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VALORIZATION OF CITRUS FRUIT WASTES: SUSTAINABLE EXTRACTION OF BIOACTIVE COMPOUNDS FOR FOOD AND HEALTH APPLICATIONS

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citrus waste, bioactive compounds, green extraction, sustainable processing, flavonoids, pectin, circular economy

ABSTRACT
Globally grown and handled citrus fruits produce a lot of by-products, including pulp, seeds, and peels. Often considered agro-industrial waste, rich in significant bioactives such as flavonoids, phenolic acids, limonoids, pectin, and essential oils, these materials are now considered attractive sustainable sources. This review explores recent developments in green extraction techniques, including ultrasonic-assisted, microwave-assisted, enzyme-assisted, supercritical fluid, pressurized liquid extraction, and natural deep eutectic solvents. Key parameters like solvent type, temperature, duration, and particle size are evaluated for their influence on yield and quality. Green methods provide better selectivity, scalability, and environmental benefits than traditional approaches. Citrus-derived compounds have promise in antimicrobial packaging and cosmetics beyond their application as nutritional supplements and food preservatives. Combining intelligent optimization techniques with circular biorefinery designs indicates a bright future for citrus waste valorization. The review emphasizes the change toward environmentally friendly technology for sustained value recovery despite difficulties in cost and regulation.

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ВАЛОРИЗАЦИЯ ОТХОДОВ ПЕРЕРАБОТКИ ПЛОДОВ ЦИТРУСОВЫХ: ЭКОЛОГИЧНАЯ ЭКСТРАКЦИЯ БИОАКТИВНЫХ СОЕДИНЕНИЙ ДЛЯ ПРИМЕНЕНИЯ В ПИЩЕВЫХ ПРОДУКТАХ И УЛУЧШЕНИЯ ЗДОРОВЬЯ

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КЛЮЧЕВЫЕ СЛОВА:
отходы цитрусовых, биоактивные соединения, «зелёная» экстракция, экологичная переработка, флавоноиды, пектин, экономика замкнутого цикла

АННОТАЦИЯ
Во всем мире в результате выращивания и переработки плодов цитрусовых образуется большое количество побочных продуктов, таких как мякоть, семена и кожура. Зачастую рассматриваемые как отходы агро-промышленного производства, эти материалы, богатые важными биоактивными веществами, такими как флавоноиды, фенольные кислоты, пектин, лимоноиды, эфирные масла, в настоящее время считаются привлекательными экологичными источниками. В данном обзоре рассмотрены современные достижения в «зелёных» технологиях экстракции, включая ультразвуковую, микроволновую, ферментативную, суперкритическую флюидную экстракцию, жидкостную экстракцию под давлением, а также натуральные глубокие эвтектические растворители. Проведена оценка ключевых параметров, таких как тип растворителя, температура, продолжительность и размер частиц. «Зелёные» методы обеспечивают лучшей селективностью, масштабируемостью и пользой для окружащей среды по сравнению с традиционными подходами. Полученные из цитрусовых соединения обладают потенциалом применения в антимикробной упаковке и косметических средствах помимо их применения в качестве пищевых добавок и консервантов пищевых продуктов. Комбинирование интеллектуальных методов со схемами биопереработки замкнутого цикла означает светлое будущее для валоризации отходов переработки цитрусовых. Данный обзор сфокусирован на изменениях в направлении экологически безопасной технологии для устойчивого извлечения ценности несмотря на затруднения, связанные с затратами и законодательством.

1. Introduction

Citrus fruits (*Rutaceae family*) rank among the world's largest fruit crops, with over 150 million tons produced annually [1]. Among the citrus fruits, the world production of oranges was estimated at 69845563.99 tons in 2023, and the production of oranges in Egypt was around 3700000 tons in 2023 [2]. Large-scale juice and food processing of citrus (i. e., orange: *Citrus sinensis*, lemon: *Citrus limon*, lime: *Citrus aurantiifolia*, mandarin: *Citrus reticulate*, and grapefruit: *Citrus paradise*) yields a significant amount of waste (peels, pulp, and seeds) — roughly 40–50% of the fruit — amounting to tens of millions of tons of residual biomass every year [3]. Disposal of these citrus by-products poses environmental challenges, as much of it is still landfilled or incinerated, contributing to pollution and resource loss [4]. Yet, these so-called "wastes" are rich in valuable bioactive compounds, including flavonoids, other phenolic compounds, limonoids, pectin, and essential oils [3]. This realization has spurred growing interest in valorizing citrus processing residues as sustainable sources of high-value bioactives instead of treating them as environmental burdens [5].

