

Tomato wastes and by-products: Upcoming sources of polyphenols and carotenoids for food, nutraceutical, and pharma applications

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Abstract

Tomato pomace, a waste product consisting of peels, seeds, rich on fibrous matter, represents an underutilized source of bioactive compounds, such as polyphenols and carotenoids. Here we present a three-pronged review of the circular utilization of tomato waste in line with the United Nations Sustainable Development Goals. First, we explain why tomato waste is important, highlighting the processing techniques that generate it. The bioactive compounds in these by-products are then comprehensively reviewed, focusing especially on phenolic compounds and carotenoids and the methods used for their extraction. Finally, we examine the potential of these bioactive ingredients for application in food systems and pharmaceutical products.

Keywords: Antioxidants, bioactive compounds, *Lycopersicon esculentum*, residues, circular economy

1. Introduction

Responsible production and consumption that reduces the generation of waste is one of the sustainable development goals of the United Nations (Gunawan et al., 2020). Waste products that remain at the end of a food production process are potentially a valuable resource, rich in proteins, lipids, starch, micronutrients, bioactive compounds, and dietary fiber, but if not reused, they can be very costly for both industry and the environment (Torres-León et al., 2018). To achieve a more sustainable food chain, it is no longer sufficient to reduce waste: it is crucial to move from the idea of "waste as a problem" to "waste as a resource", a product that can be recycled through a wide range of potential applications (Dueñas & García-Estévez, 2020; Trombino et al., 2021). The advent of technical solutions for the management and safe disposal of agro-food wastes has led to the development of various valorization strategies to generate useful end-products with bioenergy, cosmetic, pharma, or food additive applications (Socas-Rodríguez et al., 2021). Situations that call for new approaches to the reuse of food waste include: (i) the growing world population, resulting in a higher demand for food production and the generation of ever larger amounts of food waste; (ii) increasing consumer interest in healthier and more sustainable products, and (iii) the need to minimize malnutrition and hunger in developing countries (Pérez et al., 2021).

The tomato (*Lycopersicon esculentum*) is the second most important crop in the world. A key component of the Mediterranean diet, its consumption is directly associated with many positive health effects (Cámara et al., 2020; Hurtado-Barroso et al., 2019a; Kumar et al., 2021; Pinela et al., 2016). In 2020, global fresh tomato production was estimated to be about 186 million tons according to FAOSTAT (*Food and Agriculture Organization of the United Nations. FAOSTAT Statistical Database*, 2022). The tomato processing industry generates considerable quantities of waste known as tomato pomace, mainly made up of peels and seeds rich on fibrous matter, which accounts for 7–7.5% of the processed material (Nour et al., 2018; Sogi et al., 2005;

Szabo et al., 2021; Vats et al., 2022). Consequently, companies concerned about sustainability are interested in implementing new systems to valorize this waste product, which to date, has been mainly used as animal feed or to produce compost (Cerdeira et al., 2018; Truong et al., 2019). Finding alternative innovative ways of recycling tomato by-products is being extensively researched with the aim of reducing their environmental impact and maximizing profits.

Tomato pomace contains high amounts of antioxidants, mainly carotenoids, phenolic compounds, and vitamin with lycopene being the most important (Vats et al., 2022). A relatively simple recovery technology would consist of the production of powders or extracts to be directly incorporated into foods (Nour et al., 2015), cosmetic and pharmaceutical products. The antioxidant activity of tomato components, associated with multiple health benefits, turns them into potential ingredients for the formulation of functional foods with multiple purposes (Cámara et al., 2020; Hurtado-Barroso et al., 2019a; Nour et al., 2015, 2018). There is evidence that the antioxidant action of tomato is associated with a lower incidence of some chronic diseases, and regular tomato consumption is associated with to reduce the risk of certain types of cancer (mainly prostate cancer) and better cardiovascular health (Canene-Adams et al., 2005; Frusciante et al., 2007). The fact that many of the major health problems currently affecting the general population, such as obesity or diabetes, are diet-related makes the use of functional foods of particular interest (Topolska et al., 2021). Additionally, tomato pomace is a potential source of natural preservatives that can be used to improve the oxidative stability of food products, such as those of the meat industry (Vats et al., 2022).

From 2010 to the present, several reviews about tomato waste have been published (Carvalho, de Camargo, et al., 2021; Kumar et al., 2022; Lu et al., 2019a; Mendez-Carmona et al., 2022; Rajan et al., 2022), focusing on specific issues such as tomato seed valorization (Kumar et al., 2022), carotenoids (Carvalho, de Camargo, et al., 2021; Lu et al., 2019a; Mendez-Carmona et

al., 2022), and possible applications (e.g., as animal feed, biodiesel fuel and fertilizer) (Rajan et al., 2022). In contrast, the present review takes a three-pronged approach to the circular utilization of tomato waste. We first describe why tomato wastes are important, highlighting the main types of tomato processing that generate waste (e.g., peeling and tomato sauce manufacture). There follows an in-depth review of the bioactive compounds in tomato pomace, prioritizing polyphenols and carotenoids, and the techniques currently used for their recovery. Finally, we examine the potential use of these bioactive compounds in both food and pharmaceutical systems.

