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Review

Valorization Potential of Tomato (*Solanum lycopersicum* L.) Seed: Nutraceutical Quality, Food Properties, Safety Aspects, and Application as a Health-Promoting Ingredient in Foods

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Abstract: The tomato is a member of the Solanaceae family and is a crop that is widely cultivated around the world due to its sweet, sour, salty, juicy, and nutritious berries. The processing of tomatoes generates a significant amount of waste in the form of tomato pomace, which includes seeds and skin. Tomato seeds are reservoirs of various nutrients, such as proteins, carbohydrates, lipids, minerals, and vitamins. These components make tomato seeds an important ingredient for application in food matrices. This review discusses the functional food properties of tomato seeds and their scope of utilization as major ingredients in the functional food industry. In addition, this review describes the development of tomato seeds as a potential nutritional and nutraceutical ingredient, along with recent updates on research conducted worldwide. This is the first review that demonstrates the nutritional profile of tomato seeds along with its diverse functional food properties and application as a functional food ingredient.

Keywords: tomato seeds; nutritional profile; food properties; food application

1. Introduction

The tomato (*Solanum lycopersicum* L.) is a common fruit that is globally produced, contributing to 182.3 million tons of annual production in 2018. China is one of the largest producers of tomatoes worldwide, contributing ~31.8% of the total global production. In addition, India, Turkey, the United States of America, and Mexico are well-known producers of tomatoes [1,2]. Fruit peels and seeds are rich sources of many beneficial health compounds, such as ascorbic acid, carotene, lycopene, and phenolic compounds [3]. Other important components are the sterols and policosanol from tomato seeds and in particular in tomato seed oil. The consumption of tomato fruit has been associated with weight management and the prevention of cardiovascular diseases and cancer [4]. Consuming gel produced from tomato seeds can enhance blood circulation, thereby preventing blood clot formation [2]. Tomatoes are used to develop a wide variety of products, including puree, dried powders, juices, sauces, and ketchup. However, peels and seeds are the most underutilized parts of the fruit, adding to the total food waste and posing an environmental threat [5]. In addition to processing and trimming, factors such as the storage conditions, fruit maturity [6], cultivar, soil, and climate conditions [7] also influence the nutritional properties of tomatoes. The arrangement of seeds in a tomato fruit and the morphology of tomato seeds are shown in Figure 1.

Tomato seed waste, which is approximately 5–10% tomato pomace, is generated during the processing of tomato-based products and is a rich source of nutritional compounds, including proteins, amino acids, fatty acids, fiber, and functional compounds with notable nutraceutical properties [8,9]. Tomato processing results in the production of tomato pomace, of which 60% is seed and 40% is peel [10]. The nutritional composition of tomato seeds includes proteins (32%) followed by total fat (27%) and fiber (18%). Due to their high protein content, tomato seeds have been used as a supplement in animal feed and as a replacement in bakery products [3,11]. Owing to their thermal stability and antioxidant properties, tomato seed oil and tomato seed extracts (TSEs) may be utilized in food preservation [12,13]. The generation of biofuels and the production of enzymes and bioactive compounds are some of the practical applications of tomato waste, along with the production of tomato seed oil [14].

Tomato seeds are constituted of 34% protein and 30% lipid. The chemical composition of defatted tomato seeds is fat (0%), protein (38.7%), insoluble dietary fiber (41.4%), soluble dietary fiber (14.2%), and lycopene (0 mg/kg), while tomato seed oil was found to contain fat (100%), protein (0%), insoluble dietary fiber (0%), soluble dietary fiber (0%), and lycopene (61.6 mg/kg) [15]. Additionally, the tomato pomace obtained after the extraction of tomato juice contains high amounts of polysaccharides, protein, and fiber. This influences the rheological properties of foods, as it enhances the water absorption capacity and thereby the food consistency. Tomato seed protein is a combination of various protein components, such as globulin, albumin, prolamine, and glutelin. Soluble proteins can be exploited wherever foaming and emulsifying properties are required in food products [16]. The use of tomato seed meal consisting of glutamic (18.99 g/100 g) and aspartic acids (11.95 g/100 g) has been studied for its flavor-enhancing properties, which are very similar to those produced by monosodium glutamate (MSG) [17].

Figure 1. Tomato and its seeds.

To the best of our knowledge, this is the first review considering the valorization potential of tomato seeds and their scope of utilization as major food ingredients in the functional food industry, along with recent updates on research conducted worldwide. Various components discussed in the manuscript are shown in Figure 2.

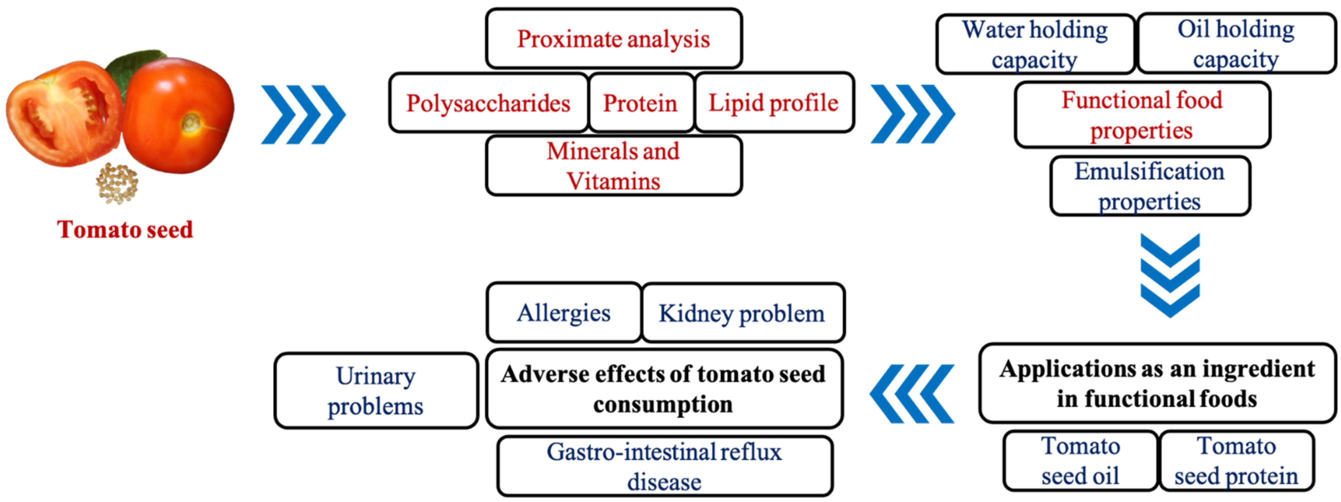

Figure 2. Various components discussed in the review article.

