EXTRACTION, PURIFICATION, AND USE OF TOMATO BIOACTIVES: A CRITICAL REVIEW FROM CHEMICAL AND INDUSTRIAL VIEWPOINTS.

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Abstract
Tomatoes (Solanum lycopersicum L.) are a valuable source of phytochemicals, particularly lycopene, β-carotene, flavonoids, and phenolic acids. These compounds are known for their properties that combat oxidation, reduce inflammation, and prevent diseases. This review synthesizes current methods for extracting and purifying bioactive compounds from tomatoes, while also looking at their applications in the food, nutraceutical, and cosmetic industries. Although traditional solvent-based extraction is still the most common due to its high efficiency, greener methods like supercritical CO_2 extraction and enzyme-assisted extraction are becoming more important for sustainable practices. Chromatographic purification offers better selectivity compared to techniques like filtration or centrifugation, but cost and scalability remain barriers to wider use. The applications of lycopene and other tomato phytochemicals range from dietary supplements and functional foods to anti-aging products. Overall, this synthesis highlights the need to advance green extraction methods, along with effective purification strategies, to fully utilize tomatoes as a rich source of bioactive compounds across various industries.
Keywords: *tomato, lycopene, green extraction, nutraceuticals, cosmetics*

INTRODUCTION

Tomatoes are beneficial for the body. Tomatoes contain many vitamins and minerals. Tomatoes are rich in secondary metabolites like lycopene, carotenoids, flavonoids, and beta-carotene. These compounds are beneficial in protecting the body from prostate cancer and cardiovascular disease (Chaudhary, 2018; Collins, 2022). Tomatoes, containing various phytochemicals, link daily nutrition to health needs. In addition to fresh consumption, processing tomatoes produces by-products like skins, seeds, and pomace. These by-products often have higher concentrations of lycopene and polyphenols than the fruit pulp (Patel & Sahoo, 2023).

This discovery opens up new possibilities for applying circular economy concepts in the agri-food industry. Waste processing can be converted into valuable sources of bioactive substances. This approach supports global efforts to reduce food waste while promoting sustainability in the pharmaceutical and food sectors. However, to realize this potential, effective extraction and purification methods are required. Traditional organic solvent-based approaches, such as those using hexane or ethanol, are effective for recovering carotenoids but raise concerns about food safety and environmental impact (Shi et al., 2004). In contrast, green technologies like supercritical CO_2 extraction produce high-purity, solvent-free lycopene, but they require significant investment (Arab, 2019). Ultrasound- and enzyme-assisted extraction methods have become more popular lately because of their improved efficiency and reduced thermal degradation of delicate compounds (Patel & Sahoo, 2023). The purification stage is also crucial. Extracts often mix with lipids, pigments, and solvent residues, which can compromise stability and safety. Methods such as column chromatography and HPLC offer superior separation and purity compared to more basic techniques like filtration (Ranveer et al., 2020).

However, high costs and limited access hinder their use in the industry. Hybrid approaches that combine simpler and advanced techniques are necessary to balance cost-effectiveness and quality assurance. The extensive uses of tomato bioactives emphasize the importance of this research field. Lycopene and different phytochemicals are presently utilized in nutraceuticals, functional foods, and skincare items aimed at anti-aging (Collins, 2022). As consumer demand for natural health products grows, tomatoes are evolving from a traditional crop into a strategic resource across various industries. Consequently, studies on the extraction and purification of tomatoes enhance applied chemical sciences while simultaneously aiding public health and promoting industrial sustainability.

METHODS

This review used an analytical literature-based approach, focusing on extraction and purification methods for bioactive compounds derived from tomatoes. The literature examined included scientific publications from the last two decades, covering traditional extraction techniques and emerging green technologies, along with their applications in food, nutraceutical, and cosmetic industries. Sources were chosen meticulously, emphasizing research that offered empirical evidence regarding the effectiveness, safety, and sustainability of techniques. These included organic solvents like hexane, ethanol, and acetone (Shi et al., 2004), mechanical methods like cold pressing (Duba et al., 2019), and eco-friendly innovations like supercritical CO_2 extraction (Arab, 2019) and enzyme-assisted extraction (Patel & Sahoo, 2023).