Recovering bioactives from citrus wastes mitigates disposal problems and creates new opportunities in the food and healthcare sectors. Studies show that citrus peels and other byproducts have potent antioxidants and antibacterial agents that could be helpful to additives and natural food preservatives [6]. Likewise, phytochemicals derived from citrus wastes (e. g., polyphenols and limonoids) show several health-promoting qualities, including antioxidant, anti-inflammatory, cardioprotective, and anti-cancer activities — thereby supporting their possible usage in nutraceuticals and drugs [7]. Green extraction processes will become sustainable substitutes for conventional solvent-based approaches if we maximize these advantages in an environmentally acceptable manner. With minimal solvent and energy required, approaches include ultrasonic-assisted extraction (UAE), microwave-assisted extraction

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(MAE), and supercritical fluid extraction (SFE), which effectively recovers citrus bioactives [8]. Natural deep eutectic solvents (NADES) have lately attracted interest as green extraction medium since they provide high efficiency, cost-effectiveness, biodegradability, and adjustable characteristics for bioactive recovery [9]. Using these creative, greener extraction techniques for citrus fruit wastes helps to convert agro-industrial waste into value-added goods for food preservation and medical uses, therefore illustrating a circular economy approach to agricultural byproducts.

Growing environmental awareness and legal limits on using dangerous solvents in the food and pharmaceutical sectors are pushing the shift toward green extraction techniques. Conventional extraction techniques can depend on organic solvents, including methanol, chloroform, or hexane, which produce large amounts of chemical waste and are poisonous and combustible [10]. On the other hand, green extraction technologies concentrate on lower energy inputs, safer solvents, less waste, and improved efficiency, and line up with the ideas of green chemistry [11]. For shorter timeframes and lower temperatures, ultrasonic-assisted extraction (UAE) breaks plant cell walls using acoustic cavitation, releasing internal chemicals. Analogous mass transfer acceleration and bioactive yield enhancement in microwave-assisted extraction (MAE) depend on dielectric heating. These creative approaches have environmental benefits and improved compound selectivity, repeatability, and scalability of extraction performance [12].

By encouraging waste reduction, responsible consumption, and clean production, the valorization of citrus waste via green extraction also helps the Sustainable Development Goals (SDGs). There is an excellent opportunity to incorporate citrus-derived bioactives into edible films, nutritional supplements, drinks, and medicinal formulations, as clean-label and functional food products become increasingly in demand. For low-sugar jams and probiotic yogurts, pectin derived from citrus peels can function as a prebiotic or gelling agent; meanwhile, limonene-rich essential oils are under investigation as natural antibacterial packaging. Beyond food applications, citrus flavonoids such as hesperidin, naringin, and rutin have demonstrated strong anti-inflammatory and antioxidant properties, which may help manage chronic conditions like cardiovascular disease and metabolic syndrome. Thus, applying green technologies to extract these compounds reduces environmental impact and adds economic value to citrus-processing industries by opening new avenues in health-focused innovation. Therefore, this review aims to provide a comprehensive and up-to-date overview of the bioactive compounds in citrus fruit wastes and critically evaluate the recent advancements in green extraction technologies for their sustainable recovery (Figure 1). Emphasis is placed on the efficiency, environmental benefits, and application potential of these techniques in the food, pharmaceutical, and nutraceutical industries, thereby supporting the valorization of citrus by-products within a circular economy framework.

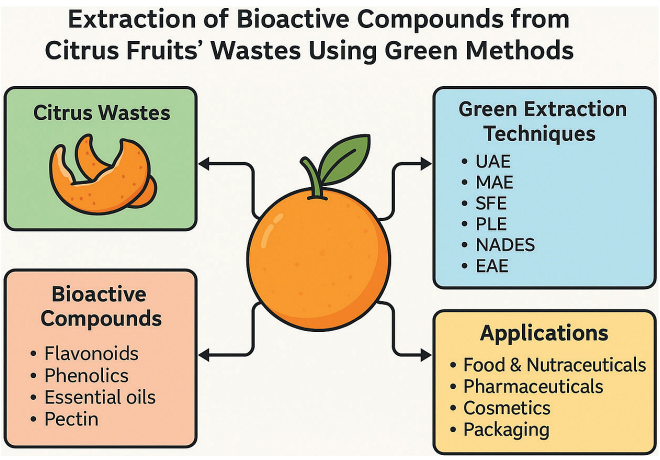

Figure 1. **Conceptual framework for the green extraction of bioactive compounds from citrus fruits' wastes and their applications**

Рисунок 1. **Концептуальная структура для «зелёной» экстракции биоактивных соединений из отходов переработки плодов цитрусовых и их применения**

2. Objects and methods

This review was conducted to critically examine recent progress in the valorization of citrus fruit waste, with a focus on sustainable green extraction methods and their potential applications in the food and health sectors. The search for and selection of literature were performed systematically to ensure transparency and reproducibility.

