh M, Rai AC. Bioactive compounds of tomato fruits from transgenic plants tolerant to drought. LWT Food Sci Technol. 2015;61(2):609–14.
59. Jez M, Wiczkowski W, Zielinska D, Bialobrzewski I, Blaszczak W. The impact of high-pressure processing on the phenolic profile, hydrophilic antioxidant and reducing capacity of puree obtained from commercial tomato varieties. Food Chem. 2018;261:201–9.
60. Katırcı N, Işık N, Güpür Ç, Guler HO, Gursoy O. Differences in antioxidant activity, total phenolic and flavonoid contents of commercial and homemade tomato pastes. J Saudi Soc Agric Sci. 2020;19(4):249–54.
61. Vogel JT, Tieman DM, Sims CA, Odabasi AZ, Clark DG, Klee HJ. Carotenoid content impacts flavor acceptability in tomato (*Solanum lycopersicum*). J Sci Food Agric. 2010;90:2233–40.
62. Stommel JR. Genetic enhancement of tomato fruit nutritive value. In: Razdan M, Mattoo A, editors. Genetic Improvement of Solanaceous Crops. Boca Raton (FL): CRC Press; 2007; 193–238.
63. Ye J, Hu T, Yang C, Li H, Yang M, Ijaz R, et al. Transcriptome profiling of tomato fruit development reveals transcription factors associated with ascorbic acid, carotenoid and flavonoid biosynthesis. PLoS ONE. 2015;10:e0130885.
64. Stahl W, Sies H. Bioactivity and protective effects of natural carotenoids. Biochim Biophys Acta. 2005;1740(2):101–7.
65. Kamiloglu S, Boyacioglu D, Capanoglu E. The effect of food processing on bioavailability of tomato antioxidants. J Berry Res. 2013;3(2):65–77.
66. Bugianesi R, Salucci M, Leonardi C, Ferracane R, Catasta G, Azzini E. Effect of domestic cooking on human bioavailability of naringenin, chlorogenic acid, lycopene and β-carotene in cherry tomatoes. Eur J Nutr. 2004;43:360–6.
67. Ryan L, O'Connell O, O'Sullivan L, Aherne SA, O'Brien NM. Micellarisation of carotenoids from raw and cooked vegetables. Plant Foods Hum Nutr. 2008;63:127–33.
68. Svelander CA, Tibäck EA, Ahrné LM, Langton MIBC, Svanberg USO, Alminger MAG. Processing of tomato: impact on in vitro bioaccessibility of lycopene and textural properties. J Sci Food Agric. 2010;90:1665–72.
70. Riedl J, Linseisen J, Hoffmann J, Wolfram G. Some dietary fibers reduce the absorption of carotenoids in women. J Nutr. 1999;129:2170–6.
71. Wootton-Beard PC, Moran A, Ryan L. Stability of the total antioxidant capacity and total polyphenol content of 23 commercially available vegetable juices before and after in vitro digestion measured by FRAP, DPPH, ABTS and Folin–Ciocalteu methods. Food Res Int. 2011;44:217–24.
72. van het Hof KH, Boer BCJ, Tijburg LBM, Lucius BRHM, Zijp I, West CE. Carotenoid bioavailability in humans from tomatoes processed in different ways. J Nutr. 2000;130:1189–96.
73. Karakaya S, Yilmaz N. Lycopene content and antioxidant activity of fresh and processed tomatoes and in vitro bioavailability of lycopene. J Sci Food Agric. 2007;87:2342–7.
74. Domínguez-Díaz L, Fernández-Ruiz V, Cámara M. The frontier between nutrition and pharma: the international regulatory framework of functional foods, food supplements and nutraceuticals. Crit Rev Food Sci Nutr. 2020;60(10):1738–46.
75. Kim JH, Lee HJ, Park Y. Lactic acid fermentation enhances the antioxidant activity and bioactive compound content in tomato juice. Food Sci Biotechnol. 2021;30(4):557–65.
76. Dominguez-Diaz L, Morales AA, Martinez AB. Development of a functional tomato sauce enriched with microencapsulated omega-3 fatty acids. J Food Sci Technol. 2022;59(6):2345–56.
77. Rahman MM, Hasan SK, Sarkar S, Ashik MA, Somrat MA, Asad AI. Effect of formulation on physicochemical, phytochemical, functional, and sensory properties of the bioactive sauce blended with tomato and pumpkin pulp. Appl Food Res. 2024;4(1):100406.
78. Valderas-Martinez P, Chiva-Blanch G, Casas R, Arranz S, Martinez-Huelamo M, Urpi-Sarda M, et al. Tomato sauce enriched with olive oil exerts greater effects on cardiovascular disease risk factors than raw tomato and tomato sauce: a randomized trial. Nutrients. 2016;8(3):170.
79. Pellegrini N, Riso P, Porrini M. Tomato consumption does not affect the total antioxidant capacity of plasma. Nutrition. 2000;16:268–71.

