

Review

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Review

Citrus Waste Valorization: Unconventional Pathways for Sustainable Biomaterials and Bioactive Products

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Abstract

Citrus fruits are among the world's most important crops, with annual production exceeding 160 tons. However, their industrial processing generates substantial amounts of waste (mainly peels, seeds, and pulp), which can represent up to 50% of their total weight. This review examines innovative strategies to valorize these byproducts. Research shows that citrus residues (CR) have great potential for extracting high-value bio composites or converting them into biomaterials, going beyond traditional uses such as animal feed and biogas production. Special attention is paid to emerging applications in nanotechnology, nutraceuticals, biodegradable materials, and functional coatings. In line with the principles of the circular economy and green chemistry, this study highlights the potential of citrus residues to address major sustainability challenges while fostering the development of new market opportunities. The review also critically assesses current limitations related to scalability, regulatory frameworks, and consumer acceptance, with global and regional implications.

Keywords: valorization strategies; biorefinery; sustainable packaging; nutraceutical delivery; upcycling

1. Introduction

Citrus fruits, members of the *Rutaceae* family, encompass a wide variety of genera and rank as the third most important group of fruit crops globally. Their high and growing demand stems from their versatility, as they are consumed in multiple forms—primarily as juices, jellies, jams and fresh fruit, but also as sources of essential oils, flavorings, and fragrances, among others [1,2]. However, this prosperity comes at an environmental cost: approximately 40% to 60% of processed citrus fruit is discarded as waste—including peels, seeds, pulp, and pomace—contributing to environmental liabilities such as methane emissions, groundwater contamination, and landfill saturation [3,4].

Traditionally, citrus by-products have been relegated to low-value applications such as animal feed or composting, overlooking their rich biochemical composition. For instance, citrus peels alone contain 10% to 20% pectin, essential oils (e.g., D-limonene), and polymethoxylated flavones with well-documented antioxidant and anti-inflammatory properties [5].

Recent advances in green chemistry and materials science have redefined citrus waste as a strategic resource for the development of high-value, non-conventional products. Innovations range from flexible electronics based on nanocellulose to biodegradable polymers derived from limonene, positioning citrus residues at the forefront of the circular bioeconomy [6]. Despite this progress, critical challenges remain in scaling up these technologies, standardizing extraction methods, and aligning with regulatory frameworks for novel applications. This review synthesizes the current state of the art in citrus waste valorization, with a focus on underutilized bioactive compounds and emerging markets, while also addressing the sociotechnical barriers that hinder industrial adoption.

1.1. The Global Citrus Waste Challenge

The global citrus industry has expanded significantly over the past two decades, fueled by rising demand for juices, fresh fruit, and essential oils. As documented in Figure 1, worldwide citrus production increased from 106.9 million tons in 2003 to 169.4 million tons in 2023 [7], reflecting a compound annual growth rate (CAGR) of 2.3%. This growth, however, generates a proportional waste burden: approximately 40–60% of processed biomass (peels, seeds, pulp) is discarded, translating to 68 - 100 million tons of annual waste in 2023 alone. The sheer volume of residues poses critical environmental risks, including soil acidification from limonene leaching and methane emissions from decomposition [3].

Global Citrus Production Trends (2003–2023)

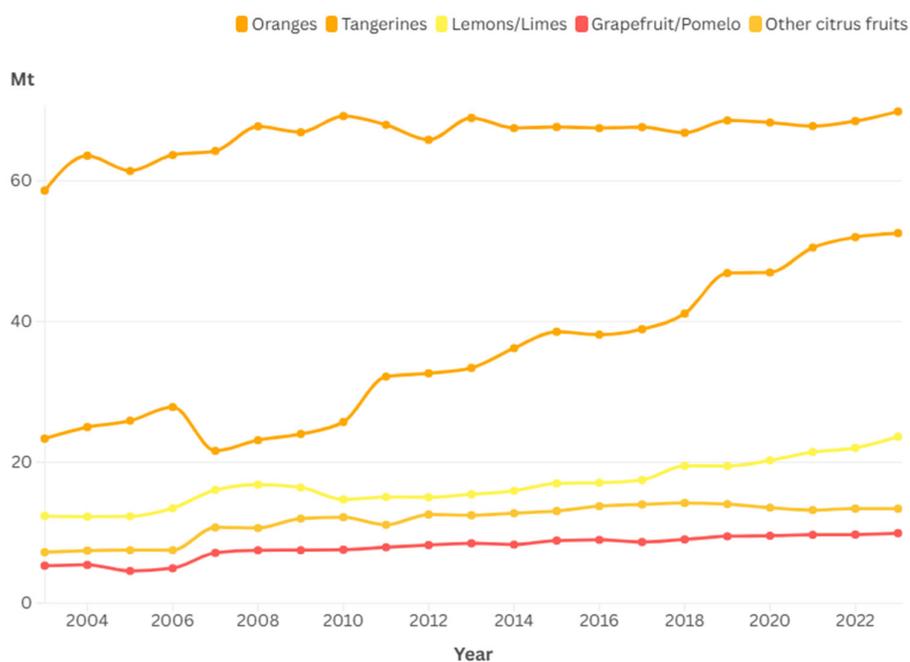


Figure 1. Annual output of oranges, lemons, mandarins, grapefruit and other citrus fruits. Source: Own elaboration with data from FAOStat (2023)[7].

The concentration of citrus production intensifies waste-related issues in specific regions. Figure 2 highlights the leading producers across the four main citrus varieties. China dominates global production, accounting for 35% of the total among the varieties shown and supplies 59% of global mandarin demand. Brazil holds 34% of the orange market share, while India produces 22% of the world's lemons. These and other regions depicted in the figure also exhibit some of the most concerning environmental pollution indicators associated with the improper handling of agro-industrial citrus waste. In many of these countries, particularly in rural areas or regions lacking adequate waste management infrastructure, these by-products are frequently discarded in landfills, dumped in open areas, or openly burned [8]. Such practices release significant amounts of greenhouse gases (CH_4 , CO_2 , NO_x), fine particulate matter ($\text{PM}_{2.5}$), volatile organic compounds, and dioxins, all of which negatively affect air quality and human health [9–11]. Furthermore, the accumulation of organic-rich residues in soils and water bodies contributes to eutrophication, foul odors, the proliferation of disease vectors, and the loss of local biodiversity [4,8]. China and other major producers have made substantial efforts to reduce the environmental impact of citrus cultivation, achieving significant progress over the past decade [12]. However, these efforts have primarily focused on the production phase, while waste management remains insufficiently addressed.

Geographic Dominance in Main Citrus Production

(2019–2023 Average)

