RSC Sustainability

CRITICAL REVIEW

View Article Online
View Journal | View Issue

Cite this: *RSC Sustainability*, 2026, 4, 1180

Sustainable extraction of bioactive compounds: a life cycle perspective on technologies, solvents, and process scale-up

Justin Z. Lian,[a] Tie Liu,[b] Jintian Yang,[b] Hengyi Zhu,[d] Nalinpat Chalermchotiwong,[b] Yemima Grain,[b] Long Yue,[b] Xiang Luo,[g] Stefano Cucurachi,[a] Jian Li,*[e] Fanran Meng *[c] and Bin Dong*[bf]

Received 30th October 2025
Accepted 1st February 2026

DOI: 10.1039/d5su00832h

rsc.li/rscsus

The extraction of bioactive natural compounds is crucial to the pharmaceutical, food, and cosmetic industries, but it often entails high energy consumption, greenhouse gas emissions, and environmental impacts associated with solvent use. Life Cycle Assessment (LCA) provides a structured approach to identify environmental hotspots and evaluate trade-offs across solvent use, energy demand, and process scale-up. This review adopts a life-cycle perspective to examine the environmental impacts from upstream stages, including agriculture, raw material processing, and transportation, to extraction, waste management, and end-of-life treatment. Extraction technologies, including microwave-assisted, ultrasound-assisted, solvent-based, pressurized liquid, and high-voltage electrical discharge methods, are compared in terms of environmental performance and process efficiency. Solvent selection is highlighted as a critical factor, with a focus on the balance between extraction yield and sustainability across water, organic, and deep eutectic solvents. The integration of LCA with simulation tools, such as SuperPro Designer and Aspen Plus, is also reviewed for its potential to support scaling-up decisions and resource optimization. Although current LCA studies provide valuable insights, gaps remain in addressing energy constraints, waste flows, and real-world implementation. Advancing sustainable extraction requires a combination of system-level design, data-driven modeling, and circular resource utilization.

Sustainability spotlight

Extraction of bioactive compounds from natural resources underpins the pharmaceutical, food, and cosmetic industries, yet current processes are often energy-intensive, solvent-dependent, and waste-generating. This review takes a full life cycle perspective to evaluate extraction technologies, solvents, and process scale-up through environmental lenses. By integrating Life Cycle Assessment with process simulation tools such as SuperPro Designer and Aspen Plus, it identifies critical trade-offs in energy use, solvent recovery, and waste management. The analysis highlights opportunities for solvent optimisation and circular resource use to advance sustainable bioprocessing. This work supports the UN Sustainable Development Goals for Responsible Consumption and Production (SDG 12), Climate Action (SDG 13), and Industry, Innovation and Infrastructure (SDG 9) by providing a framework to guide low-impact, scalable extraction technologies for natural products.

[a]Institute of Environmental Science – Industrial Ecology, Leiden University, Van Steenisgebouw, Einsteinweg 2, 2333 CC Leiden, The Netherlands
[b]Department of Pharmaceutical and Environmental Engineering, China Pharmaceutical University, Nanjing, 210009, PR China. E-mail: bin.dong@cpu.edu.cn
[c]School of Chemical, Materials and Biological Engineering, Faculty of Engineering, University of Sheffield, Sheffield, S10 2TN, UK. E-mail: f.meng@sheffield.ac.uk
[d]School of Traditional Chinese Pharmacy, China Pharmaceutical University, Nanjing, 210009, PR China
[e]Jinling Pharmaceutical Co., Ltd, Nanjing, 210009, China. E-mail: lijian@njjlzy.com
[f]Engineering Research Center for Smart Pharmaceutical Manufacturing Technologies, Ministry of Education, China Pharmaceutical University, Nanjing, 210009, PR China
[g]Department of Chemical and Environmental Engineering, The University of Nottingham Ningbo China, Ningbo 315100, PR China

1. Introduction

Bioactive compounds derived from natural resources are widely used in biomedicine, microbiology, and the food industry.[1–3] These compounds originate from diverse biological sources, including plants and animals, and are increasingly valued for their role in drug development and the formulation of sustainable products. The extraction of bioactive natural resources is a complex process that involves obtaining raw materials from nature and using various physical, chemical, or biological methods to extract the desired components.[4]

Extraction methods for bioactive natural resources can be broadly categorized into conventional solvent-based methods, emerging green technologies, and physical/mechanical processes.[5] Conventional methods, such as hot water extraction, maceration, and Soxhlet extraction, rely on thermal or solvent-driven diffusion. Other solvent extraction techniques, such as supercritical CO_2 extraction, enzymatic hydrolysis, and deep eutectic solvent (DES)-assisted extraction, can enhance selectivity and reduce toxic chemical inputs.[6] Furthermore, emerging green extraction technologies, including microwave-assisted extraction (MAE) and ultrasound-assisted extraction (UAE), aim to improve energy efficiency and reduce processing time.[7] Meanwhile, physical and mechanical approaches, such as pressurized liquid extraction (PLE) and hydrodynamic cavitation, offer solvent-free alternatives with lower environmental burdens.[8] Each method varies in terms of solvent use, energy consumption and extraction yield, so the overall sustainability of bioactive compound production is influenced.[9]

However, the extraction process is not an isolated stage but rather part of a broader resource-intensive system, where large-scale raw material collection, handling, and processing serve as necessary precursors. The cultivation, harvesting, and transportation of biomass require significant energy inputs, particularly in mechanized agricultural systems, which contribute to greenhouse gas emissions and environmental degradation.[10] Beyond raw material acquisition, pre-processing steps, such as drying, grinding, and biomass fractionation, further increase energy consumption and resource demand before the extraction phase begins. Once extraction occurs, the process can involve the extensive use of chemical solvents,[11,12] which may persist in the soil, water sources, or atmosphere, leading to long-term ecological risks.[13] Additionally, wastewater discharge and exhaust gases generated during extraction require proper treatment to prevent secondary pollution.[14] Moreover, the environmental impact of the end-of-life stage must be considered.

To address these concerns, Life Cycle Assessment (LCA) has become a widely recognized tool for evaluating the environmental performance of technologies.[15] LCA can provide analysis of environmental impacts across the entire life cycle, from raw material cultivation and processing to extraction, transportation, and end-of-life (EOL) stage.[16] Furthermore, LCA can reveal environmental hotspots and develop targeted optimization strategies.[17–19] Also, integrating LCA with process simulation tools enables scalability assessments, ensuring that sustainability claims at the laboratory level are effectively translated into meaningful industrial applications. Despite these methodological advancements, critical challenges persist in achieving truly sustainable extraction, particularly in terms of waste valorization, solvent reduction, and industrial-scale feasibility. For instance, many extraction residues are discarded rather than repurposed, resulting in inefficient resource utilization. Addressing these limitations requires a circular economy perspective, where by-products are reintegrated into production cycles rather than treated as waste.

This review examines the environmental impact of bioactive natural resource extraction from an LCA perspective and explores strategies to optimize sustainable extraction processes. We begin with a screening and review of state-of-the-art literature in Section 2, focusing on extraction technologies evaluated through LCA for their environmental impacts. Then, the agricultural production, raw material handling, and transportation stages for bioactive natural resources, following the life cycle concept, are outlined in Section 3. Next, various extraction technologies are reviewed in terms of their environmental footprint and potential improvements in Section 4. We then discuss solvent-related environmental burdens, emphasizing green solvent alternatives and optimization strategies in Section 5. Following this, the discussion shifts to industrial-scale sustainability modeling, analyzing how LCA-integrated simulation tools facilitate the scaling up of sustainable extraction technologies. Finally, waste management and end-of-life (EOL) considerations are discussed, highlighting opportunities for byproduct recovery and the utilization of circular resources. We conclude the paper with a summary that highlights key insights and outlines future research directions for advancing sustainable extraction technologies at both laboratory and industrial scales.

2. Methods

2.1. Literature searching

We collected peer-reviewed publications from 2016 to 2024 that focus on the published LCA studies of bioactive compound extraction processes. Following the guidelines of Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA),[20,21] we identified and reviewed relevant articles through a systematic process outlined in seven steps (see Fig. 1). Literature was retrieved from Web of Science, ScienceDirect, and Google Scholar using combinations of keywords such as "life cycle assessment", "life cycle analysis", "bioactive compound extraction", "natural products", and "biomass valorization". To ensure broad coverage across disciplines, additional search terms included specific biomass types (*e.g.*, "polyphenols", "algae", "hemicellulose"), extraction technologies (*e.g.*, "microwave-assisted extraction", "ultrasound-assisted extraction", "supercritical CO_2", "deep eutectic solvents"), and process evaluation approaches (*e.g.*, "techno-economic analysis", "process simulation"). Studies were selected based on their relevance to LCA-based evaluations of extraction processes or solvent systems, with particular focus on energy use, solvent impact, system boundaries, and industrial-scale considerations. Review articles, papers without environmental assessment components, and non-English publications were excluded.

Researcher bias in article selection and analysis has a negative impact on the quality of the review. To eliminate selection bias, it is critical to follow a review technique that includes a systematic and objective process for picking publications. Furthermore, employing a preliminary protocol design that specifies the analysis procedures can substantially reduce analytical bias. As a result, the before mentioned approaches were implemented to eliminate any type of bias in the selection and analysis of publications.

During the search phase, we identified 70 articles across three distinct databases and platforms: 33 from "Elsevier ScienceDirect" searches, 25 from "Web of Science" searches, and 12 from other platforms. During the evaluation phase, after duplicates were removed, 62 articles remained, as can be seen in Fig. 1.

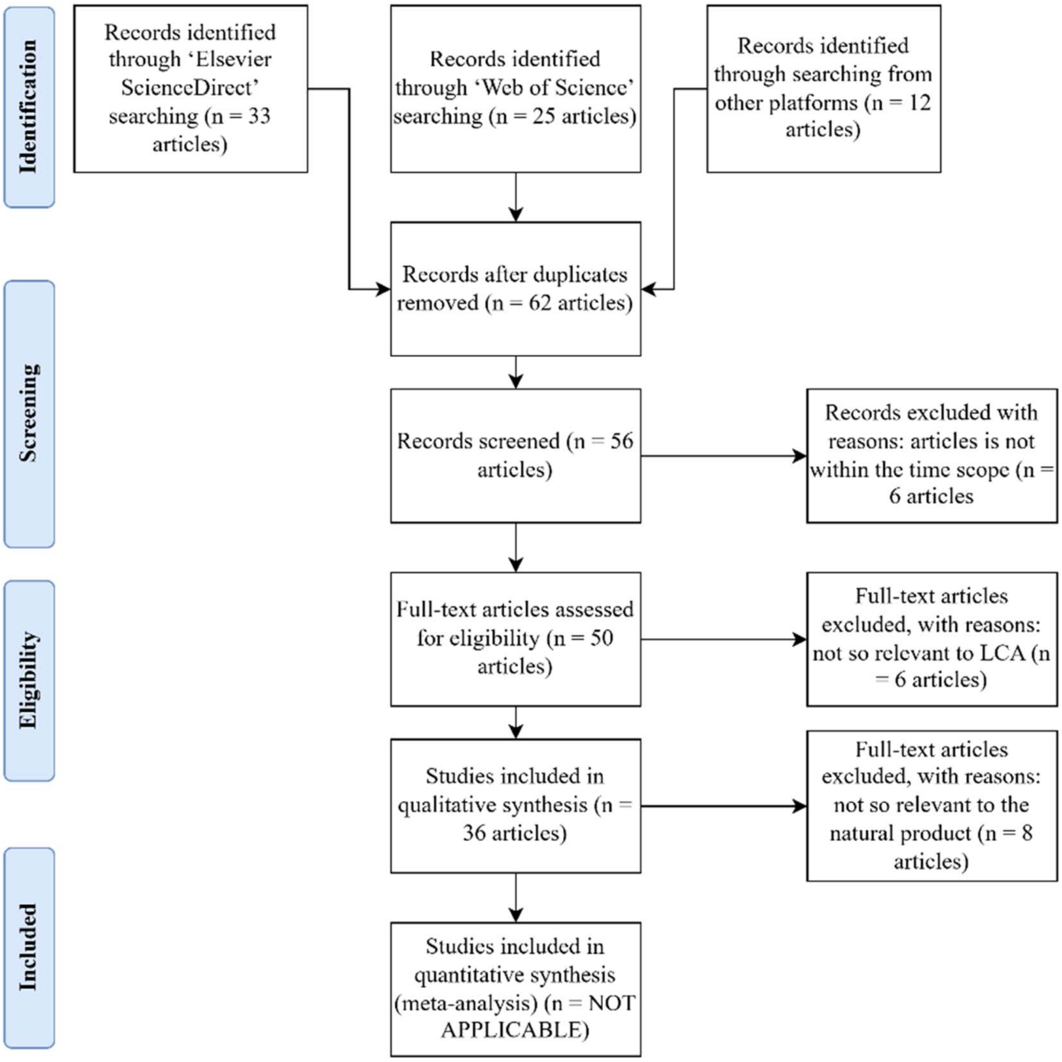

Fig. 1 The review process and associated articles based on the PRISMA guideline.