2. Nutritional Profile

Tomato processing accounts for 1–4% (*w*/*w*) of waste generation, which is primarily composed of skin and seeds [18]. Tomato seed cake contains high amounts of protein and crude fiber [19,20]. Tomato waste has been reported to contain tocopherols, polyphenols, carotenoids, and some terpenes and sterols [21].

2.1. Proximate Analysis of Tomato Seeds

Tomato seeds are composed of moisture (8.5%), crude protein (25%), crude fat (20%), total dietary fiber (35.1%), and good amounts of amino acids and minerals (3.2–6.8%) [20]. It was observed that tomato seeds contain considerable amounts of protein (24.76%) and total fat (21.87%) in contrast to tomato peels, which are rich in fiber (58.12%). Tomato seeds are rich in oil [21–23] and lysine-rich proteins [24]. Tomato oil shows a predominance of polyunsaturated fatty acids (53.72%), such as linoleic, palmitic, and oleic acids and 72.60% total unsaturated fatty acids [20,22]. In terms of amino acid content, methionine and cystine are present in higher amounts in tomato seed byproducts. Additionally, essential amino acids are higher in tomato seeds than in tomato peels [25].

2.2. Polysaccharides

Polysaccharides have remarkable applications in both the food and pharmaceutical industries. Polysaccharides may serve as stabilizers and emulsifiers in the food industry. Polysaccharides were found to prevent the oxidation of cell membranes and control the rise in blood lipid levels. Some polysaccharides were utilized to develop vaccines, as they displayed pathogenic properties. Polysaccharides have often been used to produce biodegradable materials [26]. The anticancer and anti-inflammatory properties of polysaccharides were studied and found to be of great relevance in the biomedical field. Tomato pomace contains approximately 13% (dry weight) polysaccharides [27]. The structural modification of these polysaccharides has recently gained attention. Since tomato pomace is a good source of polysaccharides, it becomes even more important to exploit the possible uses of these polysaccharides for sustainable utilization of tomato waste. A study was conducted to sequentially extract polysaccharide fractions from black tomato pomace and further investigate their emulsifying and physicochemical properties [28]. The emulsifying capacity of these polysaccharide fractions ranged from 53.17% to 82.46%, which was significantly higher than that of acid-extracted potato pectins (44.97–47.71%), apple pectins (45.34%), and citrus pectins (44.87%) but much lower than that of pomegranate pectins (96.70%). A higher pectin concentration could yield a higher droplet surface area, facilitating emulsified droplet formation. The presence of a higher number of hydrophobic groups in these pectins contributes to a higher emulsifying capacity [22]. The polysaccharide profile of tomato seed is displayed in Table 1.

Table 1. Polysaccharide profile of tomato seed.

Variety and Region	Group	Composition	References
Black tomato pomace; Nanjing, China	Fiber	28.3–34.7%	[29]
TSM; Romania	Fiber	16%	[30]
TSM; Denizli, Turkey	Total dietary fiber	34.65%	[31]
TSM; Denizli, Turkey	Soluble dietary fiber	4.11%	[31]
TSM; Denizli, Turkey	Insoluble dietary fiber	30.54%	[31]
	Pectin	243–280 μg/g	[4]
Crude tomato seed meal; Tunisia	Total sugar content	2.99%	[32]
Defatted tomato seed meal; Tunisia	Total sugar content	3.28%	[32]

Here, TSM = tomato seed meal.

2.3. Protein

Proteins in tomato seeds range from 22.2% to 40% on a dry weight basis [6,31–34]. In terms of total amino acids, tomato seeds have high glutamic acid and aspartic acid contents [21,33]. These amino acids are known as umami taste amino acids, suggesting the use of tomato seeds for developing products rich in umami flavors for both vegetarians and nonvegetarians [21]. Studies have also shown that arginine, threonine, lysine, and leucine are the predominant essential amino acids present in tomato seeds [5,32,33]. The high lysine content in tomato seed protein could be exploited to improve the protein quality of cereal products, which are low in lysine [31]. The amino acid profile (Table 1) of tomato seeds is comparable to that of other seed proteins, such as sunflower and grape seeds, which have high concentrations of glutamic acid (20.1 and 21.47 g/100 g protein, respectively), and pumpkin and watermelon seeds, which have high arginine levels (19 g/100 g protein), similar to tomato seeds [35]. The protein content and amino acid profile of tomato seed are presented in Table 2.

Table 2. Protein content and amino acid profile of tomato seed.

Variety and Region	Group	Composition	References
TSM	Protein/Amino acids	22.2–40% 23.60–24.38%	[5,32,33] [4]
Tomato seeds; Tunisia		35–41% 23.6–40.9 g/100 g	[32] [36]
Defatted TSM		26.7–27.5% (DMB)	[30]
TSM; Denizli, Turkey		30.66–32%	[24,31]
Tomato seeds; Tunisia	Histidine (His)	2.58 mg/100 g	[32]
TSM; Denizli, Turkey		713 mg/100 g	[30]
Defatted tomato seeds		23.4 mg/100 g 0.52 mg/100 g	[28] [37]
Tomato seeds; Tunisia	Isoleucine (Ile)	2.93 mg/100 g	[32]
TSM; Denizli, Turkey		1186 mg/100 g 0.78 mg/100 g	[31] [37]
Tomato seeds; Tunisia	Leucine (Leu)	6.38 mg/100 g	[32]
TSM; Denizli, Turkey		1692 mg/100 g 1.5 mg/100 g	[31] [37]
Tomato seeds; Tunisia	Lysine (Lys)	5.88 mg/100 g	[32]
TSM; Denizli, Turkey		1670 mg/100 g 1.7 mg/100 g	[31] [37]
Tomato seeds; Tunisia	Threonine (Thr)	4.32 mg/100 g 1048 mg/100 g	[32] [25]
TSM; Denizli, Turkey		1.3 mg/100 g	[31]
Tomato seeds; Tunisia	Valine (Val)	3.61 mg/100 g	[32]
TSM; Denizli, Turkey		1394 mg/100 g 1.2 mg/100 g	[31] [37]
Tomato seeds; Tunisia	Total sulfur amino acids (Met + Cys)	3.07 mg/100 g	[32]
TSM; Denizli, Turkey		941 mg/100 g 0.49 mg/100 g	[31] [37]
Tomato seeds; Tunisia	Total aromatic amino acids (Phe + Tyr)	9.02 mg/100 g	[32]
TSM; Denizli, Turkey		2385 mg/100 g 2.5 mg/100 g	[31] [37]
Tomato seeds; Tunisia	Alanine (Ala)	4.67 mg/100 g	[32]
TSM; Denizli, Turkey		2036 mg/100 g 1 mg/100 g	[31] [37]
Tomato seeds; Tunisia	Arginine (Arg)	10.62 mg/100 g	[32]
TSM; Denizli, Turkey		2696 mg/100 g 1.8 mg/100 g	[31] [37]
Tomato seeds; Tunisia	Aspartic acid (Asp)	10.32 mg/100 g	[32]
TSM; Denizli, Turkey		2894 mg/100 g 2.41 mg/100 g	[31] [37]

