Tomatoes Unveiled: A Comprehensive Exploration from Cultivation to Culinary and Nutritional Significance

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Funding: No specific funding was received for this work.

Potential competing interests: No potential competing interests to declare.

Abstract

Tomatoes are not only a culinary delight but also a nutritional powerhouse. This article comprehensively examines tomatoes, spotlighting their global cultivation, nutritional richness, and diverse applications across industries. As the second most cultivated vegetable worldwide, tomatoes are pivotal in food processing, agriculture, biotechnology, beverages, and pharmaceuticals. Their nutrient profile, characterized by significant water content and intricate composition, positions tomatoes as culinary delights and nutritional powerhouses. The article explores their role in promoting heart health, preventing cancer, supporting eye health, aiding weight management, and enhancing digestive health. Tomatoes transcend the culinary realm, finding applications in diverse industries. In food processing, they contribute to taste, color, and nutritional content. In agricultural research, tomatoes advance genetics, physiology, and biochemistry, fostering sustainable agriculture. The biotechnology industry leverages their adaptability for genetic manipulation and bioengineering. The beverage sector benefits from health-conscious options like tomato juice and the iconic Bloody Mary cocktail. In pharmaceuticals, lycopene, a potent tomato compound, features in antioxidant formulations and supplements. The article offers a thorough overview of the industrial use of different tomato parts, including seeds, peels, and pomace, in producing various products. It explores the extraction of valuable compounds

such as carotenoids and tomato seed oil for applications in diverse industries. Additionally, it discusses the potential of tomato waste in environmental remediation as an adsorption material. In essence, it underscores the remarkable versatility of tomatoes, transcending their culinary role to become a resource with implications for sustainability, innovation, and multiple scientific disciplines.

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Keywords: Tomatoes, Lycopene, Nutrients, Sustainability and Innovation.

1. Introduction

Widely regarded as the world's most consumed vegetable, the tomato, scientifically known as*Solanum lycopersicum*, stands as a fundamental ingredient in an extensive array of raw, cooked, or processed foods (Wang *et al*., 2023). While inherently a perennial herbaceous plant, it is predominantly cultivated as an annual crop, although biennial and perennial forms exist. Thriving in both tropical and temperate climates, tomatoes grace open fields or find shelter under greenhouses in temperate regions. As a proud member of the Solanaceae family, alongside other commercially significant species, the tomato transcends geographical boundaries, being cultivated globally for local consumption and as an essential export crop (Poojitha, M, 2023).

Tomatoes rank second in terms of acreage among major globally cultivated vegetable crops, surpassed only by potatoes. However, they take the lead when it comes to crops used for processing. With the current global emphasis on adopting organic agricultural methods for sustainable food production (Pinho *et al.,* 2011), tomato farming has experienced substantial growth in the last 50 years. The crop's productivity has increased by approximately 10%, attributed to its role as a vital source of vitamins and minerals for numerous countries. Moreover, recent revelations highlight tomatoes as a significant source of lycopene, a carotenoid with antioxidant properties that may contribute to preventing diseases such as cancer and cardiovascular issues (Bertin & Génard, 2018).

Various methods have been employed to explore the impact of environmental factors on tomato crop development. Changes in land use, particularly the conversion of unproductive land to arable land, influence global carbon cycles linked to climate conditions. Consequently, climate change plays a crucial role in shaping agricultural landscapes, affecting the variability of biophysical processes in agricultural productivity (Ardabili *et al*., 2013).

However, the tomato's significance extends beyond its palatable contributions to meals. Boasting a water content ranging from 93-95%, tomatoes emerge not only as flavorful additions but also as hydrating and nutritionally dense components. Comprising solid matter content of 5.5-9.5%, with a mere 1% attributed to seeds and skin, tomatoes exhibit a complex nutritional profile. The insoluble solids in tomato juices, constituting 15-20% of total solids, are primarily composed of lignin, cellulose, and pectin. While sucrose content is negligible, not surpassing 0.1%, glucose and fructose take the spotlight as the main reducing sugars, contributing 50 to 60% of tomato solids. The total sugar content varies between 2.19 to 3.55%. Additionally, tomatoes house a variety of polysaccharides like xylem, pectin, cellulose, and arabinoxylan, constituting about 0.7% of tomato juices (Zhang *et al*., 2023).

In essence, the tomato transforms from a botanical entity to a nutritional powerhouse, embodying both culinary delight and healthful attributes (Yong *et al.,* 2023). This comprehensive overview unravels the multifaceted nature of the tomato, from its global cultivation patterns to the intricate details of its nutritional composition.

2. Nutrient Profile and Antioxidant Properties

Tomatoes stand as a nutritional powerhouse, offering a wealth of essential vitamins and minerals vital for overall well-being (Martínez *et al.,* 2024). With notable concentrations of vitamin C, potassium, folate, and vitamin K, tomatoes contribute significantly to a balanced diet. What sets them apart is the presence of lycopene, a potent antioxidant responsible for their vibrant red hue and providing unique nutritional benefits (Table 1). Beyond their visual appeal, tomatoes boast a comprehensive nutritional profile: per 100 grams, they contain a mere 18 calories, comprising 95% water, 0.9 grams of protein, 3.9 grams of carbohydrates, 2.6 grams of sugar, 1.2 grams of fiber, and 0.2 grams of fat (Wang *et al.,* 2023). This low-calorie, high-water content combination makes tomatoes not only a flavorful addition to various dishes but also a healthy and hydrating option. Their nutritional richness positions tomatoes as a versatile and valuable ingredient, contributing not only to culinary delights but also to the overall health and vitality of those who incorporate them into their diet (Coelho *et al*., 2023).