2.2 Literature evaluation

Following further screening, 56 articles advanced to the eligibility assessment phase. Among them, 6 articles were excluded because they fell outside the study's time frame, 6 articles were excluded due to low relevance to LCA, and an additional 8 articles were excluded due to low relevance to natural products. Ultimately, 36 relevant LCA articles were included in the qualitative synthesis analysis (Table 1).

We found that most of the studies defined the scope of "cradle-to-gate" and "gate-to-gate", of which there were 22 articles (61%) on "cradle-to-gate", 12 articles (33%) on "gate-to-gate", and only two articles on "cradle-to-grave" (refer to Table 2). LCA studies in the extraction industry have mainly focused on material transportation and substance extraction stages. The environmental impacts of the extracts and the waste generated during the process have not received adequate attention. This heterogeneity in system boundaries limits the direct comparability of environmental performance across extraction technologies. In particular, studies that exclude upstream agricultural inputs or downstream waste treatment may underestimate total life cycle impacts and yield overly favorable results. The dominance of partial system boundaries also reflects a broader methodological challenge in current LCA research on bioactive compound extraction, where data availability and modeling complexity constrain the inclusion of full life cycle stages.

2.3 Classification and scope

After confirming the relevance of all selected studies to LCA, we organized the literature along two main dimensions. First, we categorized the extraction technologies assessed, including conventional solvent-based methods, green alternatives (*e.g.*, MAE, UAE), and mechanical or hybrid techniques (*e.g.*, PLE, HVED). Second, we grouped studies by system performance and scalability, focusing on those that used simulation tools to connect lab-scale processes with industrial applications. To capture broader variations across studies, Table 2 further lists the specific subjects, target compounds, and analytical scopes covered, providing additional context beyond the two primary

Table 1 Inclusion and exclusion criteria for the articles

Article selection method	PRISMA guidelines		
Search strings	Life cycle assessment, life cycle analysis, bioactive compound extraction, natural products, biomass valorization, green extraction technologies, microwave-assisted extraction, ultrasound-assisted extraction, supercritical CO_2 extraction, deep eutectic solvents, process simulation, techno-economic assessment		
PICOS criteria	Criteria	Inclusion	Exclusion
	Population	LCA studies of extraction processes for bioactive compounds/natural products	Studies not focused on extraction (*e.g.*, synthesis, cultivation only)
	Intervention	Any extraction technology (MAE, UAE, SFE, PLE, *etc.*) or solvent system	
	Comparator	Conventional extraction methods or other novel methods	
	Outcomes	Environmental impact indicators (GWP, energy use, *etc.*), system boundaries, inventory data	Studies without quantitative environmental assessment (*e.g.*, only review or techno-economic)
	Study design	Peer-reviewed journal articles, original LCA studies	Review articles, conference abstracts, non-English publications
	Time frame	2016–2024	Published before 2016 and after 2024
Databases	Web of Science, ScienceDirect, and Google Scholar		
Analysis method	Narrative synthesis		
Reporting structure	PRISMA guidelines		
Search criteria	("Life cycle assessment" OR "life cycle analysis") and ("bioactive compound extraction" OR "natural products" OR "biomass valorization") and ("microwave-assisted extraction" OR "ultrasound-assisted extraction" OR "supercritical CO_2" OR "deep eutectic solvents")		
Whom do the screening and eligibility checking?	Authors independently		

themes. Where applicable, we also classified the studies by LCA system boundaries (cradle-to-gate, gate-to-gate, cradle-to-grave) and highlighted recurring environmental hotspots, including energy use, solvent selection, and process-level trade-offs. This work follows a life cycle structure, enabling a stage-by-stage analysis from upstream inputs to waste and end-of-life management.

Before discussing each life-cycle stage in detail, Fig. 2 provides an overview of the major stages involved in the production of bioactive compounds. The system begins with agricultural cultivation and biomass harvesting, followed by raw material processing, such as drying, grinding, and fractionation. These materials are then transported to extraction facilities, where various technologies, including conventional solvent-based methods, MAE, UAE, PLE, and HVED are applied. The extracted products undergo solvent recovery and purification before entering waste management or by-product valorization pathways. Finally, end-of-life (EOL) treatment addresses disposal, recycling, and circular utilization of process residues. This flow chart establishes the framework for the subsequent sections, which analyze each life-cycle stage in turn from an environmental perspective.

3. LCA on agricultural stages, material handling and transportation of raw materials

Agricultural production, raw material processing, and transportation form the foundation of extraction processes and can represent major contributors to environmental impact. Yet these upstream stages generally receive less attention compared to extraction itself. As LCA studies have shown, early-stage inputs, such as electricity, fertilizer, and logistics, can significantly affect the footprint of bioactive compound production, and their influence varies by region, technology, and system boundaries. Several studies confirm that the agricultural phase is frequently the most impactful. For example, Khatri *et al.* investigated the impact of system variables, including oilseed processing scale and distribution methods, on LCA results.[22] The results showed that the agricultural phase had the most significant impact on all assessed environmental impact categories. The key factors in this phase include electricity consumption, fertilizer production, emissions from agricultural activity, and the transportation of inputs. The analysis suggested that the environmental impact of small-scale processing was higher than that of medium-scale and large-scale processing. Furthermore, the allocation method used to assess the environmental impacts of industrial and agricultural products, and their by-products, can also significantly impact the assessment results. To mitigate these environmental burdens, precision farming techniques, energy-efficient irrigation, and optimized fertilizer application are strategies to reduce emissions and resource consumption at the agricultural stage.

Material handling also introduces non-negligible emissions, particularly through electricity use and waste generation. In a study on mustard oil production, Gaurav *et al.* found that seed cleaning and filtration stages drove global warming, eutrophication, and toxicity impacts, mostly due to energy intensity.[23] These results suggest that without process optimization, for instance, through the use of energy-efficient machinery, advanced emission controls, and improved wastewater treatment, the environmental benefits of natural extraction may be lost further upstream. Automation and machine learning-based

Table 2 Papers collected for LCA-bioactive natural resource extraction techniques in this study

Subjects	Title	System boundary	Functional unit (FU)	Authors (Year)	DOI
LCA of various extraction technologies	Life cycle assessment of tannin extraction from spruce bark	Cradle-to-gate	1 kg tannin yield after post extraction treatment	Ding *et al.* (2017)	https://doi.org/10.3832/ifor2342-010
	Extraction of phenolic compounds from oregano using high voltage electrical discharges-sustainable perspective	Cradle-to-gate	A treatment of oregano	Nutrizio *et al.* (2022)	https://doi.org/10.1111/ijfs.15476
	Life cycle assessment for identification of critical aspects in emerging technologies for the extraction of phenolic compounds from spruce bark	Cradle-to-gate	1 kg of polyphenols in kg GAE	Carlqvist *et al.* (2022)	https://doi.org/10.1016/j.jclepro.2021.130093
UAE and crude glycerol aqueous solution extraction process optimization	Life cycle assessment of greenhouse gas emissions of upgrading and refining bitumen from the solvent extraction process	Cradle-to-gate	1 bbl of bitumen	Soiket *et al.* (2019)	https://doi.org/10.1016/j.apenergy.2019.02.039
	Ultrasound-assisted lipid extraction from *Chlorella* sp.: Taguchi design and life cycle assessment	Gate-to-gate	1 kg of EO (essential oil)	Phan *et al.* (2023)	https://doi.org/10.1007/s12033-023-00836-6
	Early-stage life cycle assessment and optimization of aqueous crude glycerol extraction and nanofiltration concentration of tomato leaf residue	Gate-to-Gate	1 g of TPC (total phenolic content)	Li *et al.* (2024)	https://doi.org/10.1021/acssuschemeng.3c06655
	Life cycle assessment for evaluation of novel solvents and technologies: a case study of flavonoids extraction from Ginkgo biloba leaves	Gate-to-Gate	1 g of FGBL (flavonoids from Ginkgo biloba leaves)	Wang *et al.* (2024)	https://doi.org/10.1016/j.scitotenv.2024.171319
	Life cycle and environmental cost assessment of ultrasound-assisted alkaline extraction of hemicellulose by sugarcane bagasse pith	Gate-to-gate	1g WHC (water-soluble hemicellulose) or AHC (alkali-soluble hemicellulose)	Guo *et al.* (2023)	https://doi.org/10.1016/j.jclepro.2023.137420
The sustainability and economics of high-value compound extraction methods	Phytochemical compounds or their synthetic counterparts? a detailed comparison of the quantitative environmental assessment for the synthesis and extraction of curcumin	Cradle-to-grave	1 kg of curcumin	Zerazion *et al.* (2016)	https://doi.org/10.1039/C6GC00090H
	Life cycle assessment of supercritical CO_2 extraction of caffeine from coffee beans	Cradle-to-gate	1 kg of decaf blend coffee beans (constituted by 600 g of Arabica and 400 g of Robusta) corresponding to 11.4 g of dry caffeine recovered from the blend	De Marco *et al.* (2018)	https://doi.org/10.1016/j.supflu.2017.11.005
	Environmental and yield comparison of quick extraction methods for caffeine and chlorogenic acid from spent coffee grounds	Gate-to-gate	125 mg of chlorogenic acid needed for 100 g of a face cosmetic cream	Bouhzam *et al.* (2023)	https://doi.org/10.3390/foods12040779

Table 2 (*Contd.*)

Subjects	Title	System boundary	Functional unit (FU)	Authors (Year)	DOI
	Techno economic and life cycle assessment of lycopene production from tomato peels using different extraction methods	Gate-to-gate	300 kg of tomato peels per day	Yadav *et al.* (2023)	https://doi.org/10.1007/s13399-023-04676-x
LCA of mustard oil production and semi-mechanical extraction processes	Life cycle assessment of extraction of edible oil from mustard seeds: a case study of an oil industry	Gate-to-gate	1 ton of mustard oil output	Gaurav *et al.* (2023)	https://doi.org/10.1016/j.matpr.2023.01.055
	A cradle-to-gate assessment of environmental impacts for production of mustard oil using life cycle assessment approach	Cradle-to-gate	1 kg of mustard oil	Khatri *et al.* (2017)	https://doi.org/10.1016/j.jclepro.2017.08.109
	An environmental impact analysis of semi-mechanical extraction process of sago starch: life cycle assessment (LCA) perspective	Gate-to-gate	1 ton of sundried sago starch	Yusuf *et al.* (2018)	https://doi.org/10.1088/1755-1315/147/1/012036
Enzyme-assisted and sol–gel microencapsulation methods and the application of novel bio-solvents	Life cycle assessment of chemical *vs.* enzymatic-assisted extraction of proteins from black soldier fly Prepare for the preparation of biomaterials for potential agricultural use	Cradle-to-grave	0.403 g and 0.5 g of bioplastic	Rosa *et al.* (2020)	https://doi.org/10.1021/acssuschemeng.0c03795
	Extraction of palm carotene from crude palm oil by solvolytic micellization: Economic evaluation and life cycle assessment	Gate-to-gate	1 kg tannin yield after post extraction treatment	Hoe *et al.* (2024)	https://doi.org/10.1080/00986445.2022.2047664
	Life cycle energy and carbon emissions of colorants extraction from *Hibiscus sabdariffa*	Cradle-to-gate	1 g of colorant extract of *H. sabdariffa*	Monteiro *et al.* (2022)	https://doi.org/10.1016/j.egyr.2022.01.034
	Life-cycle assessment of microwave-assisted pectin extraction at pilot scale	Cradle-to-gate	150 g pectin	Garcia–Garcia *et al.* (2019)	https://doi.org/10.1021/acssuschemeng.8b06052
Environmental and economic impact of novel biorefinery and extraction systems	Environmental and techno-economic evaluation of β-carotene production from dunaliella salina. a biorefinery approach	Cradle-to-gate	1 kg of β-carotene	Espada *et al.* (2020)	https://doi.org/10.1002/bbb.2012
	Environmental life cycle assessment of cascade valorisation strategies of South African macroalga Ecklonia maxima using green extraction technologies	Harbour-to-gate	1 t DM *E. maxima* feedstock	Zhang *et al.* (2021)	https://doi.org/10.1016/j.algal.2021.102348
Application of LCA in waste treatment and recycling	Valorization of pumpkin seed hulls, cucurbitin extraction strategies and their comparative life cycle assessment	Cradle-to-gate	1 kg of cucurbitin	Massironi *et al.* (2023)	https://doi.org/10.1016/j.jclepro.2023.139267
		Cradle-to-gate	1 metric ton of olive pomace		https://doi.org/10.3390/pr8050626

Table 2 (*Contd.*)

