



Lycopene as a Functional Food Ingredient: Bioavailability, Health-Promoting Properties, Food Applications, and Future Perspectives

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Lycopene is a naturally occurring red carotenoid found predominantly in tomatoes, watermelon, pink guava, papaya, and other red-coloured fruits. Its extended conjugated double-bond system enables it to quench singlet oxygen and participate in antioxidant reactions. These properties have stimulated interest in lycopene as a functional food ingredient for developing products with enhanced nutritional value. Research has investigated its potential association with cardiovascular health, protection against oxidative stress, skin photoprotection, and the prevention or modulation of certain chronic disease processes. However, evidence varies across laboratory studies, animal experiments, observational studies, and human clinical trials, and lycopene should not replace established medical treatment. Its application in food systems is influenced by its poor water solubility, susceptibility to oxidation and light, thermal isomerization, and limited bioavailability in some formulations. Food processing, dietary fat, matrix composition, encapsulation, and other delivery technologies can substantially influence its stability and absorption. Lycopene has potential applications in beverages, dairy products, bakery products, sauces, emulsions, snacks, and functional food supplements. This review examines lycopene's chemical characteristics, natural sources, bioavailability, biological properties, food-processing stability, technological applications, safety considerations, and commercial prospects. It also highlights formulation strategies and research gaps that must be addressed to translate its biological potential into safe, stable, evidence-based functional foods.

Keywords: Lycopene; functional foods; carotenoids; antioxidant activity; bioavailability; encapsulation; food fortification; nutraceuticals.

Introduction

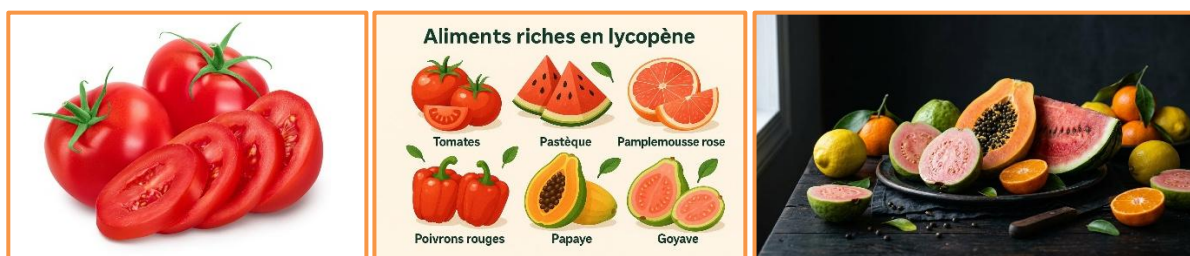
Functional foods have gained considerable attention because consumers increasingly seek foods that provide nutritional benefits beyond basic energy and essential nutrient requirements. This has encouraged research into naturally occurring bioactive compounds, including polyphenols, phytosterols, dietary fibers, omega-3 fatty acids, and carotenoids. Among these compounds, lycopene has attracted substantial interest because of its distinctive red color, antioxidant properties, and potential role in supporting human health. Lycopene is a lipophilic carotenoid responsible for the red colour of tomatoes and several other fruits. Unlike β -carotene, it lacks provitamin A activity because its molecular structure cannot be converted into vitamin A. Nevertheless, its conjugated double-bond system enables efficient singlet-oxygen quenching under appropriate conditions, making it an important subject of research into oxidative stress and food-derived bioactive compounds. Tomatoes and tomato-based foods are particularly relevant dietary sources because they contain substantial amounts of lycopene and can be incorporated into familiar food products. Interestingly, processing does not always reduce its nutritional accessibility. Heating, homogenization, and disruption

of plant tissues may improve lycopene release from the food matrix, although excessive heating, oxygen exposure, and unsuitable storage conditions can cause degradation. Lycopene therefore presents a promising opportunity for functional food development, provided that its concentration, stability, bioaccessibility, sensory characteristics, and biological effects are adequately evaluated.