The nutritional value of tomatoes is primarily attributed to their phytonutrients, with lycopene being the most extensively studied carotenoid (Górecka *et al*., 2020). Lycopene serves as a potent radical scavenger, providing protection against cellular oxidative damage in humans (Caseiro *et al.,* 2020). While lycopene plays a crucial role in the health benefits of tomatoes, other bioactive compounds also exhibit potential health-protective effects when interacting with various food components. Notably, whole tomato fruit has been reported to offer superior protective and antioxidant properties compared to standalone lycopene supplementation (Gholami *et al*., 2021).

Previous studies have highlighted the preventive effects of plant phytochemicals on chronic degenerative diseases such as diabetes microvascular complications (Ho *et al*., 2022), viral diseases (Choe *et al.,* 2022), and cancers (Ng *et al.,* 2013). These phytochemicals often interact with each other, producing synergistic, additive, or antagonistic health effects (Fleming & Luo, 2021). Diets rich in plant phytonutrients, like the Mediterranean diet, have been associated with a reduced risk of cancers, cardiovascular diseases, and diabetes (Farinetti *et al*., 2017). The link between the Mediterranean diet and

disease prevention supports the concept of food synergy. For example, the traditional Mediterranean-style tomato sauce known as sofrito, comprising tomatoes, onion, garlic, and olive oil, with additional herbs and vegetables in various recipes, serves as an illustrative example of food synergism (Beltrán Sanahuja *et al.*, 2019). In a Prevención con Dieta Mediterránea trial, Estruch et al. (2013) found a positive association between an extra virgin olive oil-supplemented Mediterranean diet, including sofrito, and a reduced risk of cardiovascular events. Sofrito contains 40 plant polyphenols and significant amounts of carotenoids (Rinaldi de Alvarenga *et al.*, 2019). Storniolo et al. (2020) demonstrated that hydroxytyrosol, naringenin, and lycopene in sofrito collectively induced antioxidant activity. Additionally, the combination of polyphenols and carotenoids exhibited an additive inhibitory effect on intestinal epithelial cancer cell growth, DNA synthesis, and eicosanoid biosynthesis.

Tomatoes emerge as versatile allies for heart health due to their high potassium content, playing a crucial role in blood pressure regulation and reducing the risk of cardiovascular diseases. The synergy of antioxidants and bioactive compounds not only enhances the culinary experience but also contributes to improved cholesterol levels, emphasizing tomatoes as promoters of cardiovascular well-being (Løchen, M. L, 2023). In terms of cancer prevention, various studies suggest the potential of lycopene in tomatoes to lower the risk of specific cancers, including prostate cancer. The combination of anti-inflammatory and antioxidant properties works synergistically, combating oxidative stress and fortifying the body's defenses against the formation of cancerous cells (Martí *et al.*, 2016). Tomatoes, rich in beta-carotene, lutein, and zeaxanthin, significantly contribute to maintaining eye health and reducing the risk of age-related macular degeneration (AMD). Regular consumption establishes a protective shield against various eye disorders, positioning tomatoes as an essential component of ocular well-being (Coelho *et al.,* 2023). With their low-calorie and high-water content, tomatoes become an excellent choice for weight management. The presence of chromium may additionally contribute to improved insulin sensitivity and glucose metabolism, making tomatoes a valuable asset for those aiming for metabolic balance (Jeong *et al.*, 2023). Furthermore, tomatoes, rich in dietary fiber, actively support digestive health by promoting regular bowel movements and preventing constipation. The fiber content induces a feeling of fullness, aiding in weight control and enhancing overall digestive well-being (Wu *et al.*, 2023).

Phytonutrients, natural constituents with immune-modulating properties, play a pivotal role in various positive pharmacological effects such as antioxidation, anti-inflammation, and antimutagenesis. Tomatoes are recognized as rich sources of phytonutrients, including phenolic acids, flavonoids, lycopene, β-carotene, and glycoalkaloids (Ali *et al.*, 2020). Phenolic acids (Figure 1a) and flavonoids (Figure 1b), both major groups of phenolic compounds, are particularly abundant in the skin of tomato fruit, with smaller-sized varieties exhibiting higher phenolic compound content due to their increased surface-area-to-volume ratio (Raiola *et al.*, 2014). Key phenolic acids in tomatoes, such as chlorogenic acid, gallic acid, caffeic acid, sinapic acid, ferulic acid, and p-coumaric acid, are easily absorbed by the intestines, showcasing antioxidant activities (Neeraj *et al.*, 2019). Chlorogenic acid, the most prevalent phenolic acid in tomatoes, has been associated with improved memory functions in elders, while gallic acid demonstrates a cardioprotective effect by regulating lipoprotein levels (Kato *et al.*, 2018). Flavonoids, including quercetin, rutin, naringenin, resveratrol, and kaempferol, not only contribute to the aroma and color of tomatoes but also serve as non-enzymatic antioxidants, preventing degenerative diseases such as cardiovascular diseases, diabetic microvascular complications, and cancer (Ali

et al., 2020). Carotenoids, lipophilic pigments protecting plants from oxidative damage, are prominent in tomatoes, featuring lycopene, α-carotene, β-carotene, lutein, phytoene, and phytofluene (Martí *et al.*, 2016). Lycopene, a highly unsaturated carotenoid, exhibits remarkable antioxidant activity, with the ability to quench singlet oxygen surpassing that of β-carotene and α-tocopherol (Fenni *et al.*, 2017). While β-carotene serves as a precursor to vitamin A, lycopene, responsible for tomato skin color, undergoes cis–trans isomerization influenced by light and heat, with the cis-isomer displaying higher bioactivity and bioavailability (Pinela *et al.*, 2016). Lycopene stands out as the most effective free radical scavenger among carotenoids, making tomatoes a valuable source of these health-promoting compounds (Fenni *et al.*, 2017).