Subjects	Title	System boundary	Functional unit (FU)	Authors (Year)	DOI
	Environmental assessment of olive mill solid waste valorization *via* anaerobic digestion *versus* olive pomace oil extraction			Alonso-Fariñas *et al.* (2020)	
	Insights from combining techno-economic and life cycle assessment – a case study of polyphenol extraction from red wine pomace	Cradle-to-gate	1 kg of polyphenols in kg GAE	Croxatto Vega *et al.* (2021)	https://doi.org/10.1016/j.resconrec.2020.105318
	Characterization and comparison of cellulose fiber extraction from rice straw by chemical treatment and thermal steam explosion	Cradle-to-gate	1 kg of the fiber insulator	Boonterm *et al.* (2016)	https://doi.org/10.1016/j.jclepro.2015.09.084
	Environmental impact of food preparations enriched with phenolic extracts from olive oil mill waste	Cradle-to-gate	1 g of TPC (total phenolic content)	Pampuri *et al.* (2021)	https://doi.org/10.3390/foods10050980
	Environmental performance of orange citrus waste as raw material for pectin and essential oil production	Cradle-to-gate	1 kg of pectin	da Costa *et al.* (2022)	https://doi.org/10.1016/j.fbp.2022.07.008
Evaluating the environmental impact of by-products in the food industry	Identifying the sustainability route of asparagus co-product extraction: from waste to bioactive compounds	Cradle-to-gate	1 kg of rutin	Santiago *et al.* (2021)	https://doi.org/10.1016/j.fbp.2021.08.005
	Life cycle assessment of olive pomace valorisation through pyrolysis	Cradle-to-gate	100 kg olive pomace	Parascanu *et al.* (2018)	https://doi.org/10.1016/j.renene.2018.02.027
	Pine needles as a biomass resource for phenolic compounds: trade-off between efficiency and sustainability of the extraction methods by life cycle assessment	Cradle-to-gate	1 mg of polyphenols in mg GAE	Salzano de Luna *et al.* (2023)	https://doi.org/10.1021/acssuschemeng.2c06698
	Life cycle assessment of polyphenols extraction processes from waste biomass	Cradle-to-gate	1 mg of polyphenols in mg GAE	Barjoveanu, G. *et al.* (2020)	https://doi.org/10.1038/s41598-020-70587-w
	Environmental life cycle assessment of early-stage development of ergosterol extraction from mushroom bio-residues	Cradle-to-gate	1 g of ergosterol enriched extract	Moura *et al.* (2022)	https://doi.org/10.1016/j.jclepro.2022.131623
	Comparative LCA of ultrasound-assisted extraction of polyphenols from chicory grounds under different operational conditions	Gate-to-gate	0.55 L of extract exhibiting 220 μmol Trolox equivalent antioxidant capacity	Vauchel *et al.* (2018)	https://doi.org/10.1016/j.jclepro.2018.06.042
	Ultrasound-assisted polyphenol extraction of acerola and jambolan pomaces: comparison of extraction	Cradle-to-gate	1400 mg of polyphenols in mg GAE	da Silva *et al.* (2023)	https://doi.org/10.1016/j.cep.2023.109443

Table 2 (*Contd.*)

Subjects	Title	System boundary	Functional unit (FU)	Authors (Year)	DOI
	protocols, kinetic modeling, and life cycle assessment				
	Sustainability challenges and opportunities in pectin extraction from fruit waste	Cradle-to-gate	1 kg of pectin	Nadar *et al.* (2022)	https://doi.org/10.1021/acsengineeringau.1c00025
	Multi-criteria optimization including environmental impacts of a microwave-assisted extraction of polyphenols and comparison with an ultrasound-assisted extraction process	Gate-to-gate	16.6 mM TEAC (Trolox equivalent antioxidant activity)	Bouchez *et al.* (2023)	https://doi.org/10.3390/foods12091750

predictive maintenance could reduce electricity consumption and enhance overall sustainability. Moreover, expanding the system boundary beyond the gate-to-gate scope to include upstream and downstream processes would also provide a deeper understanding of the environmental impact of mustard oil production.

Transport adds another layer of complexity. Large-scale operations typically involve long-distance movement of raw materials, which can erode some of the environmental benefits gained through efficient extraction. Yusuf *et al.* assessed sago starch extraction and reported lower emissions per ton compared to maize or cassava.[24] However, the 200 km transport distance still contributed to 325 kg CO_2-eq per ton. This highlights the relevance of transport mode and fuel type. The study excluded electricity used during processing, showing the risk of underestimating total impacts when system boundaries are narrow. These cases make clear that upstream processes are not secondary considerations, as they can shape or even outweigh the gains achieved in later extraction stages. To address this, future studies should adopt broader system boundaries and explore scalable mitigation strategies, such as electrified logistics, regional sourcing, and integration of low-carbon infrastructure. Without this, sustainability claims based solely on extraction technologies risk being incomplete or misleading.

4. LCA on bioactive natural resource extraction technologies

Extraction is typically one of the most energy-intensive steps in the lifecycle of bioactive compound production, and thus a major contributor to environmental impacts.[25–27] While emerging technologies such as microwave-assisted extraction (MAE) and ultrasound-assisted extraction (UAE) are often touted for their reduced processing times and solvent demands, their actual performance in real-world applications is less certain. Many LCA studies report environmental benefits under controlled lab conditions, but these frequently rely on limited system boundaries, idealized energy sources, or untested scale-up assumptions. A closer examination of LCA findings reveals recurring issues related to scalability, indirect emissions, and the omission of infrastructure-related burdens.

4.1 Microwave-assisted extraction

Microwave-assisted extraction (MAE) utilizes the thermal and non-thermal effects of microwaves to extract bioactive compounds from various materials rapidly. It is widely reported to reduce environmental impacts by shortening extraction times and lowering solvent consumption.[28] Garcia–Garcia *et al.* showed a 67% increase in pectin yield and an approximately 75% reduction in overall environmental impacts across all ILCD midpoint categories compared to the conventional acid-assisted process.[25] However, their assessment was limited to batch-scale operations and did not include emissions from continuous industrial processes, which typically involve inefficient heat dissipation and higher electricity consumption. Similarly, Zerazion *et al.* favored MAE over Soxhlet extraction and chemical

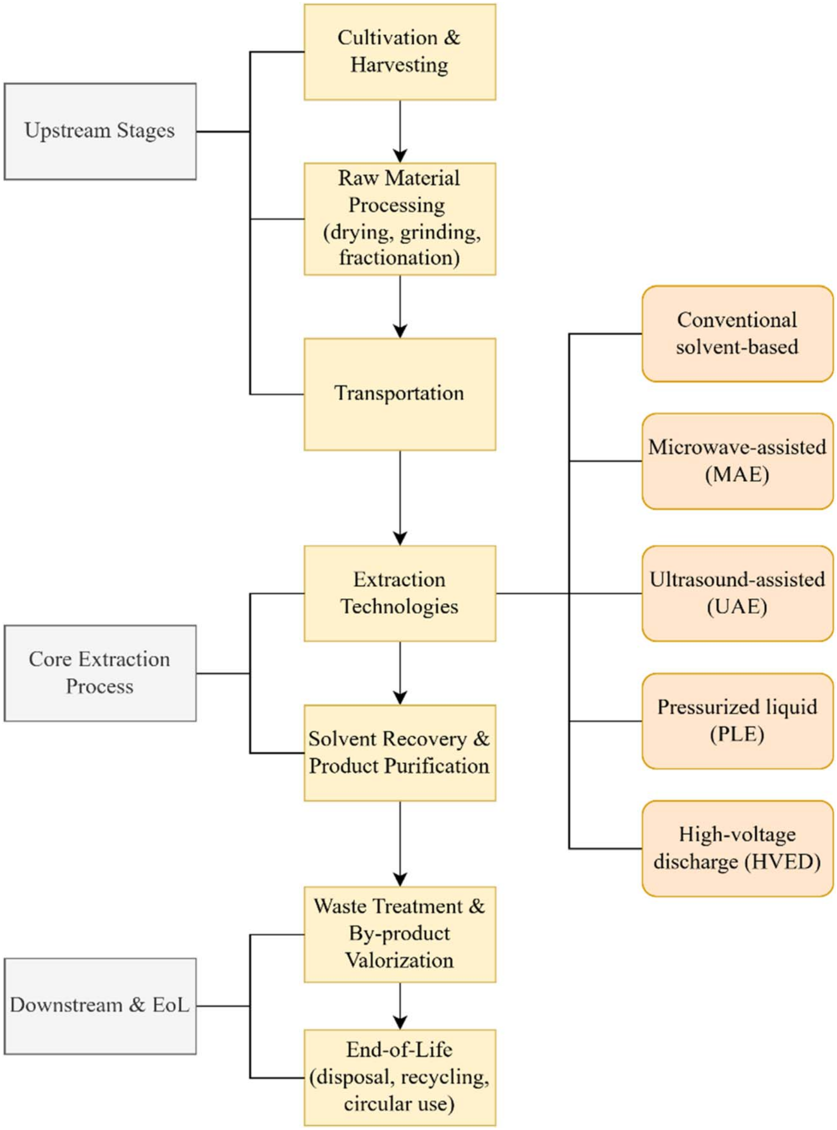

Fig. 2 Overview of the life cycle stages for bioactive compound production. The system is divided into three main phases: upstream stages (raw material acquisition, preparation and transportation), core process (extraction technologies and purification), and downstream processing & end-of-life (waste treatment and circular utilization). Arrows indicate the process flow, while the orange boxes on the right list the key extraction technologies discussed in this review.

synthesis for curcumin production but did not factor in the environmental cost of microwave equipment manufacturing or the long-term electricity dependency of dielectric heating systems.[29] The reviewed LCA studies indicate that MAE can offer environmental advantages at the laboratory scale, mainly due to reduced extraction time and solvent consumption. However, these benefits are highly sensitive to electricity demand, operating conditions, and assumed energy efficiency during scale-up. Moreover, infrastructure-related impacts and continuous-operation performance are rarely addressed in existing assessments. Therefore, further industrial-scale studies are needed to verify whether the reported advantages of MAE can be maintained beyond batch laboratory systems.

4.2 Ultrasound-assisted extraction

Ultrasound-assisted extraction (UAE) enhances solvent penetration into plant matrices through cavitation effects to improve extraction efficiency.[7,30] Yadav and Dhamole evaluated multiple lycopene extraction methods, including solvent-assisted extraction (SAE), supercritical fluid extraction (SCF), enzyme-assisted extraction (EAE), UAE, and integrated ultrasound surfactant-assisted extraction (IUSAE). Based on the LCA results, IUSAE had the lowest environmental impact, especially when powered by renewable energy sources, which reduced key environmental indicators (GWP, AP, POCP, EP, HTP) by 78–90%.[26] Economically, IUSAE also outperformed other methods with a net present value (NPV) of US$20,858 and a payback period of 4.2 years. A Monte Carlo simulation assessed the sensitivity of economic viability to cost and market conditions, confirming IUSAE's financial stability. However, the study focused on operational energy and overlooked the environmental cost of surfactant production, and the lifecycle impacts of maintenance.

Similarly, Salzano de Luna *et al.* compared UAE, MAE, and traditional maceration for extracting polyphenols from dried pine needles.[31] They found that the UAE offered the best compromise between efficiency and environmental impact in polyphenol extraction from pine needles. However, they also noted that extended electricity use could offset its benefits. Additionally, solvent selection is a key factor in environmental performance. Substituting acetone with ethanol can reduce environmental impacts across most categories; however, it lowers extraction efficiency, potentially leading to higher impacts per unit of recovered polyphenols. This suggests that while "greener" solvents may reduce toxicity-related impacts, they can also shift environmental burdens by requiring longer processing times or greater solvent volumes (see Fig. 3). Therefore, a trade-off between extraction efficiency and environmental performance must be carefully considered.

