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Review Article

Advances in Green Technologies for Bioactive Extraction and Valorization of Agro-Waste in Food and Nutraceutical Industries

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Abstract

It occurs the increasing production of the agro-industrial waste which is a great environmental problem that we need to face. Through a critical review of recent successes (2023–2024) in green extraction technologies for conversion of agro-waste to valuable bioactive compounds for use in the food and nutraceutical sectors, this study is conducted. The paper focuses on polyphenols, flavonoids and essential oils from their corresponding agro-waste sources by extraction using non-thermal techniques, namely; pulsed electric field (PEF), ultrasound assisted extraction (UAE) using deep eutedic solvents (DES) and supercritical fluid extraction (SFE-CO_2). Synergistic experiments on emerging hybrid methods of enzyme assisted microwave extraction (EA-MAE) and ohmic heating combined with solvent free extraction to enhance yield but preserve compound integrity are explored. The use of the artificial neural networks (ANN) and genetic algorithms are discussed within the context of extraction process optimization integration of artificial intelligence (ai) models. Plant based proteins, natural preservatives, nanoemulsions, probiotic synbiotics from agro-waste and its valorization pathways are reviewed focusing on the utilization of the plant-based proteins in the development of functional foods and nutraceuticals. The feasibility of these technologies is assessed using sustainability metric, such as life cycle assessment (LCA), regulatory challenge and economic viability. Then, future directions of the paper are outlined, namely the integration of zero waste and higher consumer acceptance of upcycled products to promote a circular bioeconomy.

Keywords: Agro-Waste Valorization, Circular Bioeconomy, Green Extraction Technologies, Bioactive Compounds, Functional Foods, Nutraceuticals Development, Sustainability.

1. INTRODUCTION

1.1 Global Agro-Waste Generation and Environmental Challenges

Large amounts of agro-industrial wastes are generated annually and they are creating serious environmental problems. Annually, the Food and Agriculture Organization (2019) said that 1.3 billion tons of food is wasted around the world, fruit and vegetable waste make up approximately 0.5 billion tons. If the management of these wastes is not proper, they are likely to result in an increased release of gases that are harmful to the environment and contribute to climate change. Problems aggravated by improper disposal methods (such as landfilling and open burning), allow for release of these gases into the atmosphere, including methane.

1.2 Transition to a Circular Bioeconomy

In the face of the agro-waste environmental challenges the linear economy is being replaced with a circular bioeconomy. The real switch brings this emphasis of sustainable use of resources, with the aim of reducing waste and increasing the value obtained from biomass (Kalak, 2023). This is exemplified in the European Union's Green Deal, which desires to make Europe climate neutral by 2050 through the measures of resource efficiency and sustainability. Like Italy's National Strategy for Circular Economy, it encourages the increase of the competitiveness of the secondary raw materials; it consolidates extended producer responsibility schemes; and it promotes fiscal reforms in line with the circular economy principles.

1.3 Objective of the Study

The urgent need to find solutions to agro waste challenges and the current global move towards sustainability necessitates this review that seeks to critically review recent advances in green extraction technologies for agro waste valorization into highly valuable bioactive compounds. In particular, compounds including polyphenols, peptides and polysaccharides in extraction are largely focused on owing to their potential uses in the food and nutraceutical industries (Carrasqueira *et al*., 2025). The review addresses the emergence of hybrid methods and optimization strategies by exploring non-thermal techniques, to focus on ways that are sustainable towards bioeconomy circular objectives and help towards environmental conservation.

2. OVERVIEW OF AGRO-WASTE AS A SOURCE OF BIOACTIVE

2.1 Types of Agro-Waste

Agro-industrial waste is a wide range of byproducts obtained during the processing of agro commodities (Astudillo *et al*., 2023). Fruit peels (e.g. citrus, mango, banana), seeds (e.g., grape, tomato), vegetable residues (e.g., carrot tops, beet leaves), and oilseed cakes (e.g., sunflower, hemp) are common examples of this stream of organic residues. In 99 times out of 100, these materials are rich with bioactive compounds that are being channeled to the food and nutraceutical industries.

2.2 Bioactive Compounds Present

Although the agro-waste could deem as waste by the industrial community, it is actually a rich reservoir of bioactive compounds such as (poly) phenols, flavonoids, carotenoids, dietary fibers and essential oils. Olive mill wastewater, for example, is a byproduct from olive oil production with high concentrations of polyphenols (hydroxytyrosol, oleuropein) with potent antioxidant properties. Ginger peels are also rich in gingerol and shogaol substances, which are popular anti-inflammatory and antioxidant substances. Another example is annatto seeds which are derived from the Bixa-orellana plant and contain a carotenoid called bixin and norbixin, which is also a strong antioxidant (Shaukat, Nazir & Fallico, 2023).

2.3 Health and Industrial Benefits

Various health promoting properties have been shown by bioactive compounds extracted from agro waste. Antioxidant and anti-inflammatory are what polyphenols and flavonoids are known for, which are responsible in the prevention of chronic diseases such as cardiovascular ailments and certain cancers (Barreca, Alessandro & Corrado, 2023). Bixin and norbixin are carotenoids associated with eye health and immune support. Fruit and vegetable residues dietary fibers help to provide digestive health and have prebiotic effect supporting beneficial gut microbiota. The antimicrobial properties of the essential oils extracted from agro-waste make them suitable for the natural food preservation.

