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Review

Tomato Waste as a Sustainable Source of Antioxidants and Pectins: Processing, Pretreatment and Extraction Challenges

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Abstract: Tomato processing waste (TPW), a byproduct of the tomato processing industry, is generated in significant quantities globally, presenting a challenge for sustainable waste management. While traditionally used as animal feed or fertilizer, TPW is increasingly recognized for its potential as a valuable raw material due to its high content of bioactive compounds, such as carotenoids, polyphenols and pectin. These compounds have significant health benefits and are in growing demand in the pharmaceutical and cosmetic industries. Despite this potential, the broader industrial utilization of TPW remains limited. This review explores the influence of various processing, pretreatment and extraction methods on the concentration and stability of the bioactive compounds found in TPW. By analyzing the effects of these methodologies, we provide insights into optimizing processes for maximum recovery and sustainable utilization of TPW. Additionally, we address the major challenges in scaling up these processes for industrial application, including the assessment of their ecological footprint through life cycle analysis (LCA). This comprehensive approach aims to bridge the gap between scientific research and industrial implementation, facilitating the valorization of TPW in line with circular economy principles.

Keywords: tomato processing waste; carotenoids; polyphenols; pectin; sustainability; circular economy; life cycle analysis; scale-up

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1. Introduction

According to the Food and Agricultural Organization of the United Nations (FAO), over 186 million tons of tomatoes were produced worldwide during 2022, with more than 20 million tons of tomatoes produced in Europe [1]. Most of the produced tomatoes (about two thirds) were sold fresh, while approximately one quarter to one third were processed by the food industry for obtaining different products such as tomato juice, canned tomato, puree, sauces, ketchup, powder and other products [2,3]. Depending on the final product and the processing steps used, such as peeling, deseeding, or both, there are different types of TPW—tomato peel, tomato seeds and tomato pomace (TP). Tomato processing industries generate different amounts of TP, ranging from 2% up to 10% of the total weight of processed tomato fruits [2,4–6] and consisting mainly of peel, seeds, vascular tissues and pulp residue [2,7]. Considering the given, the world tomato processing industry currently generates from around 6.2 million tons up to 9 million tons of TP per year [8]. Moreover, due to the growth of the global population, urban development and world economy, it is predicted that food processing industries will generate even more food waste, including TPW [5]. Here, it is important to emphasize that the tomato processing industries are mainly concentrated in USA, the European Union and China [3,6]. Hence, significant amounts of TP which currently have no real commercial value in global trading, can be easily collected and further managed and utilized. As reviewed by Chabi and

colleagues [9], TP has been used mainly as an organic fertilizer or animal feed and is rich in macro- and micronutrients as well as in different bioactive compounds such as antioxidants (carotenoids and polyphenols) and pectin. It is also a rich source of essential vitamins and minerals, particularly vitamins C, A and K, and it contains significant levels of the minerals potassium and iron. Further, TP is highly nutritional with an average content of 21% of crude protein, 38% of fibers, 13% of fat and 4% of ash [10].

Disposal of TPW presents a significant economic burden for a producer, primarily due to high waste management costs. In broader terms, large amounts of disposed TPW contribute to the generation of food industry waste which has a profound negative impact on global economy, climate change, biodiversity and the environment [1,11–13]. Therefore, it is particularly important to determine and investigate all aspects of further utilization of TPW as valuable raw material for other industries.

TPW is already being incorporated into circular models, which aim to reintroduce it into economic networks for further utilization by different sectors. At the industrial level, it is successfully used for the production of biodiesel fuel and electricity [14,15], soil fertilization and biosolarization [16,17] as well as for the production of biochar with agricultural applications [18].

In the last decade, the possibilities of sustainable utilization of TPW based on its nutritive value have mostly been recognized for the improvement of the nutritional value of animal feed [19,20]; development of added value products in food-, cosmetic- and pharma industries; conservation and improvement of a product's rheological and organoleptic properties [9]; and particularly, development of novel functional foods and nutraceuticals [21,22]. Therefore, the European Commission has funded numerous scientific projects focusing on their valorization. These projects, involving 24 countries, have received an overall budget of around €37 million over 35 years [23]. Considering the rising demand for natural-based products, which is expected to grow even further, TPW can be seen as a promising material for developing such products. Despite that, its broader industrial utilization is still scarce. Among the most important compounds of interest, carotenoids, polyphenols and pectin have the greatest potential for industrial utilization due to their specific physico-chemical properties and proven biological activity.

Carotenoids are natural lipid-soluble pigments that provide numerous health benefits since they play diverse roles in promoting human health. They pose strong antioxidative and anticancer properties and are implicated in reducing the risk of cardiovascular disease, improving cognitive function and reducing the progression of age-related macular eye disease and cataracts [24–27]. Carotenoids are therefore often used as functional ingredients in novel foods, pharmaceuticals and cosmetics. Complex carotenoid-rich extracts can be used in the production of nutraceutical supplements for promoting overall health and well-being. Since carotenoids are also known for their skin-protective properties they can be incorporated into skincare products like creams, lotions and serums to provide antioxidant protection and enhance skin radiance [9]. Market researchers agree that the demand for carotenoids will grow strongly in the future. The market size in 2024 is estimated to be worth USD 2.5 billion and it is prognosed to grow 6.3% annually until 2029 [28]. Another available market analysis states that the carotenoid market will be worth USD 9 billion by 2031, with an expected annual growth of 4.5% [29].

Polyphenols encompass a broad range of compounds found in nature that include simple phenols, phenolic acids, coumarins, flavonoids (such as flavanones, flavonols and flavones) and larger oligomers and polymers, like tannins and lignin. They are among the crucial components of the Mediterranean diet, known for their role in prevention of certain chronic diseases (such as metabolic syndrome, obesity, cardiovascular diseases, type 2 diabetes, and cancer) [30,31]. Polyphenols are also frequently incorporated into functional foods and pharmaceuticals [32]. In the global perspective, the polyphenol market is on the rise. One report describes the market size value as USD 1.7 billion in 2022, with an expected annual growth of 7.4% [33]. Similar information is provided by another report [34] that predicts a 7.5% annual growth and a market size of USD 2.5 billion by 2030. Today the main

sources of polyphenols for industrial application are grape seeds and green tea followed by other plants and vegetables.

Pectin is a structural plant fiber found in the cell walls and the intracellular layer of plant cells, particularly in fruits such as citrus fruit and apples. Despite its high abundance in a variety of plants, only pectin from particular sources possesses adequate functional properties and can be further utilized in industrial applications. The functionality of pectin is mostly dependent on its ability to form gels which is conditioned by the molecular size and the degree of methoxylation (DM), which can vary depending on its source and the extraction conditions [35]. Commercial pectin can be classified into low-methoxyl pectin, containing less than 50% methyl ester groups and requiring presence of calcium ions for gelation, and high-methoxyl pectin containing more than 50% methyl ester groups and requiring sugar and acid for gelation. The gel strength is primarily related to the molecular weight (Mw) of pectin, meaning that higher average Mw is related to increased viscosity of the formed gel and higher gel strength [36]. Pectin is commonly used in food and pharmaceutical products as a gelling, stabilizing, emulsifying and thickening agent. It is also prescribed as a dietary supplement or therapeutic for certain conditions like diarrhea or throat and mouth soreness [37]. The pectin market is estimated to reach a value of USD 1.8 billion by the year 2026 and it is expected to grow even further [38]. TPW can be a valuable source of pectin since dry TP consists of 10–15% of pectin [39], highlighting its potential to be exploited as a raw material for pectin production [40].

Being a rich source of carotenoids (lycopene, β-carotene, α-carotene, lutein, phytoene, phytofluene) and abundant polyphenolics (such as phenolic acids and flavonoids) [41,42] TP shows great potential as a source material for producing polycompound extracts that enhance health benefits. Fouda and colleagues [43] support the idea that single compounds may not replicate the beneficial effects seen with complex mixtures, which emphasizes the importance of considering food industry waste not only as a source of individual bioactive components but also as multicomponent extracts, which could lead to more effective dietary supplements or functional foods in health applications.

With the increasing number of publications on TPW valorization, many review articles have emerged in recent years focusing on specific aspects of TPW utilization. For example, Coelho and colleagues [44] and Laranjeira and colleagues [45] have concentrated on the chemical characterization and applications of bioactive compounds in TPW, while Eslami and colleagues [46] examined characteristics of available extraction methods. Several recent reviews [47–49] have addressed the effects of industrial processing on the content of nutrients and bioactive compounds in tomatoes.

To effectively utilize TPW, it is essential to consider all factors that significantly influence the final concentration of the desired compound(s). These include the effects of tomato processing, additional raw material pretreatment, and the applied extraction method. Furthermore, the scale-up challenges and industrial applicability of these methods must be determined, focusing on achieving sustainability by using objective, scientifically based methodology, such as LCA.