Table 1. Nutrition Profile of Tomatoes

Nutrient	Amount per 100g
Calories	34.67 kcal
Water	91.18 g
Protein	10.50 g
Carbohydrates	5.96 g
Sugars	2.6 g
Dietary Fiber	11.44 g
Lipid	3.62 g
Vitamin C	36.16 mg
Potassium	403 mg
Folate	14mg
Vitamin K	98.28 µg
Lycopene	8002 µg
β-carotene	9942 µg
Vitamin A	614IU
Vitamin E	15 µg
Total Tocopherol	1.2 mg
Phenolic Acids	25.5 mg CIAE

(Adapted from Ali et al., 2020)

3. Diverse Industrial Utilization of Tomatoes

Tomatoes extend their influence far beyond the culinary realm, finding a multitude of applications in various industries (Fig 1). Tomatoes (*Solanum lycopersicum*) are significant edible plants rich in beneficial bioactive compounds, including carotenoids, fiber, protein, and pectin. These compounds play a protective role against various human diseases. Tomatoes undergo processing to create diverse products like ketchup, paste, sauce, puree, soup, juice, and canned

tomatoes. Substantial waste is generated during this process, and these byproducts contain bioactive compounds that contribute to human health. More than half of tomato waste is composed of fiber, sugar, protein, and important carotenoids, particularly lycopene (Kiralan, M., & Ketenoglu, O, 2022)

Tomato pomace, a by-product of processing, comprises peel, seeds, and small amounts of pulp. These components are commonly repurposed in various products. Dried tomato waste finds utility as animal feed and additives in meat products. Tomato seeds, rich in oils and carotenoids, are incorporated into bakery and fermented cereal foods, enhancing the oxidative stability of the oil. Additionally, tomato seed oil can be applied in non-food sectors, such as biodiesel (Lu *et al.*, 2019).

Post-harvest processing of tomatoes results in the generation of byproducts and waste throughout the industrial stages. Tomato pomace, consisting of seeds, peel, and pomace liquid, contains valuable compounds for diverse commercial applications. The waste from tomato processing is harnessed for carotenoid extraction, adsorption material preparation, and serves as animal feed. In the realm of sustainable energy, tomato waste, including peels, cores, and leaves, serves as a rich organic feedstock for biogas production, exemplifying the resourcefulness in utilizing every part of the fruit. This byproducts/waste has potential uses in both food (e.g., seed oil, lycopene as a natural colorant, and antioxidant for food product development) and non-food domains. For instance, dried byproducts/waste can be employed as adsorption material to remove synthetic dyes and heavy metals from aqueous waste (Rajan *et al.,* 2022). Tomato seed oil can also be used in non-food applications such as biodiesel. In the cosmetics sector, compounds like lycopene, vitamin C, and potassium, sourced from tomatoes, contribute to anti-aging and skin-protective properties, making them valuable ingredients in skincare products (Eslami *et al.,* 2023).

3.1. Food Processing

Tomatoes take center stage in the food processing industry, serving as natural flavor enhancers and vibrant coloring agents in an array of products such as ketchup, sauces, and soups. The striking red pigmentation of tomatoes not only adds visual allure but also offers a natural alternative to synthetic colorings, significantly enhancing the sensory appeal of food products. These intrinsic qualities play a pivotal role in crafting healthier and visually appealing processed foods (Khan *et al.*, 2023). Employing meticulous processing methods, vibrant tomatoes undergo various transformations, contributing to a diverse range of culinary delights (López-Yerena *et al.*, 2023). Tomato sauce, beginning with blanching and pureeing, simmers to perfection while infusing flavors with herbs and spices. Iconic ketchup emerges from washed, peeled, and chopped tomatoes, undergoing flavorful alchemy with sugar, vinegar, and spices. Salsa, a lively dance of tomatoes, onions, peppers, and spices, marinates to perfection, delivering a burst of flavors. Crafted through washing, crushing, and moisture reduction, tomato paste creates a concentrated culinary essence. Canned tomatoes, in diverse shapes, endure heat processing for preservation, becoming a pantry staple. Sun-dried tomatoes, halved or sliced, bask in the sun or dehydrators, packed in oil or vacuum-sealed for an intense burst of flavor. Filtered for purity, tomato juice captures the essence of freshly crushed tomatoes, while tomato-based soup combines richness with additional savory elements. Tomato jam or chutney, a symphony of tomatoes, sugar, vinegar, and spices, simmers to a luscious

consistency. Lastly, tomato powder, created through dehydration, encapsulates the essence of tomatoes in a fine, preserved form. These culinary marvels, though nuanced in their processes, collectively celebrate the artistry of transforming tomatoes into a spectrum of delightful and versatile products (Pereira *et al*., 2023). Beyond taste and color, tomatoes offer nutritional benefits to processed foods. Their inclusion introduces essential vitamins, antioxidants, and bioactive compounds, aligning with the growing demand for functional and health-promoting food products. The versatility of tomatoes in various processed forms further expands their applications, solidifying their role as a cornerstone in the food processing industry (Silva *et al*., 2023). In essence, tomatoes not only tantalize taste buds but also provide a natural and healthy dimension to processed foods, reinforcing their crucial role in the food processing landscape.