2. Why are tomato by-products so important for a more sustainable industrial chain?

According to the latest data available from FAOSTAT (*Food and Agriculture Organization of the United Nations. FAOSTAT Statistical Database*, 2022), in 2020, the world produced 186.821.216 tons of tomatoes, with a contribution of 12% and 2% from Europe and Spain, respectively (**Figure 1**). Tomatoes are mainly consumed fresh or processed. Fresh tomatoes are defined as those sold to the consumer directly from the farm or via a retail chain without any processing, whereas processed tomatoes are those that have been blanched, squeezed, cut, or peeled (Rock et al., 2012). Compared to tomato farming, the tomato processing industries generate higher amounts of waste: approximately 8.5 million tons per year worldwide (Szabo et al., 2018). The tomato pomace that remains after the different processing regimes consists of peels, seeds, and some residual tomato tissue (**Figure 2**), its constitution depending on the final product (e.g., canned tomatoes, juice and tomato pasta) and the peeling method applied (Lu et al., 2019b). Tomato pomace is described as consisting predominantly of skin (61.5%) with a lower quantity of seeds (38.5%) (PA Silva et al., 2019), and it constitutes about 4% of the fresh fruit weight (Del Valle et al., 2006). Due to their environmental impact, disposal of these wastes represents a costly inconvenience for producers, despite their potential as a valuable source of bioactive compounds (Szabo et al., 2018). In the sustainable development agenda of the United

Nations, the reuse of waste is advocated as the main strategy for its reduction (Schroeder et al., 2019). [Figure 1 near here]

2.1.Peeling

Peeling, which consists of removing the undesirable or inedible skin, is a common practice in the tomato processing industry, being one of the first unit operations used to prepare tomatoes for further processing (e.g., to obtain whole peeled, bulk-diced, diced and fire-roasted canned tomatoes). According to the FAOSTAT database of 2019, the amount of residues generated by tomato peeling in Spain has not been estimated (*Food and Agriculture Organization of the United Nations. FAOSTAT Statistical Database*, 2022); however, the latest published data indicate that the production of peeled tomatoes has been increasing, reaching 128, 145, and 171 tonnes in 2017, 2018, and 2019, respectively, as shown in **Figure 1** (*Food and Agriculture Organization of the United Nations. FAOSTAT Statistical Database*, 2022). Considering that the weight of skin can represent 5-10% of total tomato weight (Adedeji et al., 2006), the production of peeled tomatoes is generating more than 6 to 8 tonnes of waste peel a year.

The peeling process affects the shelf life and sensory and nutritional quality of the product, as well as the overall production costs and efficiency (Gavahian & Sastry, 2020). Tomato peels have antioxidant properties due to their concentrations of lycopene, polyphenols, and other nutrients, which are higher than in pulp or seeds (Vidyarthi, El Mashad, et al., 2019). Various peeling methods are available, including the use of lye, steam, flame, cryogenics, and enzymes, and recent technologies include ohmic peeling, ultrasonic peeling, and infrared dry-peeling (Vidyarthi, El-Mashad, et al., 2019). These strategies have been optimized in many studies to improve (i) yields, (ii) water-use efficiency, (iii) wastewater management, (iv) energy and carbon footprints, (v) chemical contamination, and (vi) product quality (Pan et al., 2015). A summary of the advantages and disadvantages of both conventional and novel tomato peeling techniques is presented in **Table 1**. [Table 1 near here]

2.2. Tomato concentrates

Tomato is a unique crop that can be used to produce various processed products, the most common being juice, sauce, paste, ketchup/catsup, soup, powder, chili sauce, and canned tomatoes (Motamedzadegan & Tabarestani, 2018). Tomato paste differs from tomato purée only in the degree of concentration. In the production of both purée and/or paste, the crushed tomatoes are fed into an extractor to separate the juice, which generates a finely dispersed slurry, with seeds and skins discarded as a waste product (Amón et al., 2015; Motamedzadegan & Tabarestani, 2018).

The amount of pomace produced during processing can vary from one plant to another, depending on the characteristics of the raw material and processing conditions. For example, a study about food loss and waste in the tomato sauce supply chain found that the skins and seeds represent more than 10% of the wastes generated during the production of pulp and concentrate (Secondi et al., 2019). In another study, TP accounts for approximately 3–5% (w/w) of the raw material applied (Zuorro et al., 2011).

Considering that tomato waste management is a global problem with a serious economic and environmental impact, the recycling or reuse of these by-products is of high interest. Therefore, in the following section, the composition of these residues is analyzed with a view to their possible valorization.

3. Tomato anatomy: fruit and cell

The tomato fruit consists of the exocarp (skin or surface layer), mesocarp (intermediate layer), endocarp (innermost layer), and locular gel tissue (Z. Li & Thomas, 2016). The exocarp is covered with a thin cuticle made of polyester cutin (4–10 µm in thickness), hemicellulose, and pectin. This outer epidermal layer is extremely hydrophobic, and its main functions are controlling gas exchange between fruit tissues and the surrounding environment and protecting internal tissues

from excessive water loss and damage from weather, disease, and insects (Gavahian & Sastry, 2020; Z. Li & Thomas, 2016; Rock et al., 2012). The mesocarp, made from large thin-walled cells and vascular tissue (Z. Li & Thomas, 2016), comprises the soft edible part of the fruit (Dardick & Callahan, 2014). Inside the mesocarp is the endocarp, a unicellular layer covering the locular cavities, which contain the seeds in a gel.

Knowledge of plant anatomy helps to understand the cellular localization of bioactive compounds. Polyphenols are synthesized in a variety of cell types and tissues. Their biosynthetic pathways are complex and operate in different subcellular compartments, such as the cytoplasm, cytoplasmic phase of the endoplasmic reticulum, vacuole, and apoplast. Most plant polyphenols accumulate in either the cell walls (e.g., lignin) or inside vacuoles (e.g., anthocyanins) (Otegui, 2021). Polyphenols in vacuoles and the apoplast of plant cells are generally conjugated with mono- and polysaccharides and proteins (Bohn et al., 2015).

In the plant cell, the non-photosynthetic plastids known as chromoplasts store carotenoids. During the early stages of ripening, when the tomato fruit is still green, very little carotene is found in the plastids. As the fruit ripens, two of the most obvious metabolic changes are the loss of chlorophyll and increase of carotenoids in the tomato skin. Carotenoids are subsequently localized in diverse lipoprotein substructures and/or in crystalline bodies as well as in globular- and membrane-shaped structures in the chromoplasts (Carvalho, de Camargo, et al., 2021; Stange, 2016).

