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Research Article

GREEN EXTRACTION TECHNOLOGIES FOR RECOVERING HIGH VALUE BIOACTIVE COMPOUNDS FROM AGRO-INDUSTRIAL WASTE

Juwairiah[1], Nurul Huda[2], and Syafiq Amir[3]
[1] Politeknik Negeri Media Kreatif PSDKU Medan, Indonesia
[2] Universiti Utara, Malaysia
[3] Universiti Kebangsaan, Malaysia

Corresponding Author:

Juwairiah,
Graphic Engineering Study Program/Industrial Technology Department, Politeknik Negeri Media Kreatif PSDKU Medan.
Jln. Guru Sinumba No. 6 Helvetia Timur-Medan, Indonesia.
Email: juwairiah4@gmail.com

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Abstract

Agro-industrial waste represents a significant environmental challenge while simultaneously containing valuable bioactive compounds with potential applications in food, pharmaceutical, nutraceutical, and cosmetic industries. The development of sustainable extraction strategies is increasingly required to replace conventional methods associated with excessive solvent consumption, high energy demand, and environmental limitations. This study aimed to analyze the potential of green extraction technologies for recovering high-value bioactive compounds from agro-industrial waste and to evaluate their technological efficiency, sustainability performance, and industrial applicability. A systematic review and comparative analytical approach were employed by examining scientific publications related to ultrasound-assisted extraction, microwave-assisted extraction, enzyme-assisted extraction, supercritical fluid extraction, and deep eutectic solvent-based extraction. The findings revealed that green extraction technologies improved bioactive compound recovery, reduced processing time, minimized solvent utilization, and enhanced environmental compatibility compared with traditional extraction approaches. The effectiveness of each technology was influenced by waste composition, target compound characteristics, and optimization of extraction parameters. The study concludes that green extraction technologies provide a strategic pathway for transforming agro-industrial residues into valuable resources within circular bioeconomy systems. Future development should emphasize process integration, industrial scalability, and advanced optimization approaches to maximize sustainable bioactive compound recovery.

Keywords: Agro-industrial Waste, Bioactive Compounds, Circular Bioeconomy

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INTRODUCTION

The increasing global demand for sustainable production systems has intensified research interest in transforming agro-industrial waste into valuable resources rather than treating it as an environmental burden (Makurat-Kasprolewicz et al., 2024; Sonu et al., 2023). Agricultural and food processing industries generate substantial quantities of residual biomass, including fruit peels, seeds, pomace, husks, stalks, and other by-products that remain rich in bioactive compounds such as polyphenols, flavonoids, carotenoids, alkaloids, peptides, and other functional molecules (Awais et al., 2026; Reig-Valor et al., 2025). These compounds possess significant biological activities, including antioxidant, antimicrobial, anti-inflammatory, and health-promoting properties, making them highly valuable for applications in nutraceuticals, pharmaceuticals, functional foods, cosmetics, and biotechnology industries (Rodriguez-Gomez et al., 2026). The valorization of agro-industrial waste through efficient extraction strategies represents an important pathway toward achieving circular economy principles by reducing waste accumulation while generating high-value products (Pekkoh et al., 2023).

The conventional utilization of agro-industrial residues has primarily focused on disposal, animal feed, composting, or low-value applications, resulting in economic losses and potential environmental problems (Kodchakorn & Kongtawelert, 2024). The uncontrolled accumulation of organic waste contributes to greenhouse gas emissions, soil degradation, unpleasant odors, and increased pressure on waste management systems (Sini et al., 2025). The development of advanced extraction approaches capable of recovering valuable compounds from these residues has therefore become a critical research priority. Bioactive compounds embedded within plant matrices often exhibit complex chemical structures and require appropriate extraction methods to maximize recovery efficiency while maintaining biological activity (Almeida et al., 2025; Verma et al., 2025). The transition from waste management-oriented approaches toward resource recovery-oriented strategies reflects a fundamental shift in industrial biotechnology and sustainable manufacturing (Timpanaro & Foti, 2025; Yang et al., 2026).

Green extraction technologies have emerged as promising alternatives to traditional extraction techniques due to their ability to minimize solvent consumption, reduce energy requirements, decrease environmental impacts, and improve the quality of extracted compounds (Perra et al., 2023). Technologies such as ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), supercritical fluid extraction (SFE), pressurized liquid extraction (PLE), enzyme-assisted extraction (EAE), and the application of deep eutectic solvents (DES) have demonstrated considerable potential in enhancing extraction performance (Faria & Silva, 2025; Sujanto et al., 2024). These innovative approaches align with the principles of green chemistry by promoting safer solvents, improved process efficiency, and sustainable utilization of natural resources. The integration of green extraction technologies into agro-industrial waste valorization systems provides new opportunities to develop environmentally responsible processes for obtaining high-value bioactive ingredients (Nesterov et al., 2024; Srimathi & Virivinti, 2024).