Table 2.1: Common agro-waste sources and associated bioactive compounds

Agro-Waste Source	Main Bioactive Compounds	Potential Health/Industrial Benefits
Grape Pomace	Resveratrol, Anthocyanins, Tannins	Antioxidant, Cardiovascular health, Food colorants
Citrus Peel	Flavonoids (Hesperidin, Naringin), Pectin	Anti-inflammatory, Digestive health, Gelling agent
Mango Kernel	Phenolic acids, Tocopherols	Antimicrobial, Skin care, Nutraceutical additive
Tomato Seeds	Lycopene, Polyunsaturated fatty acids	Antioxidant, Skin protection, Oil source
Banana Peel	Lignin, Cellulose, Tannins, Phenolics	Prebiotic, Anti-bacterial, Water treatment agent
Olive Mill Wastewater	Hydroxytyrosol, Oleuropein	Antioxidant, Anti-diabetic, Natural preservatives

3. LATEST GREEN EXTRACTION TECHNOLOGIES (2023–2024 STUDIES)

3.1 NON-THERMAL TECHNIQUES

Non-thermal extraction technologies are increasingly preferred in green chemistry and sustainable food systems due to their ability to extract bioactive compounds from agro-waste with minimal degradation of sensitive phytochemicals (Martins *et al*., 2023). Unlike conventional thermal methods, these approaches maintain the structural integrity and biological activity of compounds, reduce energy consumption, and minimize environmental impacts. The primary non-thermal techniques explored in recent literature include Pulsed Electric Field (PEF), Ultrasound-Assisted Extraction (UAE), and Supercritical Fluid Extraction (SFE-CO_2).

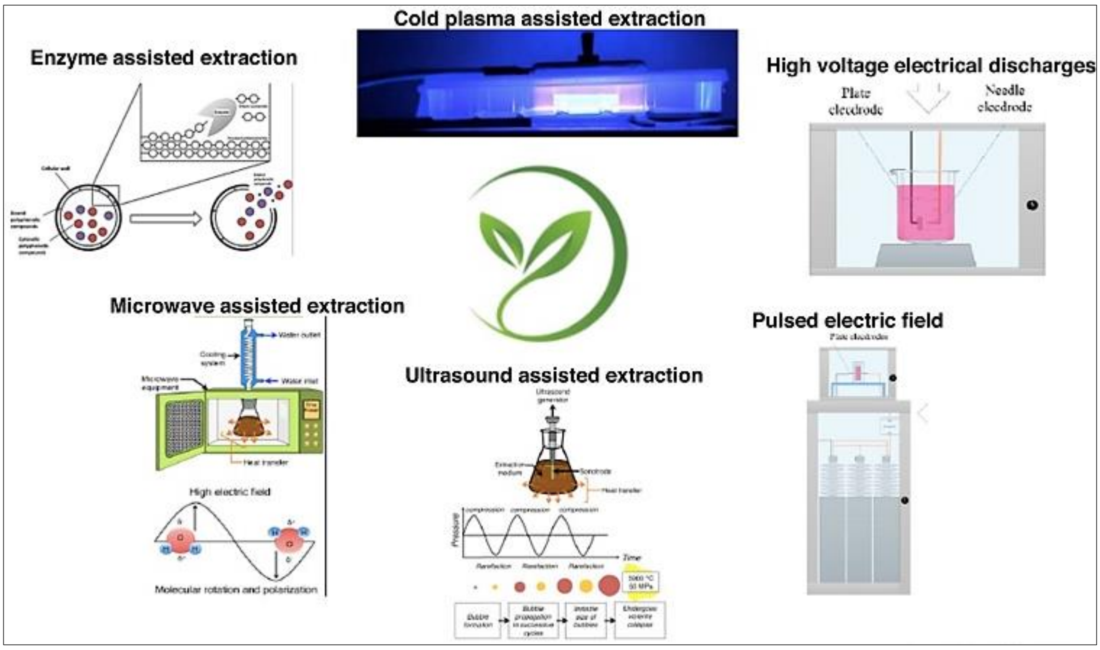

Fig. 1: Overview of innovative green extraction technologies used for the recovery of bioactive compounds from agro-waste

3.1.1 Pulsed Electric Field (PEF)

The technology of Pulsed Electric Field applies short pulses of high voltage to plant-based matrices. Then these pulses disrupt cell membranes using electroporation to enhance mass transfer and exploit intracellular contents releasing into the surrounding solvent (Carpentieri *et al.*, 2022). In recent years it has been shown that PEF is able to extract bioactive from a number of sources. To cite some examples, Carpentieri *et al.*, (2022) generate vanillin, caffeine, and limonene yields improvements from agro waste which include cocoa shells and citrus peels. We especially find that caffeine and vanillin increases grew by 34% and 14%, respectively without degradation of sensitive compounds.

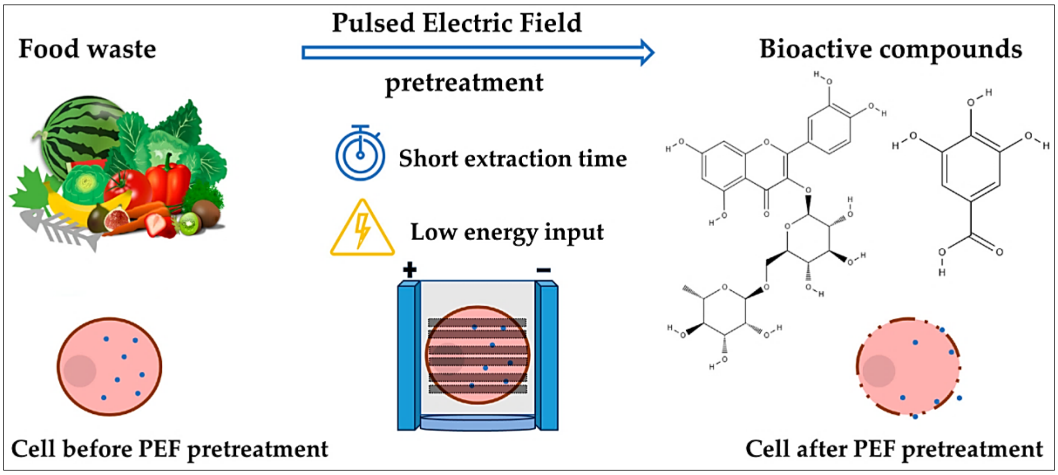

Fig. 2: Mechanism of pulsed electric field pretreatment for enhancing the extraction of bioactive compounds from food waste