3.2. Agricultural Research

In the realm of agricultural research, tomatoes emerge as key subjects, offering a genomic canvas that researchers explore to unravel the intricacies of plant biology. Studies delve into the genetics, physiology, and biochemistry of tomatoes, leading to the development of novel varieties with improved yield, disease resistance, and enhanced nutritional profiles (Schreinemachers *et al*., 2017). These advancements contribute significantly to sustainable agriculture and food security.

Tomatoes serve as model organisms for understanding fundamental biological processes in plants. Genetic studies have identified key genes responsible for traits such as flavor, color, and resistance to pests and diseases. This wealth of genetic information has paved the way for targeted breeding programs, accelerating the development of tomatoes with desirable traits (Rothan *et al.,* 2019).

Furthermore, the adaptability of tomatoes to diverse climatic conditions makes them valuable for addressing global agricultural challenges. Their resilience and versatility position tomatoes as invaluable assets in the pursuit of sustainable and resilient agriculture (Litskas *et al*., 2019).

3.3. Biotechnology Industry

Tomatoes, renowned for their genetic stability and ease of cultivation, have found a significant place in the biotechnology industry, acting as promising candidates for cutting-edge applications. The genomic stability of tomatoes makes them ideal subjects for genetic manipulation, gene therapy, and bioengineering (Gerszberg *et al.,* 2015). Researchers leverage the tomato's adaptability to explore innovative avenues, pushing the boundaries of biotechnological advancements.

The application of biotechnology to tomatoes extends beyond mere genetic modification. Scientists harness the potential of tomatoes to serve as bioreactors for the production of valuable compounds, including pharmaceuticals and industrial enzymes (Ganapathy, M, 2016). This dual role of tomatoes, as both subjects of genetic study and platforms for bioengineering, showcases their versatility and adaptability in the rapidly evolving landscape of biotechnology (Meng *et al*., 2022).

As the biotechnology industry continues to advance, tomatoes stand as key contributors, facilitating breakthroughs in

gene editing, molecular biology, and the production of bio-based materials.

3.4. Beverage Industry

Tomatoes find a distinctive place within the beverage industry, offering a spectrum of options that cater to both health-conscious consumers and those seeking indulgence. Tomato juice, a prominent beverage, stands out as a standalone refreshing drink and serves as a base for various vegetable juices. The iconic Bloody Mary cocktail, featuring tomato juice as a key ingredient, exemplifies the versatility of tomatoes in crafting unique and flavorful beverages (Kumar *et al.*, 2023).

Tomatoes contribute not only to the taste but also to the nutritional profile of beverages. Tomato juice, rich in vitamins, minerals, and antioxidants, aligns with the growing demand for functional and health-promoting beverages. The natural sweetness and acidity of tomatoes contribute to the complexity of flavors, making them a versatile and indispensable ingredient in the beverage industry (Rajoria *et al.*, 2011).

Beyond traditional applications, innovative tomato-based beverages continue to emerge, addressing diverse consumer preferences. From savory concoctions to sweet blends, tomatoes play a dynamic role in shaping the beverage landscape, offering options that go beyond conventional expectations.

3.5. Pharmaceutical Industry

In the pharmaceutical industry, tomatoes take center stage through the potent compound lycopene, a natural antioxidant abundantly present in these fruits. Lycopene extraction from tomatoes has garnered attention for its therapeutic potential, leading to its incorporation into certain pharmaceutical formulations (López-Yerena *et al.*, 2023). The antioxidant properties of lycopene make it a valuable candidate for addressing oxidative stress-related conditions.

Beyond traditional pharmaceutical applications, tomatoes extend their reach into the realm of nutraceuticals. Processed tomato products, such as supplements, harness the health benefits of tomatoes for preventive and therapeutic purposes. Lycopene's role as a natural colorant further contributes to the appeal of pharmaceutical formulations, aligning with the growing preference for natural and plant-derived ingredients (Carvalho *et al.,* 2021).

The exploration of tomatoes in the pharmaceutical sector underscores their potential to serve as sources of therapeutic compounds and highlights the intersection of food and medicine in promoting health and well-being.