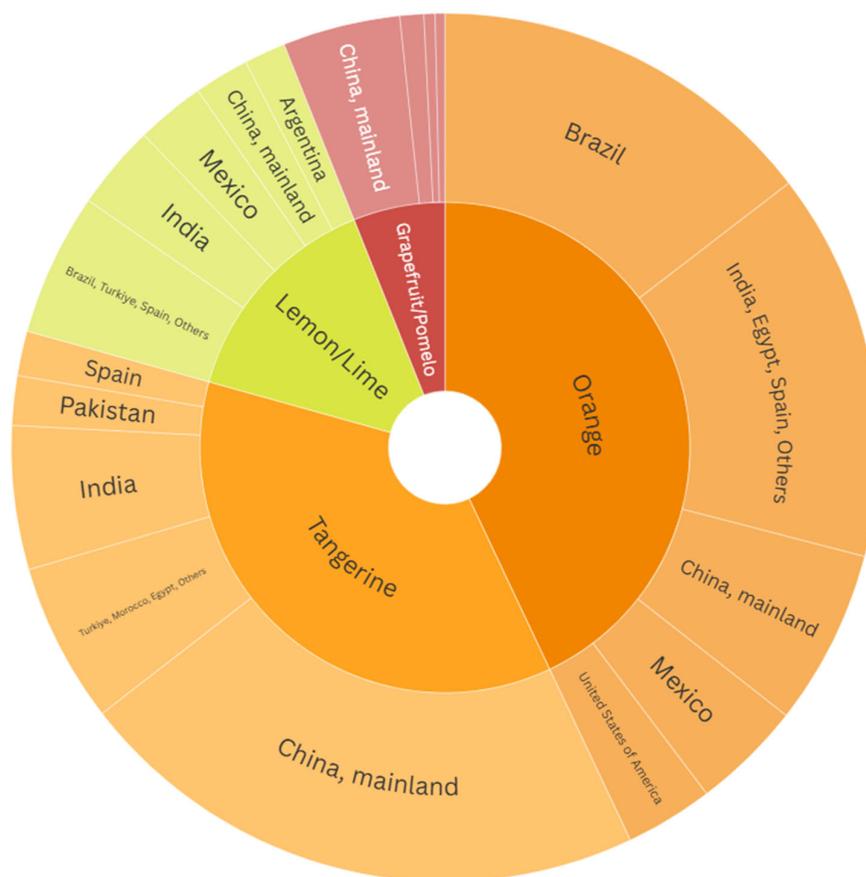


Figure 2. Geographic Dominance in Citrus Production (2019–2023 Average): Top four producing nations per variety. Own elaboration with data from FAOStat (2023) [7].

In the absence of emerging biotechnological interventions for citrus waste management, global waste volumes are projected to reach between 80 and 120 million tons by 2030. This trajectory poses a direct threat to the achievement of Sustainable Development Goals (SDGs) 12 (Responsible Consumption and Production) and 13 (Climate Action). Emerging biotechnologies offer scalable and sustainable pathways for valorizing citrus by-products; however, their successful deployment depends on the implementation of supportive policy frameworks, particularly in regions bearing the highest waste burdens [6].

1.2. Beyond Conventional Uses: The Need for Innovation

Traditionally, citrus waste has been used for animal feed, organic fertilizer production, and, to a lesser extent, biogas generation. While these conventional applications help reduce disposal costs and environmental burdens, they often do not fully exploit the potential of citrus residues as valuable bioresources. Recent research highlights that citrus waste is rich in bioactive compounds, fibers, and nutrients, making it suitable not only for animal nutrition but also for the development of high-value products in the food, agricultural, and energy sectors. For instance, innovative processing methods can transform citrus residues into animal feed with improved digestibility and protein content, thereby supporting livestock productivity and health [2,13–18]. Similarly, the use of citrus waste as an organic amendment has demonstrated benefits for soil quality and crop yields, contributing to more sustainable agricultural systems [19,20].

There is a growing motivation to utilize citrus waste as a renewable energy source. Biorefinery approaches now enable the conversion of citrus residues into biogas and biofuels, offering a sustainable alternative to fossil fuels and supporting the transition toward a circular bioeconomy [21–24]. The production of biogas from citrus waste not only mitigates greenhouse gas emissions but also generates digestate that can be used as a biofertilizer, further closing nutrient cycles in agriculture [25,26].

Despite these benefits, several challenges remain, such as the presence of anti-nutritional factors, the need for preservation methods like drying or ensiling (which can increase costs and the risk of nutrient loss), and the complexity of determining optimal inclusion rates for different animal species and growth stages. Technical and economic barriers also persist, including the need for efficient preservation and processing methods, and the optimization of valorization pathways to ensure scalability and profitability [14,23,27].

The valorization of citrus processing residues is increasingly driven by market demand for natural antioxidants, antimicrobials, and biodegradable materials, particularly within specialized sectors such as food packaging, cosmetics, pharmaceuticals, and emerging fields like wearable electronics. These residues are a rich source of bioactive compounds—including polyphenols, flavonoids, and essential oils—that exhibit potent antioxidant and antimicrobial properties. This inherent bioactivity positions citrus by-products as promising candidates for natural additives and functional ingredients in high-value applications [2,28]. In addition, the development of biodegradable polymers and biofilms from citrus-derived biopolymers directly addresses growing environmental concerns and regulatory pressures to replace conventional, non-degradable plastics. Recent studies have demonstrated the technical feasibility of producing biodegradable films and composites with built-in antioxidant and antimicrobial functions from citrus waste. These materials are suitable for active packaging and show potential for adaptation in wearable electronics and other niche markets that require sustainable and multifunctional materials [29–31]. Moreover, the unique microstructure and chemical composition of citrus residues enable the design of innovative bioinspired materials—such as fibers, fabrics, and nanostructured components—thus contributing to the transition toward a circular economy and zero-waste manufacturing models [29]. With continued advancements in consumer awareness and increasingly stringent environmental regulations, the integration of citrus waste-derived materials into specialized industries is expected to expand, driven by the dual imperatives of improved product functionality and environmental sustainability.

1.3. Objectives

This review aims to provide a comprehensive and critical synthesis of current advances in citrus waste valorization, with a focus on bridging the gap between laboratory-scale innovation and industrial-scale implementation. The specific objectives are to:

Map Emerging Technologies: Systematically catalog and evaluate advanced extraction, processing, and functionalization techniques—including green solvents, nanofabrication, and enzymatic hydrolysis—used to convert citrus residues (peels, seeds, pulp) into high-value biomaterials. Emphasis will be placed on optimizing yields, improving energy efficiency, and minimizing environmental impacts.

Evaluate Unconventional Applications: Assess the technical feasibility and commercial potential of novel products derived from citrus waste, such as smart packaging films, biomedical hydrogels, biodegradable electronics, and nutraceutical encapsulates. These applications will be benchmarked using key performance indicators, including barrier properties, mechanical strength, and bioactive compound retention.

Identify Barriers to Circular Integration: Analyze the main technical, economic, and regulatory challenges hindering the integration of citrus waste valorization into circular economy models. This includes addressing issues such as seasonal variability in waste composition, scalability constraints of biorefinery processes, and the need for robust certification frameworks for new biomaterials.

Mitigation strategies will be proposed in alignment with Sustainable Development Goals 9 (Industry, Innovation and Infrastructure) and 12 (Responsible Consumption and Production).

Formulate Roadmaps for Stakeholders: Develop actionable recommendations and strategic roadmaps for researchers (e.g., AI-driven process optimization), industry stakeholders (e.g., pilot-scale industrial symbiosis networks), and policymakers (e.g., incentives for ISO-compliant circular systems) to accelerate the market adoption of sustainable citrus waste-derived products.

2. Citrus Waste Composition: A Treasure Trove of Bioactive Resources

2.1. Key Components by Waste Type

Citrus processing waste is primarily composed of three anatomical regions: peel (flavedo and albedo), the pulp partition (segment membrane) and seeds. Each of these components exhibits distinct structural and chemical characteristics, which determine their potential for high-value applications. Figure 3 shows the parts of a citrus fruit and a brief description of the main bioactive components in each one.