4. Bioactive compounds in tomato wastes

Like tomatoes and tomato-based products, the by-products of tomato processing are an exceptional source of phytochemicals, including carotenoids, polyphenols, vitamins (ascorbic acid, tocopherols, and provitamin A), glycoalkaloids (tomatine), and minerals (K, Mn, Ca, Cu and Zn) (L. R. da Silva & Silva, 2016) (**Figure 2**). It should be stressed that the tomato variety,

farming methods, environmental factors, stage of ripening, and the industrial procedures used to transform tomatoes into juices, ketchup, pastes, purees, sauces, and soups all affect the concentration of bioactive compounds (Helyes et al., 2009; Martínez-Valverde et al., 2002; Nobre et al., 2009). [Figure 2 near here]

4.1.Phenolic compounds

Structurally phenolic compounds (PCs), found in abundance in plants, range from a simple phenolic molecule containing one hydroxyl group to a complex high-molecular-weight polymer. PC found in foods are mostly phenolic acids, and flavonoids and tannins (Shahidi & Ambigaipalan, 2015). The increasing evidence for their protection against non-communicable human diseases has generated considerable interest in PC. Accordingly, tomato processing by-products could serve as a source of functional ingredients for new food formulations (Călinoiu & Vodnar, 2018). Additionally, PCs can modulate the sensory attributes of foods by changing flavor, taste, color, and astringency (P. A. Silva et al., 2019).

4.1.1. Tomato pomace

Different methodologies have been implemented to facilitate the migration of PC during their extraction from tomato pomace and achieve better yields, such as extraction with hexane-methanol (Ćetković et al., 2012) and hexane-ethanol (Perea-Domínguez et al., 2018). In addition, as the conventional extraction methods for PCs are generally time-consuming and require intensive use of environmentally unfriendly organic solvents, alternatives such as high voltage atmospheric cold plasma pre-treatment (Bao et al., 2020), ultrasound-assisted extraction (Concha-Meyer et al., 2020) and deep eutectic solvents with ultrasound assistance (Vorobyova et al., 2022) have also been proposed. Traditional colorimetric methods are still used to determine the total phenolic content (TPC) and total flavonoid content (TFC) as well as the antioxidant capacity of tomato residues (Bao et al., 2020; Perea-Domínguez et al., 2018;

219 Vorobyova et al., 2022). More sophisticated techniques such as HPLC-DAD (Ćetković et al.,
220 2012; Perea-Domínguez et al., 2018), HPLC-MS (Concha-Meyer et al., 2020), UPLC-PAD-
221 MS/MS (Bao et al., 2020) and HPLC-DAD-MS and FTIR analysis (Vorobyova et al., 2022)
222 are useful to discern and quantify the different polyphenols that are present.

223 Differences in the TPC of extracts from tomato by-products on a dry weight basis have been
224 detected. These differences can depend on the extraction method used as well as the tomato
225 variety and other factors. Thus, a study using a cold plasma pre-treatment method obtained
226 extracts with a TPC of 104 mg gallic acid equivalent (GAE) per g from tomato pomace samples
227 and measured an antioxidant activity of 198 and 1526 μmol trolox equivalents (TE) per g by
228 the DPPH and ABTS methods, respectively. The TPC and antioxidant activity of tomato
229 pomace were higher than 0.9 and 0.8 (per gram of dry mass) (Bao et al., 2020). In contrast,
230 much lower concentrations were obtained when using choline chloride-based deep eutectic
231 solvents: a TPC of about 27 mg GAE per g and TFC of 8 mg quercetin equivalent per g of dry
232 fraction of extract (Vorobyova et al., 2022).

233 The concentration of individual PC in tomato pomace also varies between studies, predominant
234 compounds reported being phenolic acids (Bao et al., 2020; Vorobyova et al., 2022), or gallic
235 acid, chlorogenic acid and naringenin (Bao et al., 2020), or chlorogenic acid, gallic acid and
236 caffeic acid, accompanied by low concentrations of quercetin, naringenin and ferulic acid
237 (Vorobyova et al., 2022). Other studies have found flavonoids to be the most prevalent PC
238 (Ćetković et al., 2012; Concha-Meyer et al., 2020; Perea-Domínguez et al., 2018). In an
239 analysis of whole and seedless tomato pomace, the flavonoids procyanidin B2, kaempferol-3-
240 O-glucoside and quercetin accounted for more than 90% of all the analyzed compounds, with
241 higher concentrations in the whole pomace (Concha-Meyer et al., 2020). Naringenin
242 derivatives and rutin were the main compounds detected in waste obtained from various tomato
243 genotypes (Backa, Knjaz, Novosadski niski, O₂, Rutgers and Saint Pierre), representing 29 to

69% of the total analyzed compounds (Ćetković et al., 2012). Another study on tomato byproducts reported that the two most prevalent flavonoids, naringenin and quercetin, made up 38 and 18% of the studied flavonoids, respectively (Perea-Domínguez et al., 2018).

4.1.2. *Tomato seeds*

Even though tomato seeds are edible and rich in lipids, bioactive compounds and minerals, they are frequently discarded, especially in the production of tomato derivatives. Moreover, seeds have been far less studied than tomato peels in valorization studies. Phenolic extracts from tomato seeds are obtained using a simple method with ethanol or methanol and water (Concha-Meyer et al., 2020; Ferreres et al., 2010; Valdez-Morales et al., 2014; Vinha et al., 2014) and phenolic quantification has been carried out by spectrophotometric methods (Vinha et al., 2014), HPLC-DAD (Valdez-Morales et al., 2014), HPLC-MS (Concha-Meyer et al., 2020), and HPLC/UV-PAD/ESI-MSⁿ (Ferreres et al., 2010).