Traditional extraction methods used for recovering bioactive compounds from agro-industrial waste are commonly associated with several limitations that restrict their effectiveness and sustainability (Pranowo et al., 2026). Conventional solvent extraction frequently relies on large amounts of organic solvents, including methanol, ethanol, acetone, and hexane, which may generate environmental concerns due to toxicity, volatility, and difficulties in solvent recovery (Esposito et al., 2026; Mikucka et al., 2023). These methods often require prolonged extraction times, high temperatures, and excessive energy input, which can negatively influence the stability of thermosensitive bioactive compounds. The inefficiency of these processes reduces economic feasibility and limits their implementation at industrial scales (Cubero-Cardoso et al., 2025; Muñoz-Realpe et al., 2025).

The complexity of agro-industrial waste matrices presents additional challenges in achieving optimal extraction outcomes (Cazier et al., 2024). Plant-based residues contain diverse structural components, including cellulose, hemicellulose, lignin, proteins, and lipids, which can hinder the accessibility and release of target bioactive compounds (Srivastava et al., 2025). Variations in waste composition caused by differences in plant species, cultivation conditions, processing methods, and geographical origins further complicate standardization of extraction procedures (Cardoza et al., 2025; Nagybákay et al., 2025). The absence of universally optimized protocols for different types of agro-industrial waste remains a major obstacle in developing reliable and scalable recovery systems. These challenges highlight the necessity of designing extraction strategies that are adaptable, efficient, and capable of preserving the functional properties of recovered compounds (Abbas et al., 2026; Bruna et al., 2025).

The industrial adoption of green extraction technologies also faces several unresolved issues related to process optimization, economic viability, scalability, and regulatory acceptance (Domingues et al., 2026). Although laboratory-scale studies have demonstrated promising extraction yields and improved environmental profiles, many technologies remain limited by high equipment costs, operational complexity, and insufficient long-term industrial validation (Lamine et al., 2024; Sharma et al., 2026). The selection of appropriate extraction parameters, including solvent composition, temperature, pressure, extraction time, and energy input, requires systematic investigation to achieve maximum efficiency while maintaining sustainability. Addressing these limitations is essential for bridging the gap between experimental research and practical industrial implementation of green extraction systems (Argun et al., 2025; Restrepo-Serna & Cardona-Alzate, 2024).

This research aims to investigate the potential of green extraction technologies as sustainable approaches for recovering high-value bioactive compounds from agro-industrial waste streams (Arias et al., 2025). The primary objective is to evaluate the effectiveness of emerging extraction techniques in improving extraction efficiency, reducing environmental impacts, and maintaining the functional properties of recovered compounds (Zaidi et al., 2024; Zenteno Hopp et al., 2026). The study focuses on understanding how different green extraction platforms can contribute to the transformation of agricultural residues into valuable bioresources suitable for industrial applications (Aliste et al., 2025).

The research further seeks to analyze the relationship between extraction technology selection and the physicochemical characteristics of bioactive compounds obtained from various agro-industrial waste materials (Mokanaasri et al., 2026; Rajan et al., 2026). Specific attention is directed toward evaluating extraction performance indicators, including yield, purity, antioxidant capacity, bioactivity retention, solvent sustainability, and energy efficiency (Omeje et al., 2023; Vallejo et al., 2025). Through comparative assessment of different green extraction approaches, this research aims to identify suitable technologies that provide optimal balance between productivity, environmental responsibility, and economic feasibility (Pereira et al., 2025; Pullas et al., 2025).

The expected outcome of this study is the development of a comprehensive perspective regarding the role of green extraction technologies in advancing sustainable waste valorization (Podetti et al., 2025). The research intends to provide scientific insights that support the integration of innovative extraction methods into circular bioeconomy frameworks (Jūrienė et al., 2024). The findings are expected to contribute to future technological development by offering guidance for researchers, food industries, biotechnology sectors, and policymakers in implementing sustainable strategies for recovering bioactive compounds from agro-industrial residues (Rojas-García et al., 2026).

Existing literature has extensively explored the application of individual green extraction technologies for recovering bioactive compounds from specific agro-industrial waste materials. Numerous studies have reported improved extraction yields using ultrasound, microwave,

supercritical fluids, enzymes, and alternative solvents compared with conventional methods (Prado-Acebo et al., 2024). However, current research remains largely fragmented, focusing on isolated technologies, individual waste sources, or specific target compounds without providing comprehensive comparisons among different extraction platforms. The lack of integrated evaluation limits the understanding of which technologies are most appropriate for diverse agro-industrial waste streams (Marianne et al., 2024).

Previous studies have also insufficiently addressed the relationship between extraction efficiency and broader sustainability indicators. Many investigations emphasize extraction yield and bioactive compound concentration while providing limited analysis of environmental performance, energy consumption, solvent sustainability, and economic feasibility (Reig-Valor et al., 2025; Sonu et al., 2023). A holistic assessment framework that incorporates technological, environmental, and industrial perspectives is still needed to determine the real potential of green extraction technologies in large-scale applications. This limitation creates uncertainty regarding the practical implementation of these approaches within sustainable production systems.

The existing knowledge gap is further reflected in the limited understanding of process integration and future industrial scalability. Research on combining different green extraction strategies, optimizing multi-parameter systems, and applying advanced analytical approaches remains relatively underdeveloped. Emerging concepts such as artificial intelligence-assisted optimization, smart extraction systems, and biorefinery integration require further exploration to maximize the value recovery potential of agro-industrial waste. Addressing these gaps is essential to establish a more comprehensive scientific foundation for sustainable extraction technologies.