This review specifically explores how various processing, pretreatment and extraction methods impact the levels and stability of carotenoids, polyphenols and pectin in TPW. By providing a detailed analysis of these methodologies, we aim to offer broader insights into optimizing these processes for the maximum recovery of bioactive compounds. Additionally, we address the major obstacles to the widespread industrial utilization of TPW, including the assessment of the ecological footprint of particular processes (as analyzed by LCA) and challenges of industrial scale-up. By integrating both technical aspects and practical challenges, our review presents a comprehensive approach to bridging the gap between scientific research and industrial implementation.

2. Green Approaches in Extraction of Bioactive Compounds from Food Industry Waste

Extraction is one of the most extensively researched processes, as it can greatly influence the yields and quality of the final product. However, it also represents the most challenging step in terms of efficient scale-up to industrial level.

Among the available methods, the one that requires the simplest equipment is conventional solvent extraction (CSE). However, it often involves excessive utilization of organic solvents, prolonged extraction time and degradation of thermolabile compounds [50], directing the focus of contemporary research towards advanced extraction techniques that provide more sustainable solutions from both ecological and economical aspects. For example, in ultrasound assisted extraction (UAE) cavitation bubbles are generated and collapsed, causing disruptions in cellular structures and facilitating solvent penetration leading to more efficient extraction [51]. Another technique often used is microwave assisted extraction (MAE). It is based on the solvent absorption of microwaves leading to an increase in kinetic energy and temperature, which promotes the destruction of plant cells and the extraction of desired compounds [52]. In ohmic heating assisted extraction (OHAE) plant cell walls are disrupted by increasing the temperature of the system by applying an electrical field. Depending on the biomass characteristics, the application of the electrical field can cause electrical breakdown, electroporation and electro permeabilization of tissues and cells and improve extractability of target compounds. The temperature also enhances the penetration capability of the solvent into the sample matrix by lowering its viscosity. The increased diffusivity improves the mass transfer of dissolved compounds, thus improving the extraction efficiency [53]. Furthermore, high pressure extraction (HPE) applies high pressure (100–800 MPa) to destroy the cell wall without using high temperature, allowing the extraction process to occur at lower temperatures compared to conventional methods, thus preserving the compounds' stability [54]. It accelerates solvent permeation, shortens the dissolution equilibrium time of the target active component, and increases its diffusion rate, resulting in a high extraction rate and efficiency [55]. Special consideration is given to supercritical fluid extraction (SFE) where the solvent behaves as both the liquid and the gas under high pressure conditions. By controlling the extraction conditions, the solvent's properties can be modulated to increase the yields of the desired compounds [56]. Enzyme assisted extraction (EAE) involves using enzymatic pretreatment of raw materials to release substances bound to the cell walls, thereby increasing the total yield of extracts. EAE is affected by several factors, including medium pH, temperature, treatment time and enzyme selection. Choosing the right enzyme ensures extraction of specific compounds from an intricate matrix [57].

Future strategies should incorporate optimization methodologies to model the extraction parameters that significantly impact the yields and quality of the product, such as solvent type, extraction time, temperature, pressure and solid to solvent ratio. It can lead to more sustainable processes with reduced production costs, making the extraction economically viable. Response surface methodology (RSM) has been widely used in this context across many disciplines. It is fairly simple to model, while at the same time it can describe multiple interactions between different variables [58]. Newer approaches to modelling extraction procedures include neural networks, genetic, particle swarm and harmony algorithms [59,60]. However, few of the mentioned have been applied so far in the extractions that use tomato as a source material [61,62].

It is important to emphasize that the major issue concerning the novel extraction procedures is their scale-up ability to pilot or industrial scale in terms of technological readiness of the procedure, is the costs of scale-up or maintenance or both. Recent analysis shows that in the case of TPW utilization, industrial technology readiness level has been fully achieved only for processing the TPW into animal feed, composting it or converting it into biogas (by the process of anaerobic digestion), while the technological readiness of the extraction of total carotenoids, polyphenols and pectin is still at the laboratory level [63]. Significant efforts will have to be invested to ensure efficient, reliable, profitable, reproducible and environmentally safe extraction procedures.

3. Impact of TPW Processing and Extraction Conditions on Carotenoid Yields

The carotenoid content and extractability from TP can be significantly influenced by processing, pretreatment and extraction methods. Therefore, studying their effect is crucial for maximizing carotenoid recovery from TP, and the choice of method depends on the desired purity, yield and targeted environmental impact.

Processing of tomatoes often involves one or more heat treatments (to facilitate peeling and improve the yields and physico-chemical properties of tomato juice). Heat treatments can affect the content of carotenoids in TPW by different degrees, depending on the chemical characteristics of a particular carotenoid. Lycopene concentration generally increases after heat treatment due to improved extractability from the tomato matrix [64]. Heating breaks down cell walls and weakens the bonds between lycopene and plant tissue, enhancing its extraction [65]. However, excessive heating can degrade lycopene due to isomerization and oxidation [66]. Lycopene is relatively thermally stable, and isomerization is minimal in tomato-based foods during mild thermal treatments (up to 100 °C for 2 h) [67]. Studies comparing cold break (CB) processing at 65–75 °C and hot break (HB) processing at 85–95 °C show different lycopene contents. CB-processed samples had an average lycopene content of 41.04 ± 1.24 mg/100 g dry weight, while HB-processed samples had 9.53 ± 0.62 mg/100 g dry weight, indicating lycopene degradation at higher temperatures [68]. Hassen and colleagues found that increasing breaking and concentration temperatures significantly increased lycopene content [69]. Thermal degradation varies by compound, with lycopene losses ranging from 9% to 28% during processing into paste, while other carotenoids like beta-carotene, phytoene and phytofluene showed no consistent changes [70]. β-carotene and lutein concentrations tend to decrease after heat treatment, with more pronounced losses in the peel for β-carotene and in the pulp for lutein [64]. Jacob and colleagues confirmed that moderate heat treatment (e.g., 110 °C for 15 min) can increase total lycopene content by around 30%, but prolonged heating can cause a slight decrease [71]. Heating partially degrades these carotenoids and induces isomerization, especially for lycopene, converting all-trans (E) to various cis (Z) isomers, with Z isomer proportions increasing with longer heating [65]. It has to be considered that Z isomerization affects carotenoid bioavailability, as different isomers have unique solubility and stability. The impact of Z isomerization on bioavailability varies among different carotenoids. For lycopene, Z isomers are more bioavailable than the all-E isomer [72]. Conversely, for β-carotene, the all-E isomer is more bioavailable than the Z isomers [72,73]. The effects of Z isomerization on the bioavailability and tissue accumulation of other carotenoids, such as α-carotene and zeaxanthin, have also been studied, but the results are less definitive compared to lycopene and β-carotene [72]. Thus, the effects of heating on carotenoids in TPW depends on the type of carotenoid, temperature and duration. While heat aids the release of carotenoids from the tomato cell matrix, excessive heat or prolonged exposure can decrease their content, leading to isomerization and degradation. Therefore, thermal processes should be carefully managed when considering TPW as a source of specific carotenoids.

Pulsed Electric Field (PEF) and steam blanching enhance plant cell permeability through electroporation, which can be utilized in tomato processing to facilitate peeling, increase juice yields, and improve the valorization of TPW. Carotenoid extraction yield increased by up to 56.4%, and lycopene extraction rose from 9.84 mg/100 g to 14.31 mg/100 g of tomato residue with a PEF treatment at 1.0 kV/cm for 7.5 ms. Incorporating targeted PEF pretreatments in industrial tomato processing results in reduced energy demand and increased productivity [74]. Pataro and colleagues reported significant cuticular damage, leading to a total carotenoid yield increase of up to 188% due to PEF pretreatment of tomato peel [75]. In the same study, steam blanching was as effective as PEF, resulting in an 189% increase in total carotenoids. Interestingly, combining PEF and steam blanching (SB) significantly boosted carotenoid content showing a synergistic effect even at 60 °C (37.9 mg/100 g fresh weight tomato peels). HPLC analyses revealed that lycopene was the main carotenoid extracted, and neither PEF nor SB caused selective release or degradation

of lycopene. This study demonstrates that integrating PEF into the tomato processing line before SB enhances the valorization of TPW.

Various pretreatment techniques could have been applied to TP to enhance the extractability and quality of carotenoids and other bioactive compounds. These techniques include drying and milling.