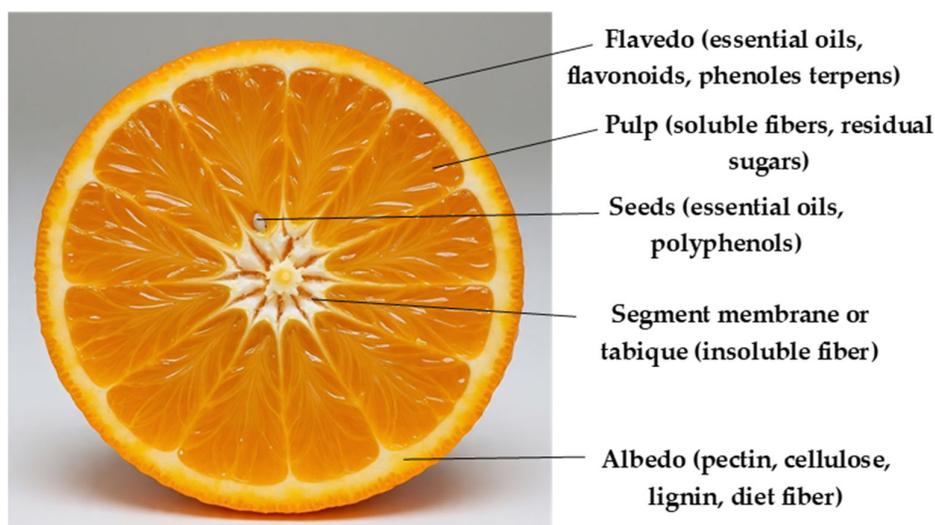


Figure 3. Anatomical Distribution of Bioactive Compounds in Citrus Fruit (*C. sinensis*): Valorization potential of Peel, Pulp, and Seed Residues. Own elaboration with data from.

The flavedo is the outermost, colored layer of the citrus peel. It is characterized by a dense cellular structure with minimal intercellular space, providing mechanical protection and reducing water loss. The flavedo is particularly rich in essential oils, carotenoids, and polymethoxyflavonoids (PMFs), as well as coumarins and various phenolic acids. Studies have shown that the flavedo contains higher concentrations of phenolic acids, flavonols, flavones, and especially PMFs compared to the albedo, contributing to its strong antioxidant activity and characteristic citrus aroma [5,32–34]. For example, in *Citrus sinensis* and *Citrus limon*, the flavedo is a significant source of nobiletin, hesperidin, quercetin, and essential oils, with vitamin C content also higher than in the albedo [35,36]. The presence of these bioactive compounds makes the flavedo a valuable raw material for the extraction of natural antioxidants, flavorings, and functional ingredients [32,34,37,38].

The albedo is the inner, white, spongy layer of the peel, located between the flavedo and the pulp. It has a high proportion of intercellular spaces, which confer excellent water and oil holding capacities and make it an effective shock absorber. The albedo is especially rich in dietary fiber, pectin, hemicellulose, and polysaccharides, as well as flavanones (such as naringin and hesperidin), phenolic acids, and small amounts of vitamin C [32,33,35,39–41].

The pulp partition, also known as the segment membrane or tabique, is the internal membrane that separates the citrus segments. This component is a notable source of dietary fiber (up to 57 g/100

g), cellulose, pectin, and residual sugars, as well as appreciable amounts of polyphenols and flavonoids, though generally at lower concentrations than in the flavedo and albedo [35,41]. The segment membrane also contains significant levels of antioxidant compounds, contributing to the overall functional potential of citrus waste streams. Its structural polysaccharides and fiber content make it suitable for use in prebiotic and functional food formulations.

Citrus seeds are notable for their lipid content, particularly rich in linoleic acid, as well as phenolic compounds, limonoids, dietary fibers, vitamins, and carotenoids. The composition varies with citrus variety, maturity, and extraction method, but seeds consistently demonstrate antioxidative, anti-inflammatory, and anticancer activities, supporting their use in functional foods, nutraceuticals, and cosmetics[5,42,43]

2.2. Comparative Analysis of Citrus Varieties

The variability in bioactive compound composition among major citrus species, such as orange, mandarin, lemon, and grapefruit, plays a fundamental role in the development of effective agroindustrial waste valorization strategies. Recent research confirms that this variability is influenced by several factors, including cultivar, species variety, growing conditions, fruit ripeness, and processing techniques. Table 1 presents updated quantitative data on the content of key bioactive compounds predominantly present in citrus peels; these compounds are currently highlighted for potential applications in biomaterials, nutraceuticals, and environmentally friendly technologies.

Table 1. Quantitative composition of key bioactive compounds in citrus peel residues under different extraction methods.

Compound	Orange	Lemon	Tangerine, mandarin or clementine	Grapefruit	Reference
Pectin (% DW)	23.02 ± 2.12	13.00 ± 1.06	16.0	8.5	[44–50]
	18.49 ± 1.74		21.95	17.92	
	18.73 ± 1.19		15.23		
Cellulose (% DW)	37.08 ± 3.10	23.06 ± 2.11	22.5	26.57	[17,44–46,50,51]
	19.73 ± 0.93		17.29 ± 1.02		
	17.02 ± 2.70				
Hemicellulose (% DW)	11.04 ± 1.05	8.09 ± 0.81	6.0	5.60	[17,44–46,50,51]
	6.33 ± 0.14		11.38 ± 0.98		
	37.2 ± 3.3				
Lignin (% DW)	7.52 ± 0.59	7.56 ± 0.54	8.8	11.6	[44–46,50,52]
	4.18 ± 0.69		0.56		
Sugars (% DW)	9.6	6.5	10.1	8.1	[44,45,50]
	21.06 ± 1.93				
Carotenoids (µg/g β-caroten)	50.94 ± 2.28	11.09 ± 0.47	98.80 ± 2.95	3.61 - 61.42	[48,53,54]
	6.30				
D-Limonene (% EO)	94.88	94.427	97.38	90.92–93.98	[48,55]
Hesperidin (mg/g DW)	2.07 ± 0.38	0.07	29.50 ± 0.32	0.071	[48,53,56]
			13.74		
			64.45		
			58.60		
TPC (mg GAE/g)	12.20	15.74	30.84	21.17	[46,48]
	66.36	18.12	152.57	12.48	
	12.59	15.22	58.68		
TFC (mg QE/g)	36.29 ± 5.69	30 ± 3	25.40	13.09 ± 0.06	[48,57–59]

Compound	Orange	Lemon	Tangerine, mandarin or clementine	Grapefruit	Reference
			7.93		
			6.38		

Abbreviations: DW = dry weight; EO = essential oil. TPC: total phenolic content expressed as mg gallic acid equivalent per g dry weight (mg GAE/g DW). TFC: total flavonoid content expressed as mg quercetin equivalent per g dry weight (mg QE/g DW). Values vary depending on extraction method (hydro distillation, supercritical CO₂, ultrasonication, high hydrostatic pressure, etc.).

The composition of citrus residues varies significantly between species, cultivation conditions, and extraction methods. Pectin, with a 13% to 23% DW content in peels, is widely used in the food and biomaterials industries for its gelling properties. Structural polysaccharides (cellulose, hemicellulose, lignin) are precursors to second-generation biofuels through hydrolysis and fermentation. D-limonene appears to be the major component in essential oils obtained from citrus residues, and yields depend largely on the extraction technology applied. Flavonoids, such as hesperidin, predominate in mandarin, the species on which the greatest amount of research has also been conducted. The total phenolic and flavonoid content (TPC, TFC) varies widely depending on the species and method, and advanced techniques, such as high hydrostatic pressure or pulsed electric fields, significantly improve yields. This variability highlights the need to standardize extraction protocols and reporting units to facilitate comparison across studies. Furthermore, the differential profiles of each citrus species suggest tailored biorefinery approaches to maximize value within a circular economic framework.

3. Emerging Extraction and Processing Technologies

Emerging extraction and processing technologies are revolutionizing the valorization of citrus waste, enabling the sustainable recovery of high-value bioactive compounds and advanced biomaterials. Recent research highlights the integration of green chemistry, nanotechnology, and biotechnology to maximize yield, efficiency, and environmental benefits.