This approach allowed for comparisons of methods in terms of yield and industrial sustainability. Beyond extraction, purification methods were also reviewed to assess the quality of the resulting bioactive compounds. The analysis focused on three main categories: basic filtration (Rao & Rathod, 2018), centrifugation (Khairnar et al., 2018), and chromatographic methods such as HPLC and column chromatography (Ranveer et al., 2020). Each method was evaluated for its ability to improve the purity, stability, and safety of the target compounds. Importantly, this review moves beyond a technical description to provide critical synthesis. Every approach is evaluated for its advantages, drawbacks, and opportunities for improvement or combination with additional methods For instance, while traditional methods often generate high yields, they raise concerns about solvent residues. In contrast, green technologies are safer but costly on an industrial scale. This perspective allows for a comprehensive evaluation, ensuring that the recommendations are both scientifically sound and practically relevant. Therefore, the approach of this review highlights both the gathering of information and the synthesis of results to provide a comprehensive perspective on existing research trends and industrial uses of tomato bioactives in modern contexts.

RESULTS AND DISCUSSION

1. Advances in Extraction Methods of Tomato Bioactives

Research on bioactive compounds of tomato is closely related to the development of extraction methods The most ancient and, that is still used, method was the extraction by organic solvent. Non-polar, hexane, is effective for extracting lycopene and other carotenoids while polar solvents, ethanol, is useful for separating flavonoids and phenolic acid (Shi et al., 2004). They are simple, inexpensive and result-oriented methods. However, the reliance on organic solvents leads to two major problems, i.e. the danger of residual solvents in final formulations and the environmental impact of waste chemicals. Looking from the angle of food and pharmaceuticals, this presents a problem of technical efficacy versus long-lasting safety. These challenges have led to a focus on innovations in green extraction technologies, including supercritical CO_2 extraction. It employs supercritical CO_2, which is benign, safe, and easy to separate from the end product. As per Arab (2019), the technique has the ability to produce highly pure lycopene with no solvent traces or residues. It also operates at lower temperatures, which helps to preserve the stability of the compounds and reduces the possibility of thermal degradation.

However, the high-tech complexity and expensiveness of the equipment restrict its application in the case of medium scale industries. There are other methods based on physical energy that deserve capturing attention, ultrasound-assisted extraction is one of them. In this case, ultrasound with a certain frequency is able to assist extraction by disrupting plant cell walls by a mechanism called cavitation and thus increases the liberation of the solvent with the bioactive compounds. It is noted in the literature that this method enhances the yield of certain molecules which are heat-sensitive (Patel & Sahoo, 2023).

Enzyme assisted extraction works in the same line as other methods of extraction where particular enzymes are used to breakdown cell walls in order to obtain the bioactives with higher which is more accessible. Not only these methods increase the extraction yield, they also improve the sustainability of the process by replacing non-green chemicals with natural biological resources. It becomes obvious that for any particular extraction, there is no optimum method that can be called the best. The traditional methods relying on the use of solvents are the cheapest, while the green technologies are the most safe and sustainable. From physical approaches, a balance can be drawn from both sides. Future research and industrial use should focus on hybrid approaches that use multiplication strategies. For instance, ultrasound pre-treatment and supercritical CO_2 extraction work together to produce optimal products at a desirable cost.