Drying TP reduces its weight, volume and water activity, significantly affecting carotenoid yields. However, results from various studies are inconsistent. For example, Lazzarini and colleagues investigated different drying methods (freeze drying, heat drying and non-thermal air-drying) and found that non-thermal air-drying produced extracts with the highest contents of lycopene and β-carotene (75.86 and 3950.08 μg/g of dried sample, respectively) compared to other methods [76]. Conversely, Moreno and Díaz-Moreno found that β-carotene concentration remained unchanged when tomatoes were dried at 50 °C, 60 °C or 70 °C [77]. Popescu and colleagues examined three drying processes (oven drying, vacuum oven drying and hot air drying) for tomato peels over 5 h at temperatures between 50 °C and 120 °C. They reported the highest lycopene amount (329 mg/100 g dried tomato peels) from hot air drying at 80 °C [78].

Milling is also an important pretreatment step, with factors such as heat, light, and oxygen exposure during milling significantly contributing to carotenoid degradation and loss, and mechanical degradation of sample influencing its extractability. While we could not find studies specifically focusing on TPW, it is crucial to consider these factors when valorizing TPW as a source of carotenoids. Namely, it was already shown that milling has a significant effect on physical properties, bioactive compounds and structural characteristics of food industry waste, such as onion peel [79]. Therefore, we believe that more studies are needed to understand the impact of milling and particle size on specific carotenoids in TPW.

Extraction methods constitute one of the most extensively researched aspects of TPW valorization. Lycopene, being the carotenoid with the highest content in TPW, has been the primary focus of investigation in the majority of studies. Optimizations of β-carotene extraction are also prevalent, while research on lutein, phytoene and phytofluene extraction has been relatively scarce. Specific carotenoids have been quantified using spectrophotometry or HPLC-DAD detection, with spectrophotometry being the predominant method for total carotenoid content. Carotenoid content is typically expressed on a dry basis of TPW, although some studies have expressed it on a wet basis or as a concentration in oleoresin or extract, as indicated in Table S1. Investigations included in this review have primarily targeted TP and tomato peel, as these parts contain the highest concentrations of carotenoids [80]. While tomato seeds contain the same carotenoids as pomace and peel, their extraction is not significant for large-scale procedures due to much lower concentrations.

As summarized in Figure 1 and Table S1 [81–98] in detail, various green extraction technologies for obtaining carotenoid-rich extracts from TPW have been developed, each offering distinct advantages. In that matter, green extraction approaches used typically involve the use of non-toxic solvents, such as water or carbon dioxide, and/or physical methods such as high pressure, ultrasound, microwaves, or enzyme pretreatment as described in previous chapter.

Kehili and co-authors investigated the recovery of lycopene from tomato peels derived from industrial processing by using SFE [82]. They reported that optimal conditions (400 bars, 80 °C, 105 min, 4 g CO_2/min and 0.4 g CO_2/g peels) achieved a maximum lycopene recovery of 72.898 mg/100 g dry weight. These results were compared to conventional extraction methods (overnight at 200 rpm and 25 °C) using hexane, ethyl acetate and ethanol as solvents and it was concluded that SFE resulted in higher extraction of lycopene than conventional methods. Hatami and coauthors also evaluated lycopene recovery by SFE-CO_2 from TP [81]. They found that the peel/seed ratio had the greatest impact on lycopene recovery, followed by pressure and temperature. The combination of pressure and temperature showed a positive synergistic effect on lycopene recovery, with pressure being more effective at higher temperatures. Due to the higher lycopene content in peels

compared to seeds, the optimized conditions (80 °C, 50 MPa and a peel/seed ratio of 70/30) resulted in the highest lycopene recovery (0.132 mg/100 g of raw material). Additionally, Popescu and colleagues identified optimal conditions for SFE-CO_2 at 450 bars, 70 °C and 11 kg/h, achieving lycopene yields of 1016.94 mg/100 g of extract and beta carotene yields of 154.87 mg/100 g of extract [83].

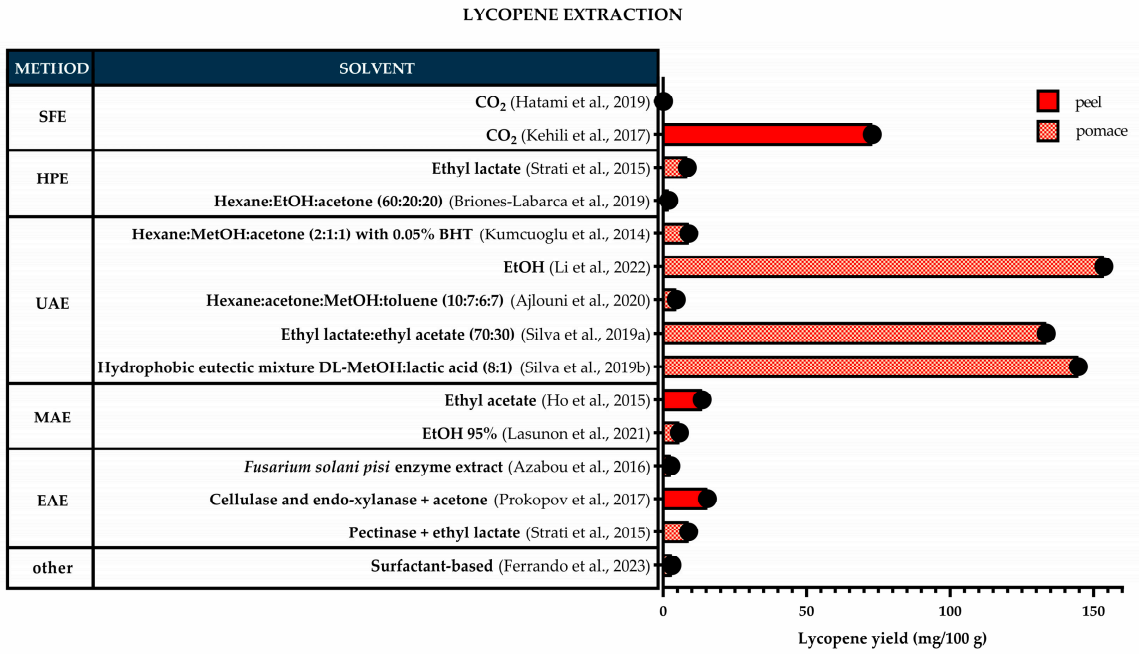


Figure 1. Available extraction protocols for obtaining lycopene from TPW. SFE-supercritical fluid extraction, HPE-high pressure extraction, UAE-ultrasound assisted extraction, MAE-microwave assisted extraction, EAE-enzyme assisted extraction, EtOH-ethanol, MetOH-methanol. References: Hatami et al., 2019 [81], Kehili et al., 2017 [82], Strati et al., 2015 [85], Briones-Labarca et al., 2019 [86], Kumcuoglu et al., 2014 [87], Li et al., 2022 [88], Ajlouni et al., 2020 [89], Silva et al., 2019a [90], Silva et al., 2019b [91], Ho et al., 2015 [92], Lasunon et al., 2021 [93], Azabou et al., 2016 [94], Prokopov et al., 2017 [96], Strati et al., 2015 [85], Ferrando et al., 2023 [97].

Regarding the HPE, Jurić and coauthors applied 1–10 passes at 100 MPa to recover lycopene from tomato peels using only water as a solvent [84]. HPE reduced the size of tomato peel particles in suspensions, leading to the complete disruption of plant cells and the release of high-value compounds. HPLC analyses confirmed that the content of lycopene recovered from tomato peels (19.3 mg/g dry weight) was significantly higher than previously reported (0.5–0.8 mg/g dry weight). Importantly, this method was sustainable, green and entirely physical, allowing the final products to be used in functional food formulations or to enhance the bioactivity of peeled tomato products. In 2018, Briones-Labarca and coauthors optimized lycopene extraction conditions by focusing on individual and interactive effects of high pressure and solvent polarity using RSM [86]. Optimal conditions were determined to be 450 MPa and with a 60% hexane concentration, which provided the maximum lycopene content (2.01 mg/100g dry weight). Thus, HPE can effectively enhance the extraction and release of carotenoids, offering insights into the combined effects of solvent polarity and HPE on the carotenoids in TPW.

UAE has been extensively researched for maximizing carotenoid yields from TPW in the past and still it remains the focus of current investigations. Ajlouni and coauthors investigated lycopene extraction from both laboratory-prepared and industrial TPW using ultrasound (45 min at 50 Hz) with a hexane:acetone:methanol:toluene, 10:7:6:7 v/v/v/v mixture [89]. The study found that UAE resulted in lycopene recoveries of 4.6 mg/100 g of dry TP, which corresponded to a significant increase in lycopene extraction yields from industrial TPW compared to the CSE in the same solvent. More recent studies have combined

ultrasound with various encapsulation techniques to improve the stability of extracted carotenoids from TPW. For instance, Li and coauthors [88] optimized UAE extraction of lycopene with ethanol using RSM. The optimal conditions led to the production of an extract with notable properties including a lycopene yield of 153.6 mg/100 g dry weight. Due to the instability of lycopene, encapsulation of the extract by spray drying was undertaken using inulin and maltodextrins as coating agents, which significantly improved its stability.