2.1. Literature search strategy

Relevant peer-reviewed articles were retrieved from databases including Scopus, Web of Science, PubMed, and Google Scholar. The search was limited to the period 2018–2023 to capture the most recent developments. Search strings combined keywords such as citrus waste, citrus peel, bioactive compounds, flavonoids, pectin, essential oils, green extraction, ultrasound-assisted extraction, microwave-assisted extraction, enzyme-assisted extraction, supercritical fluid extraction, natural deep eutectic solvents, sustainability, and circular economy. An initial pool of approximately 250 records was retrieved. After screening for relevance and applying inclusion/exclusion criteria, around 85 studies were included for detailed analysis. Reference lists of key publications were also screened to identify additional sources.

2.2. Inclusion and exclusion criteria

Articles were included if they: (i) addressed citrus fruit by-products (peels, pulp, or seeds) as primary raw material; (ii) reported bioactive compound identification, extraction, or application; (iii) emphasized green, sustainable, or non-conventional extraction approaches; and (iv) were peer-reviewed original research, reviews, or book chapters published in English. Studies were excluded if they: (i) focused exclusively on conventional solvent extraction without sustainability aspects, (ii) were conference abstracts lacking sufficient detail, or (iii) dealt with unrelated fruit by-products.

2.3. Data sources and geographic scope

The review encompassed studies conducted in diverse regions, including the Mediterranean basin (Egypt, Spain, Italy, Greece), South and East Asia (China, India), Latin America (Brazil, Mexico), and the United States. This ensured coverage of a wide range of cultivars, climatic conditions, and industrial practices.

2.4. Research subjects and analytical techniques

The primary focus was on citrus peels, pulp, and seeds, with an emphasis on the occurrence of flavonoids, phenolic acids, limonoids, carotenoids, pectin, and essential oils. The analytical methods reported in the reviewed studies included HPLC, GC–MS, spectrophotometry, and antioxidant assays, which are widely applied for compound identification, quantification, and functional evaluation. A comparative assessment of extraction yields, solvent systems, and bioactive functionalities was synthesized to highlight trends.

2.5. Review process and limitations

From an initial pool of records retrieved, a few articles satisfied the inclusion criteria and underwent a comprehensive review. We looked through the reference lists of essential papers to find more sources that were useful. The results were organized into sections based on themes. These themes included the composition of citrus waste, green extraction techniques, factors that affect them, a comparison with traditional methods, applications, and prospects.

3. Composition of citrus wastes

Citrus processing generates substantial by-products, primarily composed of peels, pulp, and seeds, accounting for nearly 50% of the total fruit mass. These waste fractions are particularly rich in a wide range of bioactive compounds (Table 1), including flavonoids (e. g., hesperidin, naringin, rutin), phenolic acids, limonoids, carotenoids, and essential oils such as limonene and linalool. Among them, citrus peels are the most valuable due to their high concentration of secondary metabolites and functional macromolecules. For example, orange and mandarin peels are known to contain significant levels of hesperidin and narirutin, whereas lemon and lime peels are richer in eriocitrin and naringin. The pulp and albedo fractions contribute additional pectin, soluble fibers, and residual polyphenols, while citrus seeds often provide lipophilic compounds like tocopherols and sterols along with protein and fatty acids.

The phytochemical profile of citrus wastes varies by tissue type and species, cultivar, maturity stage, and geographical origin. For instance, grapefruit peels have been shown to exhibit higher total flavonoid content than sweet orange peels, while lemon peels typically contain more limonene in their essential oil fraction. Moreover, citrus peels are a particularly abundant source of pectin, with concentrations ranging between 20–35% on a dry weight basis, depending on extraction conditions and fruit type. This makes citrus waste an excellent raw material for producing biodegradable food packaging and pharmaceutical carriers. Additionally, peels and albedo's insoluble dietary fiber content supports gut health and has prebiotic potential. Understanding the chemical composition of citrus wastes is essential for selecting appropriate extraction methods and guiding their valorization into functional food and nutraceutical products.

