# A Review on the Valorization of Agro-Industrial Fruit Peels Through Combined Enzyme and Microwave Extraction for Functional Ingredient Development

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**Abstract: Large volumes of byproducts are generated during the processing of citrus, plantain, and banana, much of which is discarded, contributing to environmental pollution and inefficient resource use. These agro-wastes, however, are rich sources of bioactive compounds with significant nutritional and therapeutic potential. In the context of increasing global interest in sustainable resource utilization and circular economy strategies, the valorization of fruit peels represents a promising pathway for developing high-value functional ingredients for food and pharmaceutical applications. This review synthesizes current knowledge on the major phytochemicals present in these wastes with particular emphasis on total phenolics, flavonoids, including quercetin and its derivatives, carotenoids, and sulfur-containing compounds. The reported biological activities of these compounds, such as antidiabetic, anti-obesity, anticancer, and antimicrobial effects, are discussed in relation to their relevance for pharmacological and biomedical applications. The review further examines recent advances in green extraction technologies, focusing on enzyme-assisted and microwave-assisted extraction methods, which offer improved efficiency and sustainability compared with conventional solvent-intensive and high-temperature techniques. Additionally, emerging applications of machine learning approaches for identifying, predicting, and prioritizing bioactive compounds from complex plant matrices are briefly considered.**

***Keywords:*** *Bioactive Compounds, Phytochemicals, Total Phenolics, Agro-Wastes, Machine Learning.*

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## I. INTRODUCTION

The rapid growth of agro-industrial activities has resulted in the production of large amounts of fruit, vegetable, and crop residues, creating an urgent need for sustainable waste management approaches. Agro-industrial waste valorization has thus become a key element of the global move toward a circular bioeconomy, where biological resources are discovered, recovered, reused, and reintegrated into productive value chains rather than discarded (Mehdizadeh et al., 2025; Perea-Moreno & Muñoz-Rodríguez, 2024). This shift supports sustainable development goals by reducing pollution, decreasing reliance on landfills, and transforming organic residues into bioproducts such as biofuels, bioactive compounds, biopolymers, enzymes, and smart biomaterials (Bala et al., 2023; Silva et al., 2025).

Agro-waste streams, including citrus, banana, plantain, and other fruit peels, represent underutilized yet chemically rich biomass containing polyphenols, dietary fibers, pigments, essential oils, organic acids, and structurally important polysaccharides. These components offer significant potential for economic valorization through

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biochemical, thermochemical, microbial, and biotechnological pathways (Nargotra et al., 2024; Santiago et al., 2023). Current global trends indicate an increasing emphasis on research to convert these residues into valuable molecules for food preservation, pharmaceutical formulations, biodegradable food packaging, cosmetic ingredients, and microbial biopolymers, such as bacterial cellulose (Belkozhayev et al., 2025; Carvalho et al., 2025).

In addition, valorization of agro-waste plays a vital environmental role by decreasing greenhouse gas emissions from open dumping and landfilling, reducing the chemical burden on ecosystems, and encouraging resource-efficient industrial processes (Perea-Moreno & Muñoz-Rodríguez, 2024). Biotechnological innovations, including enzyme-assisted bioconversion, microbial fermentation, machine-learning–guided process optimization, and integrated biorefinery models, have further sped up the conversion of waste into renewable products (Silva et al., 2025; Omidi et al., 2024). Novel evidence shows that these methods not only boost extraction efficiency but also promote sustainable value chains within food, pharmaceutical, and energy industries (Bala et al., 2023).

Together, these developments highlight the tactical significance of agro-industrial waste valorization in addressing global sustainability challenges, reducing environmental burdens, and advancing circular bioeconomy frameworks. This review elaborates on the latest advances, opportunities, and innovations in converting agro-waste. Among the most prominent fruit wastes globally are the peels of banana (*Musa spp*.)**,** plantain (*Musa paradisiaca*)**,** and citrus fruits (*Citrus L*.)**,** which represent underutilized biomass reservoirs rich in bioactive compounds with significant nutritional, pharmaceutical, and functional potential.

➢ *Banana Peels:*

Banana is one of the most consumed tropical fruits worldwide, ranking as the second most popular fruit globally after tomato and the fifth-largest agricultural commodity traded internationally**,** following cereals, sugar, coffee, and chocolate. India alone produces approximately 29.2 million tons of bananas annually, underscoring its importance as both a food and industrial raw material (Bhavani et al., 2023). Despite this, banana and plantain peels, which constitute nearly 35–40% of the fruit mass, remain largely underexploited, despite their high content of polyphenols, carotenoids, dietary fibers, flavonoids, and antimicrobial phytochemicals. These compounds have demonstrated potential applications in food, nutraceutical, cosmetic, and biomaterial industries (Wani & Dhanya, 2025).