The elimination of seeds was observed to have a great impact on the phenolic content of tomato fruits, reducing it by 63% (Vinha et al., 2014). Analysis of a seed aqueous extract detected 20mg/100 g of PC, with a predominance of quercetin-3-*O*-sophoroside, kaempferol-3-*O*-sophoroside, and isorhamnetin-3-*O*-sophoroside (Ferreres et al., 2010). Higher concentrations of flavonoids were found in tomato seeds than peels, except for quercetin, whose levels were higher in peels; the most abundant phenolic acids in both seeds and peels were caffeic, vanillic, ferulic, sinapic, *p*-coumaric and chlorogenic acid, whereas the most abundant flavonoids were quercetin-3- β -*O*-glycoside, rutin, isorhamnetin, and kaempferol (Valdez-Morales et al., 2014). Tomato seeds are also described as a good source of gallic and ferulic acids (Concha-Meyer et al., 2020).

4.1.3. *Tomato peel*

267 The phenolic content of tomato peel has been analyzed in numerous studies in search of new
268 applications for this waste product. Generally, simple extraction procedures have been applied,
269 involving widely available solvents such as methanol and water. (Babbar et al., 2014; Szabo et
270 al., 2019). Other extraction methods used are microwave-assisted (Bakić et al., 2019), high
271 hydrostatic pressure (Grassino, Ostojić, et al., 2020; Grassino, Pedisić, et al., 2020) and
272 ultrasound-assisted (Grassino, Ostojić, et al., 2020). The antioxidant potential of tomato peels
273 has been determined with colorimetric assays (Babbar et al., 2014; Bakić et al., 2019; Grassino,
274 Ostojić, et al., 2020; Grassino, Pedisić, et al., 2020; Navarro-González et al., 2011), whereas
275 qualitative and quantitative analysis of PCs has been carried out with HPLC-DAD (Grassino,
276 Ostojić, et al., 2020; Grassino, Pedisić, et al., 2020) and HPLC-DAD-ESI-MS (Szabo et al.,
277 2019).

278 The TPC was investigated in peels of ten tomato varieties in Romania (Abellus, Aphen, Cristal,
279 Misrini, Lady Rosa, Tiny Tim, Taranesti roz, Taranesti portocalii, Rotunde mari, and Rosii
280 lunguete) and the values ranged between 37 and 155 mg/100 g (Szabo et al., 2019). A similar
281 TPC was found elsewhere (62- 659 g/kg), with 107 g/kg of total flavonoids (Bakić et al., 2019).
282 Another study reported a TPC of 21 mg GAE/g-DW in tomato peel, whose antioxidant activity
283 was found to be higher compared to pea pods, cauliflower waste, and potato peel (Babbar et
284 al., 2014). The extraction technique used is known to influence the TPC and TFC. Thus, the
285 optimization of an ultrasound-assisted extraction method improved the recovery, resulting in a
286 TPC of 3644 and TFC of 357 mg/100 g. It was concluded that improved extraction would
287 reduce waste disposal costs and benefit consumers through the formulation of healthy food
288 products with the isolated compounds (Grassino, Ostojić, et al., 2020).

289 Regarding individual PCs in tomato peel, several phenolic acids have been identified and
290 quantified. *P*-coumaric acid (3 to 111 mg/kg) and a derivative of chlorogenic acid (10.5 to 109
291 mg/kg) were found to be predominant, with smaller amounts of chlorogenic acid, a *cis-p*-

coumaric acid derivative, *cis-p*-coumaric acid hexoside, and caffeic acid hexoside I and II (Bakić et al., 2019). Another study also identified *p*-coumaric acid and a chlorogenic acid derivative as the major compounds in tomato peel waste (Grassino, Pedisić, et al., 2020). The flavonoid profile in peels also depends on the tomato variety or extraction method. The predominant flavonoids appear to be kaempferol-3-*O*-rutinoside (Bakić et al., 2019), quercetin-3-*O*-rutinoside (Bakić et al., 2019; Navarro-González et al., 2011; Szabo et al., 2019), naringenin chalcone (Szabo et al., 2019), and naringenin (Navarro-González et al., 2011). As shown in **Table 2**, several other flavonoids have also been identified in tomato peels, although in low concentrations. The variable concentration of phytochemicals reported in tomato peel may depend on the production location, variety, degree of ripeness, and type of processing (Sánchez-Rodríguez et al., 2012) as well as genetic factors (Choi et al., 2014). [Table 2 near here]

4.2. Carotenoids

Carotenoids are a group of natural pigments that provide the yellow, orange, and red colors of many fruits and vegetables and exhibit strong antioxidant properties. As humans are unable to produce carotenoids, they must be obtained through diet, the primary food sources being tomatoes and tomato-based products. Carotenoids can be separated into xanthophylls, such as lutein, which contain one or more oxygen atoms, and hydrocarbon carotenoids, such as α -carotene and lycopene (Przybylska, 2020).

Although nine carotenoid pigment compounds were identified by HPLC analysis by Rizk (2014) (Rizk et al., 2014), lycopene, β -carotene, and lutein are the principal carotenoids found in waste produced by tomato processing companies (**see Table 3**), mainly peels and pomace. To maximize carotenoid extraction from waste, multiple studies have optimized parameters such as the type of solvent, extraction time and temperature, and extraction stages. As most tomato carotenoids are lipophilic compounds, organic solvents are used for their extraction.

According to Strati et al. (2011), in comparison with acetone, ethyl acetate, ethanol, and hexane, the ecologically friendly ethyl lactate had the maximum carotenoid output (243.00 mg/kg of dried tomato waste (DW)) at 70° C (Strati & Oreopoulou, 2011). Methanol/ethyl acetate/petroleum ether (1:1:1, v/v/v) were employed in another study where ten tomato types were tested for their carotenoid content (for the individual content of lycopene, β -carotene, and lutein in peels, see **Tables 3, 4 and 5**, respectively) (Szabo et al., 2019).