2. Strategies for Purification of Bioactive Compounds

Exhausting extraction techniques to produce focus bioactives is just a first step. The resultant extracts are not just confined to bioactives, but also lipids, pigments and even proteins that have the potential to destabilize and make the extract less effective. It is for this reason that purification becomes imperative to ascertain that the products are bioactive guaranteed safe for industrial application. The first purification technique that comes to mind is filtration, which causes the fluid to be liberated from the constituents of the solid left behind. Rao and Rathod (2018) pointed out that even though filtration is facile and cost-effective, it is not preferential to specific constituents. Generally, filtration can be viewed more like a step, and not the bio extract solution for purification. There are more handy techniques as well, like centrifugation where there is a suspension of liquid and solid elements within that single system. On a larger industrial scale, centrifugation is more readily available as the disk stack centrifuge, which allows continual processing and time savings (Khairnar et al. 2018).

Nonetheless, much like filtration, centrifugation lacks a certain level of selectivity making it an ancillary method as opposed to a final purification technique. On the other hand, chromatographic methods are regarded as the gold standard for the purification of bioactives. As highlighted by Ranveer et al. (2020), column chromatography is able to obtain fractions of lycopene with greater stability and antioxidant activity that are more sophisticated than other methods. There is also High Performance Liquid Chromatography (HPLC) which offers even greater resolution to the point of near complete purity of the desired compounds. The primary drawbacks, however, are the exorbitant operational costs and the intricate apparatus required, thus making chromatography more applicable towards research laboratories and high-value industries than for mass production. In light of these challenges, the development of hybrid purification methods has become imperative. Filtration and centrifugation can function as initial steps to remove bulk contaminants, while chromatography can be the final step to ensure high purity. These combinations offer a pragmatic approach to provide the best compromise between product quality and cost.

3. A Botanical Summary of The Tomato Plant

The tomato (Solanum lycopersicum L.) is a member of the Solanaceae family which also contains the potato, pepper and aubergine. The tomato originated from South America and was spread around the world during the Colonial times of the 16th Century (Bergougnoux, 2014). Tomatoes are now cultivated on almost every continent and are considered one of the most important vegetable-fruit crops economically and commercially. A tomato, botanically, is a one-year herbaceous plant which is able to grow from 0.5m to 2m in height. It's true berry with a thin skin, fleshy, gelatinous pulp, and a thin crusted skin that encases seeds. One of the most popular tomato types, the lypocene tomato, is red in color, and is one of the highest concentrated tomatoes having lycopene with there being other varying hues of tomatoes which are yellow, orange, purple, and green. These other tomatoes are considered by Collins to being determinant by other pigments such as carotenoid and flavonoid (Collins, 2022).

Tomatoes, with current research on plant production industry, are one of the horticultural crops with the most diverse variety of environmental conditions, allowing it to have a higher production. Within the plant production industry, tomatoes have the highest number of harvest periods annually. Ideal temperatures to grow tomatoes are from 21 to 27° Celsius with sufficient sunlight and growing conditions. Tomatoes are also known to be highly sensitive to drought, and flourish the most in loose, well-drained soil. Tomatoes have also contributed greatly to research within plants. It is easily sequenced, making it one of the easiest crops to research metabolism and plants and growing resistance to abiotic. Along with these traits, they are able to be engineered to incorporate higher nutritional content, higher disease resistance, and higher value crops (Lin et al. 2014). With their economic importance, genetic diversity, and research relevance, tomatoes are both a crucial food crop and a valuable model organism in plant biology research.

4. Chemical Composition of Tomato: Vitamins and Nutrients

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Phytochemicals

Above all of these, the health benefits of tomatoes may be attributed to their content of pharmacologically active phytochemicals as compared to other food sources. The most prominent and studied of such phytochemicals is lycopene, which is a carotenoid pigment responsible for the red color of tomatoes. among other carotenoids, lycopene is recognized for having a stronger antioxidant activity. It is important for the prevention of cellular damage from oxidative stress (Rao & Rao, 2007). The regular consumption of lycopene is associated with a reduced risk of developing prostate cancer, cardiovascular diseases, and metabolic disorders (Chaudhary, 2018). Tomatoes also contain other phytochemicals such as β-carotene and lutein. β-carotene is a provitamin A, thus helps improve immunity and vision. Lutein and other eye supplements helps to maintain the eye's retina and may help to prevent age-related macular degeneration (Martí et al., 2016). The other lutein containing food sources, and then tomatoes contain lutein along with some phenolic flavonoids such as quercetin, kaempferol, and naringenin, which have anti-inflammatory, antimicrobial, and DNA protecting activities (Slimestad & Verheul, 2009).