Table 1. **Summary of bioactive compounds in citrus wastes and their health effects**

Таблица 1. **Краткая информация о биоактивных соединениях в отходах переработки цитрусовых и их влияние на здоровье**

Bioactive compound	Citrus waste source	Major citrus type(s)	Health effects	References
Hesperidin	Peel, albedo	Orange, mandarin	Antioxidant, anti-inflammatory, vasoprotective	[7]
Naringin	Peel, albedo	Grapefruit, lime	Antioxidant, anti-obesity, neuroprotective	[13]
Eriocitrin	Peel	Lemon	Antioxidant, anti-diabetic, anti-inflammatory	[14]
Limonene	Essential oil in peel	Orange, lemon, lime	Antimicrobial, anti-cancer, anxiolytic	[15]
Pectin	Peel, pulp	Sweet lime, orange	Prebiotic, blood sugar regulation, gut health	[16]
Phenolic acids	Peel, pulp	Orange, lemon	Antioxidant, anti-inflammatory	[17]
Carotenoids	Peel, albedo	Orange, mandarin	Antioxidant, provitamin A, skin and eye health	[18]
Dietary fibers	Peel, pulp	All citrus types	Gut microbiota modulation, cholesterol-lowering	[19]
Limonoids	Seeds, peel	Orange, grapefruit	Anti-cancer, liver detox enzyme modulation	[20]

4. Green extraction techniques

The valorization of citrus processing wastes through green extraction methods has gained traction as an eco-conscious solution that meets both industrial and environmental demands. These techniques aim to efficiently isolate bioactive compounds while minimizing solvent toxicity, energy consumption, and waste generation. Below, each method is discussed in detail in the context of citrus waste utilization.

4.1. Ultrasound-assisted extraction (UAE)

Ultrasound-assisted extraction (UAE) is a promising green technique that uses high-frequency sound waves to create acoustic cavitation. This phenomenon involves the rapid formation and collapse of microscopic bubbles in the solvent, which generates intense mechanical forces that disrupt plant cell walls and enhance the release of intracellular bioactive compounds. UAE has been effectively applied to citrus wastes, particularly peels, to extract flavonoids, phenolic acids, and essential oils. For instance, Manzur et al. [21] demonstrated that the UAE of *Citrus latifolia* waste yielded high levels of total phenolics suitable for developing bioactive delivery systems. The method offers several benefits, including improved mass transfer, reduced solvent usage, and shorter extraction times. To guarantee commercial practicality, issues such as the deterioration of heat-sensitive compounds at high intensities and the difficulty of scale-up resulting from non-uniform energy dispersion must be resolved.

4.2. Microwave-assisted extraction (MAE)

Microwave-assisted extraction (MAE) rapidly heats polar molecules within plant tissues using microwave radiation, triggering cell rupture and enabling the release of target compounds into the extraction solution. Specially fit for time- and energy-efficient extractions, this dielectric heating technique speeds solvent penetration and solubilization of bioactives. MAE has shown great promise in citrus waste valorization. Kumar et al. [22] utilized MAE to extract high-quality pectin from *Citrus limetta* peel waste, achieving high yields and preserving its functional properties. MAE is particularly advantageous for its rapid operation, high energy efficiency, and compatibility with various green solvents. However, it is limited by issues such as the risk of local overheating (hot spots) and poor penetration depth, which can complicate scale-up in industrial settings.

4.3. Supercritical fluid extraction (SFE)

Supercritical fluid extraction (SFE) utilizes fluids (most commonly carbon dioxide (CO_2)) above their critical temperature and pressure, where they exhibit both gas-like diffusivity and liquid-like solvating power. In this supercritical state, CO_2 is particularly effective for extracting non-polar bioactives such as limonene and other essential oils from citrus peels. Granone et al. [23] demonstrated that SFE can efficiently recover aroma-rich limonene from orange and lemon peels without leaving toxic residues, making it highly suitable for food, cosmetic, and pharmaceutical applications. SFE is advantageous due to its selectivity, solvent-free nature, and recyclability. However, the high equipment cost and limited effectiveness for polar compounds, unless co-solvents are used, can restrict its broader application in extracting diverse citrus bioactives.