Table 2. *Cont.*

Variety and Region	Group	Composition	References
Tomato seeds; Tunisia	Glutamic acid (Glu)	19.44 mg/100 g	[32]
TSM; Denizli, Turkey		4839 mg/100 g 14.3 mg/100 g 5.4 mg/100 g	[31] [28] [37]
Tomato seeds; Tunisia	Glycine (Gly)	4.80 mg/100 g	[32]
TSM; Denizli, Turkey		1418 mg/100 g 14.2 mg/100 g	[31] [28]
Tomato seeds; Tunisia	Proline (Pro)	4.26 mg/100 g	[32]
TSM; Denizli, Turkey		1381 mg/100 g 0.92 mg/100 g	[31] [37]
Tomato seeds; Tunisia	Serine (Ser)	4.51 mg/100 g	[32]
TSM; Denizli, Turkey		1357 mg/100 g 1 mg/100 g	[31] [37]

Here, DMB = dry matter basis and TSM = tomato seed meal.

It is evident from their protein content and amino acid composition that tomato seeds can be used as an excellent source for human dietary supplementation, primarily due to the presence of 13% more lysine than soybean proteins [32–34]. They can also be used to further improve the protein quality of commercial cereal products [24,31,32]. Furthermore, protein fractions such as water-soluble albumins and salt-soluble globulins in the range of 55–10 kDa have been reported in tomato seeds [33,34] through sodium dodecyl sulfate-polyacrylamide gel electrophoresis (SDS-PAGE).

Few studies have demonstrated the important bioactive properties of tomato seed proteins and their associated peptides. These bioactivities include hypocholesterolemia and antioxidant properties [5,33,34]. A study conducted by Shao et al. [5] showed that defatted tomato seeds reduced low-density lipoprotein (LDL) cholesterol concentrations and the plasma total cholesterol content in male hamsters [5]. Mechmeche et al. [33] assessed the use of protein isolates from defatted tomato seed meal (DTSPI) as a source for bioactive peptides due to their high content of essential amino acids. DTSPI showed superior antioxidant properties, exhibiting IC_{50} values of 40.89 μg/mL for DPPH and 18.45 μg/mL for $ABTS^{\bullet +}$ radical scavenging activity. DTSPI can be regarded as a high-quality protein, with essential amino acids accounting for 35.89% of the total amino acid content. Amino acids such as leucine, lysine, aspartic acid, and glutamic acid constitute the major portion of DTSPI. The aromatic amino acids in DTSPI can donate protons to electron-deficient radicals. The aromatic amino acids tryptophan, phenylalanine, and tyrosine participate in van der Waals interactions and have the potential to receive and donate protons, owing to their distinct chemical structures [33]. These results reveal that tomato seed protein is an inexpensive potential source of powerful natural antioxidants that are important for the health food, nutraceutical, and pharmaceutical industries and can be used in formulating protein-rich food ingredients. Furthermore, complementary studies evaluated the functional properties of tomato seed protein. They showed good water absorption and emulsifying capacities superior to commercial soybean protein isolate [5,34].

2.4. Lipid and Oil Profile

The quality of edible oils from plants is dependent on their lipid content and fatty acid composition, primarily unsaturated fatty acids (UFAs), which have diverse applications in the food and nonfood industries. Lipids obtained from tomato seeds can be used as food additives and biofuels and as a source of antioxidants [33,38,39]. Tomato seeds contain 20–37% lipids on a dry weight basis with high levels of UFAs (68–82%) [31,33,38]. Few studies have characterized the oil profile of tomato seeds. The major fatty acids are linoleic

(C18:2, 48.2–56.1%), oleic (C18:1, 22.2–23.8%), palmitic (C16:0, 12.3–17.2%), stearic (C18:0, 5.2–5.4%), and linolenic (C18:3, 2.1–2.7%) [5,29,33,40]. In terms of linoleic acid composition, tomato seed oil is comparable to sunflower, soybean, and corn oils, which have 59.5%, 49.5%, and 48% linoleic acid, respectively. The oleic acid concentration is similar to those of flaxseed and canola oil, being 22.1% and 23.2%, respectively. Furthermore, the palmitic acid concentration of tomato seed oil is comparable to olive oil, with 11.5% palmitic acid [40]. The lipid content and fatty acid profile of tomato seed are shown in Table 3.

The edible physicochemical qualities of 15 tomato seed oils and the effects of the hot break, cold break, and harvest year were examined through seed pressing by Giuffrè et al. [38]. The free acidity levels in virgin and extra virgin olive oils were in the normal range. The oxidative stability was determined by very low peroxide and p-anisidine values, as well as a high phenol content and DPPH radical scavenging activity. The low free acidity, peroxide value, spectrophotometric characteristics, high phenol content, and radical scavenging activity values suggest that tomato seed oil is potentially edible. The amount of saturated fatty acids in the tomato seed oil was minimal. The cholesterol concentration ranged from 200 to 346 mg/kg, which was higher than those of common edible vegetable oils. The physicochemical qualities of tomato seed oil were unaffected by hot or cold breaks, but the fatty acid content was affected by the harvest year [41]. Soxhlet-petroleum ether extraction was used by Giuffrè and Capocasale [42] to obtain oil from tomato seeds. Three tomato cultivars from South Italy (Principe Borghese, Rebelion F1, and San Marzano) were studied. Policosanol is a mixture of long chain linear fatty alcohols (n-alkanols), and its content and composition were found to be highly and significantly influenced by cultivar. Seven fatty alcohols were detected: docosanol (C22-ol), tricosanol (C23-ol), tetracosanol (C24-ol), pentacosanol (C25-ol), hexacosanol (C26-ol), heptacosanol (C27-ol), and octacosanol (C28-ol). The highest policosanol content was found in Principe Borghese at 71.88 mg/Kg. Octacosanol was the linear alcohol present in the highest quantity (i.e., 38–42% of the total linear alcohols detected in tomato seed oils (TSOs)). The sum of even long chained fatty alcohols was always more than 95% of the total policosanol content [42].