Monteiro *et al.* assessed the environmental impact of extracting edible colorants from Hibiscus sabdariffa and found that UAE had the lowest cumulative energy demand (CED). The

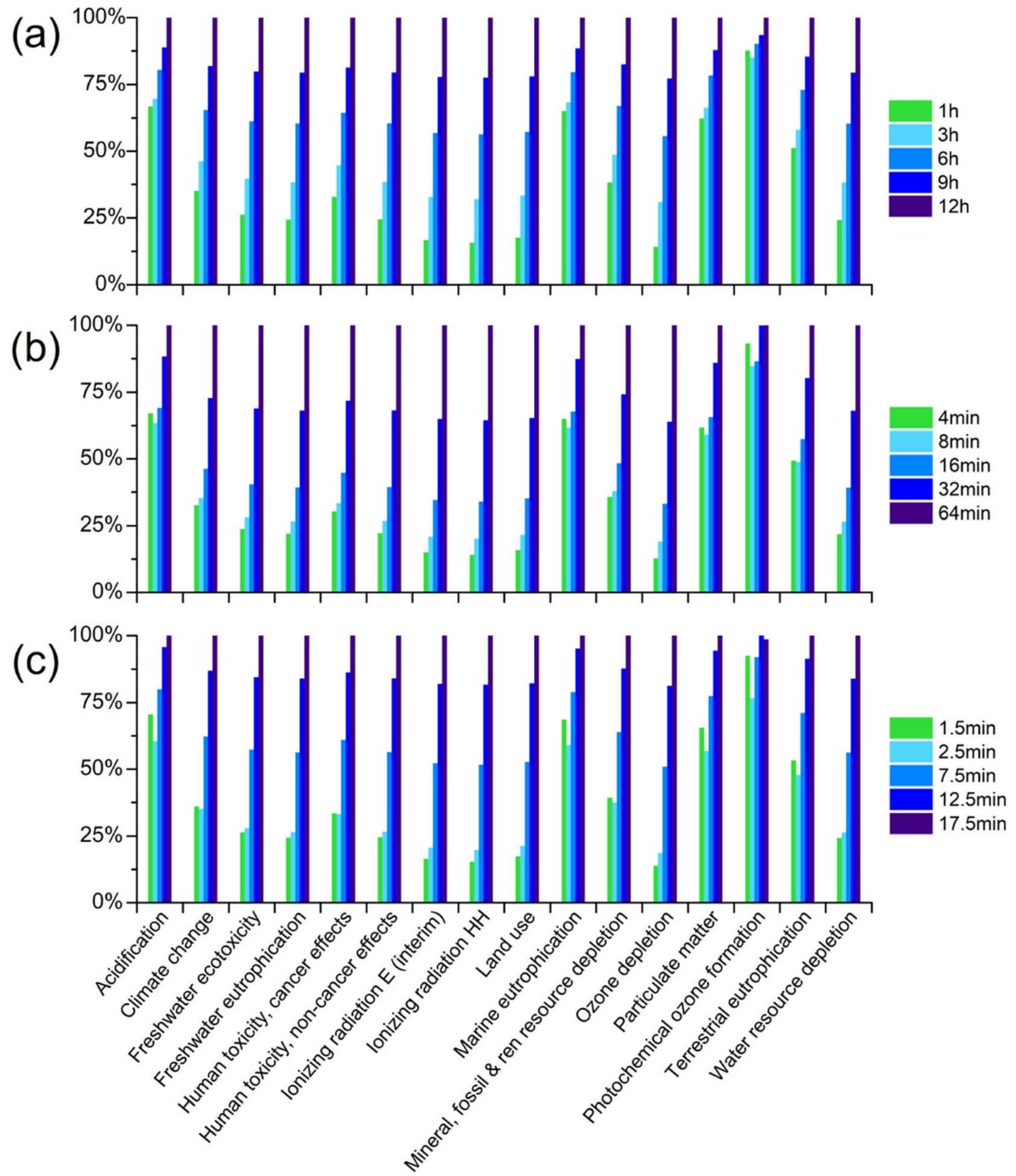

Fig. 3 (a) conventional maceration, (b) ultrasound-assisted extraction, and (c) microwave-assisted extraction. Single-score results for 1h of conventional maceration (CM), 4 min of ultrasound-assisted extraction (UAE), and 1.5 min of microwave-assisted extraction (MAE) obtained using ethanol/water (70/30 v/v) as an extraction medium. Dashed boxes correspond to the aggregated single score obtained with acetone/water.[31] Adapted with permission from M. Salzano de Luna *et al.* Copyright 2023 ACS.

study reported a primary energy demand of 109 MJ and carbon emissions of 5 kg CO_2-eq per gram of extract, making it the most environmentally favorable option. However, the dominant environmental burden was attributed to spray-drying, which accounted for over 80% of total energy consumption and emissions. Although the study focuses on energy efficiency, it does not explore alternative heat sources like biomass-based, which could further reduce emissions.[32]

Electricity use consistently appears as a critical hotspot across UAE studies. Barjoveanu *et al.* used LCA to compare three lab-scale methods for extracting polyphenols from spruce bark: solvent extraction, alkaline-assisted extraction with NaOH, and UAE.[27] Their results showed that electricity for heating and ethanol production were the main sources of environmental impact. To improve performance, the study explored scaling up the UAE by replacing electric heating with a biomass boiler and utilized a 30-Liter extraction vessel. This change led to a clear reduction in environmental impact, with potential for industrial use. The study also included a sensitivity analysis to test the reliability of the lab-scale data. It was found that energy use had the strongest effect on the final results.

Despite promising lab-scale data, the feasibility of MAE and UAE in industrial settings remains questionable. As mentioned earlier, studies highlight reduced impacts under optimal conditions, but rarely assess the stability of those gains when scaled.[25,26] In regions with unreliable renewable energy supplies, large-scale and continuous ultrasound operations would require energy storage or backup generation, which may increase impacts. Similarly, industrial-scale dielectric heating for MAE may result in significant grid dependency and capital intensity, as also overlooked by Zerazion *et al.*[29] Meanwhile, the proposed "closed-loop" improvements of many studies, such as solvent recycling in MAE/UAE or pomace valorization in anaerobic digestion (AD), are theoretically promising but may lack empirical validation of infrastructure feasibility. For example, Bouchez *et al.* suggested hybrid MAE-UAE setups for greater efficiency but ignored the production and maintenance emissions of combined systems.[33] da Silva *et al.* found that UAE was energy-efficient for acerola extraction, yet did not consider potential land-use impacts from expanding tropical fruit production.[34] These gaps reflect a pattern in LCA studies where cleaner inputs or new solvents are shown to lower environmental impacts at the process level. However, the practical issues associated with large-scale implementation, such as increased energy consumption, unstable operation, and additional infrastructure, are often overlooked. When these factors are ignored, the results may give an overly positive view of how green extraction methods would perform outside the lab.

4.3. Solvent-based extraction

Solvent-dependent systems face inherent trade-offs between technical performance and environmental efficiency. For instance, hot water extraction (HWE) uses the physicochemical properties of water to extract bioactive compounds from natural sources, offering a chemical-free alternative to conventional solvent extraction. However, the environmental profile of HWE varies depending on process configurations and extraction yield efficiency. Carlqvist *et al.* evaluated the LCA of three techniques for extracting phenolic compounds from spruce bark: HWE, UAE and supercritical fluid extraction (SFE).[35] The results showed that the HWE process had a lower environmental impact per kilogram of extracted phenolic compounds than UAE or SFE in large-scale production. The environmental burden primarily arises from ethanol use in the UAE and from SFE processes, accounting for more than 70% of the total environmental load (see Fig. 4). However, the study did not consider whether solvent recovery would be cost-effective, nor did it explore options such as heat recovery that could help reduce energy use. It also overlooked key practical aspects, such as equipment complexity and maintenance needs, which could impact both environmental and economic performance at scale.

The process parameters of HWE also influence its environmental performance. Ding *et al.* assessed the LCA of tannin extraction from spruce bark using HWE. Their study identified tannin yield variability as a major source of uncertainty, with significant differences observed across extraction and post-

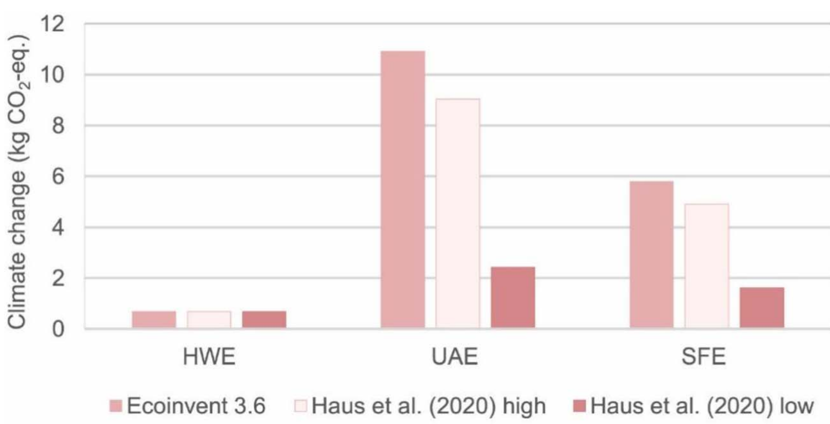

Fig. 4 Potential impact on climate change for the production of 1 kg phenolic compounds, measured as gallic acid equivalents, using the three different extraction technologies hot water extraction (HWE), ultrasound-assisted extraction (UAE), and supercritical fluid extraction (SFE).[35] Adapted with permission from K. Carlqvist *et al.* Copyright 2022 Elsevier.

extraction scenarios.[36] The results showed that energy consumption per functional unit (FU) varied depending on the number of extraction cycles and post-extraction treatment. Repeated extractions increased total tannin yield but also increased environmental burdens, as water and energy use increased. Conversely, cold water pre-extraction reduced non-tannin compounds in the final product but had a lower overall environmental performance. Furthermore, energy demand increased in scenarios where tannin concentration was lower, as more material had to be processed to achieve the same FU. These findings suggest that even chemical-free processes can have high energy demands if not optimized for yield and scale.

Supercritical fluid extraction (SCF) has a great advantage owing to its high selectivity. However, due to its lower extraction efficiency, this technology may not be suitable for all types of substances, particularly those with large molecular weights or high polarities, and has a significant environmental impact. Espada *et al.* assessed the environmental and techno-economic implications of β-carotene production from Duna algae using two distinct biorefinery processes. They conducted LCA to evaluate solvent extraction and supercritical CO_2 extraction (SC-CO_2).[37] The results indicated that the supercritical extraction process is energy-efficient and reduces greenhouse gas emissions, but is limited by lower extraction yields. This inefficiency required a large amount of nutrients, which increased the toxicity and cost of β-carotene. Although SC-CO_2 had lower carbon and water footprints, the need for greater material inputs and nutrients to compensate for yield losses increased both toxicity and cost. Although cheaper, solvent extraction involved the disposal of toxic solvents, thereby increasing downstream environmental impacts. Their techno-economic assessment revealed that environmental advantages alone were insufficient to justify the use of SC-CO_2. From this analysis, we must consider both environmental sustainability and economic factors in biorefinery operations to achieve a balanced approach to production.

These cases reveal a recurring pattern: improving environmental performance can sometimes reduce extraction yield, while efficiency gains may increase energy use or introduce toxic waste. Lifecycle thinking, including process integration (*e.g.*, heat or solvent recovery) and system boundary expansion, is essential to avoid misleading conclusions based on partial data. Future work should move beyond idealized scenarios and examine how real-world constraints, such as infrastructure, operating cost, and process stability, shape the sustainability of solvent-based extraction systems.

4.4 Other extraction techniques and integrated approaches

Beyond conventional solvent-based systems, several alternative extraction techniques have been proposed to address the dual challenge of improving extraction efficiency and reducing environmental impacts. However, even though many of these methods show strong potential under lab-scale or idealized conditions, their actual sustainability depends heavily on allocation choices, energy sources, equipment durability, and waste management strategies.

Pressurized liquid extraction (PLE), supercritical fluid extraction (SFE), and supercritical CO_2 (SCF) methods have been used to extract bioactive compounds, such as rutin, from plant materials. Santiago *et al.* compared these three methods in the context of asparagus extraction and found that PLE had the best environmental profile under economic allocation assumptions.[38] However, when the allocation method was shifted to a mass-based approach, its performance dropped significantly. This illustrates how methodological choices in LCA can influence conclusions about process sustainability, an issue often under-addressed in the extraction literature.

The trade-offs between efficiency and energy use are also seen in cellulosic fiber extraction. Boonterm *et al.* compared sodium hydroxide-based chemical treatment with steam explosion for rice straw.[39] Although steam explosion reduced ecotoxicity and chemical use, it required more energy. These kinds of trade-offs highlight a common challenge: process innovations may reduce certain environmental pressures while intensifying others, requiring careful optimization rather than one-size-fits-all solutions.

High-voltage electrical discharge (HVED) has recently gained attention for its potential in large-scale phenolic extraction. Nutrizio *et al.* found that HVED not only outperformed traditional maceration and immersion in extraction yield but also reduced energy use and CO_2 emissions by operating at lower temperatures.[40] The study suggests good industrial potential, especially in the food sector; however, it acknowledges that equipment durability and maintenance requirements remain poorly understood, leaving uncertainty about long-term sustainability and cost-effectiveness at scale.

