Global Journal of Research in
Chemistry and Pharmacy
Journal homepage: https://gsjournals.com/gjrcp/
ISSN: 2980-4213 (Online)

(REVIEW ARTICLE)

Check for updates

SUSTAINABLE DRUG DISCOVERY: BRIDGING FOOD BIOSCIENCE, PHARMACOGNOSY, AND GREEN CHEMISTRY

Hamad Yakub Joda * and Sang-min Lee

Department of Food Science and Biotechnology, College of Agriculture and Life Sciences, Kangwon National University, Chuncheon, 24341, South Korea.
* Corresponding Author

ORCID Details
Author name 1: https://orcid.org/0000-0000-0000-0000
Author name 2: https://orcid.org/0000-0000-0000-0000

Global Journal of Research in Chemistry and Pharmacy, 2024, 03(04), 001–010

Publication history: Received on 14 September 2024; revised on 22 October 2024; accepted on 26 October 2024

Article DOI: https://doi.org/10.58175/gjrcp.2024.3.4.0154

ABSTRACT

The convergence of food bioscience, pharmacognosy, and green chemistry offers transformative opportunities for sustainable drug discovery. Traditional drug discovery from natural sources faces significant challenges including biodiversity loss, resource depletion, and environmental impact. The concept of a circular bioeconomy, emphasizing waste valorization and resource efficiency, provides a framework for sustainable natural product discovery. This review critically examines the interdisciplinary framework bridging food bioscience, pharmacognosy, and green chemistry for sustainable drug discovery. We evaluate the valorization of agro-industrial by-products as sources of bioactive compounds, the application of green extraction technologies for sustainable metabolite recovery, and the utilization of microbial fermentation for bioactive compound production. Furthermore, we assess the integration of these approaches within a circular economy framework, emphasizing waste reduction, resource efficiency, and environmental sustainability. Case studies demonstrating successful sustainable drug discovery from food industry by-products, including grape pomace, citrus peels, and olive mill waste, are examined. Despite significant advances, challenges including economic viability, regulatory acceptance, and standardization persist. This review identifies research gaps and discusses strategies for advancing sustainable drug discovery through interdisciplinary collaboration.

Keywords: Sustainable Drug Discovery; Food Bioscience; Green Chemistry; Circular Economy; Agro-Industrial By-Products; Bioactive Compounds

1 INTRODUCTION

Drug discovery from natural sources has historically relied on the collection of plant, microbial, and marine organisms from natural ecosystems (Atanasov et al., 2021). However, this approach faces significant sustainability challenges, including biodiversity loss, habitat destruction, and overexploitation of valuable species (Newman and Cragg, 2020). The environmental impact of conventional drug discovery processes, including solvent usage and waste generation, further compromises sustainability (Harvey et al., 2015).

The concept of a circular bioeconomy provides a transformative framework for sustainable drug discovery, emphasizing waste valorization, resource efficiency, and environmental sustainability (Marcelino et al., 2023). The convergence of food bioscience, pharmacognosy, and green chemistry offers opportunities for sustainable drug discovery through the valorization of agro-industrial by-products, the application of green technologies, and the integration of circular economy principles (Bala et al., 2023).

The agricultural and food industries generate substantial quantities of by-products and waste throughout the food supply chain. The Food and Agricultural Organization (FAO) estimates that 1.3 billion tons of food are lost or wasted globally each year (Zhou et al., 2023). The disposal of these agri-food by-products costs manufacturers significantly and has adverse environmental impacts. However, these by-products are abundant, low-cost, and renewable sources of high-value-added compounds (Zhou et al., 2023). Valorizing agri-food by-products into high-value-added compounds provides a roadmap for realizing the Sustainable Development Goals (SDGs) 12 (Responsible Consumption and Production) of the United Nations (Zhou et al., 2023).

This review examines the interdisciplinary framework bridging food bioscience, pharmacognosy, and green chemistry for sustainable drug discovery. We evaluate the valorization of agro-industrial by-products, the application of green extraction technologies, and the utilization of microbial fermentation for bioactive compound production.

2 THE CIRCULAR BIOECONOMY FRAMEWORK

2.1 Principles of Circular Bioeconomy

The circular bioeconomy integrates the principles of circular economy and bioeconomy, emphasizing resource efficiency, waste reduction, and sustainable production (Marcelino et al., 2023). Key principles include waste valorization, resource efficiency, renewable resource utilization, and ecosystem protection. The implementation of Circular Economy solutions can play a central role in converting waste into economic opportunities, while fostering a sustainable planet (Marcelino et al., 2023).