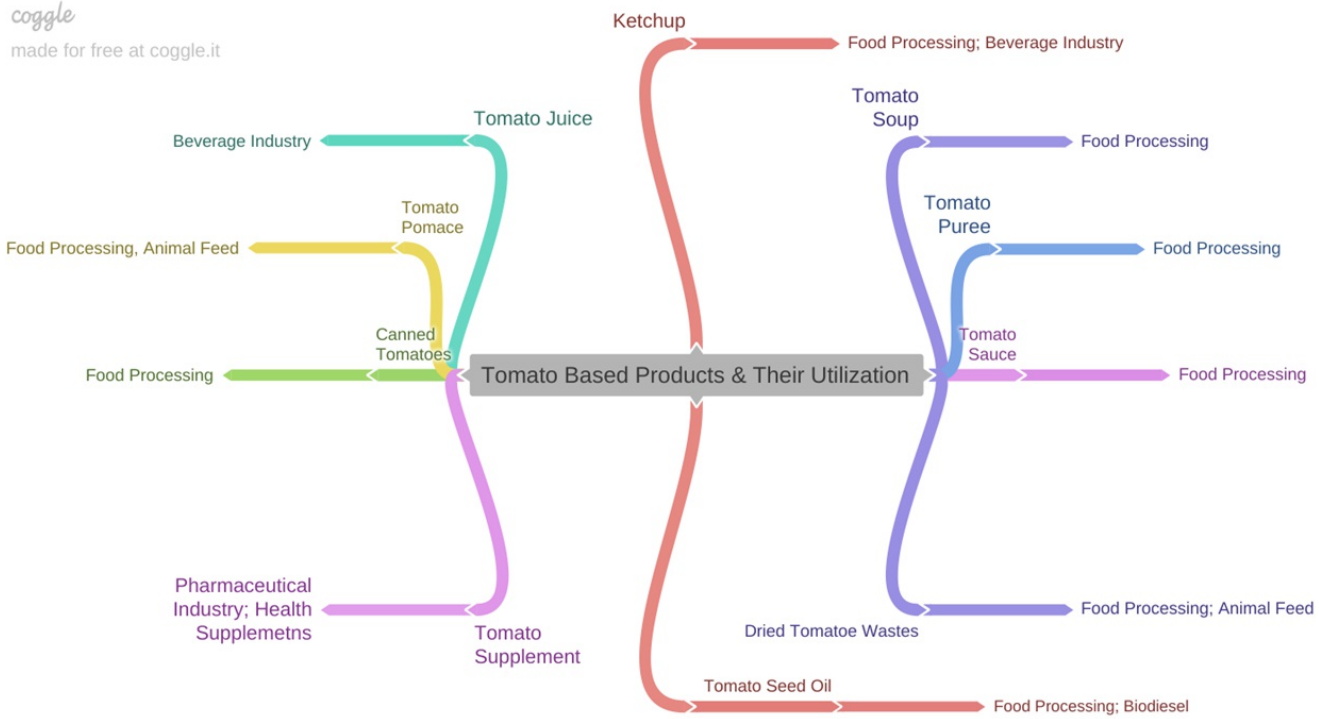

Figure 1. Utilization of Tomato-Based Products in Various Industries

4. Processing Tomato seed oil

Tomato seed oil, also known as lycopene oil, is a type of vegetable oil extracted from the seeds of tomatoes. It is rich in lycopene, a powerful antioxidant that gives tomatoes their red color. Lycopene has been shown to have various health benefits, such as reducing the risk of cancer and heart disease (Kumar *et al.,* 2022). Tomato seed oil is also high in polyunsaturated fatty acids, particularly linoleic acid, which may help lower cholesterol levels. It has a mild, slightly sweet flavor and can be used as cooking oil or in cosmetic products due to its moisturizing and anti-inflammatory properties. However, it should be noted that the yield of tomato seed oil is relatively low compared to other vegetable oils, making it more expensive.

The processing of tomato seed oil requires specialized equipment and expertise, making it more expensive than other vegetable oils with higher yields (Sangeetha *et al*., 2023). However, the demand for natural and healthy ingredients in various industries is driving research and development efforts to improve the efficiency and yield of the extraction of tomato seed oil, also known as lycopene oil, involves several steps to release the oil from the seeds and separate it from the solids (Méndez-Carmona *et al*., 2023). Here is a detailed description of the extraction process:

- **Tomato Seed Collection:** Ripe tomato seeds are collected either manually or through mechanical methods like centrifugation or flotation. Subsequently, the seeds are dried and stored for further processing.
- **Crushing:** Dried seeds undergo crushing to rupture the seed coat and release the oil. This can be achieved using a hammer mill, roller mill, or a screw press.

- **Screw Pressing:** Crushed seeds are fed into a screw press, applying pressure to extract the oil. The oil is then separated from the solids and collected.
- **Centrifuging:** An alternative method involves mixing crushed seeds with a solvent, like hexane, followed by centrifugation. This process separates the oil from solids and impurities.
- **Filtering:** The crude oil obtained is filtered to eliminate remaining solids and impurities.
- **Decolorization**: Activated carbon or clay is employed to treat the filtered oil and remove any yellowish color caused by carotenoids.
- **Deacidification**: The oil, containing free fatty acids, undergoes treatment with an alkaline solution, such as sodium hydroxide, to neutralize these acids and prevent spoilage.
- **Deodorization:** To eliminate unpleasant odors, the deacidified oil is heated under vacuum at high temperatures.
- **Packaging and Storage**: The purified oil is packaged in airtight containers, stored in a cool, dry place, and shielded from light to prevent oxidation and spoilage.

This meticulous extraction process ensures the production of high-quality tomato seed oil with optimal purity and stability.

5. Conclusion and Future Aspects

In conclusion, the tomato, often celebrated for its culinary appeal, transcends its role as a flavorful ingredient to emerge as a global resource with remarkable versatility and potential for the future. As explored in this article, its global cultivation patterns, nutritional richness, and adaptability have positioned it as a key player across various industries. The tomato's journey from farm to table is intricately woven into the fabric of the food processing industry. Beyond enhancing the taste and color of processed foods, tomatoes contribute essential vitamins, antioxidants, and bioactive compounds, aligning with the ever-growing demand for functional and health-promoting products. Looking ahead, the future of food processing holds exciting prospects, with tomatoes likely to play a central role in the development of innovative and nutritionally enhanced products.