Chemical structure, properties, and natural sources of lycopene

Chemical characteristics: Lycopene is an acyclic, fat-soluble carotenoid with the molecular formula $C_{40}H_{56}$ and a molecular mass of approximately 536.87 g/mol. Its structure contains 11 conjugated and two non-conjugated carbon-carbon double bonds. This extensive conjugation gives it its characteristic red color and important photochemical and antioxidant properties. Lycopene occurs in different geometric isomeric forms, principally the all-trans (all-E) form and various cis (Z) isomers. The all-trans form is generally predominant in fresh tomatoes, whereas cis isomers may increase during certain processing and cooking treatments. Cis isomers can show improved solubility in some environments and may incorporate more readily into mixed micelles during digestion, although absorption depends on the specific isomer and food matrix. Lycopene is practically insoluble in water but dissolves in suitable organic solvents and lipid phases. These characteristics present a formulation challenge when incorporating it into aqueous foods such as beverages, milk, yogurt, and other dairy products.

Natural sources



Important dietary sources include:

- Tomatoes and tomato products: Fresh tomatoes, tomato paste, puree, juice, sauces, and ketchup.
- Watermelon: A valuable fruit source of lycopene.
- Pink and red guava: A potentially important source in tropical regions.
- Papaya: Contains lycopene in varying amounts depending on cultivar and ripeness.
- Pink grapefruit: Contributes lycopene to the diet.
- Selected red-fleshed fruits: Lycopene concentration varies with variety, maturity, growing conditions, and postharvest handling.

Tomato processing by-products, particularly peels and seeds associated with tomato pomace, are also of interest for recovering carotenoids and developing value-added ingredients. However, lycopene recovery depends on the pigment distribution within the raw material and the extraction method used.

Lycopene as a functional food ingredient

A functional food is generally understood as a food that provides physiological benefits beyond supplying essential nutrients, when consumed as part of an appropriate diet. Lycopene can contribute to functional food development through three major characteristics:

1. Biological activity: It can participate in antioxidant reactions and influence cellular pathways associated with oxidative stress.
2. Technological functionality: It provides a natural red colour and may help delay oxidative deterioration in suitable food systems.
3. Nutritional value addition: It allows the development of foods enriched with a naturally occurring carotenoid.

These functions should be distinguished carefully. Antioxidant activity measured in a chemical assay does not automatically establish a health benefit in humans, and improved food color or oxidative stability does not prove the product prevents disease. Lycopene is therefore best regarded as a promising functional ingredient whose value depends on the final food formulation, retained concentration, bioaccessibility, safety, and supporting.

Biological properties and potential health benefits

Antioxidant activity

Oxidative stress occurs when reactive species are generated faster than biological antioxidant and repair systems can handle. Lycopene is of particular scientific interest because its conjugated double-bond structure allows it to quench singlet oxygen and participate in reactions involving reactive species. Experimental studies have also investigated lycopene's influence on lipid oxidation, cellular antioxidant responses, and inflammation-related pathways. Oxygen concentration, the surrounding chemical environment, carotenoid concentration, and interactions with other antioxidants influence its antioxidant activity. Importantly, lycopene's in vitro antioxidant capacity cannot be directly equated with its effects in the human body. Its metabolism, distribution, local concentration, and interactions with other dietary compounds must also be considered.

Cardiovascular health

Oxidative modification of lipids and disturbances in inflammatory signaling are relevant to cardiovascular disease. Researchers have investigated lycopene for possible associations with blood pressure, lipid metabolism, endothelial function, and markers of oxidative stress. Some observational studies and clinical investigations suggest potential benefits of tomato-derived products or lycopene supplementation for selected cardiovascular risk markers. However, results vary across studies, and researchers cannot necessarily attribute the effects of whole tomato products to lycopene alone. Accordingly, lycopene-enriched foods may contribute to a dietary pattern rich in fruits and vegetables, but current evidence does not justify claiming that a lycopene-fortified product independently prevents cardiovascular disease.

Cancer-related research

Lycopene has been studied extensively in relation to prostate cancer and several other malignancies. Proposed mechanisms include modulation of oxidative stress, inflammatory responses, cellular signaling, and processes associated with cell proliferation.