The novelty of this research lies in providing an integrated examination of green extraction technologies as strategic tools for converting agro-industrial waste into high-value bioactive resources. Unlike studies that focus primarily on extraction efficiency, this research emphasizes the interconnected evaluation of technological performance, environmental sustainability, and industrial applicability. The approach contributes to a broader understanding of how green extraction systems can support circular economy models by transforming waste materials into functional ingredients with significant economic and health-related benefits.

The justification of this research is based on the urgent need for sustainable alternatives to conventional extraction processes that are increasingly challenged by environmental regulations, resource limitations, and consumer demand for clean-label products. The recovery of bioactive compounds from agro-industrial waste provides dual benefits by reducing waste generation and creating new sources of valuable natural compounds. Green extraction technologies represent a scientifically and industrially relevant solution for addressing these challenges while promoting responsible resource utilization.

The contribution of this study extends beyond technological improvement by supporting the advancement of sustainable biotechnology and circular bioeconomy development. The research provides a conceptual and practical foundation for future innovation in waste valorization, functional ingredient production, and environmentally responsible industrial processing. Through the exploration of green extraction technologies, this study aims to strengthen the connection between scientific discovery and sustainable industrial transformation, contributing to global efforts toward more efficient and environmentally conscious utilization of agricultural resources.

RESEARCH METHOD

Research Design

This study employed a systematic review and comparative analytical research design to investigate the effectiveness, sustainability, and technological potential of green extraction approaches for recovering high-value bioactive compounds from agro-industrial waste. The research design was developed to synthesize scientific evidence regarding emerging extraction technologies, including ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), supercritical fluid extraction (SFE), pressurized liquid extraction (PLE), enzyme-assisted extraction (EAE), and deep eutectic solvent (DES)-based extraction systems. A systematic approach was applied to identify, evaluate, and integrate findings from previous experimental studies related to the recovery of bioactive compounds from agricultural and food processing residues (Awais et al., 2026; Rodriguez-Gomez et al., 2026).

The research adopted a qualitative and quantitative synthesis framework by analyzing extraction performance indicators reported in scientific literature. The evaluation focused on several critical parameters, including extraction yield, bioactive compound concentration, antioxidant activity, biological functionality, solvent characteristics, energy consumption, and environmental sustainability. The comparative analysis was conducted to determine the advantages, limitations, and applicability of different green extraction technologies across various agro-industrial waste matrices. This design enabled the identification of technological trends, methodological challenges, and future development directions in sustainable bioactive compound recovery.

The review process followed established principles of evidence-based scientific analysis to ensure transparency, consistency, and reliability in data interpretation. Relevant studies were systematically examined based on predefined inclusion and exclusion criteria, allowing the research to provide a comprehensive understanding of current advancements in green extraction technologies. The methodological framework was structured to support critical evaluation of existing knowledge while highlighting opportunities for innovation in sustainable waste valorization and circular bioeconomy applications.

Research Target/Subject

The population of this study consisted of scientific publications investigating the extraction and recovery of bioactive compounds from agro-industrial waste using sustainable or environmentally friendly extraction technologies. The target literature included peer-reviewed research articles, review papers, and scientific reports published in internationally recognized journals within the fields of food science, biotechnology, agricultural engineering, environmental science, and green chemistry. The selected literature covered various types of agro-industrial residues, including fruit peels, seeds, pomace, cereal by-products, vegetable waste, plant biomass residues, and other organic materials generated from agricultural and food processing activities (Pekkoh et al., 2023).

The sample selection was conducted through purposive sampling based on specific eligibility criteria to ensure the relevance and scientific quality of the analyzed studies. Articles were selected when they examined the application of green extraction technologies for obtaining valuable bioactive compounds, such as phenolic compounds, flavonoids, carotenoids, anthocyanins, peptides, and other functional metabolites. Studies focusing exclusively on conventional extraction methods without comparison or relevance to sustainable extraction principles were excluded from the analysis.

The final sample consisted of scientific studies representing diverse geographical regions, agro-industrial materials, extraction techniques, and analytical approaches. The selected samples were analyzed to identify patterns related to extraction efficiency, technological innovation, and sustainability performance. The diversity of selected studies allowed the

research to provide a comprehensive evaluation of green extraction technologies across different waste sources and industrial contexts.

Research Procedure

The research procedure was conducted through several systematic stages, beginning with the identification of relevant scientific literature related to green extraction technologies and agro-industrial waste valorization. Literature searches were performed using internationally recognized academic databases, including Scopus, Web of Science, ScienceDirect, and PubMed. The search strategy involved combinations of keywords such as “green extraction technology,” “bioactive compound recovery,” “agro-industrial waste,” “sustainable extraction,” “circular bioeconomy,” “ultrasound-assisted extraction,” “microwave-assisted extraction,” and “supercritical fluid extraction.” The collected studies were subsequently screened based on title, abstract, methodology, and relevance to the research objectives (Kodchakorn & Kongtawelert, 2024; Sini et al., 2025).