Circular economy helps to mitigate environmental and social risks caused by the accumulation of biomass by-products (Marcelino et al., 2023). The development of bioenergy and biomaterials supports the energy-environment nexus and replaces petroleum as the production feedstock, to be a cleaner and lower-carbon footprint. The incorporation of waste biomass into bioprocesses for the creation of beneficial products and metabolites contributes to benign sustainable circular bioeconomy (Production of bioactive phenolic compounds, 2023).

2.2 Agro-Industrial By-Products as Resources

Agro-industrial by-products represent substantial resources for bioactive compound recovery (Bala et al., 2023). Food processing generates significant quantities of by-products including pomace, peels, seeds, and wastewater. These by-products contain valuable bioactive compounds, including phenolics, terpenoids, and polysaccharides (Sha et al., 2023). Contemporary agro-industrial processes generate a huge quantity of diverse by-products, which are gathered sometimes at landfill sites or open farming fields that result in environmental distress including air, soil, and water pollution (Production of bioactive phenolic compounds, 2023). Organic content present in the waste residues is the profuse source of bioactive phenolic compounds that can exhibit anti-inflammatory, antioxidant, cardio-protective, anticancer potential and several other important applications (Production of bioactive phenolic compounds, 2023).

2.3 Sustainability Metrics

The assessment of sustainability requires appropriate metrics and indicators. Life cycle assessment (LCA) evaluates environmental impacts across the product lifecycle (Aslanbay Guler et al., 2024). Economic viability and social acceptability are additional sustainability dimensions. Extraction is typically one of the most energy-intensive steps in the lifecycle of bioactive compound production, and thus a major contributor to environmental impact (Life cycle assessment, 2023). LCA studies indicate that microwave-assisted extraction can offer environmental advantages at the laboratory scale, mainly due to reduced extraction time and solvent consumption (Life cycle assessment, 2023).

Table 1: Agro-Industrial By-Products as Sources of Bioactive Compounds

By-Product	Source Industry	Key Bioactive Compounds	Potential Applications	Sustainability Potential
Grape Pomace	Wine Industry	Resveratrol, anthocyanins, proanthocyanidins	Antioxidants, cardiovascular health, antimicrobial agents	High
Citrus Peels	Juice Industry	Flavonoids, hesperidin, limonene	Anti-inflammatory, antimicrobial, neuroprotective	High
Olive Mill Waste	Olive Oil Production	Oleuropein, hydroxytyrosol	Cardiovascular support, antimicrobial, anti-inflammatory	High
Fruit Wastes	Various Food Processing	Polyphenols, dietary fibers	Nutraceuticals, therapeutic supplements	Moderate-High
Aromatic Plant Residues	Essential Oil Production	Phenolic compounds, natural antioxidants	Food preservation, cosmetics, pharmaceuticals	High

3 VALORIZATION OF AGRO-INDUSTRIAL BY-PRODUCTS

3.1 Grape Pomace

Grape pomace, the solid residue from wine production, is a rich source of bioactive compounds including resveratrol, anthocyanins, and proanthocyanidins. The valorization of grape pomace for pharmaceutical applications has been extensively studied. Grape pomace has been identified as a sustainable source of bioactive compounds, with recent advancements expanding its potential particularly in the health and food industries due to their potent bioactive properties (Grape Pomace Review, 2023). Grape pomace extracts have demonstrated antioxidant, antimicrobial, and cardiovascular protective activities. Innovative, environmentally friendly extraction techniques and integrated methods have been developed for grape pomace valorization (Grape Pomace Review, 2023).

Grape pomace as a sustainable source of bioactive compounds has been characterized, with extraction, characterization, and biotechnological applications of phenolics being extensively discussed (Grape Pomace Review, 2023). The possible applications of grape pomace extracts in diverse biotechnological fields, including pharmaceutical applications, have been highlighted (Grape Pomace Review, 2023).

3.2 Citrus Peels

Citrus peels, generated in substantial quantities by juice processing, contain flavonoids including hesperidin, naringin, and polymethoxyflavones (Li et al., 2023). Orange pomace and peels as wastes are used as a sustainable raw material to make valuable products for nutraceuticals (Li et al., 2023). Citrus peel extracts have demonstrated anti-inflammatory, antimicrobial, and neuroprotective activities (Li et al., 2023).