Another extraction technology rooted in the same principle as SFE is Gas Expanded Liquids (GXL). GXL employs pressurized environmentally benign gases like CO_2, ethene, or ethylene to create a hybrid state between a conventional liquid and a supercritical fluid. When compared with SFE, GXL's extraction efficiency is significantly higher and more environmentally sustainable.[41] Its tunable properties by simply adjusting its pressure, allowing a simple tuning of the solvent's polarity, viscosity, diffusivity, and solubility, is the key advantage of this technology. GXL also typically operates at lower pressures compared to SFE. This translates to significantly lower energy consumption and equipment costs. But when compared with PLE, which also extracted a similar yield with GXL, even though GXL is more environmentally sustainable, PLE proved to be the most economically advantageous, as evidenced by the highest return on investment and the shortest payback time.[42]

These cases point to a broader conclusion: no single method is universally superior, because each technique involves trade-offs among energy input, solvent use, equipment requirements, waste treatment, and cost. Across the reviewed extraction technologies, energy consumption consistently emerges as a dominant environmental hotspot. Therefore, meaningful comparison requires more than environmental metrics alone; economic feasibility, system boundary choices, and real-world infrastructure constraints must also be considered. As summarized in Table 3, selecting an optimal extraction strategy ultimately depends on balancing technical performance,

Table 3 Summary of the investigations from the literature in the part of LCA on bioactive natural resource extraction

Extraction technologies	Extraction object	Description	Improvements to reduce environmental impacts	References
MAE	Pectin	Higher energy efficiency, higher increase, reduced use of chemicals and water resources, and reduced wastewater discharge		25
MAE	Curcumin	Shorter extraction time and lower energy consumption		29
IUSAE	Lycopene	Non-toxic surfactants used, reduced need for hazardous solvents, improved energy efficiency and simplified processes		26
UAE	Phenolic	Due to its shorter processing time and relatively lower energy consumption, it exhibits a smaller environmental impact, especially when considering the balance between efficiency and sustainability		34
UAE	Phenolic	Low energy consumption, optimization of equipment use and operating conditions		33
UAE	Phenolic	Low energy consumption, effective temperature control, and a good balance between extraction efficiency and environmental impact		31
HWE	Tannins	Cold water extraction results in lower tannin yields and therefore higher energy consumption of the FU	(1) Enhancing extraction efficiency, optimizing the drying process to reduce carbon emissions, recycling	36
SCF (environmental impact)	β-carotene	Low carbon and water footprint	waste resources as nutrient sources, substituting renewable energy for traditional grid electricity, and improving energy recovery systems to decrease reliance on external energy sources are essential strategies	37
SE (economic impact)		No need to dispose of toxic solvent wastes	(2) Selection of extraction technique (a) MAE has a smaller environmental impact, higher yields, greater energy efficiency, and simple operation	
HWE	Phenolic	Ethanol used in the UAE and SFE processes accounts for more than 70 per cent of the total environmental burden	(b) The use of IUSAE has reduced the employment of harmful solvents	43
Thermal steam explosion	Cellulose fibers	Reduced ecotoxicity and increased fiber yield	(c) MAE demonstrates superior performance in	39
HVED	Phenolic	High extraction efficiency, high extraction quality and reduced CO_2 emissions	extraction efficiency and the concentration of extracts, while UAE shows lower	40
SE (qualitative distribution)	Rutin	Lower environmental loads, efficient solvent recovery, energy efficiency and simplified processes	energy consumption and environmental impact. Therefore, combining the advantages of these two	38

Table 3 (*Contd.*)

Extraction technologies	Extraction object	Description	Improvements to reduce environmental impacts	References
			technologies may be an effective strategy to reduce environmental impacts	
PLE (economic distribution)		Reduced solvent requirements, high economic efficiency and simple operation	(3) Improvements in chemicals and solvents (a) Seeking environmentally friendly and efficient extraction solvents, and minimizing the use and loss of chemical solvents are crucial steps (b) Reducing emissions of greenhouse gases such as CO_2 is imperative	

environmental pressures, and practical constraints within specific operating contexts.

5. The impacts of extraction solvents and optimization solutions

Solvent selection plays a crucial role in determining both the efficiency and environmental impact of bioactive compound extraction. Although organic solvents are widely used due to their strong solubilizing power, their production, use, and disposal sometimes incur significant environmental costs. In contrast, water is frequently described as a more sustainable alternative, though often at the expense of extraction yield or process efficiency. These trade-offs highlight the need to weigh solubility, energy demand, and solvent toxicity when assessing overall sustainability.[44]

5.1 Water consumption

Many studies emphasize the environmental friendliness and efficiency of water as a solvent in the extraction process. For example, water extraction methods generally outperformed supramolecular solvent extraction methods in terms of environmental impact, primarily due to the production impact of the solvents (ethanol and 1-hexanol) used in the supramolecular solvent method, and particularly the lower extraction yield of chlorogenic acid, as validated by Bouhzam *et al.* They compared various methods for the extraction of chlorogenic acid (CA) and caffeine from coffee grounds.[45] They tested three extraction solvents and assessed their environmental impacts, including supramolecular solvents, vortex water, and ultrasound-assisted water. While supramolecular solvents offered selectivity, their higher environmental impact was mainly attributed to solvent production and low extraction yields. In contrast, water-based methods performed better from an environmental perspective which reduced GWP impact by 63–73% (from 1.91 kg CO_2 eq to 0.71–0.83 kg CO_2 eq).

Other studies reinforce these findings. Massironi *et al.* investigated the extraction of cucurbitacin from pumpkin seeds using water *versus* ethanol–water mixtures.[46] Their results confirmed that water-based extraction had a lower environmental impact than ethanol–water extraction, but mainly due to reduced energy consumption. In contrast, the ethanol–water method required higher energy input and introduced additional hazardous substances (*e.g.*, Antimony, Copper and Arsenic), increasing its overall environmental burden especially the carbon footprint increases by 58%. Similarly, Vauchel *et al.* studied the potential of extracting polyphenols from chicory residues for use in the food and cosmetic industries.[47] This study used LCA to assess how different operational conditions affect the environmental impact during the UAE process (as shown in Fig. 5). The study found that increasing temperature and using ethanol as a solvent increased environmental impact, whereas the UAE could reduce the climate change impact from 79.0% to 5.8%. The optimal operational conditions for the best environmental load were room temperature, water as the solvent, and ultrasound assistance.

Despite these advantages, water as a solvent presents clear limitations. Its relatively poor ability to dissolve hydrophobic compounds often leads to lower yields and longer extraction times. To overcome these drawbacks without losing environmental benefits, ultrasound and enzyme-based methods are frequently cited as effective ways to boost efficiency while keeping energy input and chemical use under control.[45,47] These cases suggest that while water is an attractive solvent from a sustainability standpoint, its application requires careful balancing of environmental and process performance. Therefore, optimizing operational parameters or integrating process intensification techniques appears essential for making water-based extraction both efficient and scalable.

5.2 Organic solvents

Water is typically considered an environmentally preferable solvent; however, its poor solubility for many natural

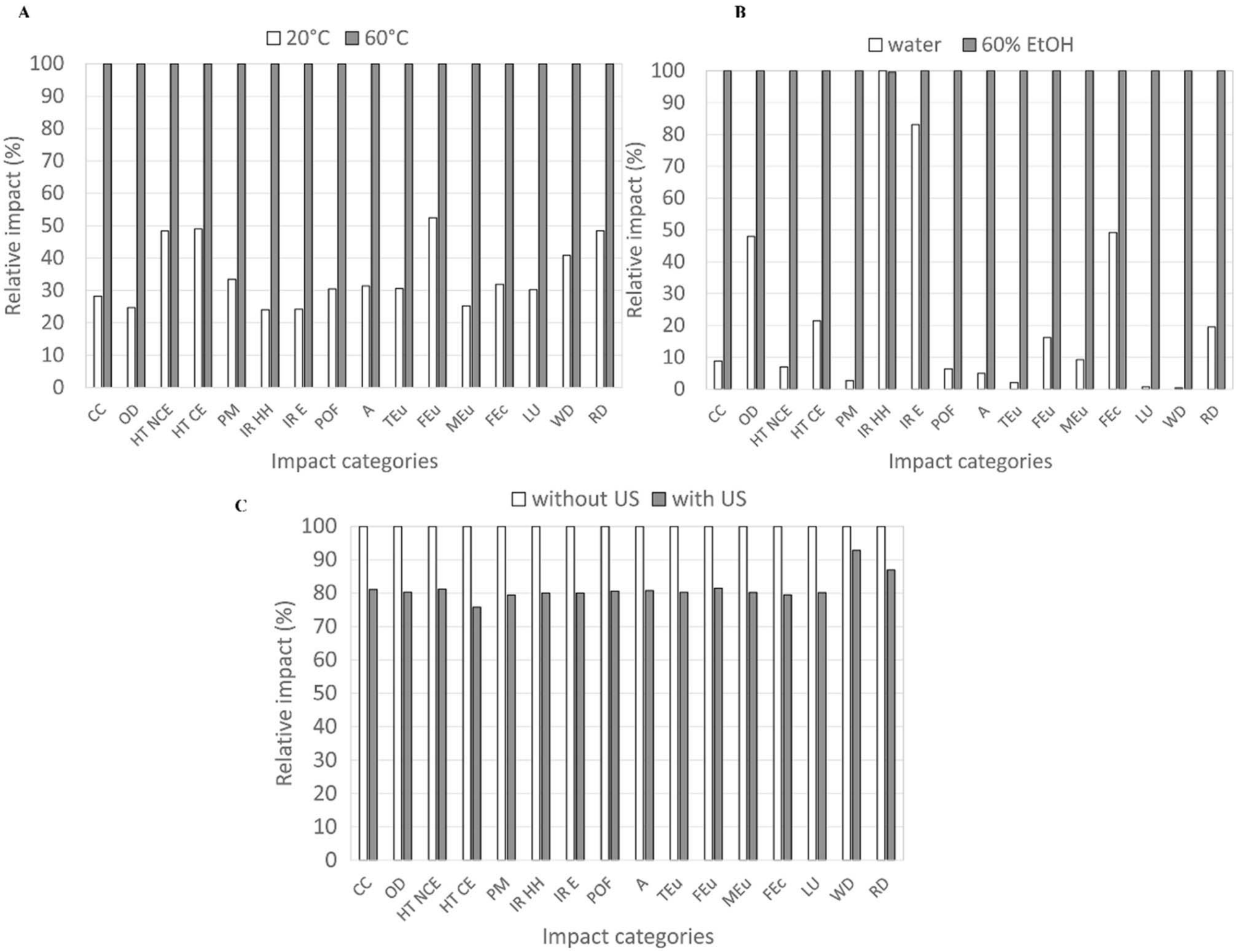

Fig. 5 (A) Temperature effect on environmental impacts: comparison of experiments 1 and 3 (water as solvent, without US); (B) solvent effect on environmental impacts: comparison of experiments 1 and 2 (temperature of 20 °C, without US); (C) US assistance effect on environmental impacts: comparison of experiments 1 and 5 (temperature of 20 °C, water as solvent). (FU: obtaining 0.55 L of chicory grounds extract exhibiting 220 μmol Trolox equivalent antioxidant capacity). Adapted with permission from Vauchel *et al.* Copyright 2018 Elsevier.

compounds limits its practical usefulness. As a result, organic solvents remain common in extraction processes due to their ability to dissolve hydrophobic substances more efficiently. However, the environmental outcomes of using these solvents vary widely. Factors such as the type of solvent, its production footprint, and the need for post-extraction treatment all contribute to determining the impact. Beyond LCA-based assessments, green chemistry metrics such as the CHEM21 toolkit provide complementary frameworks for solvent evaluation, incorporating criteria such as health and safety hazards, biodegradability, and renewability alongside environmental impacts.[48]

Pectin extraction serves as a prime example. Nadar *et al.* applied LCA to examine conventional production routes and found that key parameters, including acid type, ethanol usage, extraction pH, and electricity source, strongly influenced the environmental profile.[49] For instance, using hydrochloric acid (HCl) instead of citric acid at the same pH reduces the climate change impact by over 95%. However, organic acids initially appeared environmentally benign, they sometimes exacerbated climate-related impacts by reducing yields or increasing energy demands with 40–60% higher of impact than the renewable energy use. The study recommended switching to acid-free methods and integrating membrane separation to reduce energy use and chemical input. These recommendations align with CHEM21 principles, which advocate for solvent minimization and substitution with safer alternatives whenever feasible.

Similar complexities arise in the extraction of proteins from the black soldier fly (BSF). Rosa *et al.* compared chemical and enzymatic methods, assuming the enzymatic route would perform better due to the absence of organic solvents and fewer harsh reagents.[50] Surprisingly, the enzymatic process resulted in greater environmental impacts, primarily due to the longer hydrolysis time. Total Impact of alkaline extraction method (for 0.5 g protein) was 3.65×10^{-4} Pt, while it was 4.82×10^{-4} Pt for enzymatic extraction method (31.87% higher than chemical method). This suggests that removing solvents alone does not guarantee better outcomes. Improvements may lie in reducing reaction time, optimizing enzyme use, or operating at lower temperatures to cut down energy use. Recent applications in extraction process design have shown that a combined assessment using both LCA and CHEM21 metrics, a hazard-based screening can avoid undesirable substitutions, where a solvent with lower carbon footprint may introduce higher toxicity or regulatory risk.[51]

In solvent selection for solid–liquid extraction, Milescu *et al.* demonstrated the usefulness of Hansen Solubility Parameters (HSP) for identifying suitable green solvents.[52] Their single-stage extraction approach, using minimal solvent-to-sample ratios, proved effective for orange waste. Cyrene, a bio-derived solvent, performed especially well. Cyrene has a significantly lower PMI (805 g g^{-1}) compared to the conventional ethanol/water method (3237 g g^{-1}), indicating higher resource efficiency. When mixed with water, it surpassed traditional ethanol–water mixtures in terms of efficiency, waste generation, safety, and renewability, according to the CHEM21 toolkit assessment.

