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RESEARCH ARTICLE

Valorisation of Citrus Processing Waste with Special Emphasis on Lemon: Bioactive Compounds, Extraction Techniques, and Sustainable Applications

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ABSTRACT

A substantial proportion, which is approximately 40-50% of the biomass, is discarded as waste in the form of pomace, seeds and peels from the citrus fruits such as lemon. The generation of large quantities of agro-industrial wastes has increased the rapid expansion of the worldwide fruit processing industry. The residues, which are traditionally considered waste, pose a significant environmental challenge. With diverse therapeutic & functional properties, the recent studies highlight that those citrus wastes are a rich source of valuable biologically active compounds, including flavonoids, pectin, phenolics, essential oils & dietary fibres. By exploring the extraction methods, industrial applications & composition, this review focuses on the valorisation of citrus wastes with a special emphasis on the lemon-based by-products. In terms of sustainability & efficiency, both conventional extraction techniques and modern advanced green technologies are used, such as supercritical fluid, microwave-assisted, ultrasound-assisted & enzyme-assisted extractions. Moreover, Pectin has gained a huge significant attention due to its wide applications in pharmaceutical, food & biodegradable packaging industries among all other recovered compounds. In addition, citrus wastes can also be changed or transformed into value-added products such as functional foods, biofuels, biopolymers, eco-friendly packaging materials and nutraceuticals, supporting sustainable development and circular bioeconomy. Challenges related to large-scale implementation, process optimisation, and cost remain a major concern despite all these advancements. For the conversion of citrus waste into valuable bioresources while reducing the environmental impact and promoting a sustainable industrial practice, waste valorisation offers a promising and strong strategy.

Keywords: Citrus processing waste, Lemon waste valorisation, Bioactive compounds, Extraction techniques, Flavonoids and polyphenols, Essential oils and pectin, Sustainable applications

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INTRODUCTION

The food processing industry has led to the generation of massive quantities of agro-industrial waste, mainly & particularly from vegetables and fruits, through exponential growth. Contributing significantly to the global waste streams, the citrus fruits represent one of the most extensively processed & cultivated commodities worldwide. Approximately 35-60% of processed citrus fruits are discarded as garbage in the form of peels, pomace, seeds & wastewater [1]. There can be substantial economic losses, cumulative environmental damage, which can ultimately result in greenhouse gas emissions, foul odour generation, and environmental pollution if improper disposal of these residues happens. By taking a sustainable approach of transforming these residues into value-added products, the concept of waste valorisation has gained considerable attention in recent years. Citrus waste, mainly lemon (Citrus limon), is rich in biologically active compounds such as pectin, phenolic acids, essential oils (limonene), flavonoids, dietary fibres & carotenoids, which possess industrial, nutritional & pharmaceutical potential [2]. Due to various & wide applications among other biopolymers, Pectin remains one of the most commercially important biopolymers due to its gelling, stabilizing & encapsulating agent

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in the pharmaceutical & food industries. Modern advancements in extraction techniques have further increased & enhanced the efficiency of recovering these biologically active compounds [3]. By offering reduced energy consumption, minimal environmental impacts & higher yields, old conventional methods such as solvent & acid extraction are extensively used, emerging various cleantech & green technologies- including ultrasound-assisted, enzyme-assisted, supercritical fluid & microwave-assisted extraction [4]. Innovations can get aligned with the circular economy principles by minimising the generation of discarded waste & promoting the sustainable resource utilisation [5]. Citrus waste valorisation has expanded into numerous expansions & diverse sectors beyond food applications, including biopolymers, biofuels, nanomaterials, sustainable packaging solutions & nutraceuticals [6]. Chronic diseases such as obesity, diabetes, cardiovascular disorders & even neuropsychiatric conditions are additionally studied in recent studies by highlighting the therapeutic potential of certain citrus-derived compounds [7]. Some significant barriers remain a challenge related to various large-scale implementations, techno-economic feasibility, & regulatory constraints despite modern advancements [8]. By comprehensively analysing the valorisation of citrus waste with a special emphasis & focus on lemon waste, by integrating recent modern advancements in extraction techniques, recovery of bioactive compounds, & industrial applications, this review further explores the role of circular bioeconomy approaches in achieving sustainable waste management and highlights the future perspectives of industrial scale utilizations [9].