Andreou *et al.*, (2023) tested PEF's application in the valorization of tomato processing waste. This range of findings at 2 kV/cm and 700 pulses showed solvent extraction of lycopene increased 45% while polyphenol content doubled, indicating that PEF enhances antioxidant recovery. Similarly, a 2024 Mpakos *et al.*, study showed that, under optimized PEF conditions (0.9 kV/cm, 10 μsec pulse duration), there was a 75 % increase in total phenolic content of Cannabis sativa leaves. The technique was able to target specific phytochemicals, as most significantly enhanced were neochlorogenic acid and frolic acid.

Table 2: Comparison of different green extraction techniques based on solvent usage, extraction time, and yield improvement efficiency for bioactive compound recovery from agro-waste

Extraction Technique	Application Example	Solvent Usage	Extraction Time	Yield Improvement (%)
Pulsed Electric Field (PEF)	Polyphenol extraction from citrus peel	Minimal	5–10 min	~25–40%
Ultrasound-Assisted (UAE)	Resveratrol from grape pomace + DES	Green solvents (DES)	~30 min	~50–70%
Supercritical CO_2 (SFE)	Lycopene extraction from tomato seeds	CO_2 only	1–2 hours	~60–80%

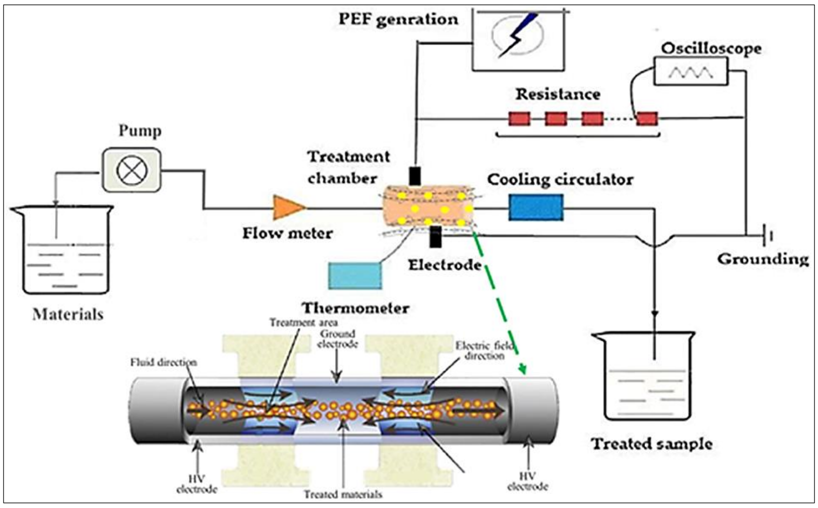

Fig. 3: Pulsed electric field treatment system for material processing with flow, high-voltage pulse generation, and temperature regulation

3.1.2 Ultrasound-Assisted Extraction (UAE)

Ultrasound extraction is carried out using high frequency sound to produce cavitation bubbles in the solvent medium. Since these bubbles collapse, localized pressure increases and localized temperature increases as well, which disrupts the mechanics in plant tissues and facilitates solute–solvent interactions (Almusallam *et al*., 2024). Date press cake (DPC) is widely studied in the UAE as a common agro-industrial residue from which bioactive are extracted recently. The extracts under optimized conditions (40 °C, 15 minutes, 60% ethanol) yielded high total phenol and flavonoid amounts as 121.73 mg GAE/g and 446.66 mg QE/g, and with antioxidant capability of 67.76% (Almusallam *et al*., 2024). For example, a second investigation of Lopes *et al*., (2025) involved raspberry pomace and shown that UAE decreased extraction time from 24 hours down to less than one hour and increased total phenolic yield by almost 29% versus maceration. The main added value of the method studied was in its energy efficiency, reduction of time, and increased bioactivity of the extracts obtained.

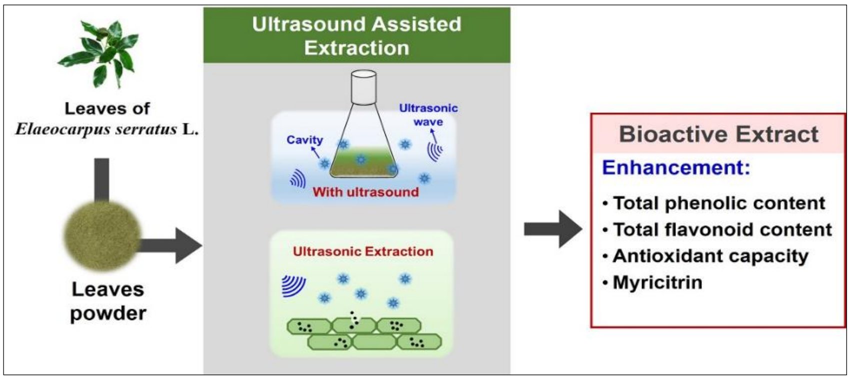

Fig. 4: Ultrasound-assisted extraction enhances bioactive compounds from plant materials

3.1.3 Supercritical Fluid Extraction (SFE-CO_2)

Carbon dioxide is exploited as a supercritical fluid for extraction of lipophilic bioactive because supercritical CO_2 possesses unique properties that allow it to dissolve and extract bioactive between its critical temperature and pressure. This technique circumvents the use of toxic organic solvents thereby working at moderate temperatures allowing the heat labile compounds to survive (Roselli *et al.*, 2024). Such additions are recent applications regarding the extraction of essential oils, carotenoids and polyphenols from agro-waste. SFE-CO_2 extracted high purity β carotene and polyphenols in the carrot and tomato waste with minimum post processing demands, and highlighted by Roselli *et al.*, (2024). Due to its higher initial capital cost compared to SFE with CO_2, commercial nutraceutical and functional food development is ideal using SFE-CO_2.