Citrus fruits contain a plethora of bioactive compounds stored in edible as well as inedible parts. Bioactives in citrus by-products are higher than the peeled fruit, which can be extracted, isolated and incorporated into food systems for development of health foods (Citrus processing by-products, 2023). The valorization of citrus peels for pharmaceutical applications offers economic and environmental benefits (Li et al., 2023). Green extraction technologies have been optimized for citrus peel bioactive recovery (Li et al., 2023).

3.3 Olive Mill Waste

Olive mill waste, generated by olive oil production, contains phenolic compounds including oleuropein and hydroxytyrosol. The reuse and valorization of olive mill by-products is getting attention in the food and drugs-cosmetics sectors, due to the recovery of their essential bioactive compounds in order to incorporate them as ingredients in functional foods, cosmetics, and pharmaceuticals (Olive mill waste valorization, 2023). Olive mill waste extracts have demonstrated antioxidant, antimicrobial, and cardiovascular protective activities (Valorization of Olea europaea, 2023).

The main applications of Olea europaea and olive oil processing by-products as therapeutic agents against cancer, cardiovascular diseases, and as antimicrobial agents have been summarized (Valorization of Olea europaea, 2023).

Advanced extraction and purification technologies have been developed for olive mill waste valorization (Palmeira et al., 2023).

3.4 Fruit Wastes

Various kinds of waste generated from fruit industries are considered a global concern (Sha et al., 2023). By utilizing fruit waste, the international goal of "zero waste" can be achieved by sustainable utilization of these waste materials as a rich source of secondary metabolites (Sha et al., 2023). Research has focused on recovering the bioactive compounds from fruit industries and obtaining a new strategy to combat certain chronic diseases (Sha et al., 2023). The separation of high-value substances from fruit waste, including phytochemicals, dietary fibers, and polysaccharides, can then be used as functional ingredients for long-term health benefits (Sha et al., 2023).

Most waste-derived secondary metabolites comprise polyphenols, which have been reported to have anti-inflammatory, insulin resistance-treating, cardiovascular disease-maintaining, probiotics-enhancing, or even anti-microbial and anti-viral capabilities (Sha et al., 2023). The review summarizes the current knowledge of fruit waste by-products in pharmacological, biological, and probiotic applications and highlights several methods for identifying efficacious bioactive compounds from fruit wastes (Sha et al., 2023).

3.5 Aromatic and Medicinal Plant Residues

Waste biomass from aromatic and medicinal plants (AMPs) encloses multifunctional compounds that could offer a poly-diverse pool of applications in sectors of food/feed, cosmetics, pharmaceuticals and agriculture (Residual biomass from AMPs, 2023). The production of essential oils constitutes the main process that generates huge amounts of waste and/or by-product streams, since more than 95% of the AMPs is left as residual biomass after distillation (Residual biomass from AMPs, 2023).

AMPs constitute a new avenue of value-added components with multi-faceted applications. Following the extraction of essential oils, the residues are rich in natural antioxidants which can be recovered employing novel and "green" methods (Residual biomass from AMPs, 2023). Besides phenolic compounds, plant biomass could be further fractionated and bioconverted into chemicals (Residual biomass from AMPs, 2023).

Table 2: Green Extraction Technologies for Agro-Industrial By-Product Valorization

Technology	Principle	Sustainability Benefits	Applications	Maturity Level
UAE (Ultrasound-Assisted Extraction)	Acoustic cavitation causing cell wall disruption	Drastically reduced solvent consumption and lower energy usage	High-yield polyphenol and flavonoid extraction	Mature
MAE (Microwave-Assisted Extraction)	Rapid internal heating via dielectric radiation	Significantly reduced extraction time and lower overall energy footprint	Polyphenol and active component extraction	Mature
SFE (Supercritical Fluid Extraction)	Solvation tuning using supercritical fluids (e.g., CO_2)	Solvent-free extraction, non-toxic, recyclable carrier fluids	Lipophilic compounds, essential oils, and lipids	Mature
PLE (Pressurized Liquid Extraction)	Accelerated extraction at elevated temperature and pressure	Reduced organic solvent usage and shorter extraction cycles	High-efficiency extraction of various phytochemicals	Mature
DES / NADES (Deep Eutectic Solvents / Natural DES)	Hydrogen bond acceptor/donor ionic liquid mixtures	Fully biodegradable, non-toxic, renewable, and tunable green solvents	Target polyphenol recovery and bioactive stabilization	Emerging
EAE (Enzymatic-Assisted Extraction)	Selective enzymatic hydrolysis of plant cell wall components	Operates under mild eco-friendly conditions; highly selective recovery	Release of matrix-bound phenolics and insoluble dietary fibers	Emerging