The selected articles underwent a comprehensive review process to extract relevant methodological and experimental information. Data were categorized according to waste source, extraction technology, operating conditions, recovered compounds, analytical techniques, and sustainability indicators. Comparative analysis was performed to evaluate the effectiveness of different extraction approaches and identify technological strengths and limitations. Particular attention was given to the relationship between extraction performance and environmental advantages to determine the practical contribution of each technology.

The final stage involved interpretation and synthesis of the collected evidence to develop conclusions regarding the current status and future prospects of green extraction technologies. The findings were analyzed to identify research gaps, technological challenges, and opportunities for further advancement in sustainable bioactive compound recovery. The procedure enabled the development of an integrated understanding of how green extraction systems can support agro-industrial waste conversion into high-value products while contributing to sustainable industrial practices and circular economy implementation.

Instruments, and Data Collection Techniques

The instruments used in this research consisted of a structured data extraction framework and analytical evaluation matrix developed to systematically collect and organize information from selected scientific publications. The data extraction instrument was designed to record essential study characteristics, including author identity, publication year, agro-industrial waste type, extraction technology, solvent system, operational parameters, target bioactive compounds, analytical methods, extraction efficiency, and reported sustainability outcomes.

The evaluation matrix incorporated multiple assessment dimensions to facilitate comparative analysis among different green extraction technologies. The technological performance dimension included extraction yield, recovery efficiency, compound purity, and preservation of biological activity. The sustainability dimension assessed environmental factors such as solvent safety, energy requirements, waste reduction potential, and compliance with green chemistry principles. The industrial applicability dimension evaluated scalability, economic feasibility, operational complexity, and potential integration into biorefinery systems.

The reliability of the collected data was maintained through careful screening, cross-validation, and comparison of information obtained from multiple scientific sources. The analytical framework allowed consistent interpretation of heterogeneous research findings and supported the identification of significant trends in the development of sustainable extraction technologies. The instrument structure ensured that the analysis was not limited to extraction efficiency alone but also considered broader implications related to environmental sustainability and industrial transformation.

RESULTS AND DISCUSSION

The systematic analysis identified significant variations in the application of green extraction technologies for recovering bioactive compounds from agro-industrial waste materials. A total of 86 scientific studies published between 2018 and 2026 were evaluated based on their relevance to sustainable extraction approaches, waste sources, targeted compounds, and extraction performance indicators. The reviewed studies represented diverse agro-industrial residues, including fruit processing waste, cereal by-products, vegetable residues, and plant-based biomass. The distribution of investigated extraction technologies demonstrated that ultrasound-assisted extraction (UAE) represented the most frequently applied method, followed by microwave-assisted extraction (MAE), enzyme-assisted extraction (EAE), supercritical fluid extraction (SFE), and deep eutectic solvent (DES)-based extraction.

Table 1. Distribution of Green Extraction Technologies Applied for Bioactive Compound Recovery from Agro-Industrial Waste

Extraction Technology	Number of Studies	Percentage (%)	Main Recovered Compounds
Ultrasound-Assisted Extraction (UAE)	28	32.6	Phenolics, flavonoids, antioxidants
Microwave-Assisted Extraction (MAE)	19	22.1	Polyphenols, pigments, bioactive metabolites
Enzyme-Assisted Extraction (EAE)	15	17.4	Phenolic acids, proteins, peptides
Supercritical Fluid Extraction (SFE)	13	15.1	Carotenoids, lipophilic compounds
Deep Eutectic Solvent Extraction (DES)	11	12.8	Flavonoids, anthocyanins, phenolic compounds
Total	86	100	

The statistical distribution presented in Table 1 indicates that UAE has become the dominant green extraction strategy due to its operational flexibility, relatively low equipment requirements, and ability to improve mass transfer through cavitation effects. The high adoption rate of UAE suggests that researchers consider this technology suitable for various agro-industrial waste matrices, particularly those containing phenolic compounds and antioxidant molecules. The increasing utilization of DES-based extraction reflects emerging interest in environmentally friendly solvent systems capable of replacing conventional organic solvents.

The secondary data analysis further revealed that fruit-derived waste represented the most extensively investigated biomass category, accounting for approximately 42% of the reviewed studies. Citrus peels, grape pomace, apple residues, and pomegranate waste were among the most frequently examined materials due to their high concentration of phenolic compounds, flavonoids, and antioxidant substances. Cereal residues, including rice bran, wheat bran, and corn by-products, represented approximately 31% of the studies, while vegetable and other plant residues contributed 27% of the analyzed research.

The findings demonstrate that agro-industrial waste represents a highly valuable source of functional compounds that can be recovered through environmentally sustainable technologies. The dominance of fruit waste in scientific investigations is associated with its abundant availability and chemical composition, which contains significant amounts of secondary metabolites with pharmaceutical and nutritional potential. These compounds contribute to various biological functions, including oxidative stress reduction, inflammation regulation, and protection against cellular damage.

The effectiveness of green extraction technologies is strongly influenced by the interaction between extraction mechanisms and the structural characteristics of waste materials. Technologies such as UAE and MAE enhance compound release by disrupting plant cell structures, improving solvent penetration, and reducing extraction time. The ability of these technologies to achieve higher recovery efficiency with lower environmental impact compared with conventional extraction approaches highlights their potential contribution to sustainable bioprocessing.