4.4. Pressurized liquid extraction (PLE)

Pressurized liquid extraction (PLE), or accelerated solvent extraction (ASE), operates by applying high pressure and temperature to maintain solvents in a liquid state above their boiling points. This enhances their ability to penetrate plant matrices and dissolve target compounds. Although less explored than UAE or MAE in the context of citrus waste, PLE has been effectively used to extract phenolic compounds and flavonoids from citrus peels with reduced solvent use and improved efficiency [24]. Ethanol-water mixtures are commonly employed as eco-friendly solvents under pressure, yielding clean and potent extracts. PLE offers automation potential and reproducibility; however, the thermal degradation of heat-sensitive phytochemicals and the complexity of equipment handling may limit its use in specific settings.

4.5. Natural deep eutectic solvents (NADES)

Natural deep eutectic solvents (NADES) are emerging green solvents formed by mixing two or more natural components — such as sugars, amino acids, or organic acids — to create a low-melting, highly soluble liquid. Their tunable polarity and biocompatibility make them suitable alternatives to conventional organic solvents for extracting a wide range of phytochemicals. In citrus waste applications, Plaza et al. [25] successfully used NADES in combination with UAE to extract polyphenols from citrus peels, achieving high recovery and antioxidant activity with minimal environmental impact. NADES offers distinct advantages, including low toxicity, reusability, and potential food-grade applications. However, challenges such as high viscosity, which can reduce mass transfer rates, and the need for regulatory clarity regarding their use in consumable products remain areas of ongoing research.

4.6. Enzyme-assisted extraction (EAE)

Enzyme-assisted extraction (EAE) utilizes specific enzymes such as cellulases and pectinases to degrade the structural polysaccharides in plant cell walls, thereby facilitating the release of bound bioactives. This method operates under mild conditions, preserving the integrity of heat-sensitive compounds while enhancing extraction yields. Citrus peel matrix applications of EAE have yielded soluble dietary fibers, phenolics, and flavonoids [26], with some research combining it with UAE or MAE to increase effectiveness even more [27,28]. The method is especially appealing for creating less processed, clean-label extracts. EAE is limited by enzyme cost, specificity, and sensitivity to environmental factors, including pH and temperature, which demand exact adjustment even with its advantages. Table 2 compares green extraction techniques applied to citrus fruit wastes.

Table 2. **Comparative overview of green extraction techniques applied to citrus fruit wastes**

Таблица 2. **Сравнительный обзор методов «зелёной» экстракции, применяемых для отходов переработки плодов цитрусовых**

Technique	Solvents used	Target compounds	Advantages	Limitations	References
Ultrasound-Assisted Extraction (UAE)	Water, ethanol, and NADES	Flavonoids, phenolics, essential oils	Short extraction time, low solvent use, improved yield	Localized heat may degrade compounds; scale-up challenges	[29]
Microwave-Assisted Extraction (MAE)	Water, ethanol	Pectin, polyphenols, flavonoids	Fast and energy-efficient, high yield	Risk of compound degradation, uneven heating	[30]
Supercritical Fluid Extraction (SFE)	CO_2 (± ethanol co-solvent)	Essential oils, limonene, limonoids	Solvent-free extracts, selective for non-polar compounds	High setup cost, limited polar compound solubility	[31]
Pressurized Liquid Extraction (PLE)	Ethanol-water mixtures	Phenolic acids, flavonoids	Efficient, automatable, green solvents	Thermal degradation risks, equipment cost	[32]
Natural Deep Eutectic Solvent Extraction (NADES)	Choline chloride + sugars/acids	Polyphenols, flavonoids, carotenoids	Non-toxic, customizable, biodegradable	High viscosity affects mass transfer	[33]
Enzyme-Assisted Extraction (EAE)	Water (with added enzymes)	Flavonoids, soluble fibers, pectin	Mild conditions, clean-label extracts	Costly enzymes, sensitive to pH/temperature	[34]

5. Factors influencing green extraction yields

A complex interaction of technological, chemical, and biological aspects controls the efficacy of green extraction methods in extracting bioactive chemicals from citrus wastes. Maximizing yield is simply one benefit of optimizing these factors; another is guaranteeing the obtained molecules' integrity, functionality, and scalability. The most important determinants are solvent choice, extraction time, temperature, solid-to-solvent ratio, particle size, plant matrix composition, and pretreatment techniques [35].

Extraction efficiency is highly influenced by solvent polarity and composition since the type of solvent determines the solubility of bioactive molecules such as phenolics, flavonoids, and limonoids [36]. Ethanol-water combinations are popular for citrus extractions because of their food-grade safety, adjustable polarity, and environmental compatibility [37]. Natural deep eutectic solvents (NADES) can likewise be tailored to target particular molecules. Temperature has two effects: while moderate heating might improve solubility and diffusion, too high temperatures may destroy heat-sensitive molecules, including certain essential oils and ascorbic acid. Balancing efficiency with thermal stability becomes crucial in methods such as MAE or PLE, where higher temperatures are applied.