These examples suggest that solvent choice cannot be guided by a single indicator, as improvements in extraction efficiency often come at the cost of increased solvent consumption or higher energy demand. Conversely, approaches that avoid harsh chemicals may introduce other trade-offs, such as longer processing times or lower yields. From a life-cycle perspective, organic solvents remain a major contributor to environmental impacts, primarily due to solvent production and energy-intensive recovery processes. Although solvent recycling can substantially reduce these impacts, reported recovery rates are frequently based on assumptions rather than empirical validation. Therefore, addressing solvent-related trade-offs requires a systems-level assessment that simultaneously considers yield, energy use, emissions, and feasibility under realistic scale-up conditions. Hybrid solvent systems and emerging bio-based solvents show potential, but their overall sustainability still depends on consistent performance and transparent life-cycle data.

5.3 Deep eutectic solvents (DES): potential and limitations

Deep eutectic solvents (DES) have received growing attention as alternatives to conventional organic solvents due to their low toxicity, biodegradability, and flexible design. Their use in extracting phytochemicals from natural resources is often framed as a step toward more sustainable extraction methods. However, recent studies suggest that the environmental benefits of DES are not guaranteed and depend heavily on their chemical composition, production processes, and downstream treatment requirements.

Several case studies report improved extraction performance with DES. For example, Jaglan *et al.* optimized DES-based extraction of phenolic and flavonoid compounds from Moringa oleifera flowers, identifying a 1 : 2 molar ratio of L-proline and glycerol at 70 °C as optimal.[53] This setup achieved high antioxidant activity and yield, supporting the potential of DES in food and pharmaceutical applications. Complementary green metrics, such as the AGREE (Analytical GREEnness Metric) tool, are used to provide a quantitative, multi-criteria score based on the 12 principles of green chemistry.[54] For instance, L Nascimento *et al.* using a glycerol-urea Natural DES for ultrasound-assisted extraction of methylxanthines from cocoa bean shells received AGREE and AGREEprep scores of 0.55 and 0.67, respectively (on a 0–1 scale), confirming its favorable alignment with green chemistry principles beyond high yield.[55] This highlights that while yield improvements are clear, environmental performance remains context-specific and must be evaluated holistically.

Indeed, the assumption that DES's inherently green is increasingly being questioned. Wang *et al.* conducted an LCA comparing DES-based extraction with conventional solvent methods for flavonoids from Ginkgo biloba leaves.[9] While the DES method delivered superior yields, it also exhibited higher environmental impacts across nearly all categories, primarily due to the energy-intensive production of DES components, such as choline chloride and ethylene glycol. The study further demonstrated that switching from maize-derived ethanol to sugarcane- or wood-based ethanol could significantly reduce environmental burdens by 30–80%. This highlights the significance of feedstock origin in achieving solvent sustainability, a factor also emphasized in life cycle-oriented green chemistry toolkits like CHEM21. Bouhzam *et al.* compared water, 20% ethanol, and a DES composed of choline chloride and 1,6-hexanediol for polyphenol extraction from spent coffee grounds.[56] However, their LCA revealed that DES performed worst environmentally, largely due to its complex preparation and the use of resins during adsorption. Sensitivity analysis showed that even with 90% DES reuse and reduced resin use, DES still performed poorly environmentally. Both ethanol and water outperformed DES across all impact categories, suggesting that even moderate ethanol concentrations may offer better overall sustainability in some scenarios.

These findings demonstrate that the "greenness" of a solvent cannot be inferred solely from its origin or chemical composition. Properties such as polarity, volatility, acidity, and toxicity jointly influence extraction efficiency and life-cycle environmental performance. While water consistently appears as the lowest-impact solvent in most LCA models, it often yields lower extraction yields, creating trade-offs between environmental efficiency and product output. In contrast, ethanol and DES frequently exhibit higher extraction performance but incur greater environmental costs, particularly when derived from energy-intensive or unsustainably sourced feedstocks. Tools like AGREE provide a complementary, multi-criteria perspective by scoring methods against core green chemistry principles, helping to navigate these complex trade-offs.

From a life-cycle perspective, the development of sustainable solvent systems therefore requires more than a shift toward bio-derived or low-toxicity labels. It must explicitly account for full life-cycle impacts, scalability, and the feasibility of solvent recovery and reuse under industrial conditions. Enzyme-assisted and hybrid solvent systems may help bridge the gap between extraction efficiency and environmental performance, but their practical viability remains insufficiently validated. DES in particular continues to show promise, yet its sustainability cannot be generalized without more robust, empirical life-cycle

Table 4 Summary of the investigations from the literature on the Evaluation of the LCA based on the extraction solvent

Extraction technologies	Extraction object	Optimal solvent	Key environmental metrics (per FU)	Effect/description	References
Water extraction	Chlorogenic acid and caffeine	Water	• Using water instead of supramolecular solvent reduces CED by 65–70% (from 29.6 MJ to 9.52–10.8 MJ) and lower GWP by 63–73% (from 1.91 kg CO_2 eq to 0.71–0.83 kg CO_2 eq)	• Environmentally friendly	45
			• All other impact categories (AP, EP, HTP) are reduced by 66–67%	• Easy to handle	
Solvent extraction	Cucurbitin	Water	• Using water instead of an ethanol/water mixture reduces the carbon footprint by 37% (from 1.88×10^6 to 1.19×10^6 kg CO_2 eq per kg of cucurbitin)	• Requires less energy consumption	46
			• Most of the impact categories for water extraction are lower, except for FET and HNCT, where the impact of FET driven by antimony and copper emission and HNCT which mostly impacted by arsenic, cadmium and zinc	• Eliminates ethanol use for precipitation • Reduces emissions and energy-intensive processes	
UAE	Polyphenols	Water	• Using ultrasound-assisted water solvent at room temperature instead of ethanol reduces the climate change (CC) impact from 79.0% to 5.8% of total impact	• Lower environmental load in the material phase	47
			• The reduction is even more extreme for resource-related categories; WC reduced from 99.4% to 0.3% and LU from 98.2% to 0.5%	• Requires less energy in the extraction phase	
Acid (water) extract	Pectin	Acids	• Using hydrochloric acid (HCl) in water at pH 1.5 reduces the CC impact by over 95% (from 200.1 kg CO_2 eq to 9.69 kg CO_2 eq per kg of pectin) compared to using citric acid (CA) at the same pH	• Organic acids require a higher quantity to reach pH	49
			• However, using organic acid, the impact is still 40–60% higher than using ethanol reduction and renewable energy	• Leads to higher environmental load	
Alkaline extraction (chemical method)	Protein	NaOH	• Even though alkaline extraction method used strong alkali, strong acid, and organic solvent, it results in significantly higher and purer extraction yield (protein, lipid, and chitin). This offsets the chemical footprint	• Water-soluble	50
			• Total impact of alkaline extraction method (for 0.5 g protein) was 3.65×10^{-4} Pt, while it was 4.82×10^{-4} Pt for enzymatic extraction method (31.87% higher than chemical method)	• Aqueous solutions biodegradable after treatment • Reduces long-term environmental impact	
	Lipid	Petroleum ether		• Non-polar solvent • Low volatility • Less likely to be released into the atmosphere	

Table 4 (*Contd.*)

Extraction technologies	Extraction object	Optimal solvent	Key environmental metrics (per FU)	Effect/description	References
				• Reduces air quality impact	
	Chitin	HCl		• Strong acid • Efficient protein precipitation • Smaller quantity needed • Reduces chemical use	
Solid–liquid extraction	Flavonoids	New bio-solvents Cyrene	• The Furacell process to produce Cyrene presents a global warming potential (1.4 kg per CO_2e per kg solvent) lower than that of NMP synthesis	• From renewable sources	52
			• Cyrene is 99% biodegradable within 14 days, exhibits low toxicity, and is non-mutagenic	• High biodegradability	
			• Cyrene has a significantly lower PMI (805 g g^{-1}) compared to the conventional ethanol/water method (3237 g g^{-1}), indicating higher resource efficiency	• Low toxicity	
			• Mild heating of cyrene-water mixtures showed up to 11× higher extraction yields for hesperidin and rutin compared to ethanol–water systems	• Non-flammable • Reduces energy consumption and chemical waste	
DES	Polyphenol	Polyphenol	• Ethanol-based UAE has the least impact in 15 out of 18 impact categories	• Ethanol production is key to the environmental impact	9
			• In sensitivity analysis, the use of sugarcane-based ethanol showed a reduction of 30–80% in GWP, FEP, FET, FRS and WC	• Sugarcane-based ethanol has a lower environmental burden	
DES	Polyphenol	20% ethanol	• Despite higher TPC yields, DES performed worse environmentally than water or ethanol 20% in 11 out of 16 impact categories, mainly due to the DES preparation and adsorption steps	• Higher extraction yield	56
			• Sensitivity analysis showed that even with 90% DES reuse and reduced resin use, DES still performed worse than water or ethanol 20% in 11 out of 16 categories	• Fewer resource inputs • Lower overall environmental burden	

data. The main findings discussed in this section are summarized in Table 4.

6. Production optimization using LCA-combined sustainability modeling tools

Scaling up extraction processes from laboratory to industrial levels usually reveals environmental and economic trade-offs that are not apparent under controlled conditions. LCA-combined simulation tools provide a means to anticipate these challenges by enabling the virtual modeling of resource flows, emissions, and costs prior to full-scale deployment. Software such as SuperPro Designer, Aspen Plus, and STAN enable researchers to integrate process conditions with sustainability metrics, helping to identify hotspots, cost drivers, process feasibility at scale, and evaluate alternatives. However, their predictive value depends heavily on the quality of the input, system assumptions, and the inclusion of region-specific parameters.

SuperPro designer can be used for mass and energy balance calculations, process configuration comparison, and techno-economic assessment of batch and semi-continuous systems. It has been widely used across fields such as chemical engineering, bioengineering, environmental engineering, food processing, and the pharmaceutical industry. Pereira da Silva *et al.* applied it to model starch extraction from mango kernels, comparing two process configurations: one focused solely on starch (Process A) and another extracting starch, polyphenols, and fats (Process B).[57] LCA results identified the starch purification stage as the key environmental hotspot. Simulations showed that, although both processes improved with scaling, Process A consistently out-performed Process B across all scenarios (see Fig. 6). This suggests that co-product recovery, while attractive in principle, may not always yield better environmental outcomes unless additional impacts are carefully mitigated.

Another example of LCA-integrated process simulation is provided by Croxatto Vega *et al.*, who combined techno-economic assessment and LCA to compare solvent extraction (SE) and pressurized liquid extraction (PLE) for polyphenol recovery from wine pomace.[58] Their study highlighted solvent consumption and equipment cost as key drivers of both environmental and economic performance. While PLE offered technical advantages, SE proved more favorable in both dimensions, owing to its lower solvent-to-dry-weight ratio and lower capital cost. Subsequent industrial simulations using SuperPro Designer confirmed these trends and demonstrated that solvent minimization was the most effective approach to reducing environmental burden. Their use of Multi-Criteria Decision Analysis (MCDA) further emphasized that different weightings of economic *vs.* environmental criteria can lead to different process recommendations.

The Simulation Tool for Aquatic Systems (STAN) is software designed specifically for simulating aquatic and aquaculture ecosystems. STAN focuses on material and resource flow analysis and is especially useful for assessing water- and energy-intensive systems where regional resource constraints play a critical role. Zhang *et al.* applied STAN to assess two new marine algae extraction systems, subcritical water extraction (SWE) and HWE, for the brown macroalga Ecklonia maxima.[59] Though the new systems used less freshwater than the reference process, their carbon footprint was higher because South Africa's electricity grid is coal-heavy. This study demonstrated the need to account for regional energy profiles and highlighted how improvements in one impact category (*e.g.*, water use) can come at the expense of others (*e.g.*, GHG emissions). Scenario analysis further showed how altering energy sources and resource flows can improve the sustainability of biorefinery operations.

Aspen Plus is particularly well-suited for thermodynamic modeling and detailed simulation of continuous chemical processes, enabling a closer representation of industrial operating conditions. In some recent studies, Aspen Plus has also been applied in LCA-integrated modeling.[60] Hoe *et al.* modeled carotene extraction from crude palm oil at a commercial scale using dissolution microencapsulation.[61] Their analysis indicated economic viability for a plant processing 50 000 kg of CPO per day, with the primary cost arising from raw material inputs. LCA results identified the methanol recovery stage as an environmental hotspot, suggesting that targeted improvements in solvent management could enhance both sustainability and cost efficiency.

Although software-based simulations offer valuable insights into industrial-scale sustainability, their accuracy depends heavily on the quality of input data and the assumptions embedded in the models. LCA-based process modeling can refine predictions; however, real-world deviations due to energy efficiency losses, material inconsistencies, and unforeseen operational challenges may still occur. Therefore, while scaling laboratory findings is essential for sustainability assessments, process validation through pilot-scale experiments remains necessary to ensure accurate impact estimates.