Banana peels have gained increasing scientific attention as a promising substrate for value-added bioproducts due to their rich biochemical profile and extractability potential. Recent work highlights multiple extraction routes, including solvent extraction, enzymatic treatment, ultrasound-assisted techniques, and microwave-assisted methods, that significantly enhance the recovery of polyphenols, flavonoids, and other functional metabolites from banana peel matrices (Putra et al., 2022). Advances in sustainable bioprocessing similarly underscore the potential of banana peel-derived compounds in food, pharmaceutical, and environmental applications, emphasizing the relevance of green extraction approaches for circular bioeconomy models (Okorie & Eleazu, 2015; Esonu et al., 2024). Furthermore, recent analytical studies using advanced spectroscopic and chromatographic methods have reaffirmed the nutritional richness and bioactive component diversity of banana peels, positioning them as a viable feedstock for nutraceutical and functional material production (Rawat et al., 2024). Emerging literature continues to expand on valorization pathways, demonstrating substantial innovation in optimizing yield, purity, and functionality of extracted compounds (Putra et al., 2022; Okorie & Eleazu, 2015).

➢ *Plantain Peels:*

Peels of plantain have gained increased scientific attention as a high-value agro-industrial residue due to their abundant nutritional and phytochemical composition and their potential for conversion into bioenergy, biomaterials, and functional ingredients (Alvarez & Galan, 2025). Recent reviews highlight that plantain agricultural waste constitutes a largely untapped biomass stream that can significantly contribute to sustainable energy systems and circular bioeconomy pathways when appropriately valorized (Alvarez & Galan, 2025). Comprehensive compositional studies show that both ripe and unripe plantain peels contain substantial levels of polyphenols, flavonoids, dietary fibers, essential minerals, and bioactive metabolites that exhibit antioxidant, antimicrobial, and functional health-promoting properties (Johri & Sharma, 2025; Uzairu & Kano, 2021; *Nutritional Phytochemical Composition*, 2024). Similar analyses of fruit and vegetable peels further confirm that horticultural residues like plantain peels are rich repositories of high-value compounds suitable for food, pharmaceutical, and cosmetic applications (Kumar et al., 2020).

Recent technological advances have accelerated plantain peel valorization, most especially through innovative extraction, bioconversion, and pretreatment methods. Non-thermal green extraction techniques, such as ultrasound, enzyme-assisted, and microwave-assisted extraction, have been identified as key approaches for efficient, low-energy recovery of bioactive compounds (Usman et al., 2023; Bhatt et al., 2024). In parallel, bioconversion research demonstrates that plantain peels serve as an excellent substrate for generating renewable energy through anaerobic digestion, with optimized pretreatment and neural-network-assisted modeling yielding improved biogas yields (Nweke et al., 2023). Additional studies gave prominence to the broader environmental significance of diverting plantain peel waste from landfills, where improper disposal contributes to pollution, greenhouse gas emissions, and loss of potentially valuable biomass (Gupta et al., 2023).

Collectively, current research underscores that plantain peels, once considered a low-value waste, represent a strategically important feedstock for sustainable biotechnology. Their upcycling through integrated green technologies supports global efforts toward circular

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bioeconomy, waste minimization, and development of natural, functional bioactive ingredients.

➢ *Citrus Peels:*

Citrus fruits, including lemon, orange, grapefruit, citron, clementine, and pomelo, contribute to an annual global production exceeding 100 million tons, placing them among the most widely cultivated fruit groups worldwide (Zou et al., 2016). Historically, citrus fruits have been used as traditional medicinal resources in Asia to treat a variety of illnesses. Modern research confirms that citrus peels are rich in flavonoids, phenolic acids, essential oils, pectins, carotenoids, and limonoids, which exhibit antioxidant, anti-inflammatory, antimicrobial, and chemopreventive activities (Abirami et al., 2014; Okwu, 2008; Maqbool et al., 2025). Suri, Singh, and Nema (2022) further emphasize that citrus processing residues, including peels, seeds, albedo, and pomace, can be converted into value-added products such as prebiotics, nano-encapsulated antioxidants, cosmetic actives, and pharmaceutical intermediates, supporting circular bioeconomy strategies.

The recovery of bioactive compounds from plant materials has traditionally depended on conventional techniques such as maceration, Soxhlet extraction, hydrodistillation, and solvent-based methods. While effective, these methods often require long processing times, large solvent volumes, and high temperatures, which can degrade thermolabile compounds and reduce selectivity. In contrast, modern extraction techniques, including enzyme-assisted extraction (EAE), microwave-assisted extraction (MAE), ultrasound-assisted extraction (UAE), supercritical fluid extraction (SFE), and pressurized liquid extraction (PLE), offer improved efficiency, faster processing, reduced solvent use, and higher selectivity for sensitive bioactives (Chakanaka et al., 2024; Bhadange et al., 2024). Combining conventional and modern methods is increasingly recommended to maximize yield, preserve bioactivity, and enhance the functional properties of plant-derived compounds.