4 GREEN TECHNOLOGIES FOR SUSTAINABLE DRUG DISCOVERY

4.1 Green Extraction Technologies

Green extraction technologies, including ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), supercritical fluid extraction (SFE), and pressurized liquid extraction (PLE), offer sustainable alternatives to conventional extraction methods (Zhou et al., 2023). Several novel extraction technologies like ultrasound-assisted extraction, pressurized liquid extraction, and supercritical fluid extraction could provide an alternative approach for successful extraction of the valuable bioactives from fruit waste for their utilization as nutraceuticals, therapeutics, and value-added products (Sha et al., 2023). These technologies reduce solvent consumption, energy requirements, and extraction times (Zhou et al., 2023).

The application of green extraction to agro-industrial by-products enhances sustainability. The optimization of green extraction parameters is essential for maximizing yields and sustainability. Green extraction techniques of bioactive compounds have been reviewed as a state-of-the-art approach (Green Extraction Techniques, 2023).

4.2 Deep Eutectic Solvents (DES) and Natural Deep Eutectic Solvents (NADES)

Deep eutectic solvents (DESs) have recently acquired popularity for extracting and valorizing polyphenols due to their superior ability to solubilize polyphenols (Zhou et al., 2023). DESs align with the 12 principles of green chemistry and have many remarkable advantages, such as low cost, ease of synthesis, tunable characteristics, good recyclability, and high biodegradability (Zhou et al., 2023). DESs are claimed to be green and safe, especially for pharmaceutical and food applications (Zhou et al., 2023).

Natural deep eutectic solvents (NaDES) have been identified as an emerging technology for the valorisation of natural products and agro-food residues (Natural deep eutectic solvents review, 2023). A review paper on NaDES application to the extraction of bioactives from natural products and agri-food wastes has been introduced (Natural deep eutectic solvents review, 2023). DESs and DESs-assisted with advanced techniques offer promising opportunities to recover polyphenols from agri-food by-products efficiently, contributing to a circular and sustainable economy (Zhou et al., 2023).

4.3 Enzymatic-Assisted and Fermentation-Assisted Extraction

Recent research is starting to highlight the bioactive roles played by bound phenolics (BPC) in human health (Vilas-Franquesa et al., 2024). A critical update on recent advances in green techniques for the recovery of BPC has been provided, focusing on enzymatic-assisted extraction (EAE) and fermentation-assisted extraction (FAE) as well as in the combination of technologies, showing variable yield and features (Vilas-Franquesa et al., 2024).

The higher antioxidant activity of BPC compared to free phenolics, coupled with their affordable by-product source, make them medicinally potent and economically viable, promoting their integral upcycling and generating new revenue streams, business, and employment opportunities (Vilas-Franquesa et al., 2024). In addition, EAE and FAE can have a biotransformative effect on the PC itself or its moiety, leading to improved extraction outcomes (Vilas-Franquesa et al., 2024). Recent research on BPC extracts has reported promising anti-cancer and anti-diabetic activity (Vilas-Franquesa et al., 2024).

5 MICROBIAL FERMENTATION FOR BIOACTIVE PRODUCTION

5.1 Fermentation Strategies

Recycled agroindustrial waste has been of great interest during the last decade as a low-cost and sustainable substrate for fermentation processes (Astudillo et al., 2023). Microbial fermentation offers sustainable alternatives for bioactive compound production using renewable substrates (Astudillo et al., 2023). The types of products, yields, and potential applications depend mainly on the waste composition, which varies in terms of proteins, carbohydrates, and/or polyphenolic compounds (Astudillo et al., 2023).

The most commonly reported microbial products are enzymes, pigments, biosurfactants, antibiotics, and phenolic compounds for different industrial applications (Astudillo et al., 2023). Advances in research on novel wastes as nutrient sources and the optimization of fermentation processes can help these materials transition from laboratory applications to an industrial level (Astudillo et al., 2023). Solid-state fermentation and submerged fermentation are employed for different applications (Astudillo et al., 2023).

5.2 Food Industry Applications

The food industry has extensive experience with fermentation for food production. This knowledge can be translated to pharmaceutical applications (Astudillo et al., 2023). Fermentation of food processing by-products for bioactive compound production offers sustainability benefits. Agro-industrial residues have been used as substrates for the production of bioaroma compounds with basidiomycetes (Agro-Industrial Residues, 2023). The potential of several basidiomycete fungi in the production of bioaromas using biotechnological methods has been compiled (Agro-Industrial Residues, 2023).