The oleoresins isolated from tomato seeds by supercritical CO_2 showed 48.5% polyunsaturated fatty acids (PUFAs), 23.6% monounsaturated fatty acids (MUFAs), and 27.9% saturated fatty acids (SFAs). The oleoresins extracted from the tomato seed were also found to be very similar to those isolated from corn, with SFAs, MUFAs, and PUFAs amounting to 25.1, 26.8, and 48%, respectively [37,43]. GC-MS analysis of the tomato seed oleoresins showed linoleic acid as the most abundant fatty acid (C18:2 n-6, 44.8%), followed by oleic (C18:1 n-9, 23.1%), palmitic (C16:0, 18.8%), stearic (C18:0, 7.4%), and linolenic acids (C18:3 n-3, 3.7%). Additionally, margaric (C17:0), myristic (C14:0), arachidic (C20:0), and palmitoleic acids (C16:1) were other fatty acids observed in lower amounts (0.5–0.6%) [44]. These fatty acids are major components of the cell membrane structure, modulate gene transcription, function as cytokine precursors, and serve as energy sources in complex, interconnected systems. It is increasingly apparent that dietary fatty acids influence these vital functions and affect human health [45]. Sterols are one of the most important classes of components contained in the unsaponifiable fraction of tomato seed oil. The most important sterols in TSO include campesterol, stigmasterol, β-sitosterol, and δ^5-avenasterol as the most abundant sterols in tomato seed oil, with trace or minute levels of 24-methylenecholesterol, brassicasterol, δ^7-campesterol, clerosterol, $\delta^{7,24}$-stigmastadienol, δ^5-stigmastanol, δ^7-avenasterol, and erythrodiol. The total sterol content of crude tomato oil ranged from 325 to 533 mg/100 g, with an average of 455 $\pm$ 89 mg/100 g, and that of purified oil was between 225 and 368 mg/100 g, with an average of 315 $\pm$ 60 mg/100 g. Furthermore, cholesterol was discovered at a concentration of 16%, making it the second most quantitatively important sterol in tomato seed oil after β-sitosterol [46]. An attempt was made to investigate the effect of the Calabrian cultivars, namely Principe Borghese, Rebelion F1, and San Marzano, on the sterol composition [47] and n-alkane (saturated linear hydrocarbons) composition [48] of TSO. The oil from Principe Borghese contained the greatest amount of β-sitosterol (57.47%, 1088.33 mg/kg) and the highest apparent β-sitosterol content (67.59%, 1279.62 mg/kg). When it came to cholesterol levels, Rebelion F1′s seed oil was the poorest of the bunch (15.76%, 275.90 mg/kg). It was found that the seed oil of the three tomato cultivars studied contained an average of 1700–1900 mg/kg of sterols, a high cholesterol concentration of 11.80–15.76%, low campesterol/stigmasterol ratios of 0.36–0.50%, and a sitosterol content of 54–58% (similar to sunflower seed oil, corn seed oil, safflower seed oil, or soybean oil) [47]. The n-alkanes in the TSOs of all cultivars were found to be nC25, nC21, nC23, and nC29. The TSO contained mainly odd-chain carbon number n-alkanes (79.09–89.35%), and among them, n-C25, n-C21, n-C23, and n-C29 were prevalent in all cultivars. The Σ odd-chain carbon number to Σ even-chain carbon number ratio was 8.39 in "Principe Borghese", 3.78 in "Rebelion F1", and 7.60 in "San Marzano". In relation to the total n-alkane content, Principe Borghese and Rebelion F1 produced an oil with a better attitude for biodiesel use, whereas the San Marzano TSO showed better edible characteristics [48].

Table 3. Lipid contents and fatty acid profiles of tomato seed.

Variety and Region	Group	Composition	References
Tomato seeds; Tarhana, Turkey Tomato seeds, San Marzano cultivar; Lecce, Italy	Lipids/Fatty acid profile	19.9–36.9% 27%	[31,32,38] [33]
TSO; Timis county, Romania Tomato seeds, San Marzano cultivar; Lecce, Italy Tomato seeds; Greece	SFA	27.9% 16.19–18.59% 20%	[22] [33] [49,50]
TSO; Timis county, Romania Tomato seeds, San Marzano cultivar; Lecce, Italy Tomato seeds; Greece	MUFA	23.6% 30% 17.79–18.26%	[22] [33] [50,51]
TSO; Timis county, Romania Tomato seeds, San Marzano cultivar; Lecce, Italy Tomato seeds; Greece	PUFA	48.5% 85% 63.23–66.02%	[29] [33] [46,51]
Tomato seeds; Greece	n-3 PUFA	1.39–1.5%	[46]
Tomato seeds; Greece	n-6 PUFA	61.73–64.63%	[50,52]
Tomato seeds, San Marzano cultivar; Lecce, Italy Tomato pomace; Greece Tomato seeds; Illinois, USA TSO; Timis county, Romania Tomato seeds; Greece	Linoleic acid (C18:2 n-6)	44.8% 50% 48.22% 47–73% 53.7%	[33] [46] [22] [29] [50,52]
Tomato seeds, San Marzano; Lecce, Italy cultivar Tomato seeds; Illinois, USA TSO; Timis county, Romania TSO; Greece Tomato seeds; Greece	Oleic acid (C18:1 n-9)	23.1% 9.2% 8–21% 23.8% 17.33–17.88%	[33] [22] [29] [45] [50,52]
Tomato seeds, San Marzano cultivar; Lecce, Italy Tomato seeds; Illinois, USA TSO; Timis county, Romania Tomato seeds; Tarhana, Turkey Tomato seeds; Greece	Palmitic acid (C16:0)	18.8% 17.18% 14–25% 13.7% 12.43–14.42%	[33] [22] [29] [32] [46,51]

Table 3. *Cont.*

Variety and Region	Group	Composition	References
Tomato seeds, San Marzano cultivar; Lecce, Italy TSO; Timis county, Romania Tomato seeds; Tarhana, Turkey Tomato seeds; Greece	Stearic acid (C18:0)	7.4% 0.5–1% 5.4% 3.59–3.95%	[33] [22,28] [32] [44,45]
Tomato seeds, San Marzano cultivar; Lecce, Italy TSO; Timis county, Romania Tomato seeds; Tarhana, Turkey Tomato seeds; Greece	Linolenic acid (C18:3 n-3)	3.7% 2–6% 2.1% 1.39–1.5%	[33] [23,29] [32] [44,45]

Here, TSO = tomato seed oil.