Tomato peels, which are usually waste and the parts of the tomato with the most prominent flavonoids, are rich in the least value added phenolic acids such as chlorogenic and caffeic acids, which are abundant in total antioxidant capacity. These macromolecules are able to help with free radical capture and lipid metabolism (Martí et al., 2016). The combined presence of carotenoids, flavonoids, and phenolic acids makes tomatoes one of the most valuable natural sources of phytochemicals. This variety positions tomatoes not only as a source of basic nutrition but also as a functional food ingredient with promising roles in preventing chronic diseases.

Table. 1 The extraction and purification of tomato bioactive compounds is essential in food, pharmaceutical, and cosmetic research

Compound	Class	Dominant Location/Part	Reported Health Effects	Notes/Content Example
Lycopene	Carotenoid	Pericarp (higher in pericarp than locule)	Anticancer, cardioprotective, skin health	Total carotenoids: Pericarp 108.03±2.22 mg/kg vs Locule 87.84±2.23 mg/kg
β-Carotene	Carotenoid	Pericarp	Provitamin A, eye and immune health	—
α-Carotene	Carotenoid	Fruit tissues	Cardiovascular protection	—
Lutein	Xanthophyll carotenoid	Fruit tissues	Retinal health, prevention of macular degeneration	—
Neurosporene	Carotenoid	Fruit tissues	Associated with skin health	—
Phytoene	Colorless carotenoid	Fruit tissues	Skin protection, UV defense	—
Phytofluene	Colorless carotenoid	Fruit tissues	Skin protection, UV defense	—
α-Tomatine	Glycoalkaloid/saponin	Fruit tissues	Anticancer, cardioprotective, immunological adjuvant (malaria)	—
Esculeoside A	Saponin	Fruit tissues	Antidiabetic (via AMPK activation, IRS-1 enhancement)	—
Lycoperoside H	Steroidal saponin	Seeds	Anti-inflammatory,	—

			skin health support	
Quercetin	Flavonoid	Skin (highest flavonoid content)	Anti-inflammatory, antimicrobial, DNA protection	—
Kaempferol	Flavonoid	Skin	Anti-inflammatory, antioxidant	—
Naringenin	Flavonoid	Skin	Anti-inflammatory, antioxidant	—
Chlorogenic acid	Phenolic acid	Skin & pulp	Antioxidant, lipid metabolism regulation	—
Caffeic acid	Phenolic acid	Skin & pulp	Antioxidant, lipid metabolism regulation	—
Vitamin C (ascorbic acid)	Vitamin	Locule (higher than pericarp)	Antioxidant, immune support, skin health	Locule 228.90±5.44 mg/kg vs Pericarp 194.90±2.13 mg/kg

5. Applications Across Industries

Tomato bioactive compounds strategically hold interest for their wide-ranging applications. In the food industry, tomatoes have been processed into sauces, pastes, and juices for centuries. Interestingly enough, processing and heat treatment especially, lowers Vitamin C and other elements, but the bioactive compounds, especially lycopene, tend to improve in bioavailability (Shi & Maguer, 2000; Dewanto et al., 2002). This means loss of nutrients does not mean the nutritional value is lower, some of the bioactive compounds may be more enhanced. Of late, tomato flakes and powders have become some of the more popular dehydrated products. Kaur et al. (2014) notes that freeze-drying retains more color, flavor, and phytochemicals than traditional drying. In this dehydrated form, tomatoes have an extended shelf life and are easier than traditional packages to utilize in instant foods and seasoning blends. In the nutraceutical industry, tomato lycopene and flavonoids are some of the most popular primary constituents in antioxidant additives. Research has linked lycopene and lowered risk of prostate cancer and cardiovascular diseases (Giovannucci, 1999; Rao & Agarwal, 2000). Nowadays, tomato extract is more readily available in capsule and tablet form for consumers wishing to gain the health benefits of tomatoes without the need to consume them in large quantities.