80. Szabo K, Diaconeasa Z, Cătoi AF, Vodnar DC. Screening of ten tomato varieties processing waste for bioactive components and their related antioxidant and antimicrobial activities. Antioxidants. 2019;8:292.
81. Szabo K, Dulf FV, Diaconeasa Z, Vodnar DC. Antimicrobial and antioxidant properties of tomato processing byproducts and their correlation with the biochemical composition. LWT Food Sci Technol. 2019;116:108558.
82. Popescu M, Iancu P, Plesu V, Todasca MC, Isopencu GO, Bildea CS. Valuable natural antioxidant products recovered from tomatoes by green extraction. Molecules. 2022;27:4191.
83. Szabo K, Dulf FV, Eleni P, Boukouvalas C, Krokida M, Kapsalis N, et al. Evaluation of the bioactive compounds found in tomato seed oil and tomato peels influenced by industrial heat treatments. Foods. 2021;10:110.
84. Szabo K, Teleky B, Ranga F, Roman I, Khaoula H, Boudaya E, et al. Carotenoid recovery from tomato processing by-products through green chemistry. Molecules. 2022;27:3771.
85. Rajkowska K, Otlewska A, Raczyk A, Maciejczyk E, Krajewska A. Valorisation of tomato pomace in anti-pollution and microbiome-balance face cream. Sci Rep. 2024;14(1):20516.
86. Fouda K, Mabrouk AM, Abdelgayed SS, Mohamed RS. Protective effect of tomato pomace extract encapsulated in combination with probiotics against indomethacin induced enterocolitis. Sci Rep. 2024;14(1):2275.
87. Skwarek P, Karwowska M. Fatty acids profile and antioxidant properties of raw fermented sausages with the addition of tomato pomace. Biomolecules. 2022;12(11):1695.
88. Kontaxi NI, Panoutsopoulou E, Ofrydopolou A, Tsoupras A. Anti-inflammatory benefits of grape pomace and tomato bioactives as ingredients in sun oils against UV radiation for skin protection. Appl Sci. 2024;14(14):6236.
89. Sahin K, Yenice E, Tuzcu M, Orhan C, Mizrak C, Ozercan IH, Sahin N, Yilmaz B, Bilir B, Ozpolat B, Kucuk O. Lycopene protects against spontaneous ovarian cancer formation in laying hens. J Cancer Prev. 2018;23(1):25.
90. El Basett H, Hajjaj H. Optimization of lycopene extraction from tomato processing by-products with essential oils and effect of extract on oxidative stability of refined olive oil. J Food Meas Charact. 2024;18(11):9398-409.
91. Maldonado-Torres R, Morales-Camacho JI, López-Valdez F, Huerta-González L, Luna-Suárez S. Assessment of techno-functional and nutraceutical potential of tomato (Solanum lycopersicum) seed meal. Molecules. 2020;25(18):4235.
92. Firrman J, Narrowe A, Liu L, Mahalak K, Lemons J, Van den Abbeele P, Baudot A, Deyaert S, Li Y, Yao Y, Yu L. Tomato seed extract promotes health of the gut microbiota and demonstrates a potential new way to valorize tomato waste. Plos one. 2024;19(4):e0301381.
93. Mechmeche M, Ksontini H, Hamdi M, Kachouri F. Impact of the addition of tomato seed oil on physicochemical characteristics, antioxidant activity and microbiological quality of dried tomato slices. J Food Meas Charact. 2018;12(2):1378-90.