The reported range in the fatty acid profile content when comparing the mentioned studies may have been due to modification of the oil extraction protocol and differences in the cultivars of the tomato seeds used for the analyses. However, these results show that tomato seed wastes are a potential source of edible oil, with an excellent profile of essential fatty acids such as omega-6 (linoleic acid) and omega-9 (oleic acid). Additionally, no harmful compounds or antinutritional factors have been reported in tomato seeds, making them a potential source for numerous industrial applications [33,51].

The ratio of polyunsaturated and saturated fatty acid contents (PUFA/SFA) found in the tomato seed oleoresins was 1.73. Ratio values over 0.45 are suggested to be ideal for daily human ingestion. Consumption of UFAs from plant sources has been proven to have significant health benefits, such as the prevention of diabetes, coronary heart diseases, and different types of cancers [45]. Therefore, the presence of these useful fatty acids in tomato seeds makes them ideal for their use in functional food formulations. One can also consider the tomato seed oil fraction a healthy option for daily human consumption.

2.5. Minerals and Vitamins

Minerals are inorganic compounds vital for several physiologic and metabolic processes in the human body, such as immune functions, oxygen transport, muscle contraction, nerve impulses, enzyme activation, and bone health. The daily mineral requirement of an adult is approximately 2000 mg of potassium (K), 1000 mg of calcium (Ca), 800 mg of phosphorus (P), 370 mg of magnesium (Mg), 10 mg of zinc (Zn), 9 mg of iron (Fe), 2 mg of manganese (Mn), and 900 µg of copper (Cu). Tomato seed meal is an excellent mineral source, having approximately 1074 mg/100 g of P, 977 mg/100 g of K, 504 mg/100 g of Mg, 135 mg/100 g of Ca, 24 mg/100 g of Fe, 9.7 mg/100 g of Zn, 7.8 mg/100 g of Mn, and 1.9 mg/100 g of Cu [31].

Vitamins are also essential micronutrients required for many specific physiological functions in the human body, such as enzyme cofactors (i.e., vitamins A, K, C, and B-complex), biological antioxidants (i.e., vitamins C and E), hormones (i.e., vitamins A and D), and photoreceptive cofactors in vision (i.e., vitamin A) [52,53]. Tomato seeds are rich in fat-soluble vitamins (A, D, E, and K) that play an essential role in human health [22,29,38]. Vitamin C, which is vital for a strong immune system, is also abundantly found in tomato seeds. Additionally, the most biologically active form of vitamin E (α-tocopherol) was found in tomato seed oleoresins (148 µg/g oleoresin), which indicates that tomato seeds can be a great vitamin source in the human diet [50]. Tomatoes can help alleviate many diseases, especially chronic diseases, due to high concentrations of natural antioxidant chemicals such as carotenoids (carotenoids and lycopene), ascorbic acid (vitamin C), tocopherol (vitamin E), and bioactive phenolic compounds (quercetin, kaempferol, naringenin, and lutein, as well as caffeic, ferulic, and chlorogenic acids), Scavenging free radicals, limiting cellular proliferation and damage and inhibiting apoptosis as well as metal chelation, the modification of enzyme activity, cytokine production, and signal transduction pathways are all positive effects of these substances [53,54]. Lycopene is the fifth major carotenoid in tomatoes, and it is responsible for their red color. Anticancer, anti-inflammatory, antidiabetic, anti-allergenic, anti-atherogenic, antithrombotic, antibacterial, antioxidant, vasodilator, and cardioprotective properties are among the pharmacological activities of lycopene and other phenolic compounds [55]. Therefore, utilization of tomato seeds in the human diet could increase the added value of wastes and decrease their negative environmental impact. The mineral and vitamin profiles of the tomato seed are illustrated in Table 4.

Table 4. Mineral and vitamin profiles of tomato seed.

Variety and Region	Group	Composition	References
	Minerals		
TSM; Denizli, Turkey	Phosphorus (P)	1074 mg/100 g 24 mg/100 g	[31] [32,54]
TSM; Denizli, Turkey	Potassium (K)	977 mg/100 g 650 mg/100 g 237 mg/100 g	[31] [37] [32]
TSM; Denizli, Turkey	Magnesium (Mg)	504 mg/100 g 400 mg/100 g 11 mg/100 g	[31] [37] [32]
TSM; Denizli, Turkey	Calcium (Ca)	135 mg/100 g 10 mg/100 g 153 mg/100 g	[31] [32] [37]
TSM; Denizli, Turkey	Iron (Fe)	24 mg/100 g 0.3 mg/100 g 25 mg/100 g	[31] [32] [37]
TSM; Denizli, Turkey	Zinc (Zn)	9.7 mg/100 g 0.2 mg/100 g 12 mg/100 g	[31] [32] [37]
TSM; Denizli, Turkey	Sodium (Na)	5 mg/100 g	[32]
TSM; Denizli, Turkey	Manganese (Mn)	7.8 mg/100 g 13 mg/100 g	[31] [37]
TSM; Denizli, Turkey	Copper (Cu)	1.9 mg/100 g 1.10 mg/100 g	[31] [37]
	Vitamins		
Tomato seeds, San Marzano cultivar; Lecce, Italy	Vitamin E (α-tocopherol)	148 µg/g	[34]
	Vitamin A	282 µg/g	[50,54]
	Phytosterol	50 µg/g 11 µg/g	[32] [54,56]
	Gallic acid	315.9 mg/100 g	[32]
	Total carotenoids	252.3 µg/g 13.59–47.61 mg/100 g	[32] [51,53]
Tomato seeds; Greece	β-carotene	3.41–5.03 mg/100 g 4.5 µg/g	[53,54] [54,56]
Tomato seeds; Greece	Vitamin C (ascorbic acid) Thiamine Niacin	9.5 µg/g 13.7–23.4 mg/100 g 0.6 mg/100 g	[32] [26] [32]

Here, TSM = tomato seed meal.