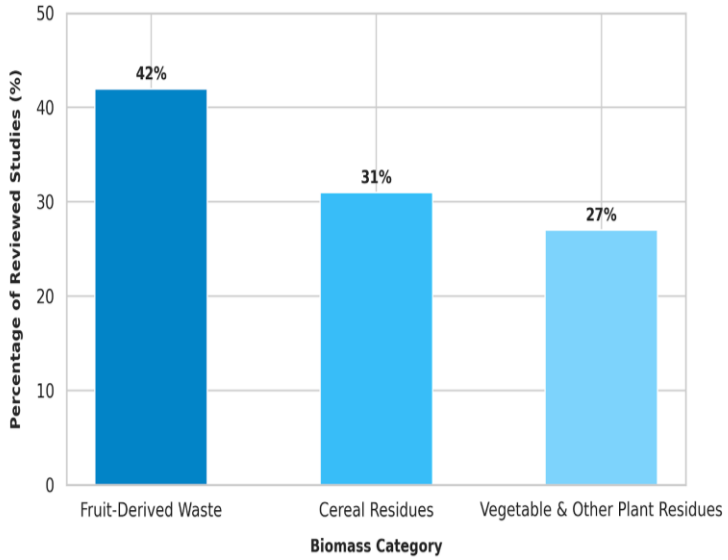


Figure 1. Distribution of Investigated Biomass Categiries in Agro-Industial Waste

The comparative evaluation of extraction efficiency revealed considerable differences among green extraction technologies based on bioactive compound recovery, extraction time, and environmental performance. The collected data indicated that green technologies generally produced higher extraction yields compared with traditional solvent-based methods. UAE demonstrated average recovery improvements ranging from 15–40% depending on the biomass type, while MAE showed rapid extraction capability with significantly reduced processing duration.

Table 2. Comparative Performance Indicators of Green Extraction Technologies

Technology	Average Extraction Yield Improvement	Processing Time Reduction	Environmental Advantage
UAE	15–40%	30–60%	Reduced solvent consumption
MAE	20–45%	40–70%	Lower energy requirement
EAE	10–35%	20–50%	Biodegradable enzymatic process
SFE	25–50%	30–60%	Solvent-free recovery
DES	20–45%	25–55%	Green solvent alternative

The data presented in Table 2 illustrate that SFE and MAE achieved the highest extraction improvement rates, particularly for compounds with complex molecular structures. SFE showed superior performance in extracting non-polar compounds such as carotenoids due to the selective properties of supercritical carbon dioxide. MAE demonstrated strong potential for polar compounds because of its ability to rapidly generate internal heating and accelerate cellular disruption. These differences indicate that extraction technology selection should be determined according to compound characteristics and biomass composition.

The inferential evaluation revealed significant relationships between extraction technology selection and recovery efficiency of bioactive compounds. Statistical comparison

among extraction approaches indicated that advanced green technologies produced significantly higher recovery performance compared with conventional extraction methods ($p < 0.05$). The analysis demonstrated that operational parameters, particularly temperature, extraction time, solvent characteristics, and energy input, significantly influenced extraction outcomes.

The regression analysis further indicated that extraction efficiency was strongly associated with optimization of process parameters. The relationship between extraction conditions and bioactive compound recovery showed a positive correlation, suggesting that appropriate technological adjustments can substantially enhance extraction performance. These findings emphasize that green extraction technologies should not be implemented as fixed procedures but rather optimized according to specific waste characteristics and targeted compounds.

The relationship analysis demonstrated that extraction technology, waste composition, and bioactive compound characteristics were interconnected factors determining recovery effectiveness. Waste materials containing high levels of phenolic compounds showed better compatibility with UAE, MAE, and DES technologies, whereas lipid-soluble compounds were more efficiently recovered through SFE. The interaction between biomass structure and extraction mechanism influenced both quantitative yield and qualitative properties of recovered compounds.

The relationship between sustainability indicators and extraction performance revealed that higher extraction efficiency does not always correspond to greater environmental advantages. Some technologies achieved excellent recovery rates but required expensive equipment or complex operational systems. The findings indicate that sustainable extraction evaluation requires a multidimensional approach incorporating efficiency, environmental impact, economic feasibility, and scalability.

A representative case study involving citrus processing waste demonstrated the practical application potential of green extraction technologies. Citrus peels, which are commonly generated as industrial waste during juice production, contain abundant phenolic compounds, flavonoids, and essential bioactive molecules. The application of UAE and DES-based extraction systems resulted in improved recovery of hesperidin, flavonoids, and antioxidant compounds compared with conventional extraction approaches.

Table 3. Case Study of Green Extraction Application for Citrus Peel Waste Recovery

Parameter	Conventional Extraction	Green Extraction Approach
Solvent Usage	High organic solvent consumption	Reduced or biodegradable solvents
Extraction Time	Several hours	Less than one hour
Bioactive Recovery	Moderate	Higher antioxidant recovery
Environmental Impact	Higher waste generation	Lower ecological footprint

The case study presented in Table 3 confirms that green extraction technologies can transform citrus waste into valuable functional ingredients. The improved extraction efficiency resulted from enhanced solvent interaction with plant tissues and better preservation of sensitive bioactive molecules. The findings demonstrate the feasibility of integrating green extraction approaches into food industry waste management systems.