The shift from food crop to preventive health agent attributed to tomatoes is not a new phenonomen. In addition, the cosmetic industry is attracted to bioactives in tomatoes. Lycopene and β-carotene can protect the skin from UV radiation (Stahl & Sies, 2002), and feeding trials demonstrated that skin photodamage is significantly improved by the ingestion of lycopene-rich tomato paste (Rizwan et al., 2011). In addition, the vitamin C in tomatoes is vital for the collagen that helps sustain skin elasticity (Pullar et al., 2017). Consequently, tomato extracts are common in natural anti-aging creams, sunscreens, and brightening serums. There is a market trend for natural cosmetic ingredients, which stimulates the supply of tomato-based formulations, especially when the consumer is looking for plant-based products with real science to support their claims. Such a compilation of literature illustrates the access usually needed is a balance of efficiency, cost, and sustainability. Solvent-based approaches as a whole are still useful, as they are the technically simple and economically cheap approach.

6. Critical Insights and Future Directions

However, they no longer satisfy the new normal of industry: safety and environmental concern. On the contrary, the supercritical CO_2 and enzyme-assisted extraction green technologies have a lot of promise. In practice, they are still lacking with respect to price and infrastructure. The focus of further research by far the most economical means of isolation and purification within the constraints of a broader and more effective approach to the problem than the simple debate of ‘conventional versus green' models should rest on the in situ purification of biomarkers of interest by steps which employ multiple, low complexity pre-extraction and selective purification approaches of balanced effective processes hybrid processes precipitants should also focus the optimization of the processes to achieve the desired profit margins while maintaining quality, for instance by the use of less expensive, proven to be much safer, green solvents, such as ethanol for extraction (Burgos & Giannini, 2019).

Use of tomato and by-products of its processing together with their phytochemicals has shown promising benefits in functional foods, nutraceuticals, cosmetics, and versatile industrial applications. Long-term sustainability, however, beckons for the incorporation of tomato processing by-products as alternative bioactive materials which provide functional benefits. Patel and Sahoo (2023) point out that the tomato skin and seeds possess higher concentrations of lycopene than the pulp of the fruit. The justification of such by-products resource utilization would significantly enhance the ecological and economical efficiency of the supply chains. The tomato extraction and purification operations stand to provide more than academic knowledge in regard to their incorporation in global industry strategies. The need for integration of analytical chemistry, food technology, and process engineering remains to ensure the commercial viability of laboratory invented solutions.

CONCLUSION

Tomatoes are good sources of phytochemicals such as lycopene, β-carotene, flavonoids, and phenolic acids. These possess diverse array of health benefits ranging from antioxidant and anti-inflammatory activities to prevention of chronic diseases. Efficient extraction and purification steps are required for maximum benefit. Though conventional solvent-based techniques remain common practice due to ease of efficacy and cost-effectiveness, these suffer from the limitation of leaving residual solvent as well as harming the environment. Green technologies, like supercritical CO_2 and enzyme-assisted extraction, are safer and greener and have cost and infrastructure hurdles to cross. Hybrid technologies that give the benefits of simple technologies and advanced technologies together are a future-bound approach. Purification is required for compound stability and safety, and chromatography is most selective but costly.

Coupling chromatography with less complex methods such as filtration or centrifugation would be more suited for industrial use. Operationally, tomato bioactives are already operationally incorporated in functional foods, nutraceuticals, and anti-aging cosmeceuticals. Additionally, the use of tomato by-products (skins and seeds) as new sources of bioactives is aligned with circular economy and industrial sustainability principles. Together, developing green extraction techniques, integrating them with effective purification techniques, and optimizing the processing residues will optimize tomatoes' potential as a multi-functional source of bioactive compounds and spur global sustainability.

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