3.2 Emerging Hybrid Methods

The convergence of various types of green technologies is to emerge hybrid extraction methods to the bio sacrupous of such agro waste more efficient and sustainably. Most of these approaches combine thermal approaches with non-thermal techniques and combine the benefits of both of them with the advantages of circumventing the issues of each. Particularly effective have been hybrid methods to break down complex lignocellulosic structures in order to increase the extractable yield and with minimal loss of structural integrity of thermolabile compounds. Recently, two important hybrid approaches that are gaining popularity in the recent studies were studied: Enzyme Assisted Microwave Extraction (REA-MAE) and Ohmic Heating in combination with Solvent Free Extract.

3.2.1 Enzyme-Assisted Microwave Extraction (EA-MAE)

Enzyme assisted microwave extraction utilizes enzyme pretreatment that specifically degrades plant cell wall components followed by microwave assisted extraction that increases the release of intracellular compounds by localization heat and pressure. The hybrid strategy is specifically applicable for agro-wastes containing substantial lignocellulosic such as rice bran, wheat straw, and fruit pomace (Ali *et al.*, 2022). Recently, Khruengsai *et al.*, (2023) have used EA-MAE for prebiotic oligosaccharides and phenolics extraction from rice bran, an underutilized agro industrial by product. Both xylanase and cellulase enzymes were used to disrupt hemicellulose and cellulose matrices through which microwave extraction efficiency significantly increased. This study reported a 48% increase in prebiotic fiber yield and a 33% increase in total phenolic content in prebiotic fiber yields with use of enzyme, however compared to an enzyme alone or microwave alone method (Coelho *et al.*, 2021).

Malenica *et al.*, (2024) also utilized EA-MAE on apple pomace to minimize enzymatic hydrolysis time and microwave power settings. Enzymatic pre-treatment of the matrix made it softer so the microwaves can more uniformly penetrate which resulted in an extraction of up to 85% of polyphenols (including chlorogenic acid and phloretin). It not only reduced processing time, solvent consumption but also enhanced the level of bioactivity (antioxidant and anti-inflammatory) of the extracted compounds. Such an outcome provides a promising opportunity for valorizing agro-waste in functional foods and nutraceuticals by means of EA-MAE.

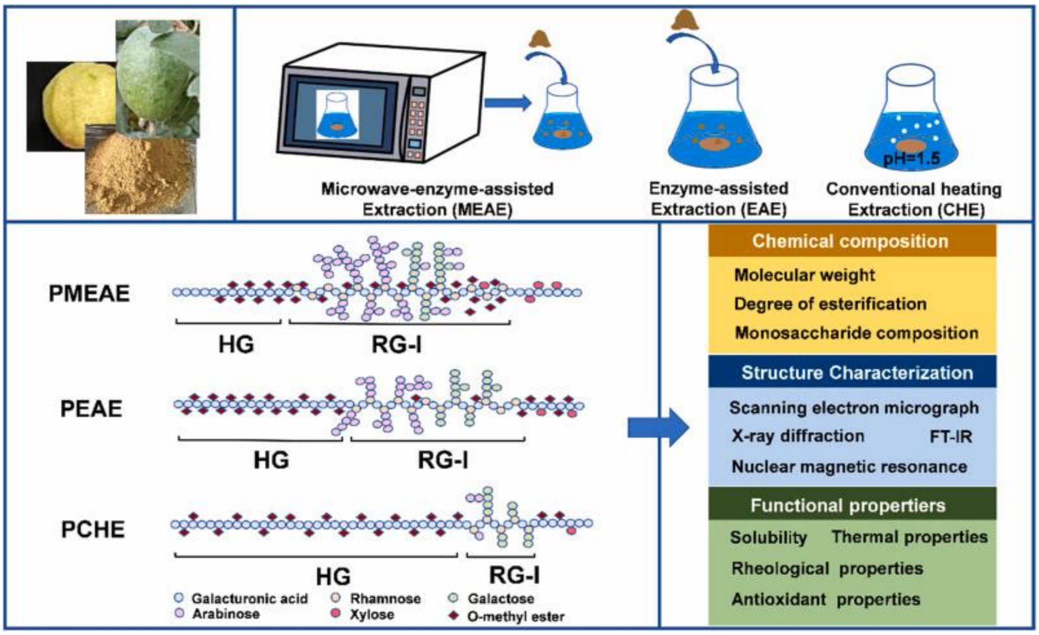

Fig. 5: MEAE System extraction techniques influence the properties of extracted plant compounds

3.2.2 Ohmic Heating Combined with Solvent-Free Extraction

Ohmic heating (OH) is the method of passing electric current through moist biomass and generating internal heat due to electrical resistance of the sample. As a result, it offers uniform, rapid heating with minimal thermal degradation. Thus, it can be employed in combination with solvent free extraction (SFE) to facilitate the recovery of thermolabile compounds without the detriment of organic solvents (Hadidi *et al*., 2024). Safarzadeh, Teixeira & Rocha (2022) deposited this hybrid method on olive mill wastewater (OMWW). The researchers successfully recovered high purity hydroxytyrosol and tyrosol at 60–70 °C using ohmic heating for less than 10 minutes without the need for any additional solvents. The use of this method reduced energy use by 35% and removed the need for post treatment solvent recovery over conventional extraction.