MAE was investigated in several studies and was found suitable for efficient lycopene recovery. Ho and coauthors optimized MAE of lycopene from tomato peels and evaluated the effect of treatment on all-trans and isomer yields [92]. Optimum MAE conditions were determined to be a 0:10 solvent ratio at 400 W, resulting in a yield of 13.592 mg/100 g of extracted all-trans lycopene. RSM suggested that ethyl acetate was more efficient for MAE lycopene recovery compared to hexane. MAE significantly improved all-trans and total lycopene yields compared to CSE that demonstrated higher proportions of cis isomer yields. In a recent study by Lasunon and coauthors, lycopene was extracted with ethanol [93], obtaining the highest levels of trans lycopene and beta-carotene (with 5.74 mg of lycopene per 100 g and 4.83 mg of beta-carotene per 100 g) using MAE at 300 W for 60 seconds.

EAE is often characterized with superior extractability of lycopene compared to ultrasonic, microwave and high-pressure methods [95,99]. Enzymes with pectinolytic, cellulolytic and hemicellulolytic activities, such as pectinase, cellulase and hemicellulase, hydrolyze the cell wall structure, resulting in increased extractability of lycopene. Parameters that affect EAE are various and include type of enzyme, solid to crude enzyme solution ratio, number of extractions, extraction time, temperature, particle size and pH, which were optimized in the studies listed in Figure 1 and Table S1 in detail. However, its application is complex due to the need for multiple steps and strict pH and temperature conditions, which complicates scale-up and thus its application in industry. Also, the high cost of different enzymes makes the procedure less profitable for companies.

It is obvious from the above examples that various factors, such as temperature, solvent polarity, particle size and pH, can significantly influence carotenoid extraction efficiency from TPW. Understanding and optimizing these factors is essential for maximizing yield and quality. For example, a temperature of 55 °C was identified as optimal for maximizing lycopene yield in the extract [100]. Additionally, SFE-CO_2 of carotenoids from tomato slices showed that an extraction temperature of 70 °C was favorable for carotenoid recovery, influencing both efficiency and extract quality [83]. The choice of solvent polarity is crucial, as evidenced by the optimal ratio of ethyl acetate to TPW found to enhance lycopene yield [100]. Particle size also influences extraction efficiency, with reducing pomace particle size through milling potentially improving yield [100,101]. pH optimization, particularly in EAE methods, can enhance carotenoid recovery by facilitating cell wall breakdown and compound release [83,101].

4. Impact of TPW Processing and Extraction Conditions on Polyphenol Yields

Food processing methods, especially those involving high temperatures, can release polyphenols, potentially enhancing their availability and allowing them to exert their biological effects. Research shows that heating can impact the content of certain polyphenols, including flavonoids, by modifying their extractability through the disruption of cell walls. As a result, polyphenols bound to the cell walls may be more easily released compared to fresh tomatoes [102], supporting the idea that TPW is a suitable source of polyphenols. The content of phenolic acids, more specifically caffeic and p-coumaric acid, increased severalfold in TP exposed to heat treatment compared to fresh tomatoes, whereas the content of ferulic acid slightly decreased in the same study. Moreover, chlorogenic acid was not detected in fresh tomatoes while it was the predominant phenolic acid in TP [103].

The effect of TPW drying on the extractability and quality of polyphenols was investigated in several recent studies. Chada and coauthors proposed drying in spouted beds as a promising alternative for drying pasty materials like TP, yielding a high-quality, low-cost powder. They compared the drying in spouted beds and oven drying of TP and concluded

that this nonconventional method was significantly more efficient than the conventional oven drying in preserving the antioxidant compounds [104]. The most comprehensive study that focused on the optimal drying technology for TPW was conducted by Souza da Costa and coauthors. In their study, they investigated techniques that can be easily scaled-up to an industrial level while ensuring high shelf stability and maximum retention of valuable bioactive compounds, including polyphenols. Various dehydration methods were examined, including freeze drying, air drying at 40 °C and 60 °C, microwave-assisted drying and Spiral Flash® air drying. Authors reported that microwave dehydration enhanced the retention of flavanone-like compounds, particularly naringenin. In contrast, tomato products dehydrated with the Spiral Flash® dryer had higher concentrations of flavonols and phenolic acids. These findings suggest that industrial drying processes using the Spiral Flash® dryer, and especially with microwaves, could be promising for producing high-value ingredients from TPW [105].

Among the most extensively researched aspects of the possibilities of TPW, valorization is the best choice and offers the greatest optimization of the extraction process. Total phenolic content (TPC; typically expressed as gallic acid equivalents (GAE)) and total flavonoid content (TFC; typically expressed as catechin equivalents (CE)) are used predominantly as extraction process output parameters, probably because of being simpler, cheaper and more available compared to more sophisticated and specific chromatographic techniques. Despite simplicity and low selectivity, TPC and TFC provide valuable data about the quality of obtained extract since they provide a solid estimation of the total amount of polyphenolic compounds in obtained extract. Namely, as previously mentioned, in terms of functional properties and biological activity, complex plant extracts offer certain advantages compared to pure compounds that are either industrially produced or isolated from plants. Probably due to the presence of interacting compounds present in the whole extract that often results in additive or synergistic effect. Another downside of pure compound products is that they are often more expensive to produce, making them less profitable.

Specific polyphenols are usually detected by HPLC coupled with DAD, UV–Vis, DAD-MS or UHPLC-PAD. Chlorogenic acid, gallic acid, caffeic acid and ferulic acid are those that are determined most often. Interestingly, the above-mentioned polyphenols are not those with the highest concentration in TPW [106]. Paradoxically, those presented in higher concentrations, such as naringenin and its derivatives, are often neglected. Naringenin is a compound that is gaining increasing amounts of attention from researchers for its anti-inflammatory and immunomodulatory effects [107], anti-carcinogenic activity [106] and neuroprotective effects against degenerative diseases such as Alzheimer's [108]. Therefore, it is to be expected that naringenin would also be in the focus of future studies that examine the methods for polyphenol extraction from TPW. Moreover, some compounds that are usually presented in high concentration in TPW, such as chlorogenic acid [109], failed to be detected in some studies, possibly due to low stability of this molecule during storage of dehydrated TPW [110]. This indicates the importance of considering the stability of specific molecules when using food industry waste as their source.

Regarding the type of TPW, existing investigations of polyphenol content were mostly performed on whole TP, but there are also several studies that used tomato peel and/or tomato seed as the raw material. Concha-Meyer and coauthors compared polyphenol content in whole pomace, seedless pomace and seeds and observed that removing the peels resulted in a 63% loss of polyphenols [110]. Polyphenol content from tomato peel was compared to other types of food industry waste, and it was shown that TPC was several times higher in tomato peel extract than in lemon extract and that several types of polyphenols were detected only in TPW (compared to waste such as fennel-, carrot- or lemon-pomace), suggesting a certain superiority of TPW as a potential source of polyphenols [32,111].

Various extraction technologies have been applied for the recovery of polyphenols from TPW, each one offering distinct advantages and possibilities of applications (Figure 2 and Table S2 in detail), as described previously. Since TPW polyphenols are less lyophilic

than carotenoids, the solvents used for their extraction, such as ethanol and methanol, are less toxic than those used for carotenoid extraction. However, their extensive use still raises operating costs and environmental concerns. CSE is not effective for extracting bound phenolics from plant matrices [112] so, to enhance the extractability of bound phenolics, alkaline or acid hydrolysis is typically applied [113], which makes this approach environmentally unfriendly due to the high demand for strong acids or bases and the need for extremely high temperatures (up to 80–95 °C for acid hydrolysis) [114]. To overcome these challenges, various alternative techniques have been proposed in the literature, including UAE [32,109–111,115–118], MAE [93,118,119], Soxhlet extraction [120], HPE [115], high voltage atmospheric cold plasma assisted extraction (HVACP) [121] and fermentation assisted extraction [107], which can significantly improve polyphenol yields from TPW. Several works compared the efficiency of innovative extraction techniques for polyphenol extraction from TPW with CSE (Table S2).