Emerging technologies have been effectively used to improve the extraction process. For example, ultrasound-assisted extraction was recently applied to recover carotenoids from tomato peels. As well as reducing the processing time and quantity of solvent, it allowed the use of low processing temperatures, an important factor for the recovery of heat-sensitive compounds such as carotenoids (**Table 3**) (Szabo et al., 2021). Seeking to avoid the usage of organic solvents, Nagarajan et al. (2020) investigated the water-induced hydrocolloidal complexation of carotenoids and pectin from tomato pomace, obtaining 9 mg carotenoid fractions/100 g tomato pomace as the maximum recovery and 92% purity of carotenoid-rich fractions (Nagarajan et al., 2020). A recent review covers the latest studies on carotenoid extraction from tomato waste, focusing on alternative processes such as supercritical fluid extraction and pulsed electric field extraction, among others (Trombino et al., 2021), which benefit from using less solvent and operating at a somewhat lower temperature, as well as taking less times.

4.2.1. *Lycopene*

With 11 conjugated and two unconjugated double bonds along its 40-carbon atom chain, lycopene has no pro-vitamin A property. Its distinct structure, with a high degree of conjugation, explains why it is lipophilic, red in color, and one of the most effective antioxidants. The all-*trans* isomer, which is the thermodynamically most stable isomer, is the

predominant form of lycopene in food. Thermal processing, however, causes the all-*trans* isomer to isomerize into the *cis*-form, which is more bioavailable to humans (Hurtado-Barroso et al., 2019b; Przybylska, 2020).

Among tomato by-products, peels of fully ripe tomato fruits are the richest source of lycopene. Ranveer et al. (2013) found that tomato peel had the highest amount of lycopene (376µg/g), followed by industrial tomato processing waste (176µg/g), whole tomatoes (84 µg/g), and tomato pulp (48 µg/g), on a dry weight basis (Ranveer et al., 2013). Generally, when traditional solvent extraction techniques are used without first pretreating the plant material, very little lycopene is recovered (Zuorro, 2020). The separation and identification of lycopene pigments extracted from tomato peels revealed that lycopene was the most prevalent pigment (86.%), and the development of an optimized solvent mixture of *n*-hexane–ethanol–acetone resulted in a lycopene extraction yield higher than 95% (Zuorro, 2020). Recently, Szabo et al. (Szabo et al., 2022) used recognized safe solvents and ultrasound-assistance to extract carotenoids from tomato processing by-products following the principles of green chemistry. The solvent ethyl lactate produced the highest lycopene levels (1325 mg/g DW), which were only marginally lower when using ethyl acetate (1314 mg/g DW). Lycopene concentrations were substantially lower in extracts from freeze-dried samples, showing that carotenoids are quite vulnerable to degradation during the lyophilization process.

Numerous studies (**Table 3**) have sought to improve lycopene extraction, as current techniques tend to yield only a moderate recovery. Its localization within the thylakoid membranes of the chromoplasts and the compactness of the tomato peel tissue render lycopene inaccessible to the extraction solvent. Therefore, without suitable pretreatments, such as those based on ultrasound (Kumcuoglu et al., 2014; Y. Silva et al., 2019), microwave (Ho et al., 2015), supercritical carbon dioxide (Perretti et al., 2013) or enzymes (Catalkaya & Kahveci, 2019; Zuorro et al., 2011), extraction based on standard organic solvents is usually inefficient and

environmentally unsafe. In this regard, Silva et al. (2018) demonstrated the efficacy of a greener extraction approach utilizing ultrasound assistance by achieving an optimal lycopene yield of 1.33 g/kg (DW), which represented a 10% improvement compared to non-ultrasound extraction under the same conditions (Nzihou, 2010; Y. Silva et al., 2019). [Table 3 near here]

4.2.2. *β*-Carotene

β-Carotene, the primary precursor of vitamin A, has two retinyl groups and gives foods their yellow and orange coloration. The enzyme 15,15'-oxygenase converts this pigment into retinol in the intestinal epithelium (Gong et al., 2017). According to some studies, tomato processing by-products have higher levels of *β*-carotene (14.9 vs. 8.6 mg/100 g DW) than whole tomatoes (Kalogeropoulou et al., 2012). As with lycopene, the amount of *β*-carotene varies significantly depending on the extraction method, two crucial factors being the type of solvent and the use of an assisted extraction (**Table 4**). However, as *β*-carotene has a weaker antioxidant capacity than lycopene, studies on its recovery from tomato by-products have a lower priority. In practice, most of them select an extraction technique that yields the highest possible content from peel or pomace, without optimization for this specific carotenoid. [Table 4 near here]

4.2.3. *Lutein*

The oxygen-containing carotenoid known as lutein is also present in tomato by-products. Its distinctive yellow color is attributed to a particular polyene chain with several conjugated carbon-carbon double bonds that acts as a chromophore and is responsible for free radical detoxification properties (Saini et al., 2018). Although lutein is not a provitamin A carotenoid, it is a component of the macular pigment and has important physiological effects and therapeutic benefits. It is one of the few carotenoids with active components in the retina of the primate eye, which counteract harmful effects of UV light and provide protection from

oxidative stress, delaying the onset of age-related macular degeneration, as well as reducing the risk of many chronic diseases (Wu et al., 2022). In tomato by-products, lutein is present in smaller concentrations than lycopene and β -carotene (**Table 5**). Although consumption of lutein and antioxidant-containing products has gradually increased in recent years, daily lutein intake frequently falls below recommended daily intake levels (Johnson et al., 2010). [Table 5 near here]

In summary, the recovery of the extraction of carotenes from tomato by-products is a challenging process and the recoveries tend to be quite poor. Due to the contentious nature of organic solvents, whose toxic properties limit their application in food industries, the use of supercritical fluid extraction or other assisted extraction processes appears to be a good option to improve carotene yields. However, most cutting-edge techniques are highly aggressive and call for costly equipment that may not be readily available. An alternative and feasible approach to the recovery of these bioactive compounds is the employment of enzymes that hydrolyze the polysaccharide components of plant structures where the pigment accumulates. As hydrolytic enzymes weaken the structural integrity of cell walls, the intracellular contents become more accessible for extraction. Therefore, enzyme-assisted extraction techniques are being increasingly applied for the extraction of carotenes (Catalkaya & Kahveci, 2019). Water-induced hydrocolloidal complexation, a green extraction technique that uses water as the solvent for a carotenoid-pectin complexation process, is another technique potentially suitable for use with tomato pomace.