Additionally, Oliveira *et al*., (2024) subjected pomegranate peel waste to ohmic heating and solvent free procedures, thus obtaining excellent recovery of ellagitannins and punicalagin with little structural modification. Not only did this method enhance extraction, but antioxidant potency of the extracted was maintained at high levels suitable for use in active food packaging materials. Because the ohmic heating and solvent free extraction are very suitable for semi solid and liquid agro waste streams, the combination of ohmic and solvent free extraction is particularly suitable for the treatment of agro waste. This supports the ideas of green chemistry and the circular economy of solvent minimizing, waste reducing and energy efficiency.

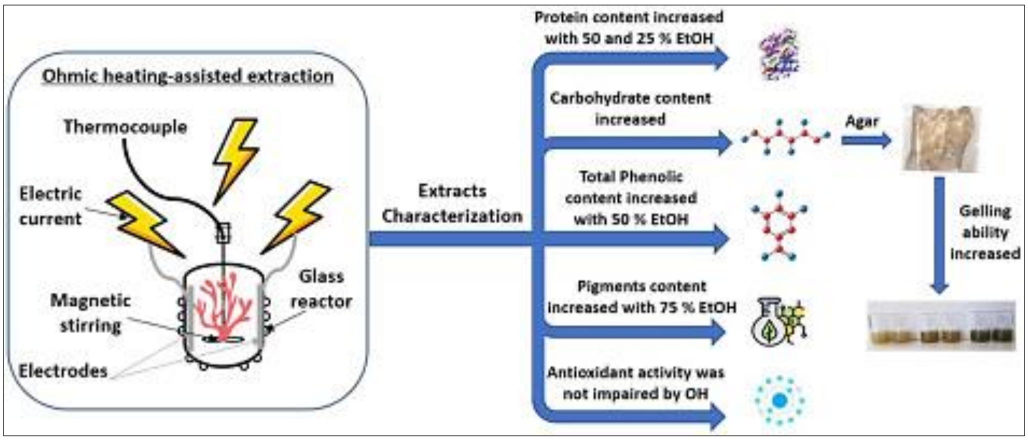

Fig. 6: Ohmic Heating Assisted Extraction System

3.3 Optimization Techniques

Complexity of vegetable origin waste and the demand for bioactive justify the use of green extraction technologies for bioactive recovery. However, the effect of these methods on bioactive is dependent on the parameter choice and tightness of the parameter optimization. Optimization results in the maximization of yield, purity and functionality of the bioactive while minimizing energy consumption and environmental impact. Recent achievements (2023–2024) are based in the development of techniques involving the integration of advanced statistical modeling and machine learning (ML) capabilities as well as real time monitoring applications to improve the effectiveness and scalability of green extraction processes. These are essential techniques in industrialization of sustainable biorefineries and business compliance with regulatory and quality standards.

3.3.1 Response Surface Methodology (RSM)

According to Response Surface Methodology (RSM), multi variable extraction processes are optimized using a widely used statistical tool. But it makes possible to choose the best parameters like temperature, time, the type of solvent and solid-to-solvent ratio to maximize the desired responses (e.g. the yield or antioxidant activity). To illustrate, Roselli *et al*., (2024) employed RSM to optimize UAE parameters for extraction of flavonoids from mango peels. The amplitude, extraction time and concentration of ethanol were varied in their experiments, and they found that amplitudes of 60%, extraction times of 20 minutes and 7% ethanol resulted in a 31% increase of flavonoids relative to baseline. RSM was used by Moutinho *et al*., (2023), as well, to optimize subcritical water extraction from grape pomace. Good green processing criteria were found at the optimal conditions (170 °C, 30 minutes, 1:20 solid to liquid ratio), which improved phenolic yield and antioxidant activity over 100 times.

3.3.2 Artificial Intelligence and Machine Learning Models

In recent days Artificial Intelligence (AI), particularly Machine Learning (ML) and Deep Learning (DL) has become a revolutionary tool to aid in optimization of the green extraction process. ML algorithms are unique in the sense that they can deal with nonlinear, high dimensional data which is precisely what is required for agro waste, as a complex biological matrix. According to Ramírez-Sucre *et al*., (2024), a Random Forest Regression Model was developed to predict the polyphenol recovery from orange peel waste using supercritical CO_2 extraction. Parameters based on pressure, temperature, and CO_2 flow rate were considered in the model. The ML model performed better ($R^2 = 0.98$) and was more generalizable to unseen datasets as compared to RSM. Haque *et al*., (2025) also worked pectin extraction from banana peels using enzyme assisted extraction; they used ANN and GA to optimize their process. The optimization using the AI based method led to optimal enzyme concentration and hydrolysis time with the maximum extraction efficiency of 12% higher than the regular methods. Therefore, AI models possess tremendous potential to scale up green technologies in dynamic industrial settings due to their continual learning ability and self-optimization.

3.3.3 Real-Time Monitoring and Feedback Systems

Another method, including pre-extraction optimization and monitoring real time during processing using sensors and spectroscopy (NIR or FTIR), such as Near Infrared or Fourier Transform Infrared, allows adjusting the extraction conditions as needed during processing. It furnishes the feedback that could be utilized in close loop control structures for quality confirmation. Thus, Lopes *et al*., (2025) have carried out Near-Infrared Spectroscopy (NIRS) to monitor total phenolic content during microwave assisted extraction of green tea processing waste. These real time feedbacks enabled automatic adjustment of microwave power and time which keep the extraction efficiency and constant batch to batch variation. Like Grigoletto *et al.*, (2024) used FTIR sensors implanted with PLC system within a pilot scale ohmic heating setup. The combination of these two allowed real time tracking of antioxidant activity and extraction kinetics from olive pomace, this resulting in reproducible and lessened manual input. Along with this, these systems also allow data collection for next round of optimization using AI / RSM.