3. Functional Food Properties of Tomato Seeds

A number of nutraceutical, techno-functional, and nutritional qualities of tomato seeds have been recently highlighted [25,57]. The interaction that proteins from food have with the medium can be used to classify their techno-functional qualities. The ability of a protein to interact with water by creating hydrogen bonds is referred to as its hydration characteristics [58]. Protein–protein interactions are the ability of a protein to establish connections with other proteins in the medium, either through hydrophilic or hydrophobic interactions. The ability to hold two immiscible phases together by guiding fluids toward the interface, resulting in a new structure known as emulsion, is referred to as the surface properties [32,57,58]. Studies have indicated that the proteins isolated from tomato seeds show high stability and good emulsifying, foaming, and oil absorption capacities. These techno-functional properties rely on the extraction and processing conditions, such as the temperature, pH, chemical composition of the solvent used for extraction, and other aspects of a solvent [4,6,12,59]. Recently, Maldonado-Torres et al. [60] evaluated the nutraceutical properties and techno-functional properties of tomato seed meal (TSM) and reported that alkaline conditions (pH 8–9) improved its techno-functional properties. Defatted TSM displayed higher emulsion stability, enhanced emulsifying activity, 50 times more foam stability, 10 times more foaming activity, and higher water (WHC) and oil holding capacities (OHC). The oil and water holding capacities determine the acceptability, sensory, mouthfeel, and softness of food products. A good WHC can result from a higher content of hydrophilic amino acid-containing proteins, better surface hydrophobicity, protein conformation, temperature, and pH, and carbohydrates and lipids associated with the proteins. A higher WHC can reduce the moisture loss from packed bakery foods and maintain the mouthfeel and freshness of baked products [60]. The carbohydrates present in TSM also contain hydrophilic portions, such as charged or polar sidechains, which can enhance the WHC. The hydrophobic protein domains and nonpolar amino acid side chains can integrate with oil molecules, further augmenting the OHC. Higher emulsion activity and stability rely on the hydrophobic-hydrophilic protein balance, the physical orientation of lipophilic amino acid side chains (toward the oil phase) and hydrophilic amino acid side chains toward the aqueous phase, and the stability of the protein. This reduces the surface tension at the interface and enhances the interaction between the oil and the aqueous phase [56,60]. Sogi et al. [25] studied the functional properties of tomato seed meals (both whole and de-oiled) and tomato seed protein concentrates. The authors reported a higher bulk density and water and fat absorption in the meals than in the protein concentrates, as well as good emulsion capacities in both meals and concentrates. A majority of the studies available on the functional compounds from tomato seeds have focused on protein recovery due to their high protein content (35–40%) [25]. Shao et al. [5] investigated defatted tomato seed meal and the effects of different industrial treatments (hot and cold breaks) on some characteristics of the protein isolates, such as the WHC, OAC, bulk density, emulsification, and foaming properties. A higher bulk density for tomato seed proteins results from the combined effects of interconnected factors, including the particle size, interparticle attraction, and density of contact [12].

A recent review summarizes how the technical functionalities of tomato seed proteins are strongly linked to the parameters used during extraction. In addition to protein, other valuable functional ingredients from tomato byproducts include fiber, pectin, and oil. Limited studies have focused on the use of tomato fiber from peels rather than seeds due to the higher fiber content of the former (41%) compared with the latter (18%) [4,52]. Tomato byproducts have great potential to be used as alternatives to apple pomace and citrus peels for pectin production, but only a few studies have addressed pectin extraction by and primarily through traditional extraction strategies [28]. Recently, Zhang et al. [29] investigated the emulsifying properties of pectic polysaccharides (water soluble, chelator extractable, and sodium carbonate extractable) and hemicellulose from freeze-dried black tomato pomace. All pectin fractions could stabilize emulsions containing a 50% oil phase at a concentration of 1.5% (w/v) and pH 4.0–8.0. Emulsion formation was facilitated by pectin's ability to increase the viscosity and decrease the surface tension, coupled with repulsion between the pectin molecules. Tomato seeds contain approximately 20.0–36.9 g/100 g of oil (on a dry basis) [29]. Shao et al. [6] determined alterations in the oxidative stability and quality of tomato seed oil, including the acid value, iodine value, saponification value, peroxide value, antioxidant activity, and color, after 50 h at 180 °C. These oils demonstrated excellent physicochemical profiles and thermal stability after heating. Polyphenols and tocopherols were the most important determinants for high thermal stability [15].

Apart from the functional properties of the various components of the tomato seed, the bioactive components of the tomato seed impart numerous health benefits to the human being. Since the major health benefits and bioactive contents of tomato seeds have already been well discussed in a recent review [51,59], here, the authors limited the discussion to the nutritional and food properties and other food applications of tomato seed. To summarize, the various bioactive components and their effects on human health are shown in Table 5.

Table 5. Bioactive compounds in tomato seeds and their impact on human health.

Compound	Major Effects	References
Carotenoids		
Lycopene	Anti-oxidant Anti-inflammatory Positive effects in case of colitis Positive effects in case of cardiovascular diseases	[30,44]
β-carotene	Anti-cancerous Prevention of atherosclerosis Prevention of photooxidative processes Prevention of congestive heart disease	[34,48,54]
β-lutein	Preservation of eye sight Role in atrophic age-related muscular degeneration Positive effects in case of cardiovascular diseases Anti-oxidant; enforces DNA against damages	[34,48]
Vitamins		
Folates	Regulation of metabolism homocysteine; anemia alleviation Decreases the risk of prostate cancer	[48]
Vitamin E	Prevention of type II diabetes Prevention of cardiovascular diseases Anti-inflammatory Role in atrophic age-related muscular degenration Antiatherogen	[34,43]
Vitamin C	Regulation of inflammation Anti-cancerous Insulin metabolism	[43,49]
Minerals	Blood pressure maintenance Muscle contraction Neuro-muscular coordination Prevents excitotoxicity Vasodilator Bone formation and maintenance	[50,60]

4. Applications as an Ingredient in Functional Foods

Tomato byproducts have been used in a range of food products [50,52]. Tomato seeds and peels are estimated to account for 20–50 g/kg of fresh tomatoes [7]. There is tremendous unexplored potential for tomato seeds and peels. A majority of studies do not specifically distinguish between the use of tomato peels or seeds, and the researchers seemed to use a more general tomato pomace as a mix of the two byproducts [8]. To assess the recovery of lycopene and β-carotene and DPPH radical scavenging activity, tomato peels were treated by various methods (hot air, freeze-drying, and fluidized bed drying). When the findings were compared, it was discovered that hot air drying at 50 °C was a good approach and alternative to freeze-drying for preserving the carotenoid components and antioxidant activity in tomato peels. Heating of the extracts caused a progressive reduction in the total carotenoids of up to about 30% after 250 min of treatment, whereas the fluorescent lighting treatment showed an almost total degradation of the carotenoids [61]. Nitrites, including potassium and sodium nitrite, are synthetic food additives in processed meat due to their ability to inhibit the growth of pathogenic bacteria such as *Listeria monocytogenes* and *Clostridium botulinum*, enhance flavor and color, and delay meat deterioration by retarding lipid oxidation. Despite this, nitrites are noticeably unhealthy due to their carcinogenicity and pose a risk of methemoglobinemia. A study aimed at investigating the effect of the supercritical liquid extract of tomato pomace containing peel fractions and seeds as an alternative for sodium nitrite in cooked pork sausages [62]. The authors used extracts from freeze-dried tomato pomace rich in phytochemicals with antioxidant activity (such as carotenoids and polyunsaturated fatty acids). Lipid oxidation is the primary determining factor affecting the shelf life and quality of a meat product, as it causes undesirable flavors and colors and rancid odors. The results showed that extracts from tomato pomace such as peppermint essential oil (having antioxidant and antimicrobial terpenoids) strongly inhibited lipid oxidation, especially when in combination with other natural antioxidants, and thus could be effectively used as a substitute for sodium nitrite in meat preservation [8].