3.1. Green Solvent Systems

A eutectic solvent is a multicomponent mixture characterized by a melting point lower than that of any of its individual pure components. This phenomenon is observed in systems with high stability in the liquid phase, where the components are virtually insoluble in the solid state. In this context, Deep Eutectic Solvents (DES) have emerged as promising tailor-made green solvents with a wide range of applications. Formulations such as choline chloride/levulinic acid/N-methylurea, glycerol, and ethylene glycol have demonstrated high efficiency and selectivity in the extraction of flavonoids—including polymethoxylated flavonoids and glycosides—as well as in the recovery of D-limonene from citrus peel waste. These systems have achieved extraction yields exceeding 85%, outperforming conventional solvents in both efficiency and environmental sustainability [60–63]. Furthermore, DES have proven effective in the extraction of microcellulose, which can subsequently be converted into cellulose nanocrystals [64], thus adding value to lignocellulosic biomass residues.

Supercritical carbon dioxide (scCO₂) extraction is a highly efficient green technology that utilizes CO₂ above its critical point (31.1 °C and 7.38 MPa), where it exhibits properties intermediate between those of a gas and a liquid. In this state, CO₂ possesses high diffusivity, low viscosity, and a tunable solvating power that can be adjusted through pressure and temperature, making it an ideal solvent for nonpolar and moderately polar compounds. This technique enables the efficient recovery of essential oils from citrus waste without exposure to high temperatures, thereby preventing thermal degradation and preserving both the bioactivity and aromatic profile of the extracted compounds. Moreover, supercritical CO₂ extraction has been shown to enhance the yield of phenolic and

antioxidant compounds, and process parameters can be optimized to maximize the recovery of high-value bioactive metabolites [65–67]. Response surface methodology has even been applied to optimize extraction conditions, identifying 28.7 MPa and 60 °C as the optimal parameters for maximizing the recovery of flavonoids, total phenolics, and antioxidant activity [67]. This technique can reduce the use of organic solvents by up to 80% and has allowed the extraction of approximately 50% of D-limonene from the extract obtained from the freeze-dried and pulverized peels [68], with even higher yields reported when using propane instead of carbon dioxide [69].

3.2. Nanotechnology-Driven Approaches to Enhance Bioactive Compound Delivery

Nanotechnology-based strategies, specifically nanoencapsulation and nanoemulsification, have emerged as effective tools to mitigate the inherent limitations of bioactive compounds derived from citrus residues. These limitations include volatility, low water solubility, susceptibility to degradation by UV radiation, oxygen exposure, and pH fluctuations, thus outperforming conventional encapsulation methods such as spray drying or emulsification, which typically exhibit low encapsulation efficiency (<40%), uncontrolled release profiles, and thermal degradation of thermosensitive compounds [70]. A comprehensive review by Oprea et al. [71] elucidates the efficacy of lipid nanostructures (liposomes, solid lipid nanoparticles, emulsions) and polymeric systems in stabilizing citrus essential oils against these adverse conditions. This stabilization process demonstrably improves biocompatibility and functional availability for food and cosmetic applications.

Collectively, these findings highlight the critical technological considerations for successful nano-delivery systems, including: formulation method (ultrasonication, emulsion phase inversion, polymeric coatings, electrospinning), bioactive compound characteristics (hydrophobicity, heat sensitivity, etc.), droplet or particle size and distribution, physical stability (PDI, zeta potential, particle size after storage), and preservation of bioactivity (antioxidant, antimicrobial). These general technical principles are established here; specific applications in health, nutrition, and functional foods are further elaborated in Section 4.1.

3.3. Biotechnological Innovations

Biotechnological innovations are at the forefront of citrus waste valorization, enabling the transformation of residues into high-value products through enzymatic hydrolysis and microbial fermentation. These approaches not only enhance resource efficiency but also support the development of sustainable bioproducts for diverse industries.

Enzymatic hydrolysis uses specific enzymes—such as cellulases, pectinases, and hemicellulases—to break down complex polysaccharides in citrus waste into fermentable sugars and bioactive oligosaccharides. This process is highly efficient and environmentally friendly compared to chemical hydrolysis. For example, optimized enzymatic cocktails can significantly increase the release of fermentable sugars, which are then used as substrates for further bioprocessing [51,72,73]. Enzymatic hydrolysis of citrus pectin generates low-molecular-weight oligosaccharides with prebiotic activity, promoting beneficial gut microbiota and increasing the production of short-chain fatty acids, which have recognized health benefits [74]. Additionally, enzymatic hydrolysis can enhance the nutritional and functional properties of citrus-derived products by increasing the content of amino acids, vitamin C, and bioactive compounds [73].

Microbial fermentation leverages the metabolic capabilities of bacteria and yeasts to convert citrus waste hydrolysates into valuable biochemicals. Recent advances include the use of engineered strains, such as *Weizmannia coagulans* and *Saccharomyces cerevisiae*, for the efficient one-step conversion of citrus waste into L-lactic acid and meso-galactaric acid, respectively [75]. These processes combine enzymatic saccharification and fermentation, achieving high product yields and reducing process costs. Fermentation is also used to produce bioethanol, biosurfactants, and high-quality animal feed, with lactic acid bacteria improving the nutritional profile and shelf life of the resulting products [51,76]. Furthermore, fermentation can increase the antioxidant activity and bioactive content of

citrus-derived products, making them suitable for functional food and nutraceutical applications [73,76]. Table 2 summarizes the main emerging technologies for the valorization of citrus waste.

Table 2. Key Technologies for Citrus Waste Valorization.

Technology	Target Product(s)	Key Advantage	Author(s)
Deep eutectic solvents (DES)	Flavonoids, microcellulose	high selectivity, green chemistry	[60,63,64]
Supercritical CO ₂ extraction	Limonene, phenolics	no thermal degradation, high purity	[65,67,77]
Ultrasonication	Pectin, CNCs	energy efficient, high yield	[64,78,79]
Nanoencapsulation	Essential oils	controlled release, enhanced food safety	[2,5,80]
Enzymatic hydrolysis	Prebiotic oligosaccharides, sugars	mild conditions, production of functional products	[81–83]
Microbial fermentation	Biosurfactants, L-lactic acid, bioethanol, feed	Biochemical diversity, sustainability, high yield	[2,51,72,76,84–87]
Enzyme production	Cellulases, pectinases, xylanases	Supports biorefineries, circular economy	[23,88,89]

4. Less Conventional Applications: From Lab to Market

This section synthesizes recent advancements in less conventional applications of citrus waste, demonstrating a shift beyond traditional uses towards innovative solutions poised for market entry. These applications span diverse sectors, including development of bioactive materials, generation of advanced biomaterials, creation of sustainable consumer goods, and novel agritech synergies. Progress in each of these areas is underpinned by a growing body of research seeking to address existing technical, economic, and regulatory barriers to market adoption.

4.1. Citrus Waste Valorization: Bioactive Innovations for Health, Wellness, and Sustainable Food Systems

Recent investigations, building upon established principles of nanoencapsulation and nanoemulsification (as detailed in Section 3.2), underscore the significant potential of citrus-derived bioactive compounds to enhance health, well-being, and sustainable food systems.

These investigations are exemplified by the incorporation of various citrus essential oils (bergamot, mandarin, orange, grapefruit, and lemon) into nanoemulsions using Tween-80 and ultrasonication, which resulted in an average droplet size of less than 50 nm [90]. The resulting nanoemulsions largely retained their antioxidant and antimicrobial activity after 30 days of storage, although some mandarin-based formulations exhibited reduced stability.

The application of lemon essential oil (LEO) nanoemulsions to fresh-cut kiwis not only reduced weight loss and enhanced firmness but also preserved nutrient content and antioxidant activity to levels comparable to 10 mg/L of vitamin C [91]. Similar research found that LEO nanoemulsions effectively inhibited the growth of *Phomopsis* sp., a major cause of postharvest decay in kiwis, thereby contributing to food security and reduced economic losses [92].