4. VALORIZATION PATHWAYS

Valorization is an approach of transforming the agro industrial waste into high value products through the use of novel, environment friendly, and economically feasible methodologies. Given the world's progression towards circular (bio) economies, the valorization of agro wastes has become of increasing interest due to its roles in resource recovery, environmental protection and bioactive compound utilization. Integration of green extraction technologies with the advances in the valorization strategy leads to the transition from waste management to value creation in the food, nutraceutical, pharmaceutical, cosmetic, and bioenergy sectors (Bhargva *et al*., 2023).

4.1 Direct Use in Functional Food and Nutraceutical Formulations

To extract bioactive biochemically, one of the most immediate valorization routes is to directly incorporate them into functional foods, beverages, dietary supplements (FBDs). The increasing consumer demand for natural and clean label ingredient leads industries to replace synthetic additives by natural derived compounds. Tang *et al*., (2024) added yogurt formulations with polyphenol rich extracts obtained from orange peel by ultrasound assisted extraction. Citrus waste as the precursor of the fortified yogurt resulted in improved antioxidant activity, improved sensory properties, prolonged shelf life and a commercially viable use in dairy products. Similarly, Motta *et al*., (2025) also evaluated the contribution of grape pomace extract addition to the energy bars to find that total phenolic content and free radical scavenging activity are increased without significant loss of taste or texture. Results are consistent with the feasibility of health promoting functional products from waste derived bioactive.

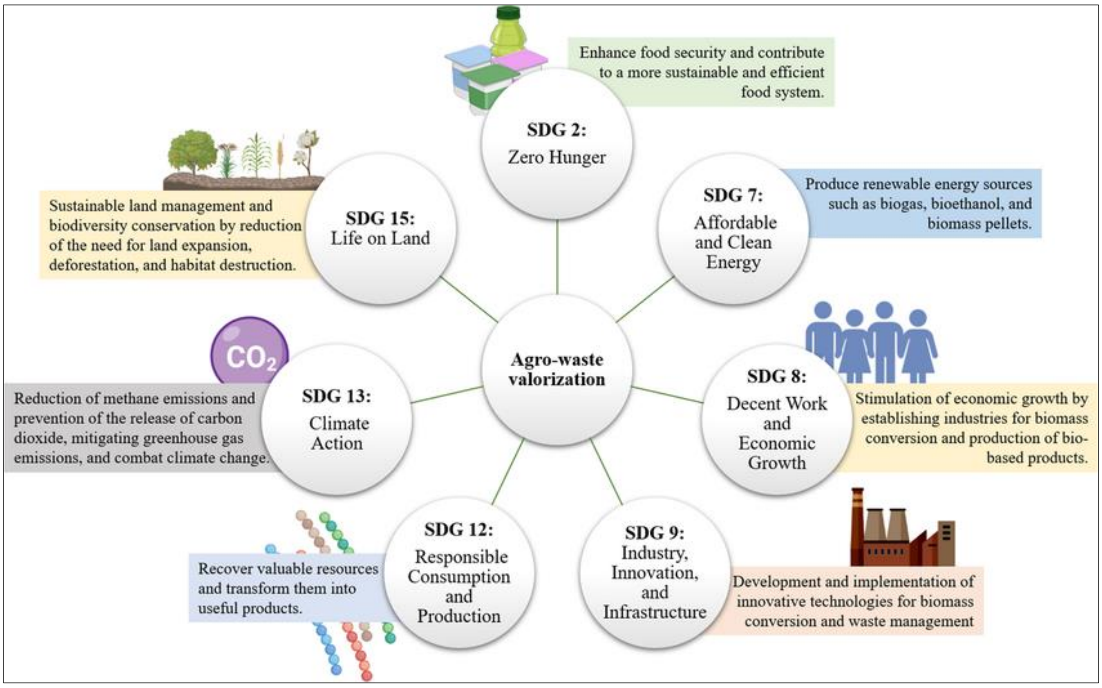

Fig. 7: Impact of Agro-waste Valorization in SDG

4.2 Conversion to Biopolymers and Edible Films

Agro waste is being increasingly extracted components such as pectin, cellulose and starch to the development of biodegradable biopolymers, coating and edible packaging films. The approach of valorizing this plastic lay among the sustainable packaging goals by replacing petroleum-based plastics. In a paper published by Said *et al*., (2023), he extracted pectin from mango peels using microwaved assisted extraction and made processed of such pectin into edible films having high tensile strength and moisture barrier properties. Essential oil formulations were enriched to these films for antimicrobial action, such that they were available for active food packaging. Bueno & Brienzo (2025) also used sugarcane bagasse derived cellulose to produce the bioplastics via green synthesis routes. The material obtained was biodegradable and was proposed to be used as a packaging material of dry food.

4.3 Biotransformation into High-Value Compounds

Another valorization strategy involves further biotransformation's of agro waste derived bioactive using microbial fermentation or enzymatic treatments to convert agro waste derived bioactive to prebiotics, bioethanol, organic acids and pigments. Using lactic acid bacteria, Castagna *et al*., (2025) fermented pomegranate peel extracts with urolithin producing bioavailable bioactivities of ellagitannins. In this way, the approach combines green chemistry with the new discipline of gut microbiome research, and facilitates next generation nutraceutical development. In the second study, Kobayashi *et al*., (2025) utilized the solid-state fermentation process by Aspergillus niger of wheat bran for the production of ferulic acid, an antioxidant highly used in skincare and medication. By valorizing the lignocellulosic material, not only was the lignocellulosic material valorized but there was a cost-effective means for producing an important compound.