CITRUS WASTE GENERATION & COMPOSITION

Citrus Waste Generation & Environmental Concerns

Fruit processing and citrus wastes are highly & increasingly recognised as valuable resources within the framework of circular bioeconomy and sustainable management of waste. Through efficient valorisation strategies, these residues, which are rich in bioactive compounds enable their conversions into high-value products [10]. Due to excellent thickening, gelling and stabilising properties, the recovery of pectin from citrus peels has gained immense attention, making it suitable for various applications in pharmaceutical, food & industrial sectors. Fruit wastes also show strong potential as substrates for single cell protein (SCP) production in addition to biomolecule recovery, offering an alternative sustainable source to conventional protein sources with reduced environmental footprint, high yield and the ability to utilise organic waste streams. Due to these approaches, the nutritional security and resource efficiency are also being addressed, making it not limited to only contributing to waste reduction [11]. From Orange peels, hesperidin is derived, exhibiting diverse notable antioxidant, anti-inflammatory & various therapeutic properties with some specific bioactive compounds such as flavonoids. These properties further highlight their potential in pharmaceutical and skin care formulations. Challenges related to large-scale processing, feedstock variability & technological implementation remain despite modern promising advancements, necessitating further research and optimisation for industrial applications. By particularly using the green extraction techniques, which can improve the recovery efficiency and can also reduce the environmental impact, the recent developments have highlighted the growing importance of sustainable approaches in citrus waste utilisation. With significant environmental, health benefits & economic fruit, waste valorisation represents a waste to wealth strategy overall [12].

Chemical Composition of Citrus Waste

Due to rich composition and diverse industrial potential, the citrus processing waste, mainly the seeds, peels and pulp, is recognised as valuable biomass. Bioactive Compounds like- phenolic compounds, flavonoids, dietary fibres, pectin, essential oils and cellulose are present in these residues significantly, and it contributes to the nutritional and functional properties respectively. Eriocitrin, limonene & hesperidin exhibit strong antioxidant, therapeutic and antimicrobial activities, making them suitable for applications in cosmetic, pharmaceutical and food industries [13]. Citrus waste also shows a promising potential as a feedstock for green diesel production in addition to bioactive recovery, where extraction methods enhance the oil yield through supercritical fluid extraction. Although we need further transformations & modifications to match the conventional fuel properties. For the production of the modern advanced biopolymers such as nanocellulose and microcrystalline cellulose, citrus biomass serves as an efficient raw material, and it approaches the offering of sustainable alternatives to wood-based resources and supports the growing demands for bio-based materials [14]. By further highlighting the economic importance, products like flavouring agents, confectionery ingredients & industrial compounds utilise the citrus waste into value-added products. Despite several advantages & benefits, evaluation of biological efficacy remains, challenges related to large-scale processing, optimisation of extraction methods, indicate the need for further research to fully exploit the potential of citrus waste valorisation [15].

Structural Components (Polymers & Biomass)

By holding a significant environmental & industrial value, Citrus waste is not only a source of biologically active compounds but also a rich reservoir of structural biomaterials like hemicellulose, cellulose, lignin & seed-derived biomass. By enabling the use of sustainable materials such as paper, packaging & other bio-based products, the peel fraction constitutes a major portion of citrus wastes containing structural polymers along with complex carbohydrates that contribute to its functional properties & mechanical strengths [16]. Citrus waste has shown promising potential in the transformation conversion processes like activated carbon, biochar & nano catalyst production from a biomass utilisation perspective, where the structural characteristics like surface area, adsorption capacity & porosity are important. By allowing the conversion of low-value waste into high-performance environmental materials, these transformations often involve thermal processes such as carbonisation & pyrolysis [17]. Along with the structural components, the citrus peel biomass also contains a diverse list of secondary metabolites such as essential oils, coumarins & flavonoids, which contribute to its multifunctional nature & also broaden its Industrial application potential in both biomedical fields & materials [18]. The eco enzymes containing the enzymes, bioactive compounds and organic acids can be converted using the fermented fruit waste, which has numerous beneficial applications such as air purification, wastewater treatment & natural cleaning formulation. In Sustainable Environmental Management, the eco-friendly alternatives further highlight the role of citrus biomass [19]. An underexposed yet valuable biomass component is represented by the citrus seeds. They demonstrate their applications in pharmaceutical, food & packaging industries & they are also rich in proteins, oils & phytochemicals. By enhancing the industrial relevance, these bioactive profiles also contribute to antimicrobial, anti-inflammatory and antioxidant properties. Citrus waste demonstrates its potential as a supporting sustainable materials development, renewable biomass resource & circular bioeconomy concept based on its overall structural composition [20].