Enzyme-assisted extraction (EAE) and microwave-assisted extraction (MAE) have unfolded as particularly promising techniques for citrus, banana, and plantain peel valorization. EAE enhances cell-wall disruption by employing hydrolytic enzymes such as cellulases, proteases, and pectinases, improving extract yield, selectivity, and bioavailability (Maled et al., 2024; Suthar et al., 2024). MAE accelerates solvent penetration and disrupts plant cell matrices through rapid, uniform heating, allowing better extraction of thermolabile compounds (Yaqoob et al., 2020). Integrated EAE/MAE strategies synergistically reduce solvent consumption, minimize energy use, shorten extraction time, and enhance the stability and functionality of recovered bioactives (Das et al., 2021; Łubek-Nguyen et al., 2022).

Recent advancements in green and circular extraction technologies further enhance these approaches. Eco-friendly solvents, biodegradable catalysts, and low-energy extraction pathways maximize recovery while reducing environmental burden (Anwar, 2025; ResearchGate, 2025). Beyond functional ingredients, agro-wastes such as banana, plantain, and citrus peels can be transformed into bio-plastics, bio-enzymes, dietary fibers, and nutraceutical components, supporting waste-to-value initiatives and the reduce, reuse, recycle paradigm (Koul et al., 2022).

In parallel, the valorization of underutilized and forgotten crops offers complementary opportunities to enhance nutritional security, dietary diversity, and sustainable food systems. Many indigenous fruits and plant-based resources, often neglected in conventional agriculture, are rich in bioactive compounds, vitamins, minerals, and dietary fibers, making them suitable candidates for functional food and nutraceutical development (Kaur et al., 2020; Omotayo & Aremu, 2020). Integrating these underutilized crops into value-added products not only contributes to nutritional adequacy and health promotion but also supports sustainable agriculture and local economies. Recent studies highlight the opportunities and challenges of leveraging underutilized fruits and vegetables, including accessibility, cultivation practices, post-harvest processing, and consumer acceptance, pointing to significant research potential for bioactive recovery and functional applications (Saikia et al., 2024).

Altogether, these studies highlight the enormous prospect of citrus, banana, and plantain peels, as well as underutilized crops, as feedstocks for functional bioactive recovery. Integrating EAE with MAE provides an efficient, eco-friendly, and scalable solution for valorizing these agro-wastes and neglected crops. This integrated approach improves the efficiency of the extraction of bioactive compounds for application in functional foods, nutraceuticals, pharmaceuticals, and biomaterials, while advancing global sustainability goals and circular bioeconomy frameworks.

## II. AGRO-WASTES SIGNIFICANCE OF CITRUS, BANANA, AND PLANTAIN PEEL GENERATION

➢ *Peel Generation Volume*

Fruit processing generates substantial amounts of agro-waste, particularly peels, which are rich in bioactive compounds and represent a significant portion of the total fruit mass. Citrus peels constitute approximately 50% of the fruit weight, reflecting the high volume of biomass discarded during juice processing and other industrial applications (Maqbool et al., 2025; Suri et al., 2022). Similarly, banana peels account for roughly 30–40% of the fruit, while plantain peels contribute 35–50% of the total fruit weight (Bhavani et al., 2023; Wani & Dhanya, 2025). These substantial peel volumes highlight their possibility as raw materials for bioactive compound extraction, functional ingredient production, and integration into circular bioeconomy strategies.

The chemical composition of these peels underlines their functional and industrial value. Agro-wastes such as citrus, banana, and plantain peels are rich in polyphenols,

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flavonoids, carotenoids, dietary fibers, and other bioactive metabolites, which can be recovered and utilized in functional foods, nutraceuticals, natural preservatives, and value-added ingredients (Nirmal et al., 2023). The recovery of these compounds is further enhanced by innovative extraction technologies such as enzyme-assisted extraction (EAE), microwave-assisted extraction (MAE), ultrasound-assisted extraction (UAE), and green solvent extraction, which maximize bioactive yield while reducing energy and solvent use (Das et al., 2021; Łubek-Nguyen et al., 2022).

The following table summarizes peel generation volumes, bioactive composition, and potential applications of citrus, banana, and plantain peels:

Table 1 Peel Generation Volumes, Bioactive Composition and Potential Applications of Citrus, Banana and Plantain Peels.

| Fruit Peel | Peel Generation (% of fruit weight) | Major Bioactive Compounds | Potential Application | References |
|---|---|---|---|---|
| Citrus | Approx. 50% | Flavonoids (hesperidin, naringin), phenolic acids, carotenoids, essential oils, pectin, limonoids | Functional foods, nutraceuticals, antioxidants, natural preservatives, pectin-based gels and encapsulation | Abirami et al., 2014; Maqbool et al., 2025; Suri et al., 2022 |
| Banana | Approx. 30%-40% | Polyphenols, catechins, tannins, carotenoids, dietary fiber, vitamins B & C, minerals (K, Mg) | Functional bakery products, nutraceuticals, animal feed, biodegradable films, antioxidant fortification | Bhavani et al., 2023; Wani & Dhanya, 2025; Omotayo & Aremu, 2020 |
| Plantain | Approx. 35%-50% | Phenolic compounds, flavonoids, tannins, carotenoids, starch, dietary fiber | Functional foods, nutraceuticals, antioxidants, dietary fiber enrichment, bioactive ingredients | Bhavani et al., 2023; Nirmal et al., 2023 |

Utilizing these peels not only adds value to underexploited biomass but also supports circular bioeconomy strategies**,** reduces environmental burden, and contributes to the development of health-promoting and functional food products. By integrating green extraction technologies and bioactive recovery, citrus, banana, and plantain peels can serve as a sustainable source of functional ingredients for food, nutraceutical, and pharmaceutical applications, making them a high-priority target for research and industrial valorization.