4.4 Integration into Bioenergy and Biofertilizer Production

In fact, these post extraction residues are viewed as secondary waste, but can also provide good sources of bioenergy (biogas, bioethanol, biodiesel), or biofertilizers. It ensures both zero waste and better economic feasibility of biorefineries. Simultaneous saccharification and fermentation (SSF) of apple pomace residues comprising polyphenol extraction was shown by Rebolledo-Leiva *et al*., (2024) to convert them to bioethanol. With the dual use strategy, we can simultaneously recovery nutrients and generating renewable energy. Negrea *et al*., (2025) also employed composted citrus peel residues as biofertilizers that are biofertilizers rich in potassium and micronutrients. Compost was beneficial for circular farming systems because these composts improved soil structure and crop yield.

4.5 Industrial Implementation and Circular Bioeconomy Models

Recently, integrated valorization pathways of various industries using biorefinery models where various form of agro-waste is being processed in a cascading manner to produce multiple value-added products are being adopted in many industries. Based on the sustainability metrics, techno economic assessment and life cycle analysis (LCA), these models are designed. For example, in the case of the citrus waste biorefinery model suggested by Lee, Park & Park (2024), they first extract essential oils and polyphenols then convert the remaining biomass to pectin, biogas, and animal feed. As a result, it cut costs of waste disposal in this system and improved resource efficiency, both of which are aligned with EU's circular economy strategies.

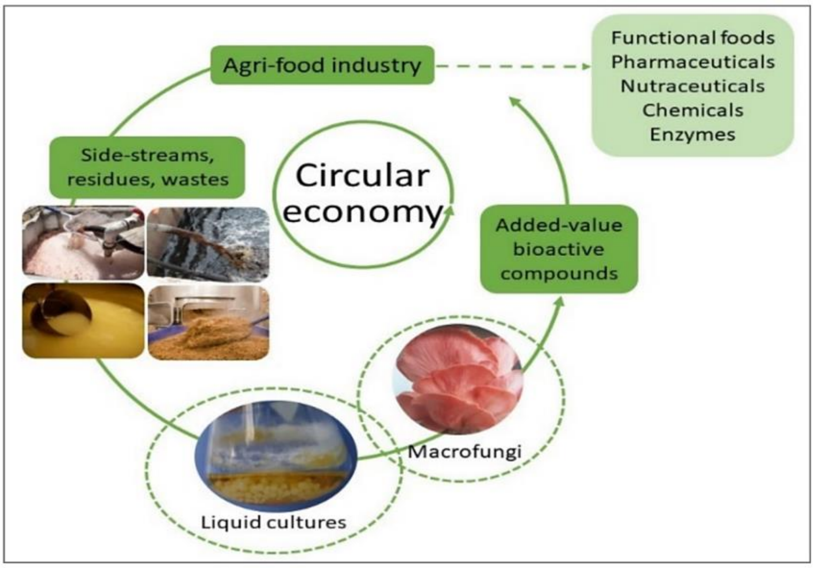

Fig. 8: Agri-food byproducts utilized within a circular economy framework to generate beneficial bioactive substances

5. SUSTAINABILITY METRICS AND CHALLENGES

Green extraction technologies for agro waste valorization need to be evaluated at the sustainability levels so that the environmental, economic and social benefits can be ensured. While these technologies are intended to reduce environmental impact and promote resource efficiency, many challenges remain in broad adoption and optimization of these technologies.

5.1 Sustainability Metrics

Assessing the sustainability of green extraction processes involves multiple metrics that collectively determine their environmental footprint and efficiency.

5.1.1 Environmental Impact Assessment

Life Cycle Assessment (LCA) is an essential (if not the most important) tool to examine the environmental footprint of a product from the raw material extraction to its manufacturing, distribution anywhere in the product's implementation (use) and ultimate disposal. In recent time LCA has been pointed out as an essential means of identifying hotspots and options for improvement of green extraction processes.

5.1.2 Energy and Resource Efficiency

The extraction processes require metrics like energy consumption per unit of extracted bioactive compound, solvent usage, water footprint, etc. To encompass the environmental impact of extraction from the collection of biomasses to the end of the process, innovations such as Path2Green have been developed to develop a holistic metric.

5.1.3 Economic Viability

Cost-benefit analyses are essential to evaluate the economic feasibility of green extraction technologies. These analyses consider capital and operational expenditures, potential revenue from bioactive compounds, and savings from waste reduction.

5.1.4 Social Impact

Metrics assessing job creation, community engagement, and health and safety implications are vital to ensure that green extraction technologies contribute positively to society. Engaging stakeholders and incorporating their feedback can enhance the social sustainability of these technologies.

Fig. 5.1: Sustainability in the economy and business, potentially within the agri-food sector.

5.2 Challenges

Despite the potential benefits, several challenges hinder the scalability and effectiveness of green extraction technologies.

5.2.1 Technological Limitations

Many green extraction methods, such as supercritical fluid extraction and microwave-assisted extraction, require specialized equipment and conditions, which can be cost-prohibitive for small-scale operations.

5.2.2 Standardization Issues

The lack of standardized protocols for extraction processes leads to variability in the quality and yield of bioactive compounds. This inconsistency poses challenges for industrial applications where uniformity is crucial.