Functional foods contain compounds with beneficial and healthy properties, such as polyphenols and carotenoids, which are plentiful in tomato byproducts. Tomato powder can be manufactured from byproducts of tomato processing, such as peels and seeds, after dehydration. The powder, which contains natural compounds with known antioxidant properties such as lycopene and β-carotene, can be utilized as an additive for cheese, bread, and other foods. As a result, the finished product is a reddish-brown color with a high concentration of natural antioxidant compounds [63]. Abid et al. [64] also used an extract from tomato processing byproducts rich in antioxidants and investigated its effects on the storage stability of traditional Tunisian butter. The authors found that 400 mg of tomato pomace extract per kilogram of Tunisian butter could greatly inhibit the formation of conjugated dienes and peroxides and prevent the disintegration of unsaturated fatty acids into their oxidation products. Higher concentrations of the extracts acted as pro-oxidants, as indicated by the higher peroxide values [64]. Concha-Meyer et al. [65] used dried tomato pomace powder at 5% and 10% inclusions in bread and carried out sensory analysis with 231 consumers, evaluating the appearance, color, overall liking, flavor, texture, sweetness, and aftertaste. After completing the sensory analysis, the consumers were provided with information on the pomace powder, and the consumers' relative purchase intents were measured. Both inclusion levels resulted in an increase in liking of the appearance and color. The 5% inclusion did not decrease the overall liking or that of the flavor, texture, sweetness, or aftertaste. In terms of the efficacy of information, both the nutrition and sustainability messages proved to be valuable in increasing consumers' purchase intentions [65].

Tomato seeds are enriched in components that have been shown in recent investigations to have nutritional, technological, and nutraceutical effects. As a result, processors and researchers have focused on the use of tomato seeds for animal feeding, as a bakery ingredient, and as a raw material for the extraction of oil and proteins in order to reduce environmental problems caused by tomato wastes while also taking into account the properties from tomato seeds [56]. Because of their high protein content, most alternative uses of tomato seed wastes are focused on animal feed, being used as a supplement for animal feed because it boosts the output and fat content of cow milk and the growth of sheep [66]. Tomato pomace meal and tomato seed powder have been used in several examples of research to make crackers and bread, respectively. Although replacing wheat flour enhanced the protein level of new products, changes in the texture and flavor quality of new products may impact acceptance to some extent [67]. Mironeasa and Codina [68] investigated the effect of wheat flour substitution with tomato seed flour (TSF) at the levels of 5%, 10%, 15%, and 20% on dough's rheological properties and microstructure. This substitution increased the viscosity, stability, and time of dough development and decreased alpha-amylase activity. An increase in dough development time with a reduction in the water holding capacity could result from a reduced gluten content of the blends and encapsulation of the gluten proteins and starch granules by TSF lipids. Higher dough stability may be attributed to the emulsifying and foaming capacity of TSF, which can augment the emulsifying activity of the dough system, forming a highly stable three-dimensional network [68]. Interactions between proteins and starch can bridge glutens to lipids or starch granules, increasing the stability and structure of the dough. These blends also displayed highly dynamic moduli, which could result from the gluten aggregation favored by TSF lipids, increasing the flour elasticity. Previous studies by the same group indicated that 10% inclusion of TSF in wheat flour resulted in acceptable bread quality [69,70]. These findings indicate that such flour blends can be successfully used in a number of highly nutritious low-gluten bakery products. Similarly, wheat flour was supplemented with tomato waste (skin and seeds) at 6% and 10% (w/w flour), and the effects on the sensory, baking, and physicochemical qualities of the prepared bread were assessed [71]. The bread showed a reduction in crumb porosity and specific volume and an increase in crumb elasticity, titratable acidity, and moisture content. Flour blends containing 6% dry tomato waste showed superior qualities and acceptability, while blends with 10% tomato waste decreased the acceptability of the bread. Similarly, wheat flour partially substituted by dried tomato pomace meal at 4%, 8%, and 12% was used in soda cracker production. The inclusion of tomato pomace increased the protein, fiber, and mineral contents of the crackers. Sensory analysis with 48 subjects showed that the panelists liked the crackers equally in terms of color, smell, flavor, crispiness, and overall acceptability. However, inclusions higher than 12% were not recommended [69]. The incorporation of tomato peels into gluten-free bread formulation based on corn and chickpea flours increased the maximum dough height, total CO_2 production, and CO_2 retention coefficient compared with unenriched gluten-free dough [72,73].

Karthika et al. [74] used dried and milled tomato peels (0–30%) and seeds (0–5%) to manufacture corn- and rice-extruded snacks. The addition of tomato pomace increased the fiber and protein contents of the final snack products. The sensory results from 10 semi-trained panelists indicated that up to 30% tomato pomace was acceptable for inclusion. The best formulation was 40% corn flour, 30% rice flour, 25% tomato peels, and 5% tomato seed [74]. A new interesting application of tomato waste in food was shown by Mechmeche et al. [33]. The authors reported the use of protein isolates from defatted tomato seeds as a suitable medium to grow kefir cultures, with the aim of developing a new dairy-free functional food.

Bendini et al. [75] produced an olive oil co-milled with defrosted or freeze-dried tomato pomace. The co-milling resulted in a significant lycopene enrichment in the olive oil, which could be marketed as “olive oil rich in lycopene” or “condiment produced using olives and tomato byproducts” [75]. Ketchup was prepared from tomato pomace powder and compared with one developed by fresh tomato pomace [76]. The final product had a high dietary fiber content due to the presence of seeds, higher yield stress and thixotropy (so it could be packed into tubes), and improved thermal stability (so it could be used as a filling in baked products) compared with the ketchup made from fresh tomato pomace. The higher values for the yield stress resulted from the greater specific surface of the tomato and seed particles and their increased bond formation with the polysaccharides. Higher thixotropy and lower flow behavior can result from higher shear rates, which cause breakage of the noncovalent interactions between the hydrocolloid network and particles and breakage of the bonds present across the hydrocolloid network [75,76]. Previtera et al. [77] enriched a tomato puree with 0.5%, 1%, 2%, and 3% lyophilized and powdered tomato pomace. This resulted in an increase in the micronutrients compared with the control puree and did not cause any negative effect on the taste or appearance. Sensory analysis was carried out by 20 trained judges who scored the samples on a 9-point hedonic scale for color, taste, flavor, and overall acceptability [77]. The effect of seeds containing tomato waste powder at different replacement levels (2%, 4%, and 8%) was tested on the organoleptic, rancidity, and physicochemical properties of cookies at different storage intervals (0, 15, 30, and 45 days) [78]. The 4% inclusion was preferred by the small sensory panel (14-judge panel, both experienced and untrained), and all inclusions had positive effects on the rancidity parameters during the 45-day storage period. The authors suggested that tomato pomace powder could be used to improve the storage stability of food products. Similarly, cookies prepared by seed containing tomato pomace powder (0%, 5%, 10%, 15%, 20%, and 25%) were evaluated for their physicochemical and sensory qualities. The cookies with a 5% substitution of pomace powder were found to be acceptable [79].