Nanoencapsulation techniques have demonstrated the ability to improve the bioaccessibility of citrus pulp polyphenols. By encapsulating these compounds within various colloidal systems (liposomes, emulsions, etc.), researchers have enhanced their solubility, stability, and subsequent absorption within the body. Furthermore, active coatings combining LEO nanoemulsions with gelatinous matrices show promising barrier properties against water loss and browning in fresh produce [93,94], potentially prolonging shelf life, reducing food waste, and simultaneously delivering beneficial bioactive compounds directly to the food surface.

However, careful monitoring of several critical parameters is essential to maximize the functional effects of nanoencapsulated citrus bioactives. These include the selection of the encapsulation matrix (proteins, polysaccharides, biodegradable polymers), the bioactive compound loading, the particle/droplet size and Polydispersity Index (PDI), the zeta potential for colloidal consistency, stability during storage (temperature, time, light exposure), retention of biological activity (antioxidant, antimicrobial), and the sensory properties within the food matrix. Meticulous optimization of these variables is crucial for ensuring both the efficacy and consumer acceptance of these innovative products.

In the domain of functional material development for extending food shelf life, antimicrobial films infused with citrus essential oils (CEOs) are gaining traction. These films, typically combining citrus-derived pectin with complementary biopolymers such as xanthan gum, alginate, chitosan, or starch (all Generally Recognized As Safe, GRAS), offer desirable mechanical and barrier properties. CEOs, particularly those rich in D-limonene, provide broad-spectrum antimicrobial and antioxidant effects while enhancing the film's ability to modulate gas and moisture exchange. Fabrication methods, such as solution casting, extrusion, spraying, and dipping, allow for tailoring to specific applications, while ultrasound-assisted hydrodistillation provides an environmentally friendly alternative for extracting active volatile compounds [95–97].

The versatility of citrus-derived compounds extends beyond food applications, offering promising avenues for promoting overall health and well-being. Citrus peels serve as a rich reservoir of bioactive compounds with diverse therapeutic potential. Among these, hesperidin (Hesp), a glycosylated flavanone, has garnered significant attention for its multi-faceted properties, including anti-inflammatory, antioxidant, anti-cancer, and neuroprotective effects. Several studies have demonstrated hesperidin's efficacy in mitigating inflammation and oxidative stress in various models, such as cisplatin- and methotrexate-induced nephrotoxicity [8,47,98]. In these studies, hesperidin enhanced antioxidant capacity, reduced lipid peroxidation, and preserved renal architecture by upregulating cytoprotective proteins such as Nrf2 [99]. Novel nanoformulations, such as bilosomes (HES-BS), have further improved bioavailability and systemic efficacy, demonstrating their potential in advanced drug delivery systems for targeted therapeutic interventions [100].

Beyond nephroprotection, hesperidin and its derivatives (e.g., α -glucosyl hesperidin) have shown promise in ophthalmological applications by promoting corneal regeneration without inflammatory infiltration [101]. They have also demonstrated efficacy in managing metabolic disorders such as non-alcoholic fatty liver disease, where supplementation reduced key inflammatory markers (TNF- α , CRP, NF- κ B) [99]. Emerging evidence even suggests a role for hesperidin in sports medicine, attenuating exercise-induced inflammation during post-exertion recovery [102]. These findings, coupled with improved formulation strategies, position hesperidin as a promising candidate for nutraceuticals and therapeutic biomaterials targeting both chronic and acute inflammatory conditions.

Collectively, these innovations reflect the increasing potential of citrus by-products, contributing to sustainability and overall well-being.

4.2. Advanced Biomaterials

Citrus-derived biomaterials have garnered increasing attention for their potential to replace synthetic counterparts in biomedical and sensing applications, aligning with sustainability and circular economy principles. Among them, pectin-based hydrogels are emerging as promising

candidates for 3D-printed wound dressings. They have emerged as versatile candidates for advanced wound care systems [64]. Pectin, a heteropolysaccharide, contains reactive carboxyl and hydroxyl groups that facilitate ionic cross-linking (e.g., with Ca^{2+}) and chemical modifications for targeted functions.

The incorporation of auxiliary biopolymers—such as gelatin, carboxymethylcellulose (CMC), or chitosan—improves the mechanical integrity and aqueous stability of these hydrogels, expanding their therapeutic utility. Innovative formulations combining pectin with ZnO nanoparticles and chitosan have demonstrated accelerated wound healing and intrinsic antimicrobial activity without cytotoxic effects [103]. Moreover, oxidation-mediated self-healing pectin hydrogels are being explored for dynamic tissue regeneration applications [104]. Recent advances include bio-inks integrating pectin, CMC, and nanoparticles, enabling patient-specific dressing fabrication via 3D printing [103]. These findings underscore the promise of pectin hydrogels as scalable, eco-friendly platforms in next-generation biomedical materials.

In parallel, carbon quantum dots (CQDs) are a class of zero-dimensional carbon nanomaterials that exhibit unique properties such as intense fluorescence, biocompatibility, and tunable emission wavelengths and can be synthesized from citrus peel waste. These biodegradable nanomaterials are gaining ground for sensing and smart packaging. These plant-derived CQDs, usually obtained by hydrothermal or microwave-assisted carbonization, offer advantages such as photostability, tunable fluorescence, and surface functionalization potential, without the toxicity associated with heavy metal-based QDs [105–107]. Citrus peels are rich in phenolic precursors (e.g., flavonoids, limonoids) that facilitate CQD synthesis under green conditions.

Functionally, these CQDs show strong antimicrobial activity and have been embedded in biopolymer matrices like chitosan-pullulan or CMC-starch films, achieving over 99% inhibition against *E. coli* and *S. aureus* [108]. In food systems, citrus CQDs enable the development of intelligent packaging films responsive to volatile spoilage compounds and are incorporated into edible coatings to prolong shelf life [106,107]. Specific applications include fluorescent sensors for detecting bacterial contamination in milk and pesticide residues in citrus juices [109].

Despite promising laboratory-scale performance, challenges remain in terms of synthesis reproducibility, scalability, quantum yield enhancement, and biosafety validation under real-use conditions [110,111]. Addressing these limitations through standardized protocols and comprehensive toxicological assessments will be critical for translating citrus-derived CQDs into market-ready, sustainable diagnostic platforms.

4.3. Sustainable Consumer Goods

Leveraging the inherent biocompatibility, biodegradability, and functional properties of citrus-derived compounds, emerging innovations are enabling the creation of eco-friendly textiles, smart packaging, and biodegradable electronics that align with circular economy principles and low-impact manufacturing.

4.3.1. Citrus Fiber Composites in Sustainable Textiles

Citrus-derived fiber composites are gaining momentum in the textile industry as biodegradable, low-toxicity alternatives to petroleum-based materials. *Citrus sinensis* peels serve as a rich source of microcrystalline cellulose (MCC), whose extraction through environmentally benign protocols—alkaline pretreatment, acid hydrolysis, and chlorine-free bleaching—yields material with high crystallinity (~72%) and thermal stability (~308 °C). Scanning electron microscopy reveals a rod-like morphology with microfibrillar architecture, while elemental analysis confirms a high carbon and oxygen content, consistent with desirable reinforcement properties [112].

This citrus-derived MCC has been effectively incorporated into biopolymer-based composites, enhancing mechanical strength and thermal resistance while enabling circular use of agro-industrial waste [97]. Additionally, the transformation of citrus pulp into textile fibers has been industrialized

by companies such as Orange Fiber S.r.l., demonstrating the viability of citrus-based fabrics with aesthetic, durable, and sustainable performance [97,113].

Beyond structural materials, citrus essential oils—including lemon, orange, and lime—are being utilized in functional textiles via microencapsulation. This strategy preserves volatile compounds and facilitates controlled release of bioactives with antimicrobial, antioxidant, insect-repellent, and aromatic properties [114]. When incorporated into coating matrices like chitosan, alginate, or gum arabic, and applied through padding techniques on cotton, wool, and polyester, these oils generate multifunctional textiles with enhanced UV resistance and biocidal effects [114,115]. The integration of plant-derived nanomaterials further imparts self-cleaning and energy-harvesting capabilities, while minimizing environmental impact. These innovations position citrus fibers and oils as key enablers of sustainable, high-performance textile ecosystems.