5.2.3 Regulatory Hurdles

Navigating the complex regulatory landscape for food and nutraceutical products can be daunting. Ensuring compliance with safety and quality standards requires rigorous testing and documentation, which can be resource-intensive.

5.2.4 Market Acceptance

Consumer perceptions and acceptance of products derived from agro-waste can influence market success. Educating consumers about the benefits and safety of these products is essential to drive demand.

5.2.5 Supply Chain Constraints

The seasonal and geographical variability of agro-waste availability can disrupt the consistent supply of raw materials for extraction processes. Developing robust supply chains and storage solutions is necessary to mitigate this issue.

Table 3: Environmental Impacts of Extraction Techniques (LCA Based)

Technique	Energy Consumption (MJ/kg extract)	Water Use (L/kg extract)	CO_2 Emissions (kg CO_2-eq/kg)	Remarks
Conventional Solvent Extraction	~200–250	~50–100	~15–20	High solvent residue, toxic waste
Ultrasound-Assisted Extraction	~50–80	~20–30	~5–7	Lower time and solvent consumption
Supercritical CO_2 Extraction	~70–90	~10–20	~3–5	Recyclable CO_2, low environmental impact
PEF-Assisted Extraction	~40–60	~15–25	~2–4	High efficiency, low thermal load

6. FUTURE DIRECTIONS

The evolution of green extraction technologies is pivotal in advancing sustainable practices for the valorization of agro-waste. Future research and development are anticipated to focus on enhancing efficiency, scalability, and environmental compatibility of these technologies.

6.1 Integration of Hybrid Extraction Techniques

Use of multiple green extraction methods, also called hybrid techniques, to gain the extraction efficiency and selectivity is becoming more popular. An example of synergistic effects is the integration of ultrasound assisted extraction (UAE) with microwave assisted extraction (MAE) with the use of UAE having higher yields of bioactive compounds compared to the use of MAE alone. Indeed, such hybrid approaches can be optimized for the energy consumption and the processing time, and thus can be applied in the industrial purposes.

6.2 Advancement in Green Solvents

Environmental benign solvents development and use are critical to the development and application of environmentally benign extraction processes. Future directions are then explored and include using natural deep eutectic solvents (NaDES) and bio-based solvents that can be hazardous and provide low toxicity, biodegradability, and the ability to extract a broad array of bioactive. Depending on the needs, they can be tailored to be the right solvent for a given extraction application, making for a more selective process.

6.3 Process Intensification and Automation

Process intensification such as combining the extractive steps with in line purification may improve the plant ability, or lessen resource consumption and streamline operations. Process control, increasing product quality and scale up from laboratory to industrial levels is also expected to rely on automation and real-time monitoring of extraction parameters.

6.4 Valorization of Diverse Agro-Waste Streams

The expanded scope of the agro waste valorization includes widening insignificant by products of fruits, seeds and agricultural residues. The development of suitable extraction protocols for these various materials will open doors to new sources of bioactive compounds that can contribute to the reduction of wastes as well as the invention of novel functional ingredients.

6.5 Integration with Circular Economy Models

In the case of advocating green extraction technologies within the context of circular economy principles, one should design the processes that would lead to the reuse and recycling of materials and hence minimize the waste. The overall systems may be capable of utilizing closed loop processes in which not only solvents are recovered from extractive processes, but also energy is, in order to improve the overall sustainability.

6.6 Regulatory and Standardization Frameworks

It is important to establish clear regulatory guidelines and standardization protocols for green extraction methods for their wider use. Later on, it may involve international standards to define extraction process criteria for green processes restricting safety, efficacy, and compliance to environment.

7. CONCLUSION

With the current transition towards sustainable industrial practices, green extraction technologies have currently become the focus of agro-waste valorization in the food and nutraceutical areas. They are essential to meet global pressures that lead to environmental degradation, waste generation, and resource scarcity at the same time allowing the recovery of valuable bioactive compounds from a wide range of agro-industrial residues (Roselli *et al*., 2024; De-Souza *et al*., 2024). Today, researchers and industries utilize the advance method, such as ultrasound assisted extraction (UAE), microwave assisted extraction (MAE), supercritical fluid extraction (SFE) etc. to increase the efficiency, reduce the use of the solvent and carbon footprint. Finally, hybrid extraction strategies in combination with response surface methodology (RSM) or artificial intelligence (AI)-based modeling appeared promising in improving processing outcomes while ensuring economical value (Zheng *et al*., 2025; Sridhar, Akram & Banat, 2024). In addition, these approaches are important towards scalability and reproducibility for industrial adoption. It not only helps in the formation and development of circular economy ecosystem but also helps in functional food and nutraceutical development that serves food and health industry requirement of health oriented and ecofriendly products (product innovation from agro waste, 2023). Secondly, the use of agro-waste derived bioactive, e.g. polyphenols, flavonoids, carotenoids and dietary fibers in novel product formulation offers novel ways for earning economic growth while promoting environmental sustainability.

Despite this, there still remain several challenges to overcome such as technological limitations, high upfront investment costs, lack of standardization, and regulatory uncertainty. The solutions to these barriers will require the participation of interdisciplinary collaboration by the researchers, policymakers, and industry stakeholders. Research and development investments and their corresponding supportive regulation are needed in order to promote the adoption of these technologies globally (Roselli *et al*., 2024; Ristivojević *et al*., 2024). Future directions should be aimed at the development of multifunctional green solvents, real time online process monitoring systems and closed loop process models resulting in minimum waste and energy inputs. Aside from the development of sustainability metrics and LCA to full evaluate environmental, economic and social impacts of these innovations, the measurement of the performance of these innovations in key areas is equally important (De-Souza *et al*., 2024; Sridhar, Akram & Banat, 2024).

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