The present scenario and future scope of agroindustrial waste as substrates for submerged and solid-state fermentation processes have been discussed (Astudillo et al., 2023). This review contributes to future research endeavors to discover the key factors that will allow us to reach the market with sustainable microbial products (Astudillo et al., 2023).

5.3 Biorefinery Approaches

The concept of biorefinery, lignocellulosic biomass, and its valorization by green pretreatment strategies into biofuels and other biochemicals has been highlighted (Environment Friendly Pretreatment, 2023). The abundance of microorganisms along with their continuous production of various degradative enzymes makes them suited for the environmentally friendly bioconversion of agro-industrial wastes into viable bioproducts (Environment Friendly Pretreatment, 2023).

An integrated biorefinery uses lignocellulosic feedstock as raw material for the production of renewable biofuels and other fine chemicals (Environment Friendly Pretreatment, 2023). Biorefinery schemes based on aromatic and medicinal plants could be developed (Residual biomass from AMPs, 2023). A holistic approach of these residues in the framework of advanced biorefineries has been proposed, including biomass fractionation and bioconversion into value-added compounds (Residual biomass from AMPs, 2023).

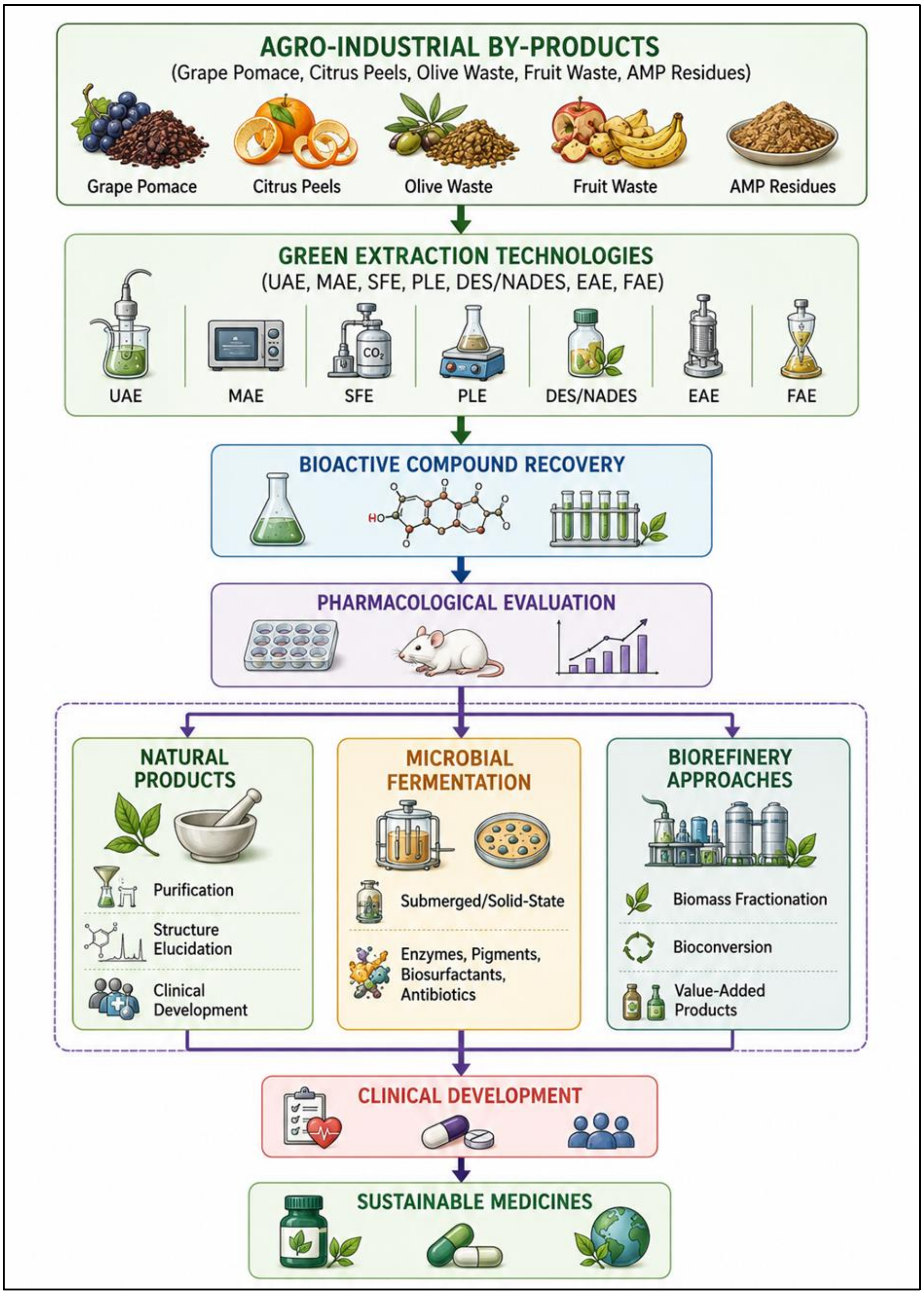

Figure 1: Sustainable Drug Discovery Framework

6 INTEGRATION WITHIN A CIRCULAR ECONOMY FRAMEWORK

6.1 Value Chain Integration

The integration of food processing and pharmaceutical industries enables the valorization of by-products for drug discovery (Bala et al., 2023). Value chain integration enhances resource efficiency and economic viability. The majority of agricultural waste is not productively used and is becoming a danger to both world health and the environment (Bala et al., 2023). Transformation of agro-waste into value-added bioproducts and bioactive compounds through micro/nano formulations and application in the agri-food-pharma sector has been reviewed (Bala et al., 2023).

This review addresses various agri-waste valorization methods, value-added bioproducts, the recovery of bioactive compounds, and their uses, and also covers the present status of bioactive micro- and nanoencapsulation strategies and their applications (Bala et al., 2023). A systematic review was conducted, aiming to identify potential applications for the valorisation of medicinal and aromatic plant residues under a sustainable approach (Marcelino et al., 2023).

6.2 Zero-Waste Approaches

Zero-waste approaches aim for the complete valorization of by-products (Sha et al., 2023). Cascading valorization strategies extract multiple compounds from by-products. Zero-waste approaches maximize resource efficiency and minimize environmental impact. By utilizing fruit waste, the international goal of "zero waste" can be achieved by sustainable utilization of these waste materials as a rich source of secondary metabolites (Sha et al., 2023).