Emerging Uses of Raw Waste

Recent years show us that Citrus waste has started gaining recognition not only after full-scale processing but also in its minimally processed form or raw form, where the early-pre-stage valorisation offers immediate economic & functional benefits [21]. For exploring therapeutic purposes directly, the fruit processing residues like pulp & citrus peels are needed, which contain bioactive compounds such as amino acids, phytochemicals and essential oils. Unrefined waste streams may serve as the low-cost alternatives for the health-related applications, and these indications come from the naturally occurring compounds like limonene and tryptophan, which have been associated with the antidepressant & neurological effects [22]. In a similar way for managing metabolic disorders such as diabetes & obesity, citrus peel-derived flavonoids are needed as they have demonstrated strong potential in the management of these diseases. Now through various multiple biological pathways like glucose regulation, cellular signalling mechanisms & influencing lipid metabolism. Challenges like low bioavailability & the need for optimised processing conditions remain concerning despite their direct applications being much promising, highlighting the importance of refining early pre-stage utilisation strategies [23]. There is a diverse range of bioactive molecules in the citrus waste that can be directly used to enhance the food quality & safety beyond the therapeutic relevance. For suitable incorporation into food preservation systems & functional food formulation, compounds such as tannins, essential oils and flavonoids are used that exhibit anti-inflammatory, antioxidant & antimicrobial properties. While maintaining product stability & shelf life, these naturally derived compounds can act as safer alternatives in comparison to the synthetic additives. Through its interaction with other natural compounds, citrus peel wastes continue to show their potential in value-added applications [24]. The ability to reduce inflammatory responses & modulate antioxidant enzyme activity supports its use in developing health-promoting products and nutraceuticals. Citrus residues can be utilised in environmental management as adsorbents for removing pollutants from various industrial effluents and can also be utilised in agriculture as compost or soil conditioners. Overall, these early-pre-stage applications highlight that the citrus waste does not necessarily require intricate processing to be valuable. Instead, it's minimally processed or direct use can already contribute to health, economic efficiency, & environmental sustainability, reinforcing its importance within the circular bioeconomy framework [25].

Bioactive Compounds in Citrus Waste

Major Bioactive Compounds

As a rich reservoir, major Bioactive Compounds like phenolic compounds, essential oils, terpenes, carotenoids & flavonoids are present in the Citrus Waste, which contributes significantly to its industrial and functional value. These biomolecules also play a crucial role in applications ranging from food preservation to advanced material synthesis and are not only responsible for the characteristic flavour, aroma and colour of citrus products. In recent years, the role of the biomolecules has expanded beyond the conventional uses with growing interest in their incorporation into green nanomaterials, Bioenergy systems & bio-adsorbents, highlighting their multifunctional nature [26]. Due to the diverse and wide applicability in pharmaceutical, food and biofuel sectors, limonene is a dominant constituent of citrus essential oils among all other compounds, and it has gained a lot of attention in various sectors. However, its utilisation & recovery require careful consideration as huge concentrations may influence the biological processes such as anaerobic digestion and fermentation [27]. This emphasises the requirement for optimised extraction and integrated processing strategies that can balance compound recovery with overall system efficiency. Rutin, naringin and other polyphenols are the flavonoids & phenolic compounds that are well known for their therapeutic & antioxidant properties. These compounds have shown great potential in lowering cholesterol levels, reducing oxidative stress & contributing to the prevention of neurodegenerative & metabolic disorders. In addition, in food industries, the applications such as colourants, natural antioxidants and gelling agents further enhance their commercial importance. Although some challenges, like bitterness and sensory acceptability, need to be addressed [28]. The Citrus derived bioactive are extremely valuable in pharmaceutical & nutraceutical formulations as they exhibit strong anti-inflammatory, anticancer, cardioprotective & antimicrobial properties. With the growing demands for clean label and sustainable products, the use of citrus derived bioactive as natural food preservatives & shelf-life enhancers is getting aligned. These compounds have shown various integration into the various food systems and demonstrated promising results in improving the product stability and safety. For multiple industries overall, the diverse range of bioactive compounds present in the citrus waste underscores its potential as a sustainable resource. By supporting both economic development & environmental sustainability, the continued modern advancements in extraction technologies & integrated biorefinery approaches are expected to further enhance the efficient utilisation of these compounds [29].