4.3.2. Limonene as a Green Solvent in Biodegradable Electronics

Limonene is emerging as a bio-based, non-toxic, and biodegradable alternative to hazardous solvents in organic electronics fabrication. Its potential for carbon-negative production through algae or microbial biosynthesis aligns with circular bioeconomy principles [116]. While its integration offers low environmental impact and compatibility with certain conjugated polymers, challenges persist concerning solvent-polymer miscibility and large-scale formulation. Binary solvent systems like limonene:indane have shown promise, enabling the processing of semiconductors like PM6 and BTP-eC9 and achieving power conversion efficiencies in OPVs approaching those of traditional toxic solvents [116]. Ongoing optimization and formulation strategies are crucial to expanding its applicability across various material systems. Interdisciplinary research, incorporating biochemistry, materials science, and green chemistry, is key to designing tailored terpene solvents. Comprehensive life cycle assessments and toxicological evaluations are essential to support the industrial transition towards green electronics based on citrus-derived inputs [116,117].

4.4. Agri-Tech Synergies

Biochar derived from citrus waste is emerging as a multifunctional input within sustainable agriculture, offering a scalable solution for soil remediation, nutrient management, and carbon sequestration. Produced through controlled pyrolysis (300–500 °C) or vermicomposting of citrus peels, this biochar exhibits high porosity, chemical stability, and surface functionality—primarily hydroxyl and carboxyl groups—making it an effective soil conditioner and adsorbent for heavy metals such as Pb, Cu, and As [118–120]. Its agronomic benefits include increased cation exchange capacity, pH regulation in acidic soils, enhanced retention of Ca, Mg, and K, and stimulation of microbial activity, all of which contribute to improved plant growth and root development [118].

Applications in crop systems have demonstrated promising results, including yield enhancement in sandy soils and disease suppression in tomatoes and peppers at application rates of 1–5% [121]. Beyond productivity, citrus biochar supports climate-smart agriculture by sequestering atmospheric CO₂ in stable carbon forms and reducing emissions of N₂O and CH₄, thanks to its high surface area and adsorptive capacity [122,123]. In citrus orchards, it has been shown to improve soil organic carbon dynamics, increasing resilience to water stress and environmental degradation.

These synergistic effects position citrus-derived biochar as a strategic tool within the Agri-TechBio framework, bridging technological innovation and circular economy principles. By transforming citrus residues into value-added amendments, this approach enables waste valorization, carbon mitigation, and agroecosystem restoration, especially in climate-vulnerable regions. As such, citrus biochar exemplifies how agri-tech integration can drive sustainable development at both farm and landscape scales.

The type of treatment that citrus waste undergoes will determine the products that can be obtained. A summary of this can be seen in Figure 4.

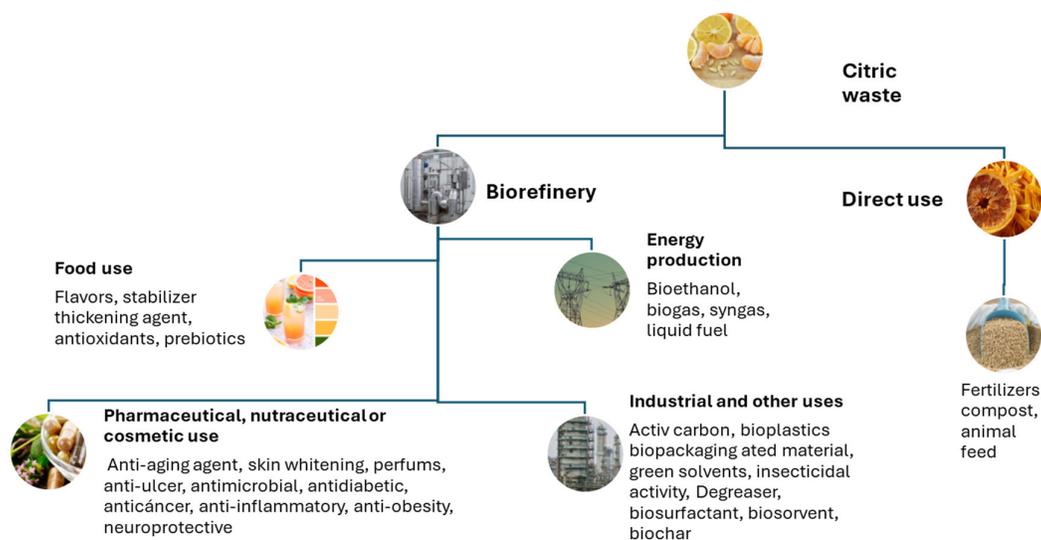


Figure 4. Conceptual map illustrating the valorization pathways of citrus waste, including direct uses and biorefinery processes.

5. Challenges and Unresolved Issues

The valorization of citrus waste is a field with great benefits, but also many challenges. The efficient and sustainable conversion of this type of waste into high-value products is challenged by technical, economic, regulatory, and environmental factors. Addressing these challenges is crucial for the development of integrated biorefinery models and the transition to a circular bioeconomy in citrus-producing regions [22,27]. The following section analyzes the main barriers and unresolved issues currently limiting the large-scale implementation of citrus waste valorization strategies.

5.1. Technical Barriers

Despite noteworthy advancements in the upcycling of citrus by products especially their conversion into bio-functional and value-added compounds considerable engineering and scientific hurdles remain. Principal limitations include the temporal and compositional variability of citrus feedstocks, as well as the susceptibility of bioactive constituents to degradation during processing. These combined challenges hinder process standardization, the achievement of reproducible results, and the successful large-scale implementation required for industrial adoption [124].

5.1.1. Seasonal Variability in Citrus Waste Composition

The biochemical composition of citrus by-products, particularly peels and pulps, is significantly influenced by factors such as varietal genotype, climatic conditions, and harvest practices [124,125]. D-limonene exhibits substantial variability (30-90%) based on citrus species, developmental stage, and geographic origin [38]. This variability significantly affects both the extraction yield and the inhibitory effects on microbial fermentation processes used in bioethanol and biogas production [22,126]. This compositional variability directly impacts the suitability of limonene as a green solvent, affecting both extraction yield and performance in electronics applications. For example, fluctuations in limonene content will affect its solvent properties, impacting polymer dissolution and device performance. Therefore, understanding and managing seasonal variability is crucial for ensuring consistent limonene quality and optimizing its effectiveness in biodegradable electronics and other applications.

5.2. Economic and Regulatory Hurdles

The implementation of sustainable technologies for the valorization of citrus byproducts—particularly in the isolation and modification of functional biomolecules and nanoscale materials—faces considerable financial and policy-related constraints. Despite their potential to substitute synthetic alternatives and reduce ecological footprint, these methods remain economically unfeasible and are frequently obstructed by the lack of harmonized regulatory standards, especially within emerging bio-economies [127–129].

5.2.1. High Costs of Green Extraction Methods

Despite their clear environmental and functional advantages, advanced green extraction methods—such as supercritical carbon dioxide (SC-CO₂), deep eutectic solvents (DES), ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), and enzymatic hydrolysis—face substantial economic and regulatory barriers when compared to conventional solvent-based techniques. These technologies align closely with green chemistry principles by reducing solvent use, enhancing the recovery of thermolabile bioactives, and improving process safety and selectivity. However, their adoption at industrial scale is often limited by high capital and operational costs. The need for specialized equipment, precise process calibration, and elevated energy input results in significant financial burdens, particularly for small- and medium-sized enterprises (SMEs) [22,48]. Additionally, infrastructural gaps, restricted access to technology, and underdeveloped markets in citrus-rich regions—such as Latin America, Africa, and Southeast Asia—further hinder scalability and commercialization [22]. To overcome these challenges, early-stage integration of techno-economic assessments and life-cycle costing is critical. Strategies such as co-location with existing agro-industrial facilities, fostering industrial symbiosis, and developing integrated multi-stream biorefineries can enhance cost-effectiveness and promote the sustainable valorization of citrus waste.