Integrating LCA with advanced simulation tools enables a more holistic understanding of industrial sustainability by incorporating environmental, economic, and process efficiency considerations. However, these tools should be used cautiously, with continuous refinement of assumptions and empirical validation. Developing adaptive modeling frameworks that account for process variability, supply chain dynamics, and regional energy dependencies will be crucial in further improving the reliability of industrial-scale sustainability assessments.

7. Waste management and end-of-life stage

Effective waste management and end-of-life (EOL) strategies are essential for improving the sustainability of bioactive compound extraction. Many current processes continue to treat byproducts and residues as waste, which limits opportunities to recover value and reduce environmental pressure. Integrating byproduct use, solvent recovery, and closed-loop process design into extraction systems can support a shift toward more circular and resource-efficient practices. Recent studies have shown that optimized extraction techniques can help recover valuable compounds from waste while enhancing process performance. Bouchez *et al.* demonstrated this in their work on degraded beet seeds, where MAE increased polyphenol content by 33 percent and antioxidant activity by 23 percent, with a significant reduction in extraction time.[33] While MAE improved recovery, UAE showed higher energy efficiency and a lower environmental impact, highlighting the need to balance yield with resource use. In a similar study, da Silva *et al.* (2023) evaluated four water-based methods for recovering polyphenols from acerola and jambolan fruit pomace.[34] A combination of ultrasound and mechanical stirring achieved the best results in both extraction yield and energy use. These examples demonstrate the potential of utilizing agricultural residues as input materials in well-optimized systems, thereby reducing the demand for virgin feedstocks and minimizing waste.

An Increasingly effective strategy is to apply an Integrated biorefinery approach, where cascade extraction processes

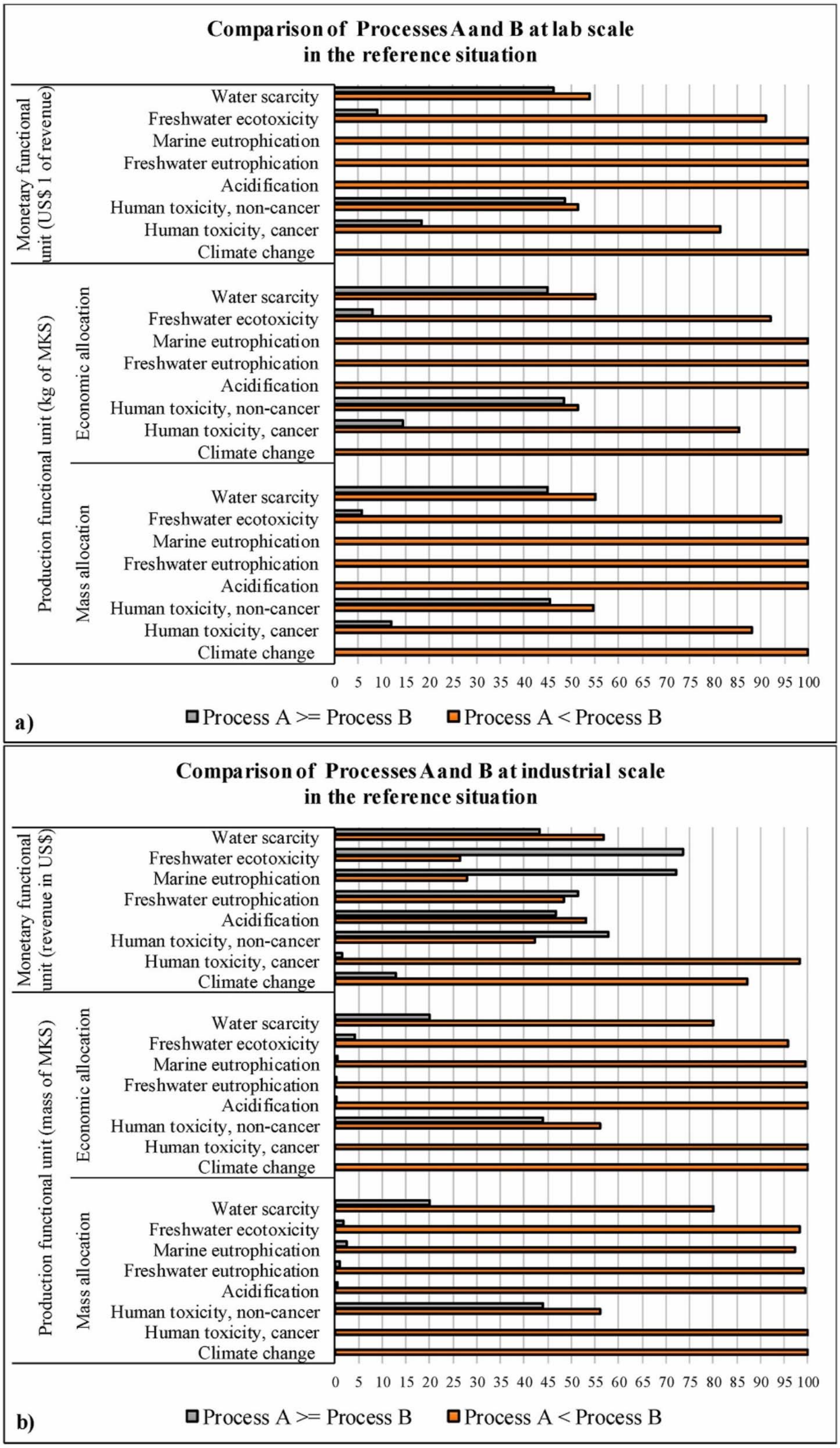

Fig. 6 Results for the comparison of processes A and B at (a) laboratory and (b) industrial scales, applying the monetary functional unit. Adapted with permission from Pereira da Silva *et al.* Copyright 2023 Elsevier.

recover multiple value-added products sequentially from the same feedstock. Yadav *et al.* outlines a comprehensive green bioconversion strategy of citrus wastes.[62] The cascade involves initial recovery of essential oils and polyphenols using solvent-free or green extraction methods (*e.g.*, microwave hydro-diffusion), followed by the enzymatic hydrolysis of remaining solids to produce bioethanol. The final lignocellulosic residue can then be directed toward anaerobic digestion (AD) for biogas production or converted into adsorbent materials. This integrated design exemplifies how coupling extraction with downstream bioconversion and AD can maximize resource recovery from a single waste stream, moving beyond standalone waste treatment to create a near-zero-waste, circular system.

Another viable direction is to couple extraction with waste valorisation *via* anaerobic digestion (AD). Alonso-Fariñas *et al.* compared AD and olive pomace oil extraction (OPOE) for treating olive mill solid waste.[63] Their LCA found that AD reduced overall environmental impacts by over 85%, compared to both natural gas combustion and pomace reuse as fuel. However, even circular solutions such as OPOE-B introduced toxicity concerns, showing that circularity alone does not guarantee lower impacts across all categories.

Moving forward, the design of extraction processes should incorporate waste streams into the input–output system rather than treating them as external concerns. This means focusing on solvent reuse, energy-efficient processing steps, and practical methods for using leftover solids. Pilot-scale validation and life cycle studies that include waste flows and reuse options will be important for confirming the environmental and economic benefits of these approaches.

8. Conclusion and outlook

LCA provides a valuable framework for evaluating the environmental impacts of bioactive compound extraction, from raw material production to end-of-life treatment. It not only enables a more systematic comparison of extraction methods and solvent systems but also helps identify hotspots and trade-offs that affect environmental performance. When combined with simulation tools, LCA supports the transition from laboratory-scale innovation to industrial-scale application by linking process efficiency with sustainability metrics.

This review has explored the environmental implications of various extraction technologies and solvents, showing that no single method is universally optimal. Green extraction approaches, such as MAE, UAE, and the use of alternative solvents like DES, can improve energy use or yield, but their benefits depend on system boundaries, solvent sourcing, and scaling assumptions. Integrating LCA with process modeling tools such as SuperPro Designer, Aspen Plus, and STAN has proven effective for predicting performance at scale. However, the reliability of these predictions depends not only on model structure but also on data quality, including the representativeness of laboratory-scale measurements, assumptions on energy efficiency, solvent recovery rates, and the treatment of co-products and losses. Without careful consideration of these factors, model-based results may underestimate industrial energy demand or overstate environmental benefits which highlights the continued need for pilot-scale validation.

A significant gap remains in how current studies address waste flows and end-of-life management. Residues and byproducts are frequently overlooked, despite their potential for reuse in circular extraction systems. Closing this gap will require both process design improvements and regulatory support to enable solvent recovery, energy integration, and byproduct valorization.

Moving forward, aligning technological advances with economic feasibility and policy frameworks will be critical. LCA alone cannot drive change without complementary efforts in regulation, investment, and market incentives. We suggest that future work should focus on integrating LCA and other tools, such as MCDA, to assess long-term performance both in environmental and economic perspectives under varying industrial and regional conditions. Through combining green process design, solvent innovation, and circular resource use, the extraction of bioactive natural compounds can evolve into a more sustainable industrial practice.

Conflicts of interest

There are no conflicts to declare.

Nomenclature

AD	Anaerobic digestion
AP	Acidification potential
BSF	Black soldier fly
CA	Chlorogenic acid
CED	Cumulative energy demand
CO_2	Carbon dioxide
CPO	Crude palm oil
DES	Deep eutectic solvents
EAE	Enzyme-assisted extraction
EOL	End-of-life
EP	Eutrophication potential
FU	Functional unit
GWP	Global warming potential
HSP	Hansen solubility parameters
HTP	Human toxicity potential
HVED	High voltage electric discharge
HWE	Hot-water extraction
IUSAE	Integrated ultrasound-assisted extraction
LCA	Life cycle assessment
MAE	Microwave-assisted extraction
MCDA	Multiple criteria decision analysis
NPV	Net present value
ODP	Ozone depletion potential
OPOE	Olive pomace oil extraction
PLE	Pressurized liquid extraction
PMI	Process mass intensity
REF	Previous production system
SAE	Solvent-assisted extraction
SCF	Supercritical fluid extraction
SCG	Spent coffee grounds
SE	Soxhlet extraction
SFE	Supercritical fluid extraction
SLE	Solid–liquid extraction
STAN	Simulation tool for aquatic systems
TEA	Techno-economic assessment
UAE	Ultrasound-assisted extraction

Data availability

No primary research results, software or code have been included and no new data were generated or analysed as part of this review.

Acknowledgements

This work was supported by the 2024 Ningbo Key Technology R&D Projects (2024T018), and also supported by National Innovation and Entrepreneurship Training Program for Undergraduate. FM acknowledges the support from the Royal Society ISPF – International Collaboration Awards (ICA\R1\231046) and University of Sheffield Institutional Open Access Fund. For the purpose of open acccess, the author has applied a Creative Commons Attribution (CC BY) licence to any Author Accepted Manuscript version arising.