Pharmacological & Therapeutic Properties

Bioactive compounds such as phenolics, carotenoids, dietary fibres, essential oils & flavonoids are extracted from the citrus processing waste, mainly from the seeds & peels, which exhibit strong anti-inflammatory & antioxidant activities. By contributing to the prevention of chronic diseases, these compounds play a key role in regulating inflammatory pathways and reducing oxidative stress. Citrus-derived bio-actives have found applications in the pharmaceutical, environmental & food sectors beyond the basic therapeutic effects. They also act as a natural preservative, functional ingredients, & sustainable alternatives, supporting circular bioeconomy & waste valorisation concepts. The presence of carotenoids & polyphenols is further highlighted in the studies of similar fruit waste with notable antimicrobial, anticancer and antioxidant properties, which can be efficiently extracted and incorporated successfully into the therapeutic & nutraceutical formulations. Due to their diverse phytochemical compositions, the citrus peels, especially the orange peel, have demonstrated additional metabolic health & cardioprotective benefits along with neuroprotective and antimicrobial effects. Studies show insecticidal & antimicrobial properties of the essential oils and their associated compounds. It also shows its potential use in dietary supplements. Although further studies are required to establish their long-term safety & bioavailability [30].

Functional & Nutritional Importance

Other Fruit processing wastes & Citrus have gained importance as sustainable sources of functional ingredients & nutrients. By contributing to their Nutritional value, these residues, especially the peels, are rich in flavonoids, carotenoids, dietary fibres & other bioactive compounds. Pectin & Cellulose are the dietary fibres that improve gut function, support digestive health, & plays a pivotal role in regulating lipid metabolism, thereby contributing to the overall human health system. By reducing the oxidative stress & enhancing the stability of food products when used as natural additives, these have antioxidant properties in addition. In the same way, the fruit by-products, such as the Banana peels, have further highlighted the nutritional potential of the agro wastes, which contain essential carbohydrates, phytochemicals & micronutrients that can be incorporated into food fortification strategies. By not only improving the nutritional quality & food security but also by promoting a proper sustainable utilisation of waste into a circular bioeconomy framework, these applications brought a lot of benefits [31].

Special Bio Products from Citrus Waste

For the production of the diverse bio products, including the single cell protein (SCP), biofuels & other speciality compounds, Citrus waste serves as a valuable raw material. Advanced modern techniques are used for the recovery of essential oils & related biomolecules, such as ultrasound-assisted & microwave-assisted extraction, that has reduced processing time, enhanced cost effectiveness & improved yield, supporting their applications in industrial & biotechnology sectors. Agro-industrial residues are being increasingly utilised in addition to the speciality products within the bio-refinery frameworks for producing nutraceuticals & biofuels, while also serving as substrate for microbial processes such as enzyme production & SCP. With environmental & economic benefits, these approaches align with circular bioeconomy principles by transforming low-cost waste into high-value products. Further research is required for efficient large-scale implementation, while challenges related to scalability, storage & process optimisation remain concerning [32].

Trends & Research Development

Within the circular bioeconomy, the recent studies on Citrus waste valorisation show a growing shift towards innovation-driven and sustainable applications. For biodegradable products such as composites, nanomaterials and biopolymers, the citrus peels are being explored as low-cost raw materials, especially in eco-sustainable, friendly food packaging, where they can further improve antimicrobial properties & shelf life. By replacing the synthetic materials, the advances in material science & green processing have further enabled the use of citrus waste in diverse industrial applications. Large-scale adoption is still limited due to the concerning issues such as moisture sensitivity, scalability, market acceptance & raw material variability. Therefore, the continued research is more focused on expanding the practical applications & improving efficiency [33].