➢ *Current Waste Disposal Challenges*

The management of fruit processing waste, particularly citrus, banana, and plantain peels, remains a significant environmental and socio-economic challenge. Improper disposal of these agro-wastes can lead to several issues:

- Fermentation and decomposition: Fruit peels are rich in sugars and moisture, which promotes rapid microbial fermentation when left untreated. This uncontrolled decomposition can produce off-odors and spoilage, reducing the aesthetic and sanitary quality of surrounding environments (Jamal Anwar, 2025; Nirmal et al., 2023).
- Landfill methane emissions**:** When fruit peels are dumped in landfills, anaerobic decomposition generates methane ($CH_4$)**,** a potent greenhouse gas contributing to climate change. Methane emissions from organic waste account for a substantial fraction of anthropogenic greenhouse gases, highlighting the need for sustainable waste valorization strategies (Maqbool et al., 2025; Jamal Anwar, 2025).
- Pest attraction and public health concerns: Accumulated fruit waste attracts flies, rodents, and other pests, creating public health risks and promoting the spread of diseases in urban and peri-urban environments (Wani & Dhanya, 2025; Omotayo & Aremu, 2020).
- Environmental burden**:** Large-scale disposal of fruit peels contributes to soil and water pollution**,** particularly when combined with chemical residues from agro-industrial processing. This environmental burden emphasizes the need for circular bioeconomy approaches that transform waste into valuable bioactive products while mitigating ecological impact (Nirmal et al., 2023; Łubek-Nguyen et al., 2022).

These challenges underscore the urgency of sustainable waste management solutions, such as bioactive extraction, composting, and anaerobic digestion**,** which can reduce environmental impact while adding economic value. Efficient utilization of fruit peels not only mitigates disposal issues but also provides a source of functional ingredients for the food, nutraceutical, and pharmaceutical industries.

Table 2 Summary of the Current Waste Disposal Challenges

| Disposal Challenge | Impact | Mitigation/Valorization Strategy | References |
|---|---|---|---|
| Fermentation & decomposition | Off-odors, spoilage, microbial contamination | Controlled composting, enzyme-assisted extraction, drying & preservation | Jamal Anwar, 2025; Nirmal et al., 2023 |
| Landfill methane emissions | Greenhouse gas emissions, climate change | Anaerobic digestion for biogas, bioactive recovery, circular bioeconomy approaches | Maqbool et al., 2025; Jamal Anwar, 2025 |

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| | | | |
|---|---|---|---|
| Pest attraction | Increased rodent and insect populations, public health risks | Timely collection, bioactive extraction, incorporation into functional foods | Wani & Dhanya, 2025; Omotayo & Aremu, 2020 |
| Environmental burden | Soil and water pollution, chemical leaching | Green extraction methods, valorization into nutraceuticals, functional ingredients | Nirmal et al., 2023; Łubek-Nguyen et al., 2022 |

## III. BIOACTIVE COMPOUNDS FROM FRUIT PEELS: FLAVONOIDS, POLYPHENOLS, AND ANTIOXIDANT POTENTIAL

Fruit peels, particularly from citrus, banana, and plantain, are rich sources of flavonoids**,** polyphenols, and other bioactive molecules with significant health-promoting properties. Flavonoids such as hesperidin, naringin, catechins, and quercetin, along with phenolic acids and carotenoids, have been shown to possess strong antioxidant, anti-inflammatory, antimicrobial, and cardioprotective activities (Intharuksa et al., 2024; Abemsana Devi & Saikia Barooah, 2025).

These bioactives function as free radical scavengers, metal chelators, and enzyme modulators, mitigating oxidative stress and contributing to cellular protection. For instance, citrus peel flavonoids reduce lipid peroxidation and enhance endogenous antioxidant enzyme activity, while banana and plantain peel polyphenols demonstrate anti-inflammatory effects and modulation of glucose and lipid metabolism (Sun et al., 2024; Wani & Dhanya, 2025).

Modern extraction strategies, such as enzyme-assisted, microwave-assisted, and hybrid methods**,** enhances efficient recovery and extraction of these bioactive compounds while preserving their functional properties. The recovered compounds have wide applications in functional foods, nutraceuticals, dietary supplements, and phytopharmaceutical formulations, supporting both health promotion and sustainable utilization of agro-wastes (Łubek-Nguyen et al., 2022; Nirmal et al., 2023).