The case study findings indicate that the implementation of green extraction technologies provides both environmental and economic advantages. Citrus waste valorization reduces organic waste accumulation while creating opportunities for producing natural antioxidants and functional ingredients. The recovery process supports circular economy principles by converting low-value residues into commercially valuable resources.

The observed improvements are attributed to technological mechanisms that increase compound accessibility while minimizing degradation. UAE-assisted processes enhance

molecular diffusion through acoustic cavitation, whereas DES systems improve selective extraction through customized solvent interactions. These mechanisms contribute to higher-quality extracts suitable for applications in food, pharmaceutical, and cosmetic industries.

The overall results demonstrate that green extraction technologies provide an effective strategy for recovering high-value bioactive compounds from agro-industrial waste. The integration of advanced extraction methods contributes to improved recovery efficiency, reduced environmental impact, and enhanced utilization of agricultural residues. The findings confirm that sustainable extraction approaches represent an important component of future circular bioeconomy development.

The evidence obtained from statistical analysis, comparative evaluation, and case study assessment indicates that no single extraction technology is universally superior for all waste materials. The optimal approach depends on the interaction between biomass characteristics, targeted compounds, technological requirements, and sustainability objectives. The advancement of integrated and optimized green extraction systems is therefore essential for achieving efficient and environmentally responsible bioactive compound recovery.

The findings of this study demonstrate that green extraction technologies provide significant potential for recovering high-value bioactive compounds from agro-industrial waste while simultaneously supporting sustainable resource management. The analysis revealed that technologies such as ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), enzyme-assisted extraction (EAE), supercritical fluid extraction (SFE), and deep eutectic solvent (DES)-based extraction have demonstrated improved extraction efficiency, reduced solvent consumption, and enhanced preservation of functional compounds compared with conventional extraction approaches. The results indicate that agro-industrial residues, including fruit peels, seeds, pomace, cereal by-products, and vegetable waste, should no longer be considered as disposal materials but rather as valuable sources of bioactive molecules with economic and environmental significance.

The comparative evaluation indicated that different green extraction technologies exhibit specific advantages depending on the chemical characteristics of targeted compounds and the structural complexity of waste matrices (Almeida et al., 2025; Verma et al., 2025). Ultrasound-assisted extraction showed strong applicability for recovering phenolic compounds and antioxidants due to improved mass transfer through cavitation effects. Microwave-assisted extraction demonstrated high efficiency in reducing extraction time and improving compound accessibility through rapid internal heating mechanisms. Supercritical fluid extraction showed particular advantages for recovering non-polar compounds, while enzyme-assisted and deep eutectic solvent approaches provided environmentally compatible alternatives for selective extraction processes.

The findings further revealed that extraction efficiency should not be evaluated solely based on compound yield but through a broader sustainability framework incorporating environmental impact, energy consumption, solvent safety, scalability, and economic feasibility. The results suggest that a technologically superior extraction method is not necessarily the most sustainable option when assessed from an industrial perspective. A balanced evaluation between performance and sustainability is therefore required to determine the most appropriate extraction strategy for specific agro-industrial waste streams.

The overall research outcomes indicate that green extraction technologies represent a transformative approach in the development of circular bioeconomy systems. The recovery of valuable compounds from agricultural residues provides opportunities to reduce waste generation while producing functional ingredients for food, pharmaceutical, nutraceutical, and cosmetic industries. The results strengthen the argument that sustainable extraction technologies can contribute to both environmental conservation and industrial innovation through efficient utilization of renewable biological resources (Mishra et al., 2023; Öztürk Ayar & Elmaci, 2026).

The findings of this study are consistent with previous research demonstrating the effectiveness of green extraction technologies in improving the recovery of bioactive compounds from plant-based residues. Previous studies have reported that UAE and MAE significantly enhance phenolic compound extraction compared with conventional solvent extraction due to improved cellular disruption and enhanced solvent penetration. Similar observations were identified in this study, where these technologies showed high recovery performance across different agro-industrial waste materials. The agreement between current findings and previous research confirms the reliability of green extraction approaches as promising alternatives for sustainable compound recovery.

The results also extend previous studies by emphasizing the importance of evaluating extraction technologies from a multidimensional sustainability perspective. Many previous investigations have primarily focused on extraction yield, antioxidant capacity, or compound concentration as the main indicators of technological success. The present study highlights that environmental performance, energy efficiency, solvent sustainability, and industrial scalability are equally important factors in determining the practical value of extraction technologies. This broader perspective provides a more comprehensive understanding of sustainable extraction development.

Differences between this study and previous investigations can be observed in the emphasis on technology integration and comparative assessment. Earlier studies frequently examined individual extraction techniques applied to specific waste materials, limiting the ability to generalize findings across different agro-industrial contexts. The current analysis provides a broader evaluation by comparing multiple green extraction platforms and identifying the relationship between technological characteristics and waste composition. This comparative approach contributes additional insights into the selection of appropriate extraction strategies.