EXTRACTION TECHNOLOGIES FOR VALORIZATION

Conventional Extraction Methods

For recovering beneficial compounds from citrus waste, especially essential oils, pectin, & other bioactive compounds, conventional extraction methods are widely used. Due to simple procedure and ease of application at both industrial & laboratory levels, these acid & alkali extraction methods are the most common approaches. These methods often require higher energy use, greater chemical use, and longer processing times, which may reduce their overall sustainability, but they are effective, too. For converting citrus waste into value-added products such as pectin, dietary fibres, essential oils & other bio-based materials, the conventional processing plays a vital role [34]. Cost-related factors, presence of volatile substances & high moisture content are the concerning issues that can affect the large-scale applications. For obtaining phenolics, flavonoids & dietary fibres from orange peel, conventional practises such as grinding, drying & solvent extraction are commonly used. These extracted components are further used in various industrial sectors like pharmaceutical, food & cosmetic industries. However, variations in processing conditions and raw materials can influence the efficiency of these methods. Therefore, conventional extraction methods continue to be the most vital extraction methods for citrus waste utilisation, but further improvements are needed in process efficiency and integration with modern techniques for better results and sustainability [35].

Green / Advanced Extraction Technologies

For the recovery of bioactive compounds from citrus waste, green extraction technologies are highly explored as alternatives to conventional solvent-based methods. While improving product quality & extraction efficiency, these approaches are designed to reduce the solvent usage, processing time & energy consumption. In comparison to the traditional methods, techniques like ultrasound-assisted extraction (UAE), supercritical fluid extraction (SFE), enzyme-assisted extraction (EAE), microwave assisted extraction (MAE) have shown better performance, especially in handling temperature-sensitive compounds [36]. By aligning with global environmental goals, their adoption also supports sustainable processing. Potential health benefits are gained from a diverse range of bioactive compounds that are present in these methods, which are closely linked to the need for better utilisation of fruit processing waste. By providing an alternative to synthetic products with lower toxicity & environmental impact, these compounds are extracted using improved techniques of extraction. For further study, standardisation of extraction conditions & validation of their biological effects remains crucial [37]. For better utilisation, citrus peels have been identified as a valuable source of flavonoids with efficient extraction & therapeutic potential. To improve yield & bioavailability, the optimisation of processing conditions, including extraction methods & temperature, is necessary. For the development of more efficient & targeted extraction strategies, advances in computational tools & data driven approaches are being very supportive. Being not only faster & more efficient but also helpful in preserving the structural integrity of bioactive compounds, which is often affected in conventional processes, the green extraction method is being highlighted in recent studies. To enhance the recovery, these methods are particularly useful for extracting dietary fibres, phenolics & essential oils and can be applied in combination or individually. By expanding across food, nutraceuticals & pharmaceutical sectors, their applications are diverse. Green technologies offer numerous advantages overall, like reduced environmental impact, higher extraction yield, & shorter processing time. Despite numerous benefits, challenges such as high initial investment, scalability issues and the need for process optimisation still limit the huge scale industrial-based applications. Therefore, to make these methods more economically viable and accessible, continuous research & technological improvements are required [38].

Specific Compound Extraction

Depending on the target applications, the citrus waste serves as a significant source of specific high-value compounds such as phenolics, dietary fibres, pectin & essential oils, which can also be selectively extracted. With various extraction methods ranging from conventional distillation to advanced modern techniques, among all these, the essential oils, which are rich in limonene, represent a major fraction. It also reduces environmental impact & improves the yield quality. Diverse bioactive compounds are present in the citrus peels, including carotenoids, flavonoids & limonoids in addition to the essential oils [39]. These bioactive compounds are associated with antimicrobial, therapeutic and antioxidant properties. Recovery of the functional components like pectin is enabled by the extraction of these compounds, while supporting their use in the pharmaceutical & food industries. By showing multiple biological activities, flavonoids & phenolic compounds are extracted from the citrus peels, and their recovery is often enhanced through the green extraction techniques that preserve the functional integrity. Conventional extraction methods may be energy intensive, so limonene extraction requires careful consideration of process efficiency & sustainability, while an integrated recovery system offers better resource utilisation. Targeted extraction of specific compounds from citrus waste highlights its capability as a raw sustainable material for various industrial-based applications [40].