Furthermore, research demonstrates that integration of green extraction technologies with advanced solvent systems not only improves yield and bioactivity retention but also aligns with circular economy principles, turning fruit peels into high-value functional ingredients (Bastos et al., 2025; Jamal Anwar, 2025).

## IV. CURRENT EXTRACTION TECHNIQUES FOR BIOACTIVE COMPOUNDS FROM FRUIT PEELS

The recovery of bioactive compounds from fruit peels, including citrus, banana, and plantain, is critical for waste valorization and functional food development. Over the years, extraction methods have evolved from conventional techniques to modern and hybrid approaches, each with distinct advantages and limitations.

Conventional methods, such as maceration, Soxhlet extraction, and solvent extraction, are widely used due to their simplicity and minimal equipment requirements. However, these methods are often time-consuming, solvent-intensive, and may degrade thermolabile compounds, limiting their efficiency for high-value bioactive recovery (Chakanaka et al., 2024; Nirmal et al., 2023).

Modern extraction techniques, including enzyme-assisted extraction (EAE**),** microwave-assisted extraction (MAE), ultrasound-assisted extraction (UAE) applies ultrasonic waves to disrupt plant tissues, further facilitating bioactive recovery with reduced solvent consumption (Bastos et al., 2025)**,** and supercritical fluid extraction (SFE)**,** offer significant improvements in yield, selectivity, and sustainability. Enzyme-assisted extraction (EAE) is a biocatalytic technique that employs specific hydrolytic enzymes to facilitate the release of bioactive compounds from plant matrices. Commonly used enzymes include cellulase, pectinase, hemicellulase, and xylanase, which hydrolyze structural polysaccharides in the cell wall, liberating phenolic compounds, flavonoids, and other secondary metabolites (Łubek-Nguyen et al., 2022; Das et al., 2021).

The mechanism involves enzymatic degradation of cellulose, hemicellulose, and pectin, which loosens the plant matrix and enhances solvent accessibility to bound bioactives. EAE is performed under mild temperature and pH conditions, reducing thermal degradation of sensitive compounds while providing high extraction yields.

Microwave-assisted extraction (MAE) is a rapid and energy-efficient technique that utilizes microwave radiation to heat the plant material and solvent simultaneously. The rapid heating induces cell rupture, enhancing mass transfer of bioactives into the solvent (Mudasir et al., 2020; Sun et al., 2024). MAE offers advantages such as reduced extraction time, lower solvent consumption, and improved yield of heat-sensitive compounds. However, care must be taken to control temperature and exposure time to avoid degradation of labile bioactive molecules (Bhadange et al., 2024). Advantages of EAE include improved efficiency, selectivity, and preservation of compound integrity. However, the technique has limitations, including the high cost of enzymes, requirement for enzyme specificity, and potential for incomplete hydrolysis if conditions are not optimized (Suthar et al., 2021; Nirmal et al., 2023).

Hybrid techniques, such as EAE-MAE or EAE-UAE**,** combine the advantages of enzymatic and physical methods, resulting in higher extraction yields and improved compound stability compared to single-method approaches (Sun et al., 2024; Suthar et al., 2021). Recent studies have also emphasized green and sustainable extraction, using eco-friendly solvents such as ethanol, water, or deep eutectic solvents, minimizing environmental impact while

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maximizing bioactive recovery (Wani & Dhanya, 2025; Zaky et al., 2024).

Despite the advancements, challenges remain, including optimization of process parameters, solvent selection, scalability, and cost-effectiveness, which are critical for industrial application (Bhadange et al., 2024; Zaky et al., 2024). Overall, the integration of modern extraction technologies and green solvents enables efficient valorization of fruit peels into functional ingredients and nutraceuticals, aligning with circular bioeconomy principles and sustainable food production strategies (Nirmal et al., 2023; Bastos et al., 2025).

## V. PREDICTIVE FUNCTIONAL ACTIVITIES OF BIOACTIVE COMPOUNDS FROM FRUIT PEELS

This section focuses on the biological and functional potential of bioactive compounds recovered from citrus, banana, and plantain peels, highlighting their health-promoting properties, mechanisms of action, and applications in food, nutraceutical, and pharmaceutical industries.

➢ *Antioxidant Activity*

Bioactive compounds such as polyphenols, flavonoids, carotenoids, and vitamin C exhibit strong antioxidant activity, scavenging free radicals and preventing oxidative stress-related cellular damage. Citrus peels are particularly rich in hesperidin, naringin, and rutin, which have demonstrated high radical scavenging activity in vitro (Łubek-Nguyen et al., 2022; Nirmal et al., 2023). Banana and plantain peels contain dopamine, catecholamines, and phenolic acids, which contribute to their antioxidant potential (Wani & Dhanya, 2025; Suthar et al., 2021).