Sustainable approaches on industrial food wastes to value-added products have been explored (Sustainable approaches, 2023). The way forward to produce nutraceuticals from agri-food processing residues has been examined, covering obstacles, solutions, and possibilities (The way forward, 2023). Efficient utilization of bioactive compounds from agro-industrial waste more effectively in food and pharmaceutical industries has been described (The way forward, 2023).

6.3 Life Cycle Assessment

Life cycle assessment (LCA) evaluates the environmental impacts of drug discovery processes (Aslanbay Guler et al., 2024). LCA enables the identification of sustainability hotspots and opportunities for improvement. A comprehensive overview of the life cycle environmental and energy assessments conducted for the extraction of metabolites has been presented (Aslanbay Guler et al., 2024).

Analysis of five extraction technologies' environmental impact on the polyphenols production from Moringa oleifera leaves using the life cycle assessment tool based on ISO 14040 has been conducted (Life cycle assessment, 2023). The reviewed LCA studies indicate that microwave-assisted extraction can offer environmental advantages at the laboratory scale, mainly due to reduced extraction time and solvent consumption (Life cycle assessment, 2023). Life cycle analysis for green extraction technologies has been reviewed from a sustainable point of view (Aslanbay Guler et al., 2024).

7 CHALLENGES AND RESEARCH GAPS

7.1 Economic Viability

The economic viability of sustainable drug discovery processes is a significant challenge. The cost of bioactive recovery from by-products may be higher than conventional sources. Economic optimization is essential for commercial viability. The high cost of extraction and purification processes remains a barrier to widespread adoption of sustainable drug discovery approaches. Economic incentives and public-private partnerships may support the development of sustainable drug discovery processes.

7.2 Regulatory Acceptance

The regulatory acceptance of sustainable drug discovery processes is evolving. The acceptance of extracts and fermentation products requires demonstration of quality, safety, and efficacy. Regulatory frameworks for sustainable drug discovery processes are developing. Sensorial and regulatory issues still hamper the wide application of aromatic and medicinal plant residues (Residual biomass from AMPs, 2023). Standardization of extraction processes and quality control methods is essential for regulatory approval.

7.3 Standardization

The standardization of sustainable drug discovery processes is challenging. Variability in by-product composition and process performance requires robust standardization. Quality control and analytical methods are essential. Further research is needed to elucidate the biological mechanisms of bioactive compounds from agro-industrial by-products and exploit the true potential of their applications (Vilas-Franquesa et al., 2024).