Efficiency, Optimisation & Challenges

By pre-treatment, method selection & process optimisation, the Extraction efficiency in citrus waste valorisation is strongly influenced. Techniques such as-microwave assisted & ultrasound - assisted extraction are highlighted in the recent studies, which improve yield quality, preserve thermolabile compounds & reduce time; however, their performance depends on careful tuning of parameters such as power input, solvent ratio and temperature [41]. Across different regions & seasons, the feedstock variability further complicates standardisation, making priority characterisation essential for maintaining product quality consistency. Large-scale implementations face constraints related to storage, fluctuating raw material quality & supply chain logistics from an industrial point of view. Within the circular bio-refinery systems, the economic feasibility depends on optimising product portfolios, energy efficiency & integration, while market & regulatory barriers also remain significant [42].

APPLICATIONS OF CITRUS WASTE DERIVED PRODUCTS

Food & Nutraceutical Applications

Due to its rich composition of bioactive compounds, essential oils & dietary fibres, the citrus waste has gained considerable importance in nutraceuticals & food sectors. For flavouring, preservation and enhancement of shelf life in beverages & processed foods, the components are widely utilised as natural additives.

Alternatives to synthetic preservatives, the antioxidant & antimicrobial properties are much more suitable, aligning with current trends of clean label products & green consumerism. Citrus-derived compounds additionally contribute to nutraceutical supplements, functional foods & dairy processing applications such as milk coagulation. Similarly, dragon fruit serves as a natural colourant & source of pectin offering both health & functional benefits, being a food peel extract. These compounds that are biologically active help & further support the development of nutraceutical formulations & value-added food products [43].

Pharmaceutical & Therapeutic Applications

With growing interest in utilisation across drugs, cosmetic industries & nutraceuticals, the citrus peel waste has emerged as a valuable bioresource in therapeutic & pharmaceutical applications. While exhibiting significant therapeutic potential, including antidepressant-like activity through modulation of neurotransmitter systems, these wastes are rich in Bioactive compounds such as amino acids, essential oils, polysaccharides & phytochemicals. Supporting their role in novel drug development, the citrus-derived flavonoids, including nobiletin, hesperidin & tangeretin, have demonstrated effectiveness in managing metabolic disorders such as cardiovascular diseases, obesity & diabetes. Their mechanisms involved various activities & pathways such as regulation of inflammatory pathways, modulation of lipid metabolism & gut microbiota & antioxidant activity. Highlighting citrus waste as low cost & substantial source for pharmaceutical applications, additional compounds such as hesperidin & naringin exhibit anticarcinogenic, antioxidant & anti-inflammatory properties [44].

Industrial & Environmental Applications

Particularly within the framework for circular bioeconomy, the citrus waste has significant potential in environmental & industrial sectors. By enabling the production of biochar, biofuels, bio-adsorbents & green synthesised nanoparticles, these citrus wastes serve as a raw material for bio-refineries. While maintaining sustainability, technologies like the Pulsed Electric Field (PEF) enhance the extraction efficiency. Contributing to waste reduction & resource efficiency, the citrus-derived materials are also utilised in catalysis, packaging films & energy storage applications. Addressing issues related to environmental pollution & global warming, citrus waste can support ethanol production & wastewater treatment in addition. The improper dumping of various citrus waste processing residues, such as pomace, can lead to ecological hazards & microbial decompositions. So, requirements for efficient & proper waste management & industrial valorisation strategies are highlighted [45].