Furthermore, the extraction time is strictly under control. While extended periods may not significantly boost yield and potentially risk oxidative degradation, short timeframes may result in inadequate cell wall breakdown and poor chemical release [38]. Additionally, the solid-to-solvent ratio influences concentration gradients and solvent saturation levels that determine the driving force for mass transfer [39]. A higher ratio generally promotes better extraction, but excessive solvent volumes can be economically and environmentally unfavorable [40].

Other influential factors (Table 3) include the particle size of citrus waste, which affects the surface area available for solvent interaction, and pretreatments such as drying, grinding, or enzymatic hydrolysis that can enhance matrix accessibility [41]. Notably, citrus species and cultivars also contribute to variability, as differences in peel thickness, wax content, and flavonoid profiles influence extractability. Hence, developing efficient and reproducible green extraction processes requires systematic optimization through experimental design tools (e. g., response surface methodology) tailored to the specific citrus matrix and target bioactive.

6. Comparison with conventional methods

Traditional extraction techniques (maceration, Soxhlet extraction, hydrodistillation, and refluxing) have long been used to isolate bioactive compounds from plant matrices, including citrus fruit wastes. While these methods are well-established and relatively simple to implement, they are increasingly considered inefficient, environmentally unsustainable, and unsuitable for industrial-scale production of clean-label products [48]. The main drawbacks of conventional methods include long extraction times, high solvent and energy consumption, and limited selectivity toward target compounds. In addition, many organic solvents (e. g., methanol, chloroform, hexane) pose significant toxicity and flammability risks, which conflict with current safety and regulatory standards, especially in the food and nutraceutical sectors.

In contrast, green extraction methods (such as UAE, MAE, SFE, PLE, NADES, and EAE) offer substantial improvements (Table 5) in terms of extraction efficiency, sustainability, and product quality [49]. For instance, UAE and MAE reduce extraction time from hours to minutes using significantly less solvent [50]. SFE with CO_2 enables the production of solvent-free essential oils with high aroma and antioxidant retention [51]. NADES and enzyme-assisted techniques allow for selective, mild, and biodegradable extractions that maintain the bioactivity and safety of compounds like hesperidin and limonene [52]. Additionally, green methods offer better process scalability, automation potential, and integration with downstream processes (e. g., encapsulation, formulation), making them more aligned with circular economy models.

Nonetheless, the green extraction paradigm is increasingly favored, particularly in the citrus industry, which generates massive quantities of bioactive-rich waste annually [53]. As global markets shift toward eco-certified, residue-free, and functionally enhanced ingredients, the demand for green extraction technologies in citrus waste valorization is expected to grow exponentially. Comparative assessments support a gradual transition from solvent-intensive, batch-based systems to sustainable, high-throughput green extraction platforms. Table 4 compares conventional and green extraction methods for citrus waste valorization.

7. Applications of extracted bioactive compounds

Bioactive compounds recovered from citrus fruit wastes through green extraction technologies possess broad-spectrum functionality and significant commercial value. Their potent antioxidant, antimicrobial, anti-inflammatory, and metabolic regulatory properties make them highly desirable for formulation into various food, health, and industrial products (Table 6). By transforming citrus by-products into value-added ingredients, industries can simultaneously meet consumer demand for natural alternatives and support sustainable processing models [58].

In the food sector, citrus-derived compounds are extensively used as natural preservatives, fortifying agents, and functional ingredients [59]. Flavonoids such as hesperidin and naringin, along with phenolic acids and limonoids, have been incorporated into beverages, dairy products, and bakery items to enhance shelf life, nutritional value, and health benefits [60]. Pectin, abundantly present in citrus peels, is a gelling, thickening, and stabilizing agent in low-sugar jams, yogurts, and fruit-based products [61]. Citrus essential oils (especially limonene-rich fractions) exhibit potent antimicrobial activity and are used in edible coatings and active packaging films to inhibit microbial spoilage and oxidation [62]. Moreover, encapsulated citrus extracts are increasingly added to nutraceutical powders, gummies, and functional snacks, offering bioactive delivery with improved stability and controlled release.