Polyphenols, including flavonoids, phenolic acids, tannins, and stilbenes, constitute one of the most biologically significant groups of plant-derived bioactive compounds, widely recognized for their antioxidant, anti-inflammatory, immunomodulatory, and disease-preventive activities (Saad et al., 2025; Intharuksa et al., 2024). These compounds are abundant in fruits, vegetables, grains, and medicinal plants, functioning as natural defense molecules with strong radical-scavenging and metal-chelating capacities (El Gharras, 2009; Kamiloglu et al., 2022). Dietary polyphenols play essential roles in human health by modulating oxidative stress, enhancing immune function, improving metabolic processes, and contributing to the prevention of chronic diseases such as diabetes, cardiovascular disorders, and neurodegenerative conditions (Saad et al., 2025). Their health-promoting features are influenced by factors such as source, food processing, bioaccessibility, and bioavailability (Kamiloglu et al., 2022; Yalcin & Çapar, 2017).

Flavonoids, such as hesperidin, naringin, rutin, catechins, anthocyanins, and quercetin, represent the largest subgroup of polyphenols and exhibit potent antioxidant effects that suppress oxidative damage at the cellular level (Intharuksa et al., 2024; Kamiloglu et al., 2022). Citrus fruits are especially rich in these compounds, with peels containing some of the highest concentrations, making them valuable functional ingredients for nutraceutical and phytopharmaceutical applications (Intharuksa et al., 2024; El Gharras, 2009).

Banana and plantain fruits and their by-products, particularly the peels, are excellent sources of dopamine, phenolic acids, catecholamines, carotenoids, dietary fiber, and vitamins, all of which contribute to significant antioxidant, anti-inflammatory, antimicrobial, and metabolic benefits (Ghag & Ganapathi, 2019; Sidhu & Zafar, 2018; Rawat et al., 2024). Recent studies demonstrate that banana peel extracts exhibit strong radical-scavenging activity due to their high concentrations of phenolics and flavonoids, suggesting potential applications in food preservation, functional food development, and therapeutic formulations (Masud Parvez et al., 2023; ResearchGate Review on Banana Peel, 2023; Food Research Journal, 2020). In vitro findings further confirm that Musa acuminata varieties possess measurable antioxidant and anti-inflammatory properties, indicating their possible use in managing oxidative-stress-related disorders (V B et al., 2023).

Overall, accumulating evidence highlights the importance of polyphenol-rich plant materials, including citrus and banana peels, as promising, underutilized sources of functional compounds with broad applications across nutrition, medicine, immunology, and food science (Saad et al., 2025; Intharuksa et al., 2024; Kamiloglu et al., 2022).

➢ *Anti-Inflammatory and Antimicrobial Properties*

Several studies report anti-inflammatory and antimicrobial effects of fruit peel extracts. Citrus flavonoids inhibit pro-inflammatory mediators, whereas banana and plantain peel polyphenols reduce bacterial growth, particularly Staphylococcus aureus and Escherichia coli, supporting their use in functional foods and natural preservatives (Das et al., 2021; Zaky et al., 2024).

Recent research highlights the strong antimicrobial and anti-inflammatory activities of polyphenols and fruit-derived bioactive extracts. Polyphenols, including flavonoids, phenolic acids, and tannins, exhibit potent inhibitory effects against a broad spectrum of clinical bacterial isolates, disrupting membrane integrity and suppressing microbial proliferation (Manso et al., 2021). Studies on fruit extracts have further shown that their antioxidant constituents enhance antimicrobial efficacy, particularly against pathogenic strains such as *Staphylococcus aureus*, *E. coli*, and *Streptococcus pyogenes* (Suriyaprom et al., 2022). Additionally, flavonoids play a key role in mitigating inflammation by downregulating pro-inflammatory cytokines and oxidative stress markers, suggesting their potential for therapeutic and functional food applications (Al-Khayri et al., 2022). Findings from citrus peel studies also confirm significant antibacterial effects, especially from lemon extracts, which demonstrate strong activity against *E. coli* and *S. pyogenes*, highlighting their potential use as natural antimicrobial agents (Saleem et al., 2023; ResearchGate source).

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➢ *Anti-Diabetic and Cardioprotective Effects*

Citrus peel flavonoids and banana peel dietary fibers have been associated with glucose regulation, lipid metabolism, and cardiovascular protection. These compounds modulate enzyme **activities** related to carbohydrate digestion and lipid metabolism, reducing postprandial glucose levels and improving lipid profiles in experimental studies (Mudasir et al., 2020; Jamal Anwar, 2025).

Citrus, banana, and plantain peels have gained significant scientific attention as rich sources of bioactive compounds with multifunctional health benefits. Citrus peels, in particular, contain high levels of flavonoids, carotenoids, limonoids, and essential oils that exhibit antioxidant, anti-inflammatory, antimicrobial, and cardiometabolic regulatory properties (Saini et al., 2022; Singh et al., 2020). Recent studies confirm that citrus peel extracts demonstrate strong free radical–scavenging activity and can modulate metabolic pathways relevant to chronic disease prevention (Samanta et al., 2023; Chakraborty et al., 2024). Evidence also shows that citrus peels are among the most effective natural sources of bioactive compounds due to their high polyphenolic and carotenoid content (Food & Humanity, 2024; *Citrus Peels Review*, 2024).