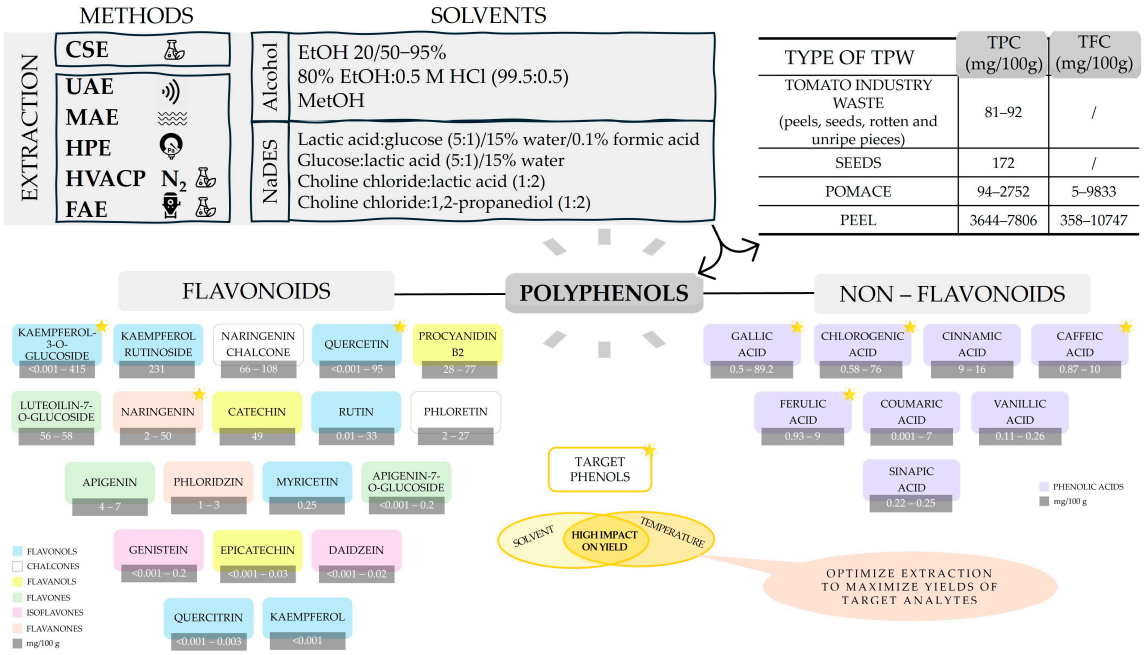


Figure 2. Available extraction protocols for obtaining polyphenols from TPW. CSE—conventional solvent extraction, HVACP—high voltage atmospheric cold plasma, TPC—total phenolic content, TFC—total flavonoid content, NaDES—natural deep eutectic solvents, TPW—tomato processing waste, composed of peel, seed and pulp.

UAE has been the most utilized method for obtaining polyphenols from TPW. Plaza and coauthors reported that optimized UAE resulted in higher TPC when compared to MAE [117]. However, it is of the highest importance to consider the extraction procedure conditions with respect to analytes of interest. Namely, another reported a UAE procedure with following parameters: water as a solvent, 100%, 90 W, 20 min, 45 °C, 3 cycles with a 10 min pause in between, failed to extract specific valuable compounds- kaempferol and quercetin from tomato seeds, and kaempferol-3-O-glucoside from seedless TP [110].

The parameters that are usually optimized in UAE include: solvent type, frequency, solid to solvent ratio, number of extractions steps, extraction time, temperature and particle size. The most commonly used solvents include ethanol (20–85%) and deep eutectic solvents (DESs), such as a mix of glucose and lactic acid [111,116], a mix of choline chloride and 1,2-propanediol or choline chloride and lactic acid [109]. DESs were proposed as simple, inexpensive, eco-friendly and robust for extraction of polyphenols. Moreover, they were also used for cosmetic formulations and showed film-forming thanks to their biocompatibilities, so the authors suggested that coupling of the extraction and formulation

by natural DESs is a way to preserve the quality of the extracts and prepare ecodesigned formulations [116].

As previously mentioned, MAE was shown to be less efficient than UAE in the extraction of polyphenols from TP [117]. However, a study conducted on tomato seeds confirmed that MAE extracts exhibited higher TPC compared to UAE (172 and 161 mg GAE for MAE and UAE, respectively) and a higher content of chlorogenic acid, rutin and naringenin (1.11, 1.38 and 2.99 per 100 g for MAE and 0.58, 0.75, and 1.93 per 100 g for UAE, respectively) [118]. These observations confirm that the selection of suitable extraction method is largely dependent on the TPW type. Bakić and coauthors evaluated effects of solvent, temperature and time with regard to TPC, TFC and specific phenolics compound content in TPW. Their results revealed that extraction time had no significant impact on TPC, TFC and particular phenolic compounds recovery (with the exception of cis-p-coumaric acid hexoside). On the other hand, the influence of temperature and chosen solvent on polyphenols yield was significant [119]. Lasunon and colleagues reported that the optimal extraction condition for MAE of total phenols was 180 W for 90 s yielding 280 mg GAE/100 g while for the optimal extraction condition of total flavonoids was 450 W for 30 s yielding 9832 CE/100 g. However, the highest antioxidant activity was the sample extracted at 300 W for 60 s [93]. These findings highlight the importance of optimizing extraction procedures for analytes of interest to maximize their yields and lowering the cost of implementing innovative methods such as MAE.

Overall extractability of polyphenols from TPW can additionally be improved by optimized atmospheric conditions before or during the extraction, such as pressure or the presence of oxygen or some other gas. HPE has been suggested as an alternative to traditional thermal methods for extracting polyphenols from tomato peel produced by the canning industry. Ninčević Grassino and coauthors [115] investigated the effects of time, temperature and various solvents at a constant pressure of 600 MPa on polyphenol yields. The results showed significant variations in the levels of many phenolic compounds based on the temperatures and solvents used. However, the duration of HPE did not affect polyphenol yields. Among the phenolic compounds, p-coumaric acid and a chlorogenic acid derivative were predominant, ranging from 0.57 to 67.41 mg/kg and 1.29 to 58.57 mg/kg, respectively, depending on the solvents and temperatures applied. Methanol (at 50% and 70%) at temperatures of 45 and 55 °C was particularly effective in enhancing the recovery of polyphenols compared to other solvents.

Kocak and colleagues examined the influence of ambient oxygen on the properties of obtained extracts by evaluating them under both atmospheric and oxygen-free conditions. They concluded that ambient oxygen significantly affected these properties. Specifically, they found that the TPC was higher when extraction was conducted without the presence of oxygen [122].

The extractability of polyphenols from the complex plant matrix can be additionally improved by modifying the biomass through creating ruptures in its cell wall structure and increasing its surface hydrophilicity. For that purpose, pretreatment of TP by high voltage atmospheric cold plasma (HVACP) with different working gases (air, Ar, He and N_2) was investigated. Treating TP with He and N_2 increased yields of phenolic compounds by nearly 10%, regardless of the type of gas used. Therefore, the authors proposed the developed HVACP pretreatment technology as a promising method for valorizing TPW [121]. Given that using He could be up to 40 times more expensive than N_2, it can be considered less applicable in the food processing industry compared to N_2.

In conclusion, understanding the impact of various processing treatments in the tomato industry and optimizing the pretreatment of TPW and extraction protocols is vital for maximizing polyphenol recovery, ensuring product quality, promoting sustainability, and improving process efficiency. By selecting the most suitable fraction of TPW and fine-tuning parameters through systematic optimization, researchers and industries can unlock the full potential of polyphenol-rich extracts from TPW for diverse applications in pharmaceuticals and cosmetics.

5. Impact of TPW Processing and Extraction Conditions on Pectin Yields

Two major industrial sources of pectin are citrus peel and apple pomace. Due to rising demands in the last decades and projected demand rise in the period 2024–2030 [123], there is an increasing interest in investigating nontraditional pectin sources. Bearing in mind growing attempts for boosting circular economy and reducing dependency on primary resources [124], the emphasis is set primarily on investigating applicability of different types of agricultural and food industry waste [125,126]. Comprehensive investigations conducted in the last 10–15 years indicate that TPW can be considered an important alternative source of pectin [127].

As shown in Figure 3 and in detail in Table S3, TPW derived pectin yields and their functional properties differ significantly, depending on the type of used raw material (whole TP, tomato peel or tomato seeds) and extraction conditions (type of extraction, solid to solvent ratio, solvent type, duration and temperature of extraction, number of subsequent extraction steps etc.). Data show that for obtaining pectin from TPW different extraction techniques have been applied: CSE, UAE, MAE, OHAE, HPE and subsequent extractions combining two techniques (UAME and UAOHE).