Chouaibi et al. [80] used commercial insoluble tomato fiber in cookies at 2.5%, 5%, 7.5%, and 10% inclusion and reported an increase in the sample's breaking strength, a decrease in their spread ratio, and an increase in antioxidant activity. The cookies enriched with 7.5% tomato fiber had similar overall acceptability to the control cookies according to a 50-member panel [80].

5. Safety Aspects of Tomato Seed Consumption

Tomatoes, a member of the Solanaceae plant family, are a safe food and one of the most widely grown vegetables in the world. Tomatoes are a popular and in-demand vegetable among adults and children due to their availability, wonderful taste, low price, and particular health benefits. Tomatoes, an important human food source, accumulate phenolic compounds, phytoalexins, protease inhibitors, carotenoids, lycopenes, and glycoalkaloids, among other secondary metabolites. Tomato seeds are good sources of proteins, oil, dietary fiber, minerals, and essential amino acids [32,81,82]. The bioactive components in tomato seeds and their major effects on human health are given in Table 5.

Gonzalez et al. [40] investigated the sensitization patterns of tomato seeds through tomato-sensitized human patients at the research laboratory at the Regional University Hospital of Malaga, UMA, Malaga, Spain. A large group of tomato-sensitized human patients (N = 96) who had at least two tomato-related episodes or a positive skin prick test (SPT) were studied. SDS-PAGE was used to determine the protein composition of raw tomato seed extract. Western blotting was utilized to determine the recognition profiles from the patients' serum. The western blotting data revealed various patterns of IgE recognition. The bands around 10 kDa were most frequently recognized, with 46 percent of the patients recognizing them. This band was found in 100% of the anaphylaxis patients' serum, 83 percent of the urticaria patients' serum, 0% of the angioedema patients' serum, and 9% of the OAS patients' serum. These preliminary findings suggest that a new tomato seed protein may be a relevant allergen, although whether it is predictive of systemic reactions remains to be determined [40]. Consumption of tomatoes is recognized as healthy, but as with all foods, there are limits and concerns to take care of. The use of tomato leaves in large amounts is unsafe and can cause poisoning. The symptoms of poisoning may include severe throat and mouth irritation, headache, dizziness, diarrhea, mild spasms, and even death in severe cases [71,83]. The adverse aspects of tomato consumption in general are given in Table 6.

Table 6. Adverse effects of tomato consumption.

Disease	Reasons	References
Allergies	B-fructofuranosidase, Lyc e 2, Lyc e 3, profilin, superoxide dismutase, pectin esterase, polygalacturonase, lipid transfer protein cyclophilin	[37,38]
Gastrointestinal reflux disease (heartburn)	Organic acids (citric and malic acids) are the most potent triggers of acid reflux in prone individuals and higher tomato consumers	[37]
Kidney problems	High potassium and oxalate concentrations; oxalate can react with calcium, increasing risk of kidney stones (calcium oxalate)	[37,81]
Irritable bowel syndrome (IBS)	High amount consumption of skin and seeds of tomato	[37,81]
Lycopenodermia	High amount of lycopene in blood	[37,65]

Table 6. *Cont.*

Disease	Reasons	References
Urinary probelms	Organic acids	[37]
Body aches, arthritis	Glycoalkaloids (tomatine and solanine), tomato and its derived products	[71]
Migraine	Tomato and its derived products	[43,71]

Tomato seeds can be used to boost health and prevent disease because of the minerals and phytochemical components they contain. Many predators, including fungi, bacteria, viruses, and insects, are protected by these compounds. Dietary fiber (35% dry weight), fat (20–30% dry weight), polyunsaturated fatty acids, proteins (25–30% dry weight), and essential amino acids, and minerals are all abundant in the seeds [37,83]. Tomato seeds contain no antinutritive agents or toxic elements, making them a better source of protein, lipids, or bioactive substances than other non-traditional sources. Furthermore, a 20 g portion of tomato seeds contributes relatively little to the tolerated upper intake limit of sodium, which is defined as the highest level of daily nutrient consumption that is unlikely to cause unfavorable health consequences in practically all people in the general population (2.2%). This contribution must be considered, because it is known that increased sodium chloride intake increases blood pressure and is associated with an increased risk of cardiovascular disease [84]. Furthermore, the seeds are an important contributor to the major antioxidants (28 ± 7% of total phenolics, 25 ± 4% of total flavonoids, 11 ± 4% of lycopene, and 19 ± 1% of ascorbic acid) and overall antioxidant activity (23 ± 5%) of tomatoes. Removing seeds from tomatoes when cooking at home and processing results in a significant loss of all the major antioxidants of tomatoes [50]. Therefore, it is important to consume tomatoes along with their seeds in order to obtain the maximum health benefits. A high amount consumption of tomato skin and seeds by humans may lead to irritable bowel syndrome (IBS) and cause bloating and diarrhea [81].

6. Conclusions and Future Perspectives

The tomato is a widely cultivated and globally in-demand commodity due to its savory flavor, rich nutrient contents, and health-promoting properties. This review has shown that seed waste generated during tomato fruit processing also carries a significant amount of nutrients, viz. proteins, carbohydrates, lipids, vitamins, and minerals. Considering the superior nutritional properties, this review also discussed the techno-functional properties, including the water holding capacity, oil holding capacity, protein solubility, foaming, and emulsification of tomato seeds and their applicability as an active ingredient in the development of functional foods.

Multidisciplinary research will improve the utilization of tomato seed as an important ingredient for application in foods. Furthermore, information on the bioavailability and bioaccessibility of nutritional components from tomato seeds in the human system is scarce. In addition, the economic viability of utilizing tomato seed as an ingredient for the development of functional food needs to be studied for improving the valorization capabilities of tomato seeds.

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