5.2.2. Lack of Standardized Regulations for Citrus-Derived Nanomaterials

The rapid advancement of citrus-derived nanomaterials—including nanocellulose, nanoemulsions, and other functional nanosystems—has outstripped the development of consistent regulatory guidelines. While these nanomaterials show great promise in applications like smart packaging, biomedical coatings, targeted drug delivery, and biosensing, their legal and safety status, especially for food-contact applications, remains largely unclear. Current guidelines from major regulatory bodies (e.g., EFSA, FDA, OECD) often don't adequately address naturally sourced nanoparticles derived from agro-industrial waste, such as citrus byproducts. This leaves significant gaps in understanding toxicity thresholds, environmental impact, and long-term exposure [48,130].

The lack of globally standardized criteria for safety assessment, labeling, and approval processes creates legal ambiguity and significantly increases the time and cost of compliance, particularly for small and medium-sized enterprises (SMEs) and research-focused projects operating in regions with fragmented or evolving regulatory environments. These challenges hinder the widespread adoption and commercialization of potentially safe and beneficial nanotechnologies [130,131].

To ensure responsible integration and commercialization, internationally harmonized frameworks are crucial. These frameworks should incorporate evidence-based toxicity criteria, clear definitions, and streamlined approval pathways for sustainable nanomaterials. Simultaneously, developing open-access data repositories and fostering interdisciplinary collaborations between academia, industry, and regulatory agencies are essential to promote regulatory convergence and accelerate the translation of citrus-based nanotechnologies from the laboratory to the Marketplace [130,131].

5.3. Environmental and Social Trade-offs

Transforming citrus waste into nanomaterials and sophisticated bioproducts offers exciting prospects for promoting a regenerative and eco-conscious bioeconomy. Nonetheless, a careful

evaluation of both ecological and societal repercussions is crucial. Two primary challenges emerge: the cradle-to-grave environmental footprint linked to the fabrication of nanostructures from citrus remnants, and the growing tension with nutritional-grade uses—especially concerning pectin, a staple in the global food industry [132,133].

5.3.1. Life Cycle Analysis (LCA) to Obtain Derivatives from Citrus Waste

While the valorization of citrus waste into nanomaterials—such as nanocellulose, carbon quantum dots (CQDs), and limonene-derived biopolymers—is often perceived as an environmentally preferable alternative to landfilling or incineration, recent life cycle assessments (LCAs) reveal a more nuanced sustainability profile. Although these approaches can mitigate certain environmental burdens, their overall impact is critically dependent on the chosen extraction technology, energy source, chemical inputs, and end-of-life management strategies [22,48]. For example, nanocellulose production frequently involves energy-intensive steps like mechanical milling, acid hydrolysis, and enzymatic treatment, often requiring significant volumes of water and reagents. These processes can generate a substantial ecological footprint, particularly when powered by fossil-fuel-based energy systems, thereby elevating the global warming potential and cumulative energy demand [134,135]. Furthermore, the synthesis of citrus-derived nanomaterials often relies on non-biodegradable surfactants, toxic catalysts, or organic solvents, raising additional environmental and health concerns [136].

Given these considerations, sustainability cannot be assumed solely based on the renewable origin of raw materials. Accurate and regionally contextualized life cycle assessments (LCAs) are imperative. These assessments must incorporate the boundaries of multifunctional systems, reflecting real-world variables such as local electricity grids, transportation logistics, and waste management infrastructure. Currently, comprehensive and standardized LCA data to produce citrus-derived nanomaterials remain limited, hindering informed decision-making by technology developers and policymakers. Future research should prioritize transparent and comparative LCA frameworks that consider environmental and social impacts across the entire product life cycle, thereby supporting the responsible advancement of citrus waste valorization [136,137].

Pectin and limonene recovery has been the subject of extensive LCA assessments, indicating that pectin extraction entails a significantly higher environmental burden than limonene recovery, mainly due to the high electricity demand and the use of ethanol as a solvent. A recent study revealed that 300 g of orange peel produces 8.22 g of pectin and 0.14 g of limonene; by replacing ethanol with more sustainable solvents, the environmental footprint of pectin production was reduced by 73.4% [66]. From a market perspective, the global pectin sector is projected to experience a compound annual growth rate (CAGR) of approximately 7% between 2023 and 2030, driven by demand in the food, pharmaceutical, and cosmetics industries. Similarly, the limonene market is exhibiting an upward trend due to its applications in cleaning products, fragrances, and bioplastics [66]. However, the economic viability of citrus waste valorization ultimately depends on process optimization and environmental impact minimization, and LCA plays a crucial role in identifying critical points and directing improvements toward sustainable industrial practices [22,27,66].

5.3.2. Competition with Food-Grade Applications

The rising demand for citrus-derived pectin, once primarily used in food products like jams and beverages, is now surging due to its expanding role in bioplastics, edible films, and biomedical applications. This diversification, while showcasing innovation in bio-based materials, has led to resource competition, supply strain, and significant price volatility in the global pectin market—impacting especially small-scale food processors in low and middle-income countries [138,139]. With prices increasing over 25% in the past five years, access to this key polysaccharide is becoming increasingly constrained due to competition from non-food sectors [124].

The shift toward high-value biomaterials from citrus waste risks undermining socially significant food uses—like artisanal jams and infant nutrition—by marginalizing smallholder farmers

and regional processors who lack the means to compete with industrial actors [140]. To balance innovation with equity, scholars recommend a tiered valorization strategy that reserves premium citrus fractions for food and pharmaceutical applications while assigning lower-grade byproducts to industrial uses [141]. Inclusive innovation frameworks are also essential to ensure that citrus bioeconomy initiatives reflect local needs and safeguard fair access to vital food-grade resources for vulnerable communities [142].

5.4. Consumer Acceptance & Market Integration in Latin America

Consumer acceptance of citrus waste-derived products in Latin America presents a duality influenced by cultural, regulatory, and market factors. While a historical preference for synthetic additives persists, particularly in processed foods, a growing demand for natural and sustainable products, driven by perceived health and environmental benefits, is reshaping consumer preferences, as evidenced by recent surveys in Brazil indicating a high valuation of sustainable packaging and sustainability labels [143,144]. Front-of-package nutrition labeling in several Latin American countries has reinforced this sensitivity towards health and transparency attributes, increasing interest in "clean" and natural ingredients and packaging [145]. Nevertheless, significant barriers remain, including caution regarding nanotechnologies in food, sensory sensitivity to essential oils in coatings, and skepticism towards unverifiable environmental claims, which puts pressure on robust certifications and traceability [146,147]. The adoption of international certifications like GRAS and "novel food" approval by the EFSA, although nascent in the region due to a lack of regulatory harmonization, is emerging as a key requirement for accessing global markets [52,148]. At the public policy level, weak and fragmented regulatory frameworks in major producers like Brazil, Mexico, and Argentina, coupled with limited enforcement and incentives for waste valorization [22], constrain investment and the sector's competitiveness. Therefore, to foster consumer acceptance and the viability of citrus waste valorization in Latin America, it is recommended to prioritize sensory-neutral designs, clear labeling, and performance validations comparable to industry benchmarks, as well as strengthen public policies, create fiscal incentives, and promote the adoption of international certifications [8,22,52,148], while also promoting regulatory harmonization and traceability to prevent greenwashing [146].