Similarly, banana and plantain peels are rich in phenolic acids, flavonoids, dopamine, and dietary fibers, contributing to their potent antioxidant, antimicrobial, and anti-inflammatory capacities (Rawat et al., 2024; Wani & Dhanya, 2025). Several reviews highlight that banana peel bioactives can improve metabolic regulation, support gut health, and serve as functional ingredients in food and pharmaceutical applications (Mandal & colleagues, 2024; Pramanik et al., 2023). Advanced extraction and processing techniques, especially green extraction, have further enhanced the recovery of these high-value compounds and expanded their applications in nutraceutical and functional food industries (Muley et al., 2022; Wani & Dhanya, 2025). Collectively, the literature underscores citrus, banana, and plantain peels as underutilized yet exceptionally valuable agro-waste resources with strong potential for industrial, nutritional, and therapeutic use.

➢ *Other Functional Activities*

Other reported functional activities include anti-cancer, hepatoprotective, and neuroprotective effects**,** although these are primarily demonstrated in in vitro and animal studies**.** Hybrid extraction methods preserving bioactive stability allow these compounds to retain their functional efficacy, increasing their suitability for food fortification and nutraceutical formulation (Bhadange et al., 2024; Sun et al., 2024).

Fruit peel valorization has gained significant attention due to their rich phytochemical composition and strong biological functionality. Recent studies highlight that citrus, banana, and other tropical fruit peels contain abundant polyphenols, flavonoids, carotenoids, terpenes, and dietary fibers, making them promising candidates for applications in food, nutraceutical, and packaging industries (Rather et al., 2023; Balogun & Kang, 2024; Munir et al., 2024). Comprehensive reviews further reveal that these bioactive compounds demonstrate antioxidant, antimicrobial, anti-inflammatory, and metabolic regulatory effects, supporting their incorporation into functional foods and biodegradable active packaging materials (Rather et al., 2023; Balogun & Kang, 2024).

Recent advancements in extraction methods, particularly microwave-assisted, ultrasound-assisted, enzyme-assisted, and supercritical fluid extraction, have significantly improved the yield, purity, and stability of fruit peel bioactives (Díaz-de-Cerio & Trigueros, 2025; Wen et al., 2020; Islam et al., 2023). Studies indicate that combined extraction technologies (e.g., Enzyme-Microwaze, ultrasound-microwave) enhance mass transfer, reduce processing time, and maintain structural stability of sensitive compounds (Wen et al., 2020; Islam et al., 2023). Specialized reviews on ultrasonic-assisted extraction also highlight its sustainability and efficiency for phenolics, flavonoids, and essential oils, making it suitable for industrial-scale valorization of fruit residues (Thilakarathna et al., 2023; Mehta et al., 2022).

Furthermore, citrus peel valorization has been emphasized due to its nutraceutical potential, with compounds exhibiting anti-diabetic, cardioprotective, antimicrobial, and anti-cancer activities (Munir et al., 2024; Balogun & Kang, 2024). Recent findings also explore the role of fruit peel extracts in innovative food products, edible coatings, and biodegradable packaging, presenting new opportunities for circular economy approaches in the food sector (FoCha, 2025; JAFR, 2025). Together, these studies demonstrate that emerging extraction technologies and expanded industrial applications make fruit peel bioresources a sustainable and high-value component of modern food science.

## VI. CHALLENGES, LIMITATIONS, AND KNOWLEDGE GAPS

Although significant technological advances have improved the extraction of bioactive compounds from natural sources, substantial limitations and unresolved knowledge gaps continue to hinder large-scale, sustainable implementation. These constraints span technical, economic, environmental, and regulatory domains.

➢ *Technological and Process-Related Limitations*

Advanced extraction systems, including MAE, UAE, SFE, PLE, NADES-based extraction, and hybrid techniques, offer improvements in yield, energy efficiency, and selectivity (Osorio-Tobón, 2020); however, their performance remains highly dependent on matrix composition, moisture content, dielectric properties, and structural rigidity of plant materials (Bhadange *et al.*, 2024). Variability among botanical matrices, particularly in agro-waste sources such as citrus, banana, and plantain peels, results in non-uniform extraction efficiency and inconsistent bioactive profiles (Scientific Bulletin Series F., 2024)

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Moreover, modern techniques often require precise optimization of multiple parameters (e.g., microwave power, solvent polarity, flow rate, and extraction pressure), yet predictive models remain limited. As highlighted by Ligarda-Samanez *et al*. (2025), many technologies underperform when transferred from laboratory-scale to industrial-scale due to insufficient scalability data and a lack of real-time process control tools**.**

- *Limitations in Sustainability and Circular Economy Integration*

Despite the growing interest in valorizing fruit and agri-food by-products, extraction processes may still generate secondary waste streams, including solvent residues, enzyme-laden effluents, or thermally degraded biomass. Oliveira *et al*. (2025) emphasize that the transition toward a circular extraction economy remains incomplete due to:

- Limited solvent recovery technologies,
- High energy requirements for some intensified systems,
- Insufficient life-cycle assessment (LCA) data,
- Lack of industrial standards for green extraction metrics.