Importantly, citrus-derived compounds also play a pivotal role in sustainable material development [63]. Biodegradable films and bioplastics based on citrus pectin or fiber residues are emerging as eco-friendly packaging alternatives. Combined with bioactive essential oils, these materials offer dual benefits of environmental safety and food preservation [64]. Integrating citrus waste-derived ingredients into such applications exemplifies a circular economy approach, where waste is not merely discarded but repurposed as a valuable resource across multiple industries.

8. Challenges and future perspectives

While green extraction technologies offer a sustainable and efficient pathway for valorizing citrus fruit wastes, several technical, economic, and regulatory challenges continue to limit their widespread adoption, especially in large-scale food and pharmaceutical applications [73]. One major hurdle is the high capital investment required for advanced equipment such as supercritical fluid systems or industrial-scale microwave reactors, which may not be feasible for small or mid-sized enterprises [74]. Additionally, although promising in lab-scale trials, methods such as enzyme-assisted extraction and NADES-based processes often face scalability issues due to factors like enzyme instability or high solvent viscosity [75]. These technical constraints must be addressed through

Table 3. **Optimization parameters influencing the yield and quality of bioactive compounds from citrus wastes**

Таблица 3. **Параметры оптимизации, влияющие на выход и качество биоактивных соединений из отходов переработки цитрусовых**

Parameter	Typical Range	Effect on Extraction	Best Practices in Citrus Waste Applications	References
Solvent type and polarity	Ethanol-water (20–80 %), NADES	Determines solubility and selectivity for target compounds	Ethanol-water (50–70 %) optimal for flavonoids and phenolics; NADES for thermolabile compounds	[42]
Temperature	25–80 °C (UAE/MAE); up to 120 °C (PLE)	Increases diffusion and solubility but may degrade sensitive bioactives	Moderate temperatures (40–60 °C) balance efficiency and stability	[43]
Extraction Time	5–60 min	Affects mass transfer and compound recovery	15–30 minutes is sufficient for UAE/MAE with minimal degradation	[44]
Solid-to-Solvent Ratio	1:10 to 1:40 (w/v)	Impacts solvent saturation and extraction capacity	1:20–1:30 are widely reported for citrus peels	[45]
Particle Size	< 0.5 mm to > 2 mm	Influences surface area and solvent penetration	Fine powders (<1 mm) enhance yield but increase filtration difficulty	[7]
pH (if applicable)	3–7	It affects enzyme activity and compound stability	Neutral pH is preferred in enzyme-assisted extractions	[46]
Pretreatment Methods	Drying, grinding, and enzymatic hydrolysis	Improves matrix accessibility and release of bound compounds	Oven drying and enzymatic pretreatment increase polyphenol yield	[47]

Table 4. **Comparison between conventional and green extraction methods for citrus waste valorization [54–57]**

Таблица 4. **Сравнение между традиционными методами и методами «зелёной» экстракции для валоризации отходов переработки цитрусовых [54–57]**

Aspect	Conventional methods	Green extraction methods
Common techniques	Maceration, Soxhlet, Hydrodistillation	UAE, MAE, SFE, PLE, NADES, EAE
Solvent type	Organic solvents (methanol, hexane, chloroform)	Water, ethanol, NADES, CO_2 (SFE)
Extraction time	Long (1–24 hours)	Short (5–30 minutes for UAE/MAE)
Temperature requirement	High (reflux temperatures)	Moderate to controlled, energy-efficient
Selectivity for bioactives	Low (co-extraction of impurities)	High (targeted extraction possible with tuning parameters)
Environmental impact	High (toxic solvents, energy-intensive)	Low (eco-friendly, minimal waste)
Product purity	Often requires post-purification	High purity, fewer contaminants
Scalability	Limited for industrial use	Better scalability and process automation
Cost	Lower initial cost but higher operating expense	Higher initial investment but lower long-term cost
Regulatory safety	Risk of solvent residues	Safer for food and pharma applications

Table 5. **Green extraction versus conventional methods [58–62]**

Таблица 5. **Зеленая экстракция по сравнению с обычными методами [58-62]**

Technique	Solvent usage	Temperature	Extraction time	Yield Efficiency	Scalability	Eco-friendliness
Conventional solvent extraction	High (organic solvents)	High	Long (hours)	Moderate	High (but low safety)	Low
UAE (Ultrasound-assisted)	Moderate	Low; Medium	Short (minutes)	High	Medium; High	High
MAE (Microwave-assisted)	Low	Medium; High	Very short (minutes)	High	Medium (limited by scale)	Medium; High
SFE (Supercritical CO_2)	No organic solvent	Medium	Short	High	Medium (costly setup)	Very high
PLE (Pressurized liquid)	Low	Medium; High	Moderate	High	Medium; High	High
NADES-based extraction	Very low (green solvents)	Low; Medium	Moderate	High (selective)	Still emerging	Very high
EAE (Enzyme-assisted)	Water-based	Low	Moderate	High (selective)	Medium	High