5.5. Public Policy & Regulatory Landscape in Latin America

The regulatory landscape in Latin America is evolving towards circular economy and extended producer responsibility (EPR) models, directly impacting active/bio-based packaging and food contact materials. Chile is leading the region, having implemented the first mandatory collection and recycling targets for packaging under Law 20.920 (EPR Law) since 2023, expanding categories in 2025 (including textiles) and reinforcing reporting and management obligations [149–151]. Mexico has enacted the General Law on Circular Economy at the federal level (with updates between 2023 and 2025) and state laws (such as in Mexico City, 2023), promoting the reduction, reuse, recycling, and valorization of waste [152]. In Brazil, ANVISA updated its guide on food contact materials in 2024, incorporating criteria for chemical recycling and biodegradable/compostable materials, aligned with the National Solid Waste Policy [153,154], and has announced increased inspections and specific restrictions for substances in contact with food [155,156]. Colombia has consolidated a National Circular Economy Strategy [157–159] with inter-institutional governance and sector-specific roadmaps, while Peru has approved Circular Economy Roadmaps for industry [160,161] and specific sectors between 2020 and 2025. Collectively, these regulatory instruments create opportunity windows for citrus waste valorization through green procurement, EPR targets for packaging, and incentives for recyclable and bio-based materials, while also demanding compliance with specific requirements (positive listing, substance migration, technical performance), thereby favoring the scaling up of biopolymers, active coatings, and compostable packaging with robust LCA evidence.

6. Future Perspectives: Roadmaps for Sustainable Valorization

The valorization of citrus waste is currently undergoing a transition toward more advanced and circular industrial models, driven by technological innovations, novel materials, and evolving regulatory frameworks. Current trends show a convergence between biotechnology, materials engineering, circular economy principles, and digitalization, opening significant opportunities to maximize the added value of these by-products while contributing to the United Nations Sustainable Development Goals (SDGs), particularly SDG 9 (Industry, Innovation, and Infrastructure) and SDG 12 (Responsible Consumption and Production).

6.1. Integration with Circular Economy Models

The effective integration of citrus waste into industrial symbiosis networks is essential to optimize resource flows and increase added value. Pilot studies have demonstrated that multifunctional biorefineries co-processing citrus and olive residues can increase biogas yields by 38–42% while preserving flavonoids, as confirmed by LCA [66,162].

Blockchain-based traceability systems, such as those implemented in the CITRUSCALE project in Spain, have improved limonene recovery efficiency to 93–97% and facilitated the certification of carbon credits [52]. Furthermore, zero liquid discharge systems—combining membrane filtration with solar crystallization—have reduced freshwater consumption in Mediterranean processing plants by up to 87% [6].

A critical challenge lies in artificial intelligence (AI)-optimized logistics for transporting waste within a radius of less than 15 km, which could reduce emissions by up to 40%, provided that real-time composition sensors are available [64].

6.2. Innovations in Materials Science

Advances in materials science are redefining citrus waste valorization by transforming underutilized residues into high-performance functional biomaterials. Cutting-edge research now focuses on multifunctional hybrid architectures that combine nanotechnology, stimuli-responsive design, and catalytic engineering. These approaches overcome intrinsic limitations of conventional biopolymers—such as low thermal stability (<120 °C) and high hydrophilicity—while enabling applications in flexible electronics, self-healing polymers, and carbon-negative construction materials [52,98,117].

6.2.1. Advanced Hybrid Biomaterials

4D-printed pectin–cellulose scaffolds: designed for controlled drug release in response to pH and temperature variations, achieving up to 94% bioavailability of hesperetin in tumor microenvironments [98].

Limonene-based vitrimers: exhibiting self-healing properties (T_g: 118–125 °C) and 85% recyclability, offering a sustainable alternative to petroleum-derived thermosets [52].

Mycelium–citrus foams: produced by growing fungal mycelium on a citrus waste substrate, these materials are lightweight, biodegradable (complete degradation in 25–30 days), have low thermal conductivity (0.07–0.09 W/m·K), and possess acoustic absorption capabilities [117].

6.2.2 Catalytic Thermochemical Conversion

Microwave-assisted pyrolysis (450 °C, ZSM-5 catalyst) of citrus residues yields:

- Hydrogen-rich syngas (52–58%)
- Biochar (28–32%) suitable for soil remediation
- Phenolic oils (14–17%) as precursors for epoxy resins [6].

6.3. Cutting-Edge Research (2020–2024)

Nanocellulose from citrus peels: Due to their low lignin and high hemicellulose content, citrus peels are ideal feedstock for nanocellulose production. Extraction methods using ultrasonication and green solvents yield nanocellulose with high crystallinity, suitable for flexible electronics and biopolymer reinforcement [6,64]. Recent patents explore its use in bio-based batteries and high-performance composites [163].

Limonene as a platform chemical: Catalytic processes now enable its transformation into polyterpenes, bio-based plastics, and sustainable coatings, replacing fossil-based materials [52,117].

AI-driven process optimization: Machine learning models are being applied to optimize extraction and conversion parameters, improving yields and reducing energy consumption [66].

6.4. Emerging Trends and Knowledge Gaps

Emerging trends:

- Circular business models based on industrial symbiosis.
- Integration of biocatalytic processes for rapid and low-impact conversion.

Knowledge gaps and priorities:

- Industrial-scale nanocellulose production without generating toxic byproducts.
- Comprehensive long-term ecotoxicological assessments of citrus-derived nanomaterials and additives.

Table 3 shows a summary of the state of the art and future research perspectives or recommendations in the valorization of citrus waste.

Table 3. State of the art and future directions in citrus waste valorization.

Focus Area	Recent Advances	Key Challenges	References
Nanocellulose	Flexible electronics, biopolymer high-performance reinforcement, composites	industrial scale-up, reproducibility, byproduct safety	[6,64,163]
Limonene-based polymers	Bio-based plastics, vitrimers, sustainable coatings	process optimization, market adoption	[52,117]
Biochar	Soil remediation, carbon sequestration, nutrient retention	standardization of pyrolysis processes, long-term agronomic trials, scaling in diverse soils	[73,81,95,96,102,164,165]
Nutraceuticals (Hesperidin & Flavonoids)	Advanced drug delivery (nanoformulations, bilosomes), anti-inflammatory therapies	clinical validation, bioavailability, regulatory approval in functional foods and nutraceuticals	[8,76–80]
AI & circular models	Process optimization, industrial symbiosis, blockchain-based traceability	technological integration, real-time compositional data, cost of implementation	[66,69,162]
Ecotoxicity & LCA	Initial risk assessments for citrus-derived nanomaterials, partial LCAs reported	long-term ecotoxicological studies, comprehensive	[112,121,166,167]

Focus Area	Recent Advances	Key Challenges	References
Consumer acceptance & market integration	Growing demand for natural additives, functional packaging, textiles (Orange Fiber S.r.l.)	cradle-to-grave life cycle analyses consumer awareness, certification frameworks, equitable access for SMEs in emerging economies	[27,75,83,125]
Policy & governance	National circular economy roadmaps, EU Green Deal alignment, pilot regulations	lack of harmonized standards for nanomaterials, limited incentives in Latin America/Asia	[22,109–112,114,115]

7. Conclusions

Citrus waste is a versatile feedstock for high-value, low-environmental-impact products, yet its full potential remains untapped. Innovations in green chemistry and nanotechnology are unlocking unconventional applications, from smart packaging to biomedical devices. To bridge the lab-to-market gap, interdisciplinary collaboration and policy support are critical. This review positions citrus waste valorization as a cornerstone of the bioeconomy, aligning with SDGs 9 (Industry, Innovation, and Infrastructure) and 12 (Responsible Consumption and Production).

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