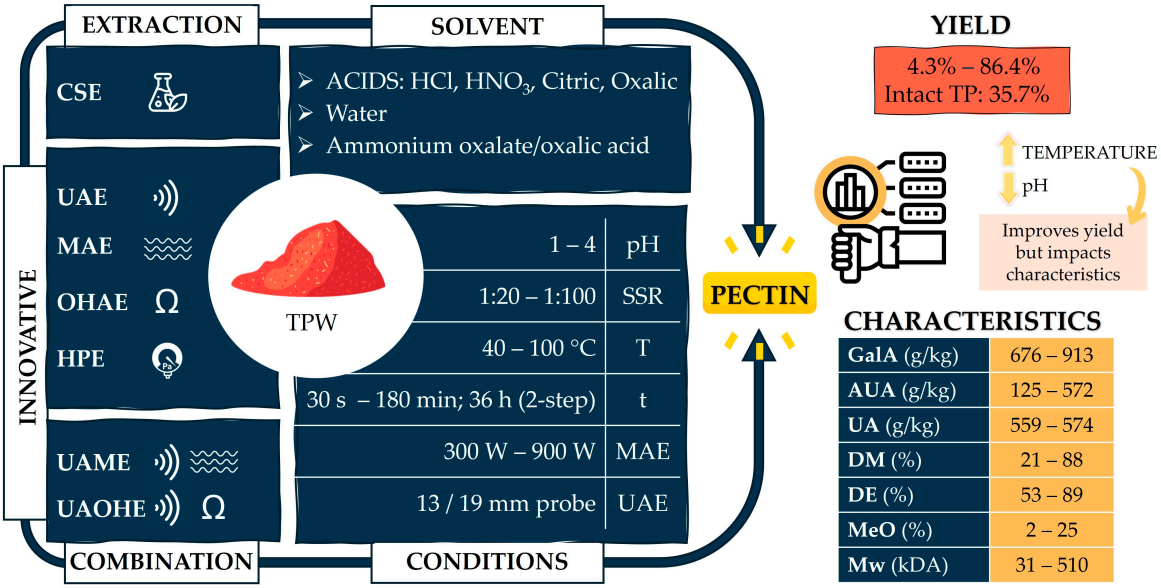


Figure 3. Available extraction protocols for obtaining pectin from TPW. UAME—ultrasound-assisted microwave extraction, OHAE—ohmic-heating-assisted extraction, UAOHE—ultrasound-assisted ohmic heating extraction, SSR—solid to solvent, TP—tomato pomace, GalA—galacturonic acid content, AUA—anhydrouronic acid, UA—uronic acid, DM—degree of methylation, DE—degree of esterification, MeO—metoxyl content, Mw—viscosimetric average molecular weight.

Obtained yields ranged from 4.3% (obtained by classical ammonium oxalate/oxalic acid extraction from black TP) up to 86.4% (obtained by high-pressure homogenization-facilitated acid extraction of alcohol insoluble residue remaining after blanching of tomatoes) [128]. Taking into account only intact TP, the highest obtained pectin yield was 35.7%, and it was obtained by UAE using ammonium oxalate/oxalic acid extraction [129].

Green extraction techniques such as UAE and MAE generally produce higher yields compared to CSE when conducted under similar conditions (time, solvent pH) [93]. When optimized to produce the highest yields, green extraction techniques are in the majority of cases significantly shorter compared to CSE. For example, Grassino and coauthors [129] obtained similar pectin yields after 36 h of CSE and 180 min of UAE. In 30 and 45 min extraction protocols, HPE resulted in 14–15% increased yields compared to CSE [115]. Among green extraction protocols, MAE seems to produce the highest yields, compared to UAE or OHAE, under optimized extraction [93,130–136]. Lasunon and colleagues

concluded that applying higher microwave power and shorter extraction times results in maximal yields in MAE [93].

Impact of the type of extraction on tomato pectin quality characteristics has been less investigated. Grassino and colleagues [129] compared chemical characteristics of pectin obtained by CSE and UAE and concluded that they are primarily affected by temperature and duration of extraction, and less by extraction technique. However, pectin obtained by MAE had a significantly higher galacturonic acid (GalA) and lycopene content compared to UAE obtained pectin, in spite of similar extraction conditions [93].

In the majority of available investigations, yields were increased by applying higher temperatures [127,132], lower pH values [93,127,128,136], and prolonged extraction times [93,127,129,132,133,136] regardless of the extraction technique (CSE, UAE, MAE). Yield improvements achieved by prolonged extraction times were not always significant. Grassino and colleagues [129] showed that prolonged duration of UAE (from 15 to 90 min) results in a non-significant increase in yield (from 15.2% to 17.2% (60 °C) and from 16.3% to 18.5% (80 °C)), but reduced quality parameters (as shown by reduced MeO (5.56–4.50/4.5–3.8); anhydrouronic acid (AUA) (37.6–31.4/33–27) and degree of esterification (DE) (87.9–84.8/89–77)). Lasunon and coauthors [93] combined MAE and UAE in the two-step extraction process and obtained higher yields compared to UAE or MAE alone (340.6 g/kg vs. 282.5 (UAE) and 301.2 g/kg (MAE)). Investigations of optimal solvents for pectin yields showed that citric acid provided higher yields and AUA compared to HCl, HNO_3 or oxalic acid [132,135], while HCl has been proven better than combination of ammonium oxalate and oxalic acid resulting in higher yields, higher GalA and DM [131]. Additionally, 1:50 SSR seems to be optimal for maximizing extraction yields; further increases in SSR did not produce significant effects [93,136].

As presented in Figure 3 and in detail in Table S3, the majority of authors provided data on chemical characteristics of pectin (content of GalA, uronic- (UA), and AUA; DM; DE; Mw; or methoxy-content (MeO)). Depending on the literature source, results of the rheological analysis, infrared radiation (IR), nuclear magnetic resonance (NMR), color, the content of particular bioactive components (polyphenols, carotenoids) or functional characteristic (corrosion inhibition) were also provided.

Chemical characteristics of TPW derived pectin differed significantly depending on the extraction conditions. GalA varied between 676 and 913 g/kg [131,133] and AUA between 125 (tomato peel) and 572 g/kg [129,130]. UA content was less variable—between 559 and 574 g/kg, but only because data were provided by one group of authors and derived from the same batch of raw material by applying similar extraction conditions [128]. The average DM was 57%, ranging from 21 [131] up to 88% [127], and the average DE was 74%, ranging from 53% [135] up to 89% [129]. Mw of tomato derived pectin was presented only by two groups of authors [127,128] but differed significantly depending on raw material used and applied extraction conditions (30.5 kDa–509.5 kDa). The MeO ranged from 1.9% (tomato peel) up to 25% [130,135].

Presented data show that the physico-chemical characteristics of TPW derived pectin can vary significantly and this is because they are influenced by different parameters: the tomato sort, type of processing, composition/quality of TPW, processing of TPW (storage, drying, milling etc.) and extraction type and conditions. Due to the general lack of scientific data, it is hard to estimate the relative importance of particular parameters for pectin yield and/or characteristics. From the work conducted by Grassino and colleagues [129,130], where similar extraction conditions were applied to both whole TP and tomato peel, it can be concluded that pectin obtained from peel contained significantly lower MeO and AUA. The only research that investigated the importance of raw material pretreatment on yields and characteristics of pectin is the work of Van Audenhove and coauthors [128], who showed that HPE of TPW prior to pectin extractions significantly increased yields (864 g/kg vs. 473 g/kg), and obtained pectin had lower DM and higher Mw.

Investigations of the impact of extraction conditions on yield and characteristics of obtained pectin are scarce, limited and inconsistent (Table 1). Applying higher temperatures dur-

ing CSE increases MeO and AUA while applying it during MAE has the opposite effect [129]. Lower pH (2/1.6 vs. 4) decreases DM, increases viscosity of obtained pectin [127,128,131] and has no effect or slightly increases GalA. Prolonged UAE (15 to 90 min 60 °C/80 °C) decreases MeO (5.56–4.50/4.5–3.8); decreases AUA (37.6–31.4/33–27) and decreases DE (87.9–84.8/89–77) [129].

Table 1. Impact of extraction conditions (temperature, pH, duration of extraction, extraction method, extraction solvent, SSR, MWP, pretreatment of raw material, posttreatment of pectin) on yields and properties of pectin.