Table 6. **Applications of citrus waste-derived bioactive compounds in various industries**

Таблица 6. **Применение биоактивных соединений, полученных из отходов переработки цитрусовых, в различных промышленностях**

Bioactive compound	Product example	Function/Benefit	Target industry	References
Hesperidin, Naringin	Functional beverages, nutraceutical tablets	Antioxidant, anti-inflammatory, and cardiovascular support	Food, Nutraceutical	[65]
Phenolic Acids	Fortified yogurts, antioxidant powders	Oxidative stress reduction, antimicrobial	Food, Pharmaceutical	[66]
Limonoids	Herbal capsules, liver health supplements	Anti-cancer, detoxification enzyme modulation	Nutraceutical, Pharma	[67]
Pectin	Low-sugar jam, edible films, bioplastics	Gelling, thickening, and the prebiotic effect	Food, Packaging	[68]
Essential oils (Limonene)	Antimicrobial food wraps, eco-cleaners	Natural preservative, fragrance, and antifungal	Food Packaging, Cosmetics	[69]
Citrus flavonoids	Skincare serums, anti-aging creams	Skin protection, UV scavenging	Cosmetics, Personal care	[70]
Citrus fiber residues	Biodegradable films, prebiotic snacks	Gut microbiota modulation, material structuring	Functional oods, Packaging	[71]
Citrus seed extracts	Oil-based supplements, dermatological oils	Vitamin E source, cholesterol-lowering, hepatoprotective	Nutraceutical, Cosmeceutical	[72]

engineering innovation, solvent standardization, and modular system designs to make green extractions more accessible and cost-effective.

From a regulatory perspective, using novel green solvents (especially NADES) and enzyme-based systems in food and nutraceuticals still require extensive toxicological evaluation and regulatory harmonization, particularly when intended for direct human consumption. Moreover, despite the growing demand for natural bioactive ingredients, the market competitiveness of synthetic additives (often cheaper and more consistent) poses a challenge to the economic viability of citrus-derived products. On the research front, the lack of standardized protocols for optimizing extraction parameters across different citrus species and plant matrices hampers reproducibility and industrial translation.

Looking ahead, integrating innovative technologies, such as artificial intelligence (AI), process modeling, and real-time sensor analytics, may enable more precise control and optimization of green extraction processes. Additionally, hybrid techniques such as UAE-NADES, MAE-Enzyme, or SFE integrated with encapsulation units could enhance extracts' yield and functional performance. On a broader scale, developing biorefinery models that simultaneously produce multiple products (e. g., pectin, antioxidants, essential oils, and dietary fibers) from the same citrus waste stream will be critical for enhancing resource efficiency and profitability. Collaborations between academia, industry, and policy-makers are essential to overcome existing barriers and promote a transition toward a circular citrus economy that transforms waste into wellness.

9. Conclusion

Citrus fruits generate vast quantities of by-products — primarily peels, pulp, and seeds — which, though often discarded as waste, are rich reservoirs of high-value bioactive compounds such as flavonoids, phenolic acids, pectin, limonoids, essential oils, and dietary fibers. The transition from conventional solvent-based extraction to green extraction technologies has opened new avenues for the sustainable recovery and application of these compounds in food, pharmaceutical, nutraceutical, cosmetic, and packaging industries. Techniques such as ultrasound-assisted extraction, microwave-assisted extraction, supercritical fluid extraction, natural deep eutectic solvents, and enzyme-assisted extraction improve extraction efficiency and selectivity and reduce environmental impact, aligning well with modern circular economy goals.

Despite current limitations (including scalability challenges, high equipment costs, and regulatory gaps), ongoing technological innovation and growing market demand for clean-label, natural ingredients are rapidly driving the adoption of green extractions. Integrating innovative optimization tools, hybrid methods, and biorefinery models will further enable the valorization of citrus fruit wastes on an industrial scale. This review highlights the substantial potential of citrus waste as a valuable resource, emphasizing the need for interdisciplinary collaboration to realize its benefits fully. In doing so, citrus waste can be transformed from an environmental burden into a renewable bioresource, contributing to a more sustainable and health-oriented future.

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