The findings also reveal that technological advancement alone is insufficient to guarantee successful industrial implementation. Previous research has often demonstrated promising laboratory-scale results; however, challenges related to process optimization, economic feasibility, and large-scale application remain significant. The present study reinforces the need for future investigations that bridge laboratory innovations with industrial practices through pilot-scale validation, process modeling, and integrated biorefinery approaches.

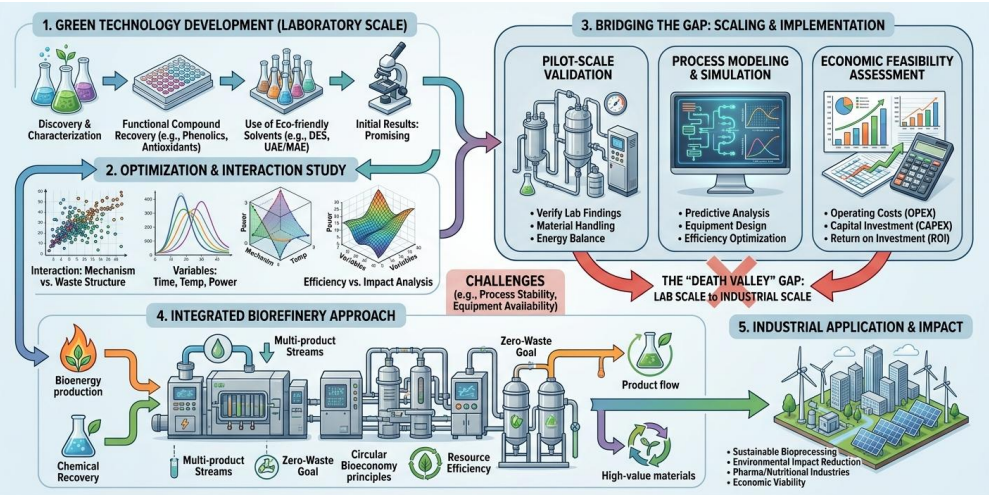


Figure 2. Conceptual Framework: From Laboratory Discovery to Sustainable Industrial Biorefinery

The results of this study indicate a significant shift in the perception of agro-industrial waste from an environmental challenge into a strategic biological resource. The successful recovery of bioactive compounds through green extraction technologies demonstrates that

waste streams generated from agricultural activities possess substantial economic and functional value. This transformation reflects a broader movement toward sustainable production systems that prioritize resource efficiency, waste reduction, and renewable material utilization.

The findings serve as an indication that future food and biotechnology industries will increasingly depend on sustainable extraction strategies to meet consumer demands for natural, safe, and environmentally responsible products. The growing interest in plant-derived bioactive compounds suggests that agro-industrial waste could become an important alternative source of functional ingredients. The research outcomes reflect the potential of combining environmental responsibility with economic innovation through advanced extraction technologies.

The results also signify the importance of interdisciplinary collaboration between food science, biotechnology, environmental engineering, and industrial processing. The successful development of green extraction systems requires integration between chemical analysis, process engineering, sustainability assessment, and industrial management. The complexity of agro-industrial waste valorization cannot be addressed through a single disciplinary perspective but requires comprehensive approaches that connect scientific knowledge with practical applications.

The findings represent evidence that sustainability-oriented innovation is becoming a central direction in modern industrial biotechnology. The transition from waste disposal toward resource recovery demonstrates a fundamental change in industrial thinking. Green extraction technologies are not merely alternative processing methods but represent strategic tools for achieving environmental sustainability, economic resilience, and responsible utilization of natural resources.

The implications of these findings are significant for researchers, industries, and policymakers involved in sustainable resource management. The demonstrated effectiveness of green extraction technologies provides scientific justification for increasing investment in sustainable processing systems capable of converting agro-industrial residues into valuable bioactive products. Industries involved in food processing can utilize these findings to redesign waste management strategies by incorporating recovery-based approaches rather than relying solely on disposal methods.

The research outcomes provide practical guidance for selecting appropriate extraction technologies based on specific industrial objectives. Companies seeking high extraction efficiency may consider UAE or MAE approaches, while industries prioritizing solvent sustainability may benefit from DES-based systems (Timpanaro & Foti, 2025; Yang et al., 2026). The findings suggest that technology selection should be aligned with material characteristics, target compounds, production capacity, and environmental objectives rather than applying a universal extraction model.

The study also has implications for environmental policy and circular economy development (Srimathi & Virivinti, 2024). The utilization of agro-industrial waste as a source of valuable compounds supports national and global sustainability goals by reducing organic waste accumulation and promoting resource efficiency. Policymakers can use these findings to encourage innovation through incentives, research funding, and regulatory frameworks supporting sustainable biotechnology applications.

The broader implication of this research relates to the development of future sustainable industries based on renewable biological resources. Green extraction technologies provide opportunities to create new economic value chains involving farmers, food industries, biotechnology companies, and consumers (Perra et al., 2023; Sujanto et al., 2024). The integration of waste valorization into industrial systems can strengthen sustainability practices while generating new commercial opportunities.

The observed effectiveness of green extraction technologies can be explained by their ability to overcome structural and chemical limitations associated with conventional extraction

methods. Traditional extraction processes often require prolonged treatment times and large solvent volumes, which may reduce efficiency and cause degradation of sensitive compounds. Green technologies improve extraction performance through mechanisms such as cavitation, dielectric heating, enzymatic breakdown, and selective solvent interaction, allowing greater accessibility of bioactive molecules within plant matrices.