In the realm of agriculture, tomatoes continue to be subjects of extensive research, contributing to advancements in genetics, physiology, and biochemistry. The future holds promise for targeted breeding programs that may yield tomatoes with enhanced nutritional profiles, disease resistance, and adaptability to changing climatic conditions. Sustainable agriculture, bolstered by the resilience and versatility of tomatoes, is poised to shape the future of food production.

The biotechnology industry leverages the genetic stability and ease of cultivation of tomatoes for cutting-edge applications. Looking forward, tomatoes are anticipated to be at the forefront of biotechnological advancements, playing crucial roles in gene editing, molecular biology, and the production of bio-based materials. The intersection of tomatoes with biotechnology holds the potential for groundbreaking innovations that could reshape various scientific fields.

As we peer into the future of the beverage industry, tomatoes stand as dynamic contributors, offering a spectrum of options that align with evolving consumer preferences. The development of innovative tomato-based beverages, addressing both health-conscious and indulgent markets, is an exciting avenue for exploration. Tomatoes are likely to

continue shaping the beverage landscape, challenging conventional expectations and expanding possibilities.

In the pharmaceutical sector, the antioxidant powerhouse, lycopene, extracted from tomatoes, hints at future therapeutic applications. Ongoing research suggests that tomatoes, with their rich bioactive compounds, could play a more significant role in preventive and therapeutic formulations. The intersection of food and medicine is poised for further exploration, with tomatoes leading the way as a source of valuable compounds.

Looking beyond, the future aspects of tomatoes extend to environmental sustainability. Utilization of tomato waste for biogas production and environmental remediation reflects a growing awareness of the importance of waste valorization. Tomatoes, with their potential for creating valuable products from byproducts, embody a sustainable approach that aligns with global environmental goals.

In essence, the future of tomatoes is marked by innovation, sustainability, and health-centric applications across diverse industries. From enhanced food products to breakthroughs in biotechnology and pharmaceuticals, tomatoes are poised to continue their journey as a botanical marvel with far-reaching implications for a healthier and more sustainable future.

References

- Ali, M. Y., Sina, A. A. I., Khandker, S. S., Neesa, L., Tanvir, E. M., Kabir, A., & Gan, S. H (2020). Nutritional composition and bioactive compounds in tomatoes and their impact on human health and disease: A review. *Foods*, *10*(1), 45.
- Ardabili, A. A., Sadeghipour, O., & Asl, A. R. (2013). The effect of proline application on drought tolerance of cowpea (Vigna unguiculata L.). *Advances in Environmental Biology*, *7*(14), 4689-4696.
- Bertin, N., & Génard, M. (2018). Tomato quality as influenced by preharvest factors.*Scientia Horticulturae*, *233*, 264-276.
- Beltrán Sanahuja, A., De Pablo Gallego, S. L., Maestre Pérez, S. E., Valdés García, A., & Prats Moya, M. S. (2019). Influence of cooking and ingredients on the antioxidant activity, phenolic content and volatile profile of different variants of the Mediterranean typical tomato Sofrito. *Antioxidants*, *8*(11), 551.
- Carvalho, G. C., de Camargo, B. A. F., de Araújo, J. T. C., & Chorilli, M. (2021). Lycopene: From tomato to its nutraceutical use and its association with nanotechnology. *Trends in Food Science & Technology*, *118*, 447-458.
- Caseiro, M., Ascenso, A., Costa, A., Creagh-Flynn, J., Johnson, M., & Simões, S. (2020). Lycopene in human health. LWT–Food Science and Technology, 127,109323.
- Choe, J., Yong, P. H., & Ng, Z. X. (2022). The efficacy of traditional medici nal plants in modulating the main protease of SARS-CoV-2andcytokine storm. Chemistry & Biodiversity, 19, e202200655.
- Coelho, M. C., Rodrigues, A. S., Teixeira, J. A., & Pintado, M. E. (2023). Integral valorisation of tomato by-products towards bioactive compounds recovery: Human health benefits. *Food Chemistry*, *410*, 135319.
- de Lima Silva, V., Leite, B. S., do Espírito Santo de Jesus, F., Martins, L. D., Assunção, L. S., Leal, I. L., & Ferreira Ribeiro, C. D. (2023). Tomato as a Natural Source of Dyes in the Food Industry: A Patent Data Analysis. *Recent*

Patents on Nanotechnology, *17*(3), 243-258.