	Examined Parameters	Yield/Properties	Physico-Chemical and Rheological Characteristics	Reference
Temperature	CSE: T > 85 °C	↑ yield		[127]
	CSE: 80 °C vs. 60 °C	↓ yield	↑ MeO (9.0 vs. 6.2) ↑ AUA (572 g/kg vs. 352 g/kg) ↑ DE (slightly, 89% vs. 85%);	[129]
	UAE: 80 °C vs. 60 °C	↑ yield (slightly)	↓ MeO ↓ AUA (slightly) ↓ DE (slightly)	
	UAE (bath, pH 2.5): 40 °C vs. 60 °C vs. 80 °C	4% vs. 6% vs. 9%		[132]
	UAE: 40 °C vs. 20 °C	↑ yield better anticorrosion properties		[135]
pH	pH 2 vs. pH 4.5	↑ yield	DM (77% vs. 88%) GalA (no effect) intrinsic viscosity (4.2 dL g^{-1} vs. 1.8 dL g^{-1}) viscosimetric average molecular weight (94.6 kDa vs. 30.5 kDa)	[127]
	pH 1.6 vs. pH 4	↑ yield	DM (74% vs. 67%) UA (no effect)	[128]
	UAE: pH 1.0 vs. pH 1.5 vs. pH 2.0	↑ yield at decreasing pH	↑ total carboxyl groups with higher pH (at SSR 1:20; no effect at higher SSR)	[93]
	CSE: HCl (pH 1.5) vs. ammonium-oxalate + oxalic acid (pH 4.5)	↑ yields	↑ GalA (84% vs. 79%) ↓ DM (20.8% vs. 29.3%) in HCl extracts	[131]
	UAE/MAE/OHAE: pH 2 vs. pH 1/pH 1.5	↓ yields at pH 2		[133]
Duration of Extraction	prolonged CSE (5 to 10 min)	↑ IST ↑ CST ↑ SDR		[127]
	MAE (300 W): 3 min vs. 5 min vs. 10 min	9.4% vs. 15.1% vs. 31.6% (effect is less significant at higher MWP (450 and 600 W))	the effect of the duration of MAE on carboxyl group content is not clear	[93]
	HPE: 10 min vs. 45 min	6.6% vs. 9.2%	↑ AUA (31% vs. 43%)	[115]
	prolonged MAE/UAE (30–150 s)	↑ yields		[136]
	prolonged OHAE (90–210 s)	↑ yields		[133]

Table 1. *Cont.*

	Examined Parameters	Yield/Properties	Physico-Chemical and Rheological Characteristics	Reference
Duration of Extraction	prolonged: UAE up to 10 min (450 W and 600 W) or 2 min (750 W); MAE up to 3 min (900 W) or 4 min (750 W); OHAE up to 5 min; UAME up to 8 min (450 W and 750 W) or 10 min (600 W)	↑ yields		[133]
	prolonged UAE up to 20 min	↑ yields (further prolongation is not relevant for yields)		[132]
	prolonged UAE (15–90 min, 60 °C/80 °C)	↑ yields (15.2% vs. 17.2%/16.3% vs. 18.5%)	↓ MeO (5.56 vs. 4.50/4.5 vs. 3.8) ↓ AUA (37.6 vs. 31.4/33 vs. 27) ↓ DE (87.9 vs. 84.8/89 vs. 77)	[129]
Extraction Method	CSE (36 h) vs. UAE (30–180 min)	31% vs. 35.5%	type of extraction does not influence characteristics of pectins (they are primarily affected by temperature and duration of extraction)	[129]
	UAE (20 min, pH 1.5) vs. MAE (10 min, pH 1.5)	282.5 g/kg vs. 301.2 g/kg	↓ GalA	[93]
	UAE vs. MAE vs. OHAE	98 g/kg vs. 120 g/kg vs. 80 g/kg		[133]
	UAE vs. MAE vs. OHAE vs. UAME vs. UOHAE	152 g/kg vs. 254 g/kg vs. 106.5 g/kg vs. 180 g/kg vs. 146 g/kg		[133]
	HPE vs. CSE (30 min)/CSE (45 min)	↑ yields (14–15%)		[115]
	Combined techniques (subsequent UAE + MAE — increases yields (340.6 g/kg vs. 282.5 (UAE) and 301.2 g/kg (MAE)))	subsequent UAE + MAE has higher total carboxyl groups content compared to UAE compared to MAE		[93]
Extraction Solvent	UAE: citric acid vs. nitric acid/hydrochloric acid	↑ yields	↑ AUA DM (no effect)	[132]
	CSE:HCl (pH 1.5) vs. ammonium-oxalate + oxalic acid (pH 4.5)	↑ yields	↑ GalA (83.9% vs. 78.2%) ↓ DM (20.8% vs.29.3%)	[131]
	UAE: citric acid vs. oxalic acid/HCl	↑ yields (18.5%)		[135]
SSR	UAE: 1:20 vs. 1:30 vs. 1:50	17% vs. 26% vs. 32%	total carboxyl groups (0.15 vs. 1.1 vs. 1.2)	[93]
	UAE/MAE/OHAE: SSR increased from 1:50 to 1:70	yields (no effect)		[133]
MWP	higher MWP at short extraction periods (3–5 min)	↑ yields	the effect on carboxyl group content is not clear	[93]

Table 1. *Cont.*

	Examined Parameters	Yield/Properties	Physico-Chemical and Rheological Characteristics	Reference
Pretreatment of Raw Material	HPE	↑ yield (864 g/kg vs. 473 g/kg)	↓ DM ↑ Mw	[128]
Posttreatment of Pectin	dynamic high pressure microfluidization (0–160 MPa)	↑ MeO (1.73 to 3.11%) ↑ AUA (19.38 to 28.37%) ↑ DE (50.77 to 62.15%) ↑ particle size	rheological properties (apparent viscosity, consistency index and flow behavior index) were significantly changed	[131]

IST—initial structuring temperature, CST—critical structuring temperature, SDR—structure development rat, MWP—microwave power.

6. Major Obstacles for Widespread Industrial Utilization of TPW as the Source of Bioactive Compounds

Despite significant utilization potential, growing interest of industry and compliance with circular economy concepts, TP is still widely underutilized on the industrial level. This is due to numerous challenges, primarily related to the sanitary safety of TPW, complex and unstable chemical composition, varying quality, inadequate (or discontinuous) availability of the raw material, the absence of proper legislation, scalability challenges and economic viability, and lastly, overall environmental and sustainability assessments.

Ensuring sanitary safety of food industry waste while including TP is often challenging, mainly due to contamination with pesticide residues or other environmental contaminants (mycotoxins, heavy metals, persistent organic pollutants etc.), which complicates its further utilization [137]. Instability and prompt degradation that can occur during storage can also impair biomass safety due to formation of toxic compounds. Therefore, there is an increasing interest for finding methods that can prevent such unwanted changes. For example, simple fermentation was used successfully for TP preservation, but it also changed the content of bioactive compounds. It increased total phenolic content but decreased the amount of aglycon polyphenols while the qualitative composition of the polyphenols did not change during fermentation (naringenin chalcone, kaempferol, gallic acid and cinnamic acid remained the most represented molecules in TP) [107].

TPW produced by different types of processing can be diverse and heterogeneous; therefore, significant efforts are necessary to make it suitable for further utilization [138]. This necessitates advanced technological equipment, which is typically costly and, therefore, often unprofitable for companies and biorefineries.

A particularly important obstacle for the large-scale utilization of TP is ensuring its continuous supply along with appropriate transportation and storage in order to retain quality and sanitary safety, since this is essential for a reliable and economically sustainable fabrication process. This is particularly challenging with seasonal crops such as tomatoes [139]. Therefore, even though TPW is free and readily available raw material [51], it was shown that biorefineries often have difficulties in establishing a lucrative business. Therefore, it is suggested to perform detailed techno-economic assessments before entering such an endeavor.

Even when the continuous supply of sufficient amounts of biomass is provided, other practical issues that limit its further utilization remain. Processing of the raw material must be performed appropriately, bearing in mind the downstream application. Drying and heating can have significant effects on the quality of the material [68,140]. Moreover, obtaining the desired particle size before extraction can strongly impact the yields of desired compounds [141]. Fraction separation of the waste, like peels and seeds in TP, might be necessary in certain cases for its efficient utilization [142].

The environmental sustainability of the production process should be analyzed by using appropriate tools, such as LCA or carbon footprint analysis, as described later [143,144].

The assessment of the ecological footprint of the particular process for obtaining bioactive substance(s) from plant material requires the implementation of the comprehensive approach that should consider the key environmental impacts across the entire process. Important factors are therefore the assessment of the effects of clearing or harvesting plant biomass on sensitive ecological receptors like protected areas and endangered species and the consideration of the renewability and long-term availability of the plant biomass used as the source material [145]. For these reasons, the concept of reusing agricultural/food industry waste for obtaining added value bioactive compounds is the first step in adjusting the technological process to the concepts of circular economy and sustainable development.

Another important factor includes the calculation of the carbon footprint and energy consumption of the process and the consideration of the toxicity of the used chemicals. This aspect of the technological process depends mostly on the type of extraction procedure. In these terms, the environmental footprint can be significantly reduced by using more efficient extraction techniques and by substituting conventional solvent extraction with advanced (green) extraction techniques [146–156]. The major environmental advantages of green extraction processes are the possibility of solvent-free extraction; reduction of solvent quantity, use of non-toxic/natural solvents and reduced energy consumption (due to shorter extraction times or improved efficiency) [157].

The development of effective regulatory policies is crucial for widespread food industry waste utilization; the lack of regulation is the reason why such utilization of TPW is in most cases still limited to scientific research and patents [158]. Currently in Europe, the use of food industry waste and byproducts as food ingredients or as natural food additives is regulated by the European Community (EC) Regulation No. 178/2002, Article 2 and Codex Alimentarius guidelines. Therefore, when food byproducts are proposed to be used as natural additives and do not match the current regulations, a proper authorization as novel food, EC Regulation No. 258/97 (1997), is required [159].