5. Current applications of tomato by-products and tomato wastes

5.1. Food sector

As mentioned above, the vast amount of waste generated by tomato processing and its content of underutilized valuable bioactive compounds, including polyphenols and carotenoids, makes

waste recovery both a great challenge and opportunity for the tomato sector. Industrial ecology concepts such as “cradle to cradle” and “circular economy” are increasingly considered as leading principles for eco-innovation, aiming at a “zero waste economy”, in which waste is used as the raw material for new products and applications (Mirabella et al., 2014). In addition, the growing interest of consumers in more natural and healthy products has driven the research and development of natural compounds with bioactive properties that can replace synthetic additives (Jimenez-Lopez et al., 2020). Finally, the nutritional content of food waste and byproducts provides an opportunity to minimize malnutrition and hunger in developing countries (Torres-León et al., 2018). All these considerations are framed in the sustainable development goals of “responsible consumption and production”, “good health and well-being” and “zero hunger” (UN General Assembly, n.d.). The following section covers the most outstanding advances achieved to date in tomato waste valorization and added-value applications in the formulation of innovative functional foods. In addition, a comprehensive summary of the advantages of using tomato residues in the food industry is provided in **Figure 3**. [Figure 3 near here]

5.1.1. Bread and derivatives

Mehta D. *et al*, observed that breads and muffins made from refined flour partially substituted with 35%-40% tomato pomace had a higher nutritional value (due to added dietary fiber, vitamin C, antioxidant activity and minerals), and a longer shelf-life in comparison with control bakery products with or without preservatives; the new products also had an acceptable color and sensory properties (Mehta et al., 2018). Adding tomato seed flour to wheat flour increased dough resistance and the nutritional value of bakery products (Mironeasa & Codină, 2019).

In another area of research, the consumer response to tomato pomace as a bread ingredient has been analyzed, focusing on the impact on perceived taste, and the effect of information about

health or environmental benefits on purchase intention (Concha-Meyer et al., 2019; Mironeasa et al., 2016, 2018; Nour et al., 2015). Concha-Meyer et al. (Concha-Meyer et al., 2019) carried out a sensory analysis of bread made with wheat flour plus dried tomato pomace powder (5% or 10%). A message of nutritional improvement and sustainability was found to increase purchase intent for the bread containing the by-product compared to the control bread. The tomato waste from a Romanian tomato processing unit was analyzed for its bioactive compound content (ascorbic acid, β -carotene, lycopene, total phenolics, mineral, and trace elements), and a dried waste product was added to wheat flour at levels of 6 and 10 % (Nour et al., 2015). The resulting bread had a higher moisture content, titratable acidity, and bread crumb elasticity, and a lower specific volume and bread crumb porosity; the 6% supplementation resulted in bread with good sensory characteristics and overall acceptability. In other studies, a mix of wheat and 10% tomato seed flour yielded acceptable bread quality (Mironeasa et al., 2016, 2018), suggesting that such flour blends can be successfully used to produce highly nutritious low-gluten bakery products. Additionally, lycopene extracted from tomato waste was used to enhance the antioxidant capacity, color, and sensory properties of bakery products (Eletr et al., 2017).

Different levels of tomato waste powder (2, 4, and 8%) were also used to prepare cookies, and the effect on organoleptic and physicochemical properties were studied during storage (Ahmad et al., 2017). All the proportions improved the rancidity parameters throughout the storage period, leading to the conclusion that tomato pomace powder can be used to increase the shelf-life of food products. The small sensory panel (a mix of experienced and untrained panelists) preferred cookies made with 4% powder. Similarly, cookies prepared with flour containing tomato pomace powder (0, 5, 10, 15, 20, and 25%) were evaluated for their physicochemical and sensory qualities, and those with 5% were found to be acceptable (M. A. Bhat & Hafiza, 2016). Finally, the antioxidant properties of cookies were enhanced by the addition of tomato powder

and raw lycopene without any adverse effects on physical and organoleptic properties (N. A. Bhat et al., 2020).

5.1.2. Meat and chicken products

Meat products can be reformulated to enhance their nutritional value and limit undesirable preservative. With this aim, tomato by-products rich in dietary fiber and bioactive compounds such as lycopene could be added to meat products to benefit consumer health (Jiménez-Colmenero et al., 2001). In an early study in this field, the effects of tomato paste at various concentrations (5, 10, or 15%, with a lycopene content of 48mg/100 g) on the sensory, physical, and chemical characteristics of ground beef patties during refrigerated storage (at 4 °C for 9 days) were investigated (Candogan, 2002). Tomato paste addition at concentrations of 10% and 15% increased ($p<0.05$) juiciness of the patties with juiciness particularly increasing with concentration increase from 5% to 10%.

Different amounts of dried tomato peel (0–6.0% w/w) were added to raw and cooked beef burgers, and the effects on sensorial and physico–chemical characteristics were studied (García et al., 2009). In both types of burgers the color parameters were increased and the texture was modified by the added fiber. The maximum concentration of dried tomato peel compatible with good general sensory acceptability was 4.5%, which resulted in a high lycopene content (4.9 mg/100 g) in the cooked burger. Another study performed a sensory evaluation of beef burgers elaborated with different levels of lycopene extracted from tomato peel (Darwish et al., 2019). Consumers preferred burger with the extract than alone, and the dose of 1% was the tastier over other concentrations (0.5, and 1.5%). However, after 12 weeks of frozen storage, the lycopene content in the beef burgers decreased significantly from 100 to 88.51%.