8 FUTURE PERSPECTIVES

The future of sustainable drug discovery lies in the continued integration of food bioscience, pharmacognosy, and green chemistry within a circular economy framework. The development of integrated value chains connecting food processing and pharmaceutical industries will enhance resource efficiency. The application of emerging technologies, including artificial intelligence and machine learning, promises to accelerate sustainable drug discovery by optimizing extraction processes and predicting bioactive compound properties. Advanced biorefinery schemes based on agro-industrial by-products and aromatic and medicinal plants could be developed for the production of multiple value-added compounds. The development of regulatory frameworks and economic incentives will support the transition to sustainable practices. Continued interdisciplinary collaboration and investment in research and development are essential for realizing the full potential of sustainable drug discovery.

9 CONCLUSION

The convergence of food bioscience, pharmacognosy, and green chemistry offers transformative opportunities for sustainable drug discovery. The valorization of agro-industrial by-products, including grape pomace, citrus peels, olive mill waste, fruit wastes, and aromatic plant residues, provides sources of bioactive compounds with pharmaceutical potential. Green extraction technologies including UAE, MAE, SFE, PLE, and DES/NADES enable sustainable recovery of bioactive compounds. Enzymatic-assisted and fermentation-assisted extraction offer additional green approaches for the recovery of bound phenolics with promising bioactivities. Microbial fermentation of agro-industrial waste provides sustainable alternatives for bioactive compound production, including enzymes, pigments, biosurfactants, and antibiotics. The integration of these approaches within a circular economy framework enhances resource efficiency, reduces environmental impact, and promotes sustainability. Biorefinery approaches enable the comprehensive valorization of biomass into multiple value-added products. Despite significant challenges, including economic viability, regulatory acceptance, and standardization, the continued development of sustainable drug discovery strategies promises to contribute to both pharmaceutical development and environmental sustainability.

REFERENCES

[1] Astudillo, A., Rubilar, O., Briceño, G., Diez, M. C., & Schalchli, H. (2023). Advances in agroindustrial waste as a substrate for obtaining eco-friendly microbial products. *Sustainability*, *15*(4), Article 3467. https://doi.org/10.3390/su15043467

[2] Atanasov, A. G., Zotchev, S. B., Dirsch, V. M., & Supuran, C. T. (2021). Natural products in drug discovery: Advances and opportunities. *Nature Reviews Drug Discovery*, *20*(3), 200–216. https://doi.org/10.1038/s41573-020-00114-z

[3] Bala, S., Garg, D., Sridhar, K., Inbaraj, B. S., Singh, R., Kamma, S., Tripathi, M., & Sharma, M. (2023). Transformation of agro-waste into value-added bioproducts and bioactive compounds: Micro/nano formulations and application in the agri-food-pharma sector. *Bioengineering*, *10*(2), Article 152. https://doi.org/10.3390/bioengineering10020152

[4] Chemat, F., & Abert Vian, M. (2023). Green extraction techniques of bioactive compounds: A state-of-the-art review. *Processes*, *11*(8), Article 2255. https://doi.org/10.3390/pr11082255

[5] Gomez, L., & Martinez, R. (2023). Production of bioactive phenolic compounds from agricultural by-products towards bioeconomic perspectives. *Journal of Cleaner Production*, *385*, Article 135680. https://doi.org/10.1016/j.jclepro.2022.135680

[6] Guler, B. A., Tepe, U., & Imamoglu, E. (2024). Sustainable point of view: Life cycle analysis for green extraction technologies. *ChemBioEng Reviews*, *11*(3), 348–362. https://doi.org/10.1002/cben.202300045

[7] Harvey, A. L., Edrada-Ebel, R., & Quinn, R. J. (2015). The re-emergence of natural products for drug discovery in the genomics era. *Nature Reviews Drug Discovery*, *14*(2), 111–129. https://doi.org/10.1038/nrd4510

[8] Kumar, A., & Singh, S. (2023). Environment friendly pretreatment approaches for the bioconversion of lignocellulosic biomass into biofuels and value-added products. *Environments*, *10*(1), Article 6. https://doi.org/10.3390/environments10010006

[9] Li, Q., Putra, N. R., & Yunus, M. A. C. (2023). Orange pomace and peel extraction processes towards sustainable utilization: A short review. *Molecules*, *28*(8), Article 3550. https://doi.org/10.3390/molecules28083550