Skin health and photoprotection

Researchers have investigated lycopene's potential to reduce certain effects of ultraviolet radiation through antioxidant mechanisms. Some human studies of tomato-derived interventions have reported changes in indicators of UV-induced skin damage. However, these effects do not match sunscreen protection. Lycopene-containing foods cannot replace broad-spectrum sunscreen, protective clothing, or other established sun-protection measures.

Inflammation and metabolic health

Experimental research has explored possible relationships between lycopene and inflammatory mediators, insulin sensitivity, obesity-related processes, and liver lipid metabolism. These areas are relevant to functional food research because chronic low-grade inflammation and metabolic disturbances contribute to several non-communicable diseases. Recent reviews have also examined lycopene delivery technologies in the context of fatty liver disease. Nevertheless, much of the mechanistic evidence remains preclinical, and specific disease-related claims require appropriately controlled human trials.

Applications of lycopene in functional food development

Successful incorporation of lycopene into food products depends on its physicochemical properties, processing conditions, sensory acceptability, and storage stability. Both purified lycopene and lycopene-rich natural ingredients may be considered, subject to applicable food regulations.

Stability of lycopene during food processing and storage

Lycopene contains numerous conjugated double bonds, making it susceptible to oxidation and changes in geometric configuration. Its retention in finished foods depends on processing severity, oxygen availability, light exposure, storage temperature, packaging, and the composition of the food matrix.

Important factors include:

- Temperature: Heating can facilitate tissue disruption and isomerization but may also cause degradation.
- Oxygen: Exposure during extraction, mixing, filling, and storage can accelerate oxidation.
- Light: Light exposure may promote photochemical degradation.
- pH and formulation: The surrounding food matrix and other ingredients may influence chemical stability and dispersion.
- Packaging: Light-barrier packaging and reduced oxygen exposure can help preserve carotenoid content.
- Storage duration: Both chemical and physical changes may accumulate over time.

For functional foods, measure lycopene at multiple stages, including after processing and throughout storage. Initial fortification levels alone are insufficient to determine how much reaches consumers. Suitable analytical methods include high-performance liquid chromatography (HPLC) to quantify lycopene and, when needed, distinguish its isomers. UV-visible spectrophotometry can help with preliminary assessment but may lack specificity when other pigments or interfering compounds are present. Color measurements using CIELAB parameters (L^* , a^* , and b^*) can supplement chemical analysis, but color retention should not be treated as a direct substitute for lycopene quantification.

Safety, regulatory considerations, and labeling

Lycopene occurs naturally in commonly consumed foods, but the safety and regulatory status of an added ingredient depend on its source, concentration, purity, production process, intended use, and jurisdiction.

Functional food developers should consider the following:

1. Confirm the identity, purity, and quality of the lycopene ingredient.
2. Assess relevant contaminants and residual solvents where applicable.
3. Establish the safety and suitability of the carrier materials used for encapsulation.
4. Determine the amount retained in the product throughout its stated shelf life.
5. Verify compliance with applicable food additive, ingredient, fortification, and labeling requirements.
6. Avoid unsubstantiated claims that the product prevents, treats, or cures a disease.

In India, developers should verify the Food Safety and Standards Authority of India (FSSAI) requirements for the intended ingredient and product category. Permission to use a pigment as a color additive does not automatically establish permission for every proposed fortification level or health claim. For scientific reporting, clearly distinguish between naturally occurring lycopene, tomato-derived extracts, purified lycopene, and encapsulated preparations.

Conclusion

Lycopene is a promising naturally occurring carotenoid for the development of functional foods because of its antioxidant properties, characteristic red colour, and potential relevance to several aspects of human health. Tomatoes, watermelon, pink guava, papaya, and processed tomato products offer practical sources, while emerging extraction and encapsulation technologies create opportunities to develop stable and bioaccessible ingredients. However, its poor water solubility, sensitivity to oxygen and light, processing-related changes, and variable bioavailability remain important limitations. These challenges are particularly relevant to aqueous beverages and dairy products, which require suitable formulation and stabilization strategies.

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