With growing health awareness among consumers, dietary habits are shifting away from red meat to chicken for nutritional and sustainable reasons. In this context, chicken sausages were

developed with 3% corn bran, 6% dried apple pomace, and 6% dried tomato pomace. The resulting products had high organoleptic acceptability and dietary fiber content and maintained microbiological safety for up to 15 days of refrigerated storage (Yadav et al., 2016). Lycopene-enriched dry fermented sausages were produced by adding tomato peel to the meat mixture. Only a slight loss of the carotenoid was observed after 21 days of ripening and the sensory and textural properties of the sausages were good (Calvo et al., 2008).

Addressing the health risks associated with synthetic food additives, tomato powder was applied to reduce the level of nitrite in frankfurters (Eyiler & Oztan, 2011), and tomato pomace was investigated as an alternative to sodium nitrite in cooked pork sausages (Šojić et al., 2020). Nitrite salts are used in meat products to prevent lipid oxidation, which is the primary factor affecting shelf life and quality, as it causes undesirable flavors, colors, and rancidity. The application of extracts from freeze-dried tomato pomace rich in phytochemicals with antioxidant activity (such as carotenoids and polyunsaturated fatty acids) strongly inhibited lipid oxidation, especially in combination with other natural antioxidants, such as those present in peppermint essential oil (also rich in antimicrobial terpenoids), indicating they could effectively substitute sodium nitrite in meat preservation (Herrera et al., 2010).

5.1.3. Tomato-based products

Tomato waste has also been applied to improve the quality of tomato-based products. Previtera et al. (Previtera et al., 2016) reported that a tomato puree enriched with 2% lyophilized and powdered tomato pomace had an enhanced content of micronutrients compared with the control puree. In the same study, a 20-member sensory panel scoring the samples on a 9-point hedonic scale for color, taste, flavor, and overall acceptability found no negative effect on taste or appearance.

5.1.4. Edible oil

Another approach to the valorization of tomato waste has been its application in the production of edible oils. The lipophilic properties of carotenoids, and to some extent phenolic compounds, from tomato processing by-products were harnessed to enrich and improve vegetable oils, especially those of low quality, such as refined olive oils, opening prospects for the elaboration of new functional food products (Benakmoum et al., 2008). Several studies have evaluated the protective effect of lycopene against the oxidation of edible oils. An olive oil produced by co-milling with defrosted or freeze-dried tomato pomace was significantly enriched in lycopene, and marketing suggestions were “olive oil dressing enriched in lycopene” or “a condiment produced using olives and tomato by-products” (Bendini et al., 2015). An oleoresin extract (containing lycopene) from tomato peel was reported to be an effective dietary stabilizer of both refined olive and sunflower oils against oxidation reactions during long storage, constituting an alternative to synthetic preservatives (Kehili et al., 2018).

Oil has also been produced from tomato seeds, which are rich in flavonoids and phenolic acids. Oil extracted from seeds contained all-*trans*-lycopene, *cis*-3-lycopene and β -carotene as the most abundant antioxidants (Eller et al., 2010). A tomato seed oil was produced and further enriched with lycopene obtained from tomato peel oleoresin (Zuorro et al., 2013). This process was then improved by pretreating the peel with cell wall-degrading enzymes, and the resulting oil had a lycopene content ranging from 30 to 600 ppm (Zuorro et al., 2014). An antioxidant-rich extract from tomato pomace was found to enhance the storage stability of traditional Tunisian butter (Abid et al., 2017).

5.1.5. Microcapsules

Encapsulation of lycopene-rich extracts from tomato waste has recently emerged as a promising strategy for incorporating this bioactive compound in food systems with diverse chemical and physical properties (Chiu et al., 2007; Corrêa-Filho et al., 2019, 2022; Gheonea et al.,

2021; Horuz & Belibağlı, 2019; J. Li et al., 2022; López-Bermúdez et al., 2022). The research carried out to date in this field has been largely focused on two aspects: the optimization of the encapsulation process and the bioavailability of lycopene in the encapsulated powder. The main technique used has been spray-drying (Corrêa-Filho et al., 2019; J. Li et al., 2022; López-Bermúdez et al., 2022), with freeze-drying (Gheonea et al., 2021), an emulsion system (Chiu et al., 2007) and electrospinning (Horuz & Belibağlı, 2019) also being applied. Most studies report an encapsulation efficiency higher than 70% (Chiu et al., 2007; Gheonea et al., 2021; Horuz & Belibağlı, 2019; J. Li et al., 2022), although 58.1% (López-Bermúdez et al., 2022) and below 30% (Corrêa-Filho et al., 2019) have also been described. In a recent study, the bioaccessibility of microencapsulated lycopene from tomato pomace was found to increase during simulated gastrointestinal digestion when it was incorporated in yogurt (Corrêa-Filho et al., 2022). Although further research is needed to fully elucidate the potential of microcapsules, the findings published so far indicate that (i) microencapsulation enhances the stability of lycopene, opening new perspectives for the design of functional and value-added foods and (ii) the recovery and reintegration of lycopene from tomato waste in food products as an additive fulfils the goals of sustainable development and the circular economy (J. Li et al., 2022).

5.1.6. Active Packaging

As well as serving as ingredients of functional foods, bioactive compounds from tomato waste have also been incorporated into food packaging to improve its functional and physical properties. Active films prepared from poly(vinyl alcohol), blended with chitosan and enriched with a tomato by-product extract, were found to have significant antibacterial activity (Szabo et al., 2020). Glycerol-plasticized composite films based on sodium caseinate and the lipid fraction of tomato pomace were described as highly suitable for use as barrier packaging materials for protection against light and water (Aloui et al., 2019). The results demonstrated that the tomato lipid fraction improved the antioxidant properties of sodium caseinate films.