While sustainable solvents such as NADES and supercritical $CO_2$ show promise, their adoption is constrained by cost, viscosity challenges, recyclability concerns, and regulatory uncertainties.

- *Economic and Infrastructural Barriers*

Cutting-edge extraction technologies, such as SFE, PLE, and high-power microwave reactors, require significant capital investment, specialized operators, skilled maintenance, and stringent safety protocols (Bhadange *et al*., 2024; Ligarda-Samanez *et al.,* 2025). These barriers restrict adoption within low-resource settings, where fruit waste generation is highest.

Additionally, operational costs such as enzyme procurement, $CO_2$ supply, and post-extraction purification increase the economic burden, reducing the feasibility of commercialization for small-scale industries.

- *Bioactivity, Stability, and Standardization Challenges*

Even when extraction yields are high, the chemical stability of polyphenols, flavonoids, carotenoids, and alkaloids remains a major limitation. Bioactive compounds are prone to oxidation, thermal degradation, or structural modification during processing and storage (Food Physiology, 2025). Current research does not sufficiently address the long-term stability of extracts, interactions between bioactives and co-extracted matrix components, and the impacts of extraction intensity on biological activity.

Furthermore, standardized protocols for quantification, purity determination, or bioactivity testing are lacking across studies and laboratories, as emphasized in the literature on advanced extraction techniques (Bhadange *et al*., 2024; Ligarda-Samanez *et al*., 2025).

- *Knowledge Gaps for Future Research*

Several critical gaps remain unaddressed in current extraction science:

- Lack of predictive models integrating thermodynamics, mass transfer, and machine-learning tools to optimize extraction conditions for diverse plant matrices.
- Incomplete mechanistic understanding of the synergy between enzyme pretreatment (EAE) and machine-assisted extraction, such as MAE or UAE.
- Limited circular-economy frameworks, especially regarding solvent recycling, zero-waste strategies, or valorization of post-extraction residues.
- Insufficient data on industrial-scale feasibility**,** including techno-economic analysis (TEA) and life-cycle assessment (LCA) for green extraction systems.
- Underexplored impacts on human health, including bioavailability, metabolomics, and dose-response relationships of extracts derived using new techniques (foods and health studies, 2024–2025).
- Insufficient regulatory guidance for extracts intended for nutraceutical or functional food applications.
- Addressing these knowledge gaps is essential for enabling the industrial-scale, economically viable, and environmentally responsible valorization of citrus, banana, and plantain peel biomass.

## VII. CONCLUSION

The valorization of citrus, banana, and plantain peels represents a critical pathway toward transitioning from linear waste disposal systems to a sustainable circular bioeconomy. Growing evidence demonstrates that these peels contain high-value bioactive compounds, such as flavonoids, phenolics, terpenes, dietary fibers, and organic acids, that can be recovered using advanced green extraction technologies (Acevedo *et al*., 2021; Odunayo, 2025; Usman *et al*., 2023). These compounds exhibit antioxidant, antimicrobial, and functional properties that support their integration into food, pharmaceutical, and biomaterial applications, thereby reducing environmental burdens associated with conventional waste disposal practices, including methane emissions, leachate generation, and resource loss (Al-Wabel *et al*., 2022).

Innovations in extraction science, including natural deep eutectic solvents (NADES), ultrasound-assisted extraction, microwave-assisted extraction, and high-pressure techniques, are redefining bioactive recovery efficiency while reducing solvent use and energy demand (Ristivojević *et al*., 2024; Vieira *et al*., 2025). Machine learning and chemoinformatic advances further enhance process optimization, compound identification, and predictive modelling, strengthening the economic feasibility of peel valorization at an industrial scale (Torres-Valenzuela *et al.*, 2025; Tsui *et al.,* 2023). These developments align with global sustainability goals by promoting renewable resource use, reducing agro-waste accumulation, and creating new value chains for food, nutraceutical, and biomaterials industries (Alzate Acevedo *et al*., 2021; Vieira *et al.*, 2025).

However, challenges remain, including variability in peel composition, limited standardization of extraction protocols, insufficient scalability data, and regulatory gaps surrounding the incorporation of bioactive-rich extracts into food and health products (Usman *et al.*, 2023; ACS Omega, 2024). Addressing these knowledge gaps will require interdisciplinary efforts integrating green chemistry, biotechnology, materials science, and circular economy frameworks.

Overall, the convergence of sustainable extraction technologies, advanced analytical methods, and circular bioeconomy strategies indicates that fruit peel valorization will continue to expand, offering environmental, nutritional, and economic benefits. Continued research and technological innovation will be essential to unlock the full industrial potential of citrus, banana, and plantain peel bioresources, supporting their transition into high-value, eco-friendly product streams (Focha, 2025; Food Processing, 2025; Oliveira *et al.*, 2025).

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