The implementation of advanced extraction techniques on industrial levels is often challenging, mostly due to technical feasibility of the method (scalability of advanced technology and process optimization), its economic viability (obtaining highest yield at lower costs) and regulatory compliance. However, current trends aiming strongly toward sustainability and minimizing ecological footprint, nevertheless favor scaling-up of green extraction approaches. In the last decade, numerous studies have been conducted on extraction process intensification and scale-up using non-conventional extraction techniques [160]. The majority of studies regarding development of sustainable and green extraction processes for bioactive compounds have been performed using laboratory-scale equipment and optimizing the extraction parameters by using different statistical/mathematical tools to obtain the maximum recoveries of target bioactive compounds/groups of compounds. Theoretically it can be assumed that the extraction processes and parameters optimized at the laboratory levels could be scaled-up to higher volume extractors or even adapted to industrial levels. However, in practice, the extraction process scale-up is much more demanding and is affected by numerous factors. The most common among them are the choice between the batch- or flow-extraction modes, solvent to raw material ratio and the solvent concentration. Additional specific factors depend on the applied technique—in UAE those are ultrasonic power/density and vessel geometry; in MAE those are the microwave power and the solvent type and its dissipation factor. Even though numerous investigations are ongoing, to our knowledge, there are no pilot- or industrial-level green processes that have been developed for obtaining bioactive compounds from TPW (even though most of them have been scaled-up for processing of other types of raw materials).

SFE is the most common nonconventional extraction technique used industrially on a large scale, usually with the utilization of carbon dioxide (CO_2) as a green solvent. SFE pilot and industrial scale-up research has recently been reviewed by Belwal and coauthors [160] who concluded that SFE is largely used for oil and fat-soluble bioactive compound extraction as one of the most convenient green extraction techniques. The application is focused either on refining the raw material (e.g., defatting cacao) or obtaining

extracts of targeted bioactive compounds. However, current research is also targeted towards the optimization of the extraction of essential oils or polyphenolic compounds from different plant matrices. In the case of TP, SFE-CO_2 was applied successfully for the extraction of carotenoids, particularly lycopene [81,82], but only at the laboratory level.

In the case of UAE, two different types of ultrasound equipment are commonly used—bath and probe systems—and both have been scaled-up to pilot or industrial scales with reactor capacities ranging from 30 to 1000 L. Recently, continuous-flow apparatuses have also been developed for laboratory and pilot scales. Scaled-up UAE was applied to different plant sources (but not TPW) for the extraction of polyphenolic compounds, volatile compounds and essential oils capsaicinoids and beta glucans [160]. The yields obtained on laboratory scales can be comparable, but also significantly higher, compared with yields obtained with the same method after scale-up [161,162].

Even though microwave reactors are also available for both the pilot and industrial scales, industrial utilization of MAE is not as common as is the use of UAE. Also, very few MAE scale-up experiments have been conducted; however, obtained results show great potential showing comparable yields of the essential oils from *Peumus boldus* leaves on both laboratory and industrial levels [163] and higher yields of polyphenols from lettuce on the industrial level [164].

Ohmic heating is widely used in the food industry, particularly for the thermal processing of fruits and vegetables and production of juices. Its application in extraction of bioactive compounds is still not as common but is gaining interest due to improved yields and reduced environmental effects. At the laboratory level, OHAE has been successfully applied in TP for the extraction of carotenoids (allowing the omitting of toxic extraction solvents) and pectin (enabling significantly shorter extraction and maintaining the high pectin yields) [133,136,165]. Pilot and industrial scale processes are scarce. Recently, a pilot-scale OHAE of wheat bran bioactive compounds was developed, resulting in satisfactory yields and a 63% energy save compared with the conventional process [166].

HPE has been shown to effectively remedy the low extraction rate and improve quality and concentrations of bioactive components obtained by using traditional extraction techniques. It has been applied to various plant materials, as reviewed by Khan and coauthors [167]. In TP, HPE was used for the efficient recovery of pectin and polyphenols, but at the laboratory scale [115]. Pilot or industrial scale HPE is often used in food industry for different purposes such as drying, enzyme or microbe inactivation etc.; however, the data on scaled-up HPE are still very scarce [168–170].

EAE is based on the enzymatic pretreatment of raw materials to achieve releasing the substances that are bound to the cell walls and thus increasing the total yield of extracts. Therefore, it should be perceived as the type of sample pretreatment step that is usually followed by conventional or green solvent extraction. It has been successfully applied to TP for the extraction of carotenoids/lycopene [85,94–96] on the laboratory scale. One of the most important industrial uses of EAE is fruit juice production, but the potential of scale-up extraction processes has also been tested for other plant materials such as soybeans, *Hypericum perforatum* herba or grape peel [160].

To conclude, to translate the encouraging results on the potential of green extraction of bioactive compounds from TPW on the laboratory scale, the process needs to be scaled-up in a way that can provide both economic and environmental benefits. It is usually performed by conducting the techno-economic analysis of the whole process that also needs to include the environmental sustainability aspects.

Even though reutilization of food industry waste for obtaining bioactive compounds conceptually fits perfectly into the concept of a circular economy and sustainable development, estimation of ecological acceptability of any kind of technological process should be based on quantifiable data rather than subjective or partial assessments. The most commonly used and the most comprehensive approach for such estimations is LCA. LCA is a technique for assessing the environmental aspects and impacts of products, activities and services along the life cycle from extraction of raw materials, through processing, man-

ufacturing, distribution, use and on to final waste management [171]. Its major advantages, compared to other available tools, are the holistic approach that ensures that all relevant environmental impacts are accounted for, rather than focusing on a single aspect (1) and the fact that it uses standardized methods to quantify different environmental impacts, rather than relying on subjective or qualitative assessments (2). By applying this methodology, it is possible to identify the life cycle stages or processes that contribute the most to the overall environmental impact, allowing for targeted improvements. This helps focus sustainability efforts where they can have the greatest impact. LCA also enables the comparison of different products, processes, or services based on their environmental performance, allowing for informed decision-making on the most sustainable options. Additionally, LCA is aligned with international standards, such as the ISO 14040 series, which enhances the acceptability and transparency of obtained results [172,173].

In the case of extracting bioactive compounds from TPW, there is only one available technoeconomic analysis that also considered the LCA, published recently by Yadav and Dhamole [174]. In this work various methods of lycopene extraction were investigated and compared, taking into consideration economic and environmental implications. The method's authors considered included solvent-assisted extraction, SFE, EAE, UAE, and integrated ultrasound surfactant assisted extraction (IUSAE). The techno-economic and LCA revealed that IUSAE surpasses other methods in terms of economic viability, with a net present value (NPV) of USD 20,858 and a payback period of 4.2 years and that it has the lowest environmental impact compared to other methods.

Future research on this topic should prioritize further enhancement of the efficiency and environmental viability of green extraction methods, while also scaling them up to pilot and industrial levels. To assess the feasibility of proposed green extraction techniques, objective analytical methods such as LCA should be implemented. Additionally, more effort should be dedicated to integrating efficient green extraction procedures into a comprehensive biorefinery approach that can offer additional benefits in terms of both economic and environmental feasibility.

7. Conclusions

TPW holds substantial potential as a valuable source of carotenoids, polyphenols and pectin—bioactive compounds of significant relevance to the pharmaceutical and cosmetics industries. However, the broader industrial exploitation of TPW is currently hindered by challenges in scaling up extraction processes from laboratory research to industrial applications. While green extraction methods offer a sustainable solution, optimizing these processes to maximize yields and preserve the quality of the extracted compounds is critical. Techniques such as RSM and emerging modeling approaches are promising, but their application in TPW extraction remains in the early stages. Moreover, the processing and pretreatment of raw materials can significantly impact the overall yields and characteristics of the targeted compounds, particularly pectin, emphasizing the need for more in-depth research in this area. Addressing these challenges will require a concerted effort to improve the efficiency, scalability and environmental sustainability of extraction methods. Integrating these processes into a biorefinery model could further enhance the economic and ecological feasibility of TPW valorization. In this context, the application of LCA will be crucial for assessing environmental impacts and guiding the development of more sustainable practices. In conclusion, while progress has been made in understanding the potential of TPW, significant efforts are still required to bridge the gap between research and industrial implementation, thereby enabling the full valorization of TPW in alignment with circular economy principles.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su16219158/s1, Table S1: Available extraction protocols for obtaining carotenoids from TPW with corresponding yields; Table S2: Available extraction protocols for obtaining polyphenols from TPW with corresponding yields; Table S3: Total yields and properties of TPW derived pectin, obtained by different extraction methods.

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