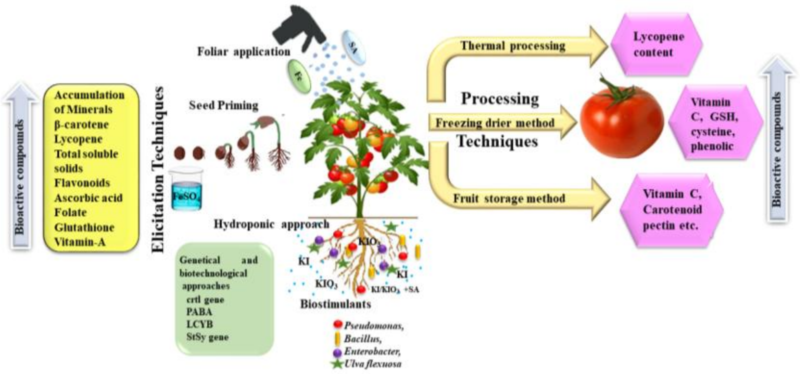

Fig. 1 Schematic representation of approaches enhancing the bioactive compounds

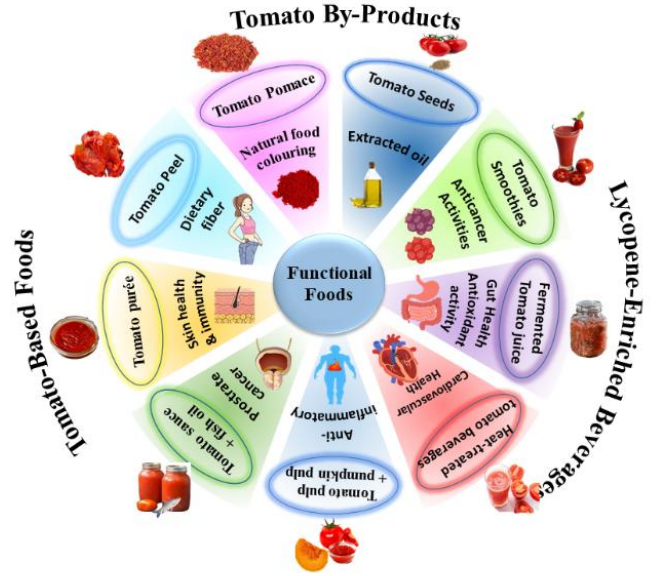

Fig 2. Conversion of Tomato By-Products into Value-Added Functional Foods and Nutraceuticals

Table 1. Application of major tomato by-products (pomace, peels, and seeds) and their associated value-added benefits

	Utility	Integration	Bioactive Compounds	Outcomes	REFERENCES
Tomato pomace	Cosmetic–pharmaceutical product	The oil extracted from tomato pomace was incorporated into a facial cream formulation.	Among fatty acids, linoleic acid was the principal component (63.6%), whereas carvotanacetone dominated the volatile fraction (25.8%).	Improved skin microbiome balance by increasing beneficial bacteria and limiting pathogenic strains, resulting in reduced inflammation, lower pigmentation, and enhanced defense against air pollution.	[86]
	Pharmaceutical	Tomato pomace extract encapsulated independently or alongside probiotics	Polyphenolic compounds, mainly ellagic acid and rutin, showed a direct association with the outcomes.	Exhibited antioxidant and potential anti-inflammatory properties through interactions with TNF-α and IL-1β cytokines; provided protection against enterocolitis, gastric ulcers, and erosion;	[87]

				and reduced oxidative stress and inflammatory markers in indomethacin-treated rats.	
	Functional foods	Freeze-dried tomato pomace incorporated into dry fermented sausages with reduced nitrite levels	Lycopene extracted from tomato pomace	Antioxidant activity increased with higher concentrations of tomato pomace; samples containing 1.5% tomato pomace exhibited the lowest Enterobacteriaceae counts; and addition of tomato pomace enhanced redness in sausages, improving consumer appeal.	[88]
Tomato peels	Cosmetic–pharmaceutical product	Bioactive compounds derived for use in sunscreen formulations	Phenolic compounds, lycopene and flavonoids	Enhanced the functional performance of sunscreen through improved antioxidant and anti-inflammatory activities, providing better photoprotection and reducing the risk of UV-induced skin disorders.	[89]

	Pharmaceutical	Dietary incorporation of lycopene was carried out in laying hens for 12 months.	Lycopene	Supplementation with lycopene markedly lowered ovarian tumor occurrence, count, and size, along with reduced adenocarcinoma incidence and oxidative stress (malondialdehyde levels); it also suppressed NF-κB and STAT3 while enhancing nuclear factor erythroid 2 and heme oxygenase-1 expression, reflecting antioxidant and anti-inflammatory activity.	[90]
	Functional additive	Lycopene extracted using essential oils and incorporated into refined olive oil	Lycopene	Enhanced oxidative stability over 5 months at 40 °C, with reduced peroxide, p-anisidine, and total oxidation values	[91]
Tomato seeds	Nutraceutical	Valorization of tomato seed waste in functional foods	Tomato seed meal and its fermented form	Fermentation using *Lactobacillus* sp. significantly enhanced antioxidant activity, achieving a twofold increase	[92]

	Nutritional supplements	Tomato seed extract in gut microbiota modulation		Significantly increased the abundance of beneficial *Bifidobacteriaceae* in the gut microbiota; elevated short-chain fatty acid levels, particularly acetate and propionate; and demonstrated prebiotic potential by positively modulating gut microbiota and promoting human health.	[92]
	Functional additive	Preservation of dried tomato slices was achieved using tomato seed oil	Phytosterol- and bioactive compound-rich tomato seed oil	Minimized quality degradation during drying; preserved moisture content and color intensity; and enhanced antioxidant levels, with the highest concentration maintaining strong antioxidant activity while inhibiting bacterial and mold growth.	[93]