References

1 S. Šafranko, D. Šubarić, I. Jerković and S. Jokić, *Pharmaceuticals*, 2023, **16**, 1081, DOI: 10.3390/ph16081081.
2 A. D. Steele, C. N. Teijaro, D. Yang and B. Shen, *J. Biol. Chem.*, 2019, **294**, 16567–16576, DOI: 10.1074/jbc.REV119.006514.
3 Z. Liu, D. J. McClements, A. Shi, L. Zhi, Y. Tian, B. Jiao, H. Liu and Q. Wang, *Crit. Rev. Food Sci. Nutr.*, 2023, **63**, 10093–10104, DOI: 10.1080/10408398.2022.2067831.
4 F. Chemat, M. Abert-Vian, A. S. Fabiano-Tixier, J. Strube, L. Uhlenbrock, V. Gunjevic and G. Cravotto, *TrAC, Trends Anal. Chem.*, 2019, **118**, 248–263, DOI: 10.1016/j.trac.2019.05.037.
5 K. Patel, N. Panchal and P. Ingle, *Int. J. Adv. Res. Chem. Sci.*, 2019, **6**, 1–12, DOI: 10.20431/2349-0403.0603002.
6 T. Lefebvre, E. Destandau and E. Lesellier, *J. Chromatogr. A*, 2021, **1635**, 461770, DOI: 10.1016/j.chroma.2020.461770.
7 L. Shen, S. Pang, M. Zhong, Y. Sun, A. Qayum, Y. Liu, A. Rashid, B. Xu, Q. Liang, H. Ma and X. Ren, *Ultrason. Sonochem.*, 2023, **101**, 106646, DOI: 10.1016/j.ultsonch.2023.106646.
8 I. Majid, S. Khan, A. Aladel, A. H. Dar, M. Adnan, M. I. Khan, A. Mahgoub Awadelkareem and S. A. Ashraf, *CYTA J. Food*, 2023, **21**, 101–114, DOI: 10.1080/19476337.2022.2157492.
9 X. Wang, Y. Wei, Z. Fan, Y. Chen and Z. Cui, *Sci. Total Environ.*, 2024, **922**, 171319, DOI: 10.1016/j.scitotenv.2024.171319.
10 A. L. B. Dias, A. C. de Aguiar and M. A. Rostagno, *Ultrason. Sonochem.*, 2021, **74**, 105584, DOI: 10.1016/j.ultsonch.2021.105584.
11 G. Wu, H. Dong, J. Li, L. Guo, Y. Cheng, Y. Geng and X. Wang, *J. Ind. Eng. Chem.*, 2022, **108**, 280–287, DOI: 10.1016/j.jiec.2022.01.010.
12 S. S. Takla, E. Shawky, H. M. Hammoda and F. A. Darwish, *J. Chromatogr. A*, 2018, **1567**, 99–110, DOI: 10.1016/j.chroma.2018.07.009.
13 G. F. Barbero, *Agronomy*, 2021, **11**, 415, DOI: 10.3390/agronomy11030415.
14 S. Armenta, S. Garrigues, F. A. Esteve-Turrillas and M. de la Guardia, *TrAC, Trends Anal. Chem.*, 2019, **116**, 248–253, DOI: 10.1016/j.trac.2019.03.016.
15 J. B. Guinee, *Int. J. Life Cycle Assess*, 2002, **7**, 311, DOI: 10.1007/BF02978897.
16 R. E. Kirchain Jr, J. R. Gregory and E. A. Olivetti, *Nat. Mater.*, 2017, **16**, 693–697, DOI: 10.1038/nmat4923.
17 D. A. Figueroa Paredes, D. S. Laoretani, B. Morero, R. J. Sánchez, O. A. Iribarren and J. Espinosa, *Sep. Purif. Technol.*, 2020, **237**, 116339, DOI: 10.1016/j.seppur.2019.116339.
18 C. van der Giesen, S. Cucurachi, J. Guinée, G. J. Kramer and A. Tukker, *J. Clean. Prod.*, 2020, **259**, 120904, DOI: 10.1016/j.jclepro.2020.120904.
19 S. Cucurachi, C. van der Giesen and J. Guinée, *Procedia CIRP*, 2018, **69**, 463–468, DOI: 10.1016/j.procir.2017.11.005.
20 D. Moher, L. Shamseer, M. Clarke, D. Ghersi, A. Liberati, M. Petticrew, P. Shekelle and L. A. Stewart, *Syst. Rev.*, 2015, **4**, 1, DOI: 10.1186/2046-4053-4-1.
21 L. Shamseer, D. Moher, M. Clarke, D. Ghersi, A. Liberati, M. Petticrew, P. Shekelle and L. A. Stewart, *BMJ*, 2015, **349**, g7647, DOI: 10.1136/bmj.g7647.
22 P. Khatri, S. Jain and S. Pandey, *J. Clean. Prod.*, 2017, **166**, 988–997, DOI: 10.1016/j.jclepro.2017.08.109.
23 G. Gaurav, V. Kumar, A. B. singh, S. Gupta, M. L. Meena, G. S. Dangayach and M. K. Jindal, *Mater. Today Proc.*, 2023, 1–6, DOI: 10.1016/j.matpr.2023.01.055.
24 M. A. Yusuf, M. Romli, S. Suprihatin and E. I. Wiloso, *IOP Conf. Ser. Earth Environ. Sci.*, 2018, **147**, DOI: 10.1088/1755-1315/147/1/012036.
25 G. Garcia-Garcia, S. Rahimifard, A. S. Matharu and T. I. J. Dugmore, *ACS Sustain. Chem. Eng.*, 2019, **7**, 5167–5175, DOI: 10.1021/acssuschemeng.8b06052.
26 R. D. Yadav and P. B. Dhamole, *Biomass Convers. Biorefin.*, 2023, **14**, 25495–25511, DOI: 10.1007/s13399-023-04676-x.
27 G. Barjoveanu, O.-A. Pătrăutanu, C. Teodosiu and I. Volf, *Sci. Rep.*, 2020, **10**, DOI: 10.1038/s41598-020-70587-w.
28 H. López-Salazar, B. H. Camacho-Díaz, M. L. A. Ocampo and A. R. Jiménez-Aparicio, *Bioresources*, 2023, **18**(3), 6614–6638, DOI: 10.15376/biores.18.3.Lopez-Salazar.
29 E. Zerazion, R. Rosa, E. Ferrari, P. Veronesi, C. Leonelli, M. Saladini and A. M. Ferrari, *Green Chem.*, 2016, **18**, 1807–1818, DOI: 10.1039/C6GC00090H.
30 D. R. Dash, S. S. Pathak and R. C. Pradhan, *J. Food Process Eng.*, 2021, **44**(4), e13658, DOI: 10.1111/jfpe.13658.
31 M. Salzano de Luna, G. Vetrone, S. Viggiano, L. Panzella, A. Marotta, G. Filippone and V. Ambrogi, *ACS Sustain. Chem. Eng.*, 2023, **11**, 4670–4677, DOI: 10.1021/acssuschemeng.2c06698.
32 H. Monteiro and B. Moura, *Energy Rep.*, 2022, **8**, 277–283, DOI: 10.1016/j.egyr.2022.01.034.
33 A. Bouchez, P. Vauchel, S. Périno and K. Dimitrov, *Foods*, 2023, **12**, 1750, DOI: 10.3390/foods12091750.
34 E. S. da Silva, A. O. Nunes and R. T. Hoskin, *Chem. Eng. Process.: Process Intensif.*, 2023, **191**, 109443, DOI: 10.1016/j.cep.2023.109443.

35 K. Carlqvist, O. Wallberg, G. Lidén and P. Börjesson, *J. Clean. Prod.*, 2022, **333**, 130093, DOI: 10.1016/j.jclepro.2021.130093.
36 T. Ding, S. Bianchi, C. Ganne-Chédeville, P. Kilpeläinen, A. Haapala and T. Räty, *IForest*, 2017, **10**, 807–814, DOI: 10.3832/ifor2342-010.
37 J. J. Espada, D. Pérez-Antolín, G. Vicente, L. F. Bautista, V. Morales and R. Rodríguez, *Biofuels, Bioprod. Biorefin.*, 2020, **14**, 43–54, DOI: 10.1002/bbb.2012.
38 B. Santiago, G. Feijoo, M. T. Moreira and S. González-García, *Food Bioprod. Process.*, 2021, **129**, 176–189, DOI: 10.1016/j.fbp.2021.08.005.
39 M. Boonterm, S. Sunyadeth, S. Dedpakdee, P. Athichalinthorn, S. Patcharaphun, R. Mungkung and R. Techapiesancharoenkij, *J. Clean. Prod.*, 2016, **134**, 592–599, DOI: 10.1016/j.jclepro.2015.09.084.
40 M. Nutrizio, A. Režek Jambrak, T. Rezić and I. Djekic, *Int. J. Food Sci. Technol.*, 2022, **57**, 1104–1113, DOI: 10.1111/ijfs.15476.
41 M. Zhang, L. Montero, J. A. Mendiola and E. Ibáñez, *J. Supercrit. Fluids*, 2026, **229**, 106801, DOI: 10.1016/j.supflu.2025.106801.
42 B. L. S. Porto, B. Acevedo-García, A. E. Kashtiban, T. Miranda Sepulveda, M. Herrero, A. Cifuentes, J. A. Mendiola and E. Ibáñez, *Green Chem.*, 2025, **27**, 11021–11035, DOI: 10.1039/D5GC02153G.
43 K. Carlqvist, O. Wallberg, G. Lidén and P. Börjesson, *J. Clean. Prod.*, 2022, **333**, DOI: 10.1016/j.jclepro.2021.130093.
44 Y. Wu, W. Li, J. Vovers, H. Thuan Lu, G. W. Stevens and K. A. Mumford, *Chem. Eng. J.*, 2022, **442**(15), 136054, DOI: 10.1016/j.cej.2022.136054.
45 I. Bouhzam, R. Cantero, M. Balcells, M. Margallo, R. Aldaco, A. Bala, P. Fullana-i-Palmer and R. Puig, *Foods*, 2023, **12**, 779, DOI: 10.3390/foods12040779.
46 A. Massironi, S. Biella, P. F. de Moura Pereira, F. Scibona, L. Feni, M. Sindaco, D. Emide, A. Jiménez-Quero, C. L. M. Bianchi, L. Verotta and S. Marzorati, *J. Clean. Prod.*, 2023, **427**, 139267, DOI: 10.1016/j.jclepro.2023.139267.
47 P. Vauchel, C. Colli, D. Pradal, M. Philippot, S. Decossin, P. Dhulster and K. Dimitrov, *J. Clean. Prod.*, 2018, **196**, 1116–1123, DOI: 10.1016/j.jclepro.2018.06.042.
48 D. Prat, A. Wells, J. Hayler, H. Sneddon, C. R. McElroy, S. Abou-Shehada and P. J. Dunn, *Green Chem.*, 2016, **18**, 288–296, DOI: 10.1039/C5GC01008J.
49 C. G. Nadar, A. Arora and Y. Shastri, *ACS Eng. Au*, 2022, **2**, 61–74, DOI: 10.1021/acsengineeringau.1c00025.
50 R. Rosa, R. Spinelli, P. Neri, M. Pini, S. Barbi, M. Montorsi, L. Maistrello, A. Marseglia, A. Caligiani and A. M. Ferrari, *ACS Sustain. Chem. Eng.*, 2020, **8**, 14752–14764, DOI: 10.1021/acssuschemeng.0c03795.
51 F. P. Byrne, S. Jin, G. Paggiola, T. H. M. Petchey, J. H. Clark, T. J. Farmer, A. J. Hunt, C. Robert McElroy and J. Sherwood, *Sustainable Chem. Processes*, 2016, **4**, 7, DOI: 10.1186/s40508-016-0051-z.
52 R. A. Milescu, M. L. Segatto, A. Stahl, C. R. McElroy, T. J. Farmer, J. H. Clark and V. G. Zuin, *ACS Sustain. Chem. Eng.*, 2020, **8**, 18245–18257, DOI: 10.1021/acssuschemeng.0c06751.
53 P. Jaglan, M. Kumar, D. Kaushik, A. Kumar, D. Argyropoulos, F. Oz and C. Proestos, *Results Chem.*, 2024, **7**, 101445, DOI: 10.1016/j.rechem.2024.101445.
54 F. Pena-Pereira, W. Wojnowski and M. Tobiszewski, *Anal. Chem.*, 2020, **92**, 10076–10082, DOI: 10.1021/acs.analchem.0c01887.
55 L. L Nascimento, P. N. A. dos Santos, L. Albuquerque, B. L. de M. Pita, L. S. de Almeida, M. L. de Oliveira, C. de A. Moreira, F. R. P. Teixeira, E. B. Caramão, F. de S. Dias and A. T. Fricks, *ACS Omega*, 2025, **10**, 44064–44076, DOI: 10.1021/acsomega.5c05241.
56 I. Bouhzam, R. Cantero, M. Margallo, R. Aldaco, A. Bala, P. Fullana-i-Palmer and R. Puig, *Sci. Total Environ.*, 2024, **955**(10), 177038, DOI: 10.1016/j.scitotenv.2024.177038.
57 A. K. Pereira da Silva, A. Cardoso, E. Benício de Sá Filho, H. Monteiro Cordeiro de Azeredo, F. Freire, F. Casimiro Filho and M. C. Brito de Figueirêdo, *J. Clean. Prod.*, 2021, **321**(25), 128981, DOI: 10.1016/j.jclepro.2021.128981.
58 G. Croxatto Vega, J. Sohn, J. Voogt, M. Birkved, S. I. Olsen and A. E. Nilsson, *Resour. Conserv. Recycl.*, 2021, **167**, 105318, DOI: 10.1016/j.resconrec.2020.105318.
59 X. Zhang, A. Border, N. Goosen and M. Thomsen, *Algal Res.*, 2021, **58**, 102348, DOI: 10.1016/j.algal.2021.102348.
60 J. Z. Lian, V. Balapa, E. Goetheer and S. Cucurachi, *Chem. Eng. J.*, 2024, **502**, 158007, DOI: 10.1016/j.cej.2024.158007.
61 B. C. Hoe, P. Arumugam, M. L. Irene Chew, J. Tan and C. W. Ooi, *Chem. Eng. Commun.*, 2022, **211**, 336–349, DOI: 10.1080/00986445.2022.2047664.
62 V. Yadav, A. Sarker, A. Yadav, A. O. Miftah, M. Bilal and H. M. N. Iqbal, *Chemosphere*, 2022, **293**, 133459, DOI: 10.1016/j.chemosphere.2021.133459.
63 B. Alonso-Fariñas, A. Oliva, M. Rodríguez-Galán, G. Esposito, J. F. García-Martín, G. Rodríguez-Gutiérrez, A. Serrano and F. G. Fermoso, *Processes*, 2020, **8**, 626, DOI: 10.3390/pr8050626.