- Eslami, E., Abdurrahman, E., Ferrari, G., & Pataro, G. (2023). Enhancing resource efficiency and sustainability in tomato processing: A comprehensive review. *Journal of Cleaner Production*, 138996.
- Estruch, R., Ros, E., Salas-Salvadó, J., Covas, M. I., Corella, D., Arós, F.,... & Martínez González, M. A. (2013). Primary prevention of cardiovascular disease with a Mediterranean diet. *New England Journal of Medicine*, *368*(14), 1279-1290.
- Farinetti, A., Zurlo, V., Manenti, A., Coppi, F., & Mattioli, A. V. (2017). Mediterranean diet and colorectal cancer: A systematic review. *Nutrition*, *43*, 83-88.
- Fleming, E., & Luo, Y. (2021). Co-delivery of synergistic antioxidants from food sources for the prevention of oxidative stress. *Journal of Agriculture and Food Research*, *3*, 100107.
- Ganapathy, M. (2016). Plants as bioreactors-a review. *Adv Tech Biol Med*, *4*(161), 2379 1764.
- Gerszberg, A., Hnatuszko-Konka, K., Kowalczyk, T., & Kononowicz, A. K. (2015). Tomato (Solanum lycopersicum L.) in the service of biotechnology. *Plant Cell, Tissue and Organ Culture (PCTOC)*, *120*, 881-902.
- Gholami, F., Antonio, J., Evans, C., Cheraghi, K., Rahmani, L., & Amirnezhad, F. (2021). Tomato powder is more effective than lycopene to alleviate exercise-induced lipid peroxidation in well-trained male athletes: Ran domized, double-blinded cross-over study. Journal of the International Society of Sports Nutrition, 18(1), 17.
- Górecka, D., Wawrzyniak, A., Jędrusek-Golińska, A., Dziedzic, K., Hamułka, J., Kowalczewski, P. Ł., & Walkowiak, J. (2020). Lycopene in tomatoes and tomato products. Open Chemistry, 18(1), 752–756.
- Hernández, T., Chocano, C., Moreno, J. L., & García, C. (2014). Towards a more sustainable fertilization: Combined use of compost and inorganic fertilization for tomato cultivation. *Agriculture, Ecosystems & Environment*, *196*, 178-184.
- Ho, K.L., Yong, P.H., Wang, C.W., Kuppusamy, U.R., Ngo, C.T., Massawe, F.,& Ng, Z.X. (2022).Peperomiapellucida(L.) Kunthandeyediseases:Areview on phytochemistry, pharmacology and toxicology. Journal of Integrative Medicine, 20(4), 292–304
- Jeong, J. H., Lee, H. L., Park, H. J., Yoon, Y. E., Shin, J., Jeong, M. Y., & Lee, S. J. (2023). Effects of tomato ketchup and tomato paste extract on hepatic lipid accumulation and adipogenesis. *Food Science and Biotechnology*, 1-12.
- Khan, N., ABIDEEN, Z., Rafique, A., Hussain, A., Osama, M., & Rauf, A. (2023). Assessment of morphological traits in tomato hybrids for improved cultivation practices. *Biological and Agricultural Sciences Research Journal*, *2023*(1), 8-8.
- Kumar, M., Chandran, D., Tomar, M., Bhuyan, D. J., Grasso, S., Sá, A. G. A., & Mekhemar, M. (2022). Valorization potential of tomato (Solanum lycopersicum L.) seed: nutraceutical quality, food properties, safety aspects, and application as a health-promoting ingredient in foods. *Horticulturae*, *8*(3), 265.
- Kumar, S., Rawson, A., Kumar, A., CK, S., Vignesh, S., & Venkatachalapathy, N. (2023). Lycopene extraction from industrial tomato processing waste using emerging technologies, and its application in enriched beverage development. *International Journal of Food Science & Technology*, *58*(4), 2141 2150.
- Litskas, V. D., Migeon, A., Navajas, M., Tixier, M. S., & Stavrinides, M. C. (2019). Impacts of climate change on tomato, a notorious pest and its natural enemy: small scale agriculture at higher risk. *Environmental Research Letters*, *14*(8), 084041.
- Løchen, M. L. (2023). One tomato a day may keep the doctor away.*European Journal of Preventive Cardiology*,

zwad393.