[10] Marcelino, S., Gaspar, P. D., & Paiva, A. (2023). Sustainable waste management in the production of medicinal and aromatic plants—A systematic review. *Sustainability*, *15*(18), Article 13333. https://doi.org/10.3390/su151813333

[11] Martin, E., & Silva, J. (2023). Grape pomace review: Valorization of grape pomace: A review of phenolic composition, bioactivity, and therapeutic potential. *Nanomaterials*, *13*(5), Article 836. https://doi.org/10.3390/nano13050836

[12] Newman, D. J., & Cragg, G. M. (2020). Natural products as sources of new drugs over the nearly four decades from 01/1981 to 09/2019. *Journal of Natural Products*, *83*(3), 703–721. https://doi.org/10.1021/acs.jnatprod.9b01285

[13] Palmeira, J. D., Araújo, D., & Mota, C. C. (2023). Fermentation as a strategy to valorize olive pomace, a by-product of the olive oil industry. *Fermentation*, *9*(5), Article 442. https://doi.org/10.3390/fermentation9050442

[14] Patel, K., & Sharma, V. (2023). Agro-industrial residues used as substrates for the production of bioaroma compounds with Basidiomycetes: A comprehensive review. *Fermentation*, *9*(12), Article 1024. https://doi.org/10.3390/fermentation9121024

[15] Rodriguez, M., & Fernandez, A. (2023). Olive mill waste valorization. *Cosmetics*, *10*(4), Article 102. https://doi.org/10.3390/cosmetics10040102

[16] Sha, S. P., Modak, D., Sarkar, S., Roy, S. K., Sah, S. P., Ghatani, K., & Bhattacharjee, S. (2023). Fruit waste: A current perspective for the sustainable production of pharmacological, nutraceutical, and bioactive resources. *Frontiers in Microbiology*, *14*, Article 1260071. https://doi.org/10.3389/fmicb.2023.1260071

[17] Silva, P., & Santos, M. (2023). Citrus processing by-products: An overlooked repository of bioactive compounds. *Critical Reviews in Food Science and Nutrition*, *63*(1), 67–86. https://doi.org/10.1080/10408398.2021.1948818

[18] Sridhar, K., & Sharma, M. (2023). Natural deep eutectic solvents (NaDES) as an emerging technology for the valorisation of natural products and agro-food residues: A review. *Trends in Food Science & Technology*, *138*, 215–230. https://doi.org/10.1016/j.tifs.2023.06.015

[19] Torres, C., & Lopez, G. (2023). Valorization of *Olea europaea* and olive oil processing by-products/wastes. *Frontiers in Nutrition*, *10*, Article 1124580. https://doi.org/10.3389/fnut.2023.1124580

[20] Vareltzis, P., & Adamopoulos, K. (2023). Residual biomass from major aromatic and medicinal flora of the Mediterranean: Challenges towards sustainable integration into food systems within the circular bioeconomy. *Journal of Food Engineering*, *339*, Article 104123. https://doi.org/10.1016/j.jfoodeng.2023.104123

[21] Verma, R., & Kumar, P. (2023). Sustainable approaches on industrial food wastes to value-added products. *Food Chemistry*, *412*, Article 135540. https://doi.org/10.1016/j.foodchem.2023.135540

[22] Vilas-Franquesa, A., Casertano, M., Tresserra-Rimbau, A., Vallverdú-Queralt, A., & Torres-León, C. (2024). Recent advances in bio-based extraction processes for the recovery of bound phenolics from agro-industrial by-products and their biological activity. *Critical Reviews in Food Science and Nutrition*, *64*(29), 10643–10667. https://doi.org/10.1080/10408398.2023.2218342

[23] Wang, Y., & Zhang, L. (2023). Life cycle assessment of green extraction technologies. *ACS Sustainable Chemistry & Engineering*, *11*(24), 8810–8825. https://doi.org/10.1021/acssuschemeng.3c01250

[24] Xu, H., & Zhao, C. (2023). The way forward to produce nutraceuticals from agri-food processing residues: Obstacle, solution, and possibility. *Journal of Food Science and Technology*, *60*(9), 2310–2322. https://doi.org/10.1007/s13197-023-05712-4

[25] Zhou, M., Fakayode, O. A., & Li, H. (2023). Green extraction of polyphenols via deep eutectic solvents and assisted technologies from agri-food by-products. *Molecules*, *28*(19), Article 6852. https://doi.org/10.3390/molecules28196852