Packaging & Bio Materials

By emerging as a promising raw material for sustainable packing & bio material development, the citrus peel, particularly the orange peel, has glorified itself. These residues, which are rich in biopolymers such as pectin, cellulose, phenolic compounds & hemicellulose, can be transformed into coatings, paper-based materials & biodegradable films with notable barrier properties & mechanical strength. While enabling active food packaging applications, the incorporation of peel extracts into polymer matrices enhances the antimicrobial & antioxidant functionality. Improvement of thermal stability & structural performance of bio composites is needed, which is done additionally by the orange peel-derived bio fillers & nanocellulose. By aligning with circular economy principles, this valorisation reduces the dependency on synthetic plastics by converting agro waste into eco-friendly, high-value materials suitable for large-scale industrial-based applications [46].

Essential Oils & Value-Added Products

Limonene-rich fractions are the citrus-derived essential oils, which represent high-value products with diverse therapeutic & industrial applications. Certain limitations may lead to thermal degradation of volatile compounds, but still, the conventional extraction techniques, such as hydro-distillation & steam distillation, are very commonly used. In contrast point of view, methods like ultrasound-assisted extraction improve yield quality & helps in retaining bioactivity. While contributing to antimicrobial, insecticidal & antifungal activities, these oils are primarily composed of limonene along with compounds such as pinene, linalool & citral. Owing to all these properties, the citrus essential oils are widely utilised as preservatives, pest control, food flavouring & cosmetics, highlighting their importance in sustainable value-added product development [47].

DISCUSSION

There is a clear transition from conventional solvent-based extraction techniques to green & intensified methods if doing a comparative evaluation of various extraction strategies. Various studies also indicate that approaches such as microwave-assisted extraction & ultrasound assisted extraction enhance yield quality, better preserve thermolabile compounds compared to traditional methods & reduce processing time. At the same time, we can see that by exhibiting significant antioxidant, anti-inflammatory & metabolic regulatory effects, the citrus-derived bio-actives, including flavonoids, phenolics and essential oils, are supporting their relevance in health-related applications. By integrating these extraction systems within bio-refinery frameworks, we can identify a sustainability perspective that enables efficient waste utilisation, aligns with circular bioeconomy goals and reduces environmental burdens [48].

CONCLUSION

While representing a sustainable approach to transform agro-industrial waste into value bioactive compounds & functional products, citrus waste valorisation became a game-changer. Modern extraction techniques combined with growing evidence of industrial & therapeutic applications highlight the potential of citrus by-products in pharmaceutical, food & environmental sectors. Despite existing challenges & concerns related to scalability, process optimization & economic viability, continued integrated bio-refinery and innovation strategies can overcome these barriers. Overall, we can see that effective & sustainable utilisation of citrus waste not only reduces environmental burdens but also contributes to the development of a circular bioeconomy and bioresource efficiency.

FUTURE PROSPECTS

According to what we observed, we can say that the focus should be on scaling green extraction technologies while maintaining efficiency & economic feasibility in future research. Further to improve the recovery of bioactive compounds with reduced energy input, we need the integration of hybrid techniques with modern advanced optimisation tools. The functional bio-composites, nanomaterials & biodegradable packaging represent promising opportunities in addition to expanding the utilisation of citrus waste in high-value applications. While strengthening academia - industry collaborations will be crucial to translate the laboratory findings into commercially sustainable & viable solutions [49]. Comparisons across studies become difficult as additional standardisation protocols for green extraction technologies are lacking. More in vivo and clinical validation is well reported, as bio-actives are needed to confirm therapeutic safety and efficiency. Furthermore, market acceptance, regulatory framework and integration into existing industrial supply chains remain underexplored, limiting large-scale commercial adoptions. Numerous critical gaps remain despite in-depth, extensive studies on Citrus waste valorisation. Most research is confined to laboratory scale optimisation, with limited translation to industrial or pilot scale processes, while creating uncertainty in real-world feasibility & cost effectiveness. While affecting consistency in extraction efficiency and product quality, variability in feedstock composition is insufficiently addressed due to geographical and seasonal factors. This limits effective translation from research to real-world applications [50].

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AUTHOR CONTRIBUTIONS

- Shreya Saha: Data Collection, Formal Analysis, Writing – Original Draft
- Rojina Khatun: Resources, Writing-Editing
- Sudeshna Sengupta: Resources, Writing-Editing
- Malavika Bhattacharya: Conceptualisation, Supervision

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