5.1.7. Non-antioxidant applications

Tomato residues have been used in a wide variety of other food products in which the strong antioxidant capacity of the phenolic and carotenoid components is the main justification for their addition. Spaghetti produced with whole meal and tomato peel flour (15%) had a higher content of carotenoids (lycopene and β -carotene) and dietary fiber, but the sensory qualities of the cooked spaghetti were lower compared to the control in terms of texture, elasticity and odor (Padalino et al., 2017). In an interesting new application of tomato waste, snacks aimed at consumers interested in following a healthy diet were formulated using apple and tomato pomace powder as a source of dietary fiber and antioxidants. The products, prepared by supplementation with up to 20% apple and tomato pomace, had an enhanced content of carotenoids, phenolic compounds and dietary fiber (El-Araby, 2022).

The addition of lycopene was found to enhance the shelf-life of butter, ice-cream, and mayonnaise. The lycopene-treated products had lower levels of peroxides and free fatty acids than the control foods, whereas their sensory attributes were similar; a significant decrease in sensory scores was observed after the 4 months of storage for all samples (Kaur et al., 2011). Another study on ice-cream reported that the addition of carotenoids extracted from tomato peels at 3% was optimal for achieving all the target functional properties while maintaining a high quality and acceptable sensory factors (Rizk et al., 2014).

5.2. Nutraceutical and pharma sectors

Among all the biologically active compounds found in tomatoes, lycopene has been the most extensively studied due to its potential applications in the pharma and cosmetic industry (Carvalho, Sábio, et al., 2021a). Lycopene has numerous biological effects and has been associated with a positive impact on human health. Studies have shown that it can attenuate cardiovascular diseases, such as type 2 diabetes or heart failure, prostate cancer, and

neurological disorders (Biddle et al., 2015; Chen et al., 2019; Graff et al., 2016; Z.-H. Sun et al., 2021). However, its use in therapeutics is constrained by its low bioavailability, which is caused by its lipophilicity and instability (Y. Sun et al., 2022). Although the *trans*-lycopene isomer is more stable, the *cis*-isomer has proved to be more bioavailable (Boileau et al., 2002; Vallverdu-Queralt et al., 2012).

Among the international actions targeting countries suffering from malnutrition is the goal of “zero hunger”, part of the United Nations 2030 agenda for sustainable development, in which nutraceuticals such as lycopene may play a significant role (Feng et al., 2021).

5.2.1. Encapsulation

Lately, new formulations have been developed based on nanotechnology that allow lycopene to reach its biological targets (Carvalho, Sábio, et al., 2021b). The encapsulation of lycopene in nanocarriers such as nano-emulsions, nano-capsules, nano-structure lipid carriers, or nano-liposomes, which serve as drug delivery systems, improves its solubility, protects it from degradation and isomerization, and increases its bioavailability (Amorim et al., 2022). Although its clinical application has not been implemented so far, lycopene is commercialized as a nutritional supplement, usually in the form of soft capsules, with the health claim of benefits for the cardiovascular system, prostate cancer, and sports (Ciriminna et al., 2016).

5.2.2. Applications in cosmetics and dermatology

Other applications of lycopene are in the sectors of cosmetics and dermatology, as it provides photoprotection against UVB/A radiation (Grether-Beck et al., 2017). Exposure to UV radiation increases the production of radical oxygen species, which can be counteracted by the systemic or topical administration of carotenoids with antioxidant properties (Zuorro et al., 2013). Moreover, it has been suggested that lycopene suppresses ornithine decarboxylase, an enzyme responsible for stabilizing DNA, and associated with carcinogenesis. Thus, lycopene has emerged as a useful natural product to treat skin disorders caused by inflammatory

processes (Esposito et al., 2019) such as erythema (Stahl et al., 2001). The use of lycopene as an ingredient in cosmetics and skin care products, such as anti-aging creams, facial moisturizers, and eye-creams, is now widespread (Barbulova et al., 2015). Several studies have demonstrated that advanced drug delivery systems, such as nanoparticles, liposomes or cyclodextrins, enhance the topical therapeutic effects of lycopene (Caseiro et al., 2020; Esposito et al., 2019).

6. Future perspectives and conclusions

The huge amounts of waste generated by tomato processing industries worldwide constitute a promising source of bioactive compounds, above all, polyphenols and carotenoids. Tomato pomace and seeds stand out as residues from which a high quantity of phenolic acids and flavonoids can be recovered, together with lycopene, β -carotene, and lutein. Lycopene is by far the compound most prioritized for recovery, but extraction techniques with solvents typically provide only a moderate yield, due to the pigment's inaccessible localization within the thylakoid membranes of the chromoplasts and the compactness of tomato peel tissue. Although new innovative methods have improved lycopene extraction, obtaining this valuable bioactive compound in adequate levels remains a challenge.

With the aim of ensuring food supplies for future generations in the scenario of a rapidly growing global population, scientists are developing novel food ingredients that are both environmentally and ethically responsible. The replacement of synthetic food additives associated with health risks is another goal. In this context, some of the first applications of bioactive compounds obtained from tomato waste, mainly lycopene, have been in bread, meat derivatives, tomato-based products, edible oils, microcapsules, and active food packaging. However, it should be born in mind that despite the advances in the development of functional foods from tomato waste, any health claims require verification through *in vitro*, *in vivo* (animal) and nutritional trials.

Finally, nutraceuticals are attracting attention for their potential for healthy purposes. The nutraceutical and pharmacological sectors have begun taking advantage of bioactive compounds from tomato residues (mainly lycopene), but their application in dietary supplements, probiotics, ready-to-use therapeutic foods, or ready-to-use supplementary foods is still a pending task.

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