- López-Yerena, A., Domínguez-López, I., Abuhabib, M. M., Lamuela-Raventós, R. M., Vallverdú-Queralt, A., & Pérez, M. (2023). Tomato wastes and by-products: upcoming sources of polyphenols and carotenoids for food, nutraceutical, and pharma applications. *Critical Reviews in Food Science and Nutrition*, 1-18.
- Lu, Z., Wang, J., Gao, R., Ye, F., & Zhao, G. (2019). Sustainable valorisation of tomato pomace: A comprehensive review. Trends in Food Science & Technology, 86, 172–187.
- Martí, R., Roselló, S., & Cebolla-Cornejo, J. (2016). Tomato as a source of carotenoids and polyphenols targeted to cancer prevention. *Cancers*, *8*(6), 58.
- Martínez, E., Fernández-Ríos, A., Laso, J., Hoehn, D., San-Román, M. F., Vázquez Rowe, I.,... & Margallo, M. (2024). Low Energy and Carbon Hydroponic Tomato Cultivation in Northern Spain: Nutritional and Environmental Assessment. *ACS Sustainable Chemistry & Engineering*.
- Méndez-Carmona, J. Y., Ramírez-Guzmán, N., Sandoval-Cortes, J., Ascacio-Valdés, J. A., Boone-Villa, V. D., Govea-Salas, M., & Aguilar, C. N. (2023). Valorization of Tomato Fruit Processing Residues. In *Agricultural Waste: Environmental Impact, Useful Metabolites and Energy Production* (pp. 215-243). Singapore: Springer Nature Singapore.
- Meng, F., Li, Y., Li, S., Chen, H., Shao, Z., Jian, Y. & Wang, Q. (2022). Carotenoid biofortification in tomato products along whole agro-food chain from field to fork. *Trends in Food Science & Technology*, *124*, 296-308.
- NEERAJ, N., Kumar, A., Kumar, V., Kumar, M., Sindhu, A. S., Goel, S. R., & Singh, G. U. R. P. R. E. E. T. (2019). Bio-nematicidal effect of botanicals against root-knot nematode (Meloidogyne incognita) in tomato (Solanum lycopersicum). *Indian Journal of Agricultural Sciences*, *89*(12), 2096-2101.
- Ng, Z. X., Chua, K. H., Tajunisah, I., Pendek, R., & Kuppusamy, U. R. (2013). Attenuated levels of pro-inflammatory markers in diabetic retinopathy patients undergoing treatment with antihyperglycemic and antihyper tensive drugs. Clinics, 68(2), 185–191.
- Pinela, J., Prieto, M. A., Carvalho, A. M., Barreiro, M. F., Oliveira, M. B. P., Barros, L., & Ferreira, I. C. (2016). Microwave-assisted extraction of phenolic acids and flavonoids and production of antioxidant ingredients from tomato: A nutraceutical-oriented optimization study. *Separation and Purification Technology*, *164*, 114-124.
- Pinho, L. D., Almeida, A. C., Costa, C. A., Paes, M. C. D., Glória, M. B. A., & Souza, R. M. (2011). Nutritional properties of cherry tomatoes harvested at different times and grown in an organic cropping. *Horticultura Brasileira*, *29*, 205-211.
- Kato, M., Ochiai, R., Kozuma, K., Sato, H., & Katsuragi, Y. (2018). Effect of chlorogenic acid intake on cognitive function in the elderly: A pilot study. *Evidence-Based Complementary and Alternative Medicine*, *2018*.
- Kiralan, M., & Ketenoglu, O. (2022). Utilization of tomato (Solanum lycopersicum) by products: an overview. *Mediterranean Fruits Bio-wastes: Chemistry, Functionality and Technological Applications*, 799-818.
- Raiola, A., Rigano, M. M., Calafiore, R., Frusciante, L., & Barone, A. (2014). Enhancing the health-promoting effects of tomato fruit for biofortified food. *Mediators of inflammation*, *2014*.
- Rajoria, A., Chauhan, A. K., & Kumar, J. (2011). Formulation of tomato juice enriched whey beverage using response surface methodology. *Journal of Dairying, Foods and Home Sciences*, *30*(1), 1-14.
- Rinaldi de Alvarenga, J. F., Quifer-Rada, P., Francetto Juliano, F., Hurtado-Barroso, S., Illan, M., Torrado-Prat, X., &

Lamuela-Raventós, R. M. (2019). Using extra virgin olive oil to cook vegetables enhances polyphenol and carotenoid extractability: a study applying the sofrito technique. *Molecules*, *24*(8), 1555.

- Rothan, C., Diouf, I., & Causse, M. (2019). Trait discovery and editing in tomato.*The Plant Journal*, *97*(1), 73-90.
- Sangeetha, K., Ramyaa, R. B., Khaneghah, A. M., & Radhakrishnan, M. (2023). Extraction, characterization, and application of tomato seed oil in the food industry: An updated review. *Journal of Agriculture and Food Research*, 100529.
- Schreinemachers, P., Sequeros, T., & Lukumay, P. J. (2017). International research on vegetable improvement in East and Southern Africa: adoption, impact, and returns. *Agricultural Economics*, *48*(6), 707-717.
- Storniolo, C. E., Sacanella, I., Lamuela-Raventos, R. M., & Moreno, J. J. (2020). Bioactive compounds of Mediterranean cooked tomato sauce (sofrito) modulate intestinal epithelial cancer cell growth through oxidative stress/arachidonic acid cascade regulation. *ACS omega*, *5*(28), 17071-17077.
- Pereira, N., Farrokhi, M., Vida, M., Lageiro, M., Ramos, A. C., Vieira, M. C., & Abreu, M. (2023). Valorisation of Wasted Immature Tomato to Innovative Fermented Functional Foods. *Foods*, *12*(7), 1532.
- Poojitha, M. (2023). Tomato Grading: A New Approach for Classifying and Predicting Tomato Quality based on Visual Features. *Journal of Advanced Zoology*, *44*.
- Rajan, A., Kumar, S., Sunil, C. K., Radhakrishnan, M., & Rawson, A. (2022). Recent advances in the utilization of industrial byproducts and wastes generated at different stages of tomato processing: Status report. *Journal of Food Processing and Preservation*, *46*(11), e17063.
- Wang, C., Li, M., Duan, X., Abu-Izneid, T., Rauf, A., Khan, Z.,... & Suleria, H. A. (2023). Phytochemical and nutritional profiling of tomatoes; impact of processing on bioavailability-a comprehensive review. *Food reviews international*, *39*(8), 5986-6010.
- Wu, X., Zhu, C., Zhang, M., Wang, S., Yu, J., Tian, J., & Hu, Z. (2023). Effects of different processed tomatoes on carotenoid release and microbiota composition during in vitro gastrointestinal digestion and colonic fermentation. *Food & Function*, *14*(22), 10177-10187.
- Yong, K. T., Yong, P. H., & Ng, Z. X. (2023). Tomato and human health: A perspective from post-harvest processing, nutrient bio-accessibility, and pharmacological interaction. *Food Frontiers*.
- Zhang, J., Liu, S., Zhu, X., Chang, Y., Wang, C., Ma, N.,... & Xie, J. (2023). A comprehensive evaluation of tomato fruit quality and identification of volatile compounds. *Plants*, *12*(16), 2947.