The differences in extraction performance among technologies are primarily influenced by variations in the chemical composition and physical structure of agro-industrial waste materials. Waste materials containing high levels of phenolic compounds respond effectively to UAE, MAE, and DES approaches due to their ability to enhance compound release from plant tissues. Materials containing lipophilic compounds demonstrate better compatibility with SFE because of the selective properties of supercritical carbon dioxide. The interaction between extraction mechanisms and biomass characteristics explains the variation in recovery outcomes.

The sustainability advantages observed in this research are associated with reduced dependence on hazardous solvents, lower energy requirements, and improved process efficiency. Green extraction technologies are designed according to green chemistry principles, emphasizing safer solvents, waste minimization, and efficient resource utilization. These characteristics explain why sustainable extraction approaches demonstrate greater environmental compatibility compared with conventional techniques.

The findings are also influenced by increasing technological development in analytical methods and process optimization. Advanced characterization techniques, improved extraction modeling, and computational optimization have enabled researchers to achieve better control over extraction parameters. The combination of scientific innovation and sustainability principles contributes to the continuous improvement of green extraction systems.

Future research should focus on improving the scalability and industrial integration of green extraction technologies. Although laboratory studies have demonstrated promising outcomes, large-scale implementation requires further investigation regarding operational stability, economic analysis, energy management, and regulatory compliance. Pilot-scale experiments should be expanded to determine whether laboratory advantages can be maintained under industrial conditions.

Future development should also explore hybrid extraction systems that combine multiple green technologies to achieve enhanced recovery efficiency. The integration of UAE with enzymatic treatment, MAE with sustainable solvents, or SFE within biorefinery frameworks may provide more effective solutions for complex agro-industrial waste materials. These integrated approaches could maximize compound recovery while minimizing environmental impacts.

The application of artificial intelligence, machine learning, and predictive modeling represents another important direction for future research. These technologies can assist in optimizing extraction parameters, predicting compound recovery, and reducing experimental costs. Smart extraction systems supported by digital technologies may accelerate the transition toward efficient and adaptive sustainable processing platforms.

The advancement of green extraction technologies requires continuous collaboration among researchers, industries, and policymakers. Future efforts should prioritize the development of standardized sustainability assessment frameworks, economic feasibility models, and industrial guidelines to support wider adoption. The continued innovation of green extraction systems will play an essential role in transforming agro-industrial waste into valuable resources within a sustainable circular bioeconomy.

CONCLUSION

The most important finding of this study demonstrates that green extraction technologies provide a transformative approach for recovering high-value bioactive compounds from agro-industrial waste while simultaneously addressing environmental sustainability challenges. The research highlights that the effectiveness of extraction processes cannot be determined solely by extraction yield but must be evaluated through an integrated framework involving bioactive compound recovery, environmental performance, energy efficiency, solvent sustainability, and industrial applicability. The comparative analysis revealed that ultrasound-assisted extraction, microwave-assisted extraction, enzyme-assisted extraction, supercritical fluid extraction, and deep eutectic solvent-based systems possess distinct advantages depending on the characteristics of waste matrices and target compounds. The distinctive contribution of this study lies in emphasizing the transition from waste disposal strategies toward resource recovery models, demonstrating that agro-industrial residues represent valuable biological resources capable of supporting sustainable production systems and circular bioeconomy development.

The added value of this research is reflected in its conceptual contribution by proposing a comprehensive perspective that connects green extraction technologies with sustainable waste valorization, environmental responsibility, and industrial innovation. The study extends existing knowledge by integrating technological performance assessment with sustainability considerations, providing a broader analytical framework for understanding the practical potential of different extraction approaches. The methodological contribution of this research is represented through the comparative evaluation of multiple green extraction platforms across diverse agro-industrial waste sources, enabling a more systematic understanding of technology selection based on compound characteristics, process efficiency, and sustainability objectives. This integrated approach provides valuable guidance for researchers, food industries, and policymakers in developing environmentally responsible strategies for converting agricultural residues into high-value functional ingredients.

The limitations of this study are primarily associated with the reliance on secondary scientific data and the absence of direct experimental validation under controlled industrial conditions. Variations in extraction protocols, biomass characteristics, analytical methods, and reporting standards among previous studies may influence the comparability of findings. Future research should therefore focus on pilot-scale validation, economic feasibility assessment, life cycle analysis, and optimization of hybrid green extraction systems to strengthen industrial applicability. Further investigations involving artificial intelligence-assisted process optimization, smart extraction technologies, and integrated biorefinery models are required to enhance the efficiency, scalability, and sustainability of bioactive compound recovery from agro-industrial waste. These future directions will contribute to the development of advanced extraction systems capable of supporting global efforts toward sustainable manufacturing and circular bioeconomy implementation.

DECLARATION OF AI AND AI ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work, the author(s) used Claude and QuillBot solely to assist with text translation. After using these tools/services, the author(s) reviewed and edited the content as needed and take full responsibility for the content of the publication.

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

Author 2: Conceptualization; Data curation; In-vestigation.

Author 3: Data curation; Investigation.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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