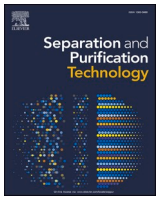
Separation and Purification Technology 395 (2026) 137731



Contents lists available at ScienceDirect

Separation and Purification Technology

journal homepage: www.elsevier.com/locate/seppur





Emerging methods to extract bioactive compounds from brown algae: a comprehensive review of performance, readiness, and sustainability

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ARTICLE INFO

Editor: M Freire

Keywords:
Emerging extraction methods
Green extraction
Bioactive compounds
Brown algae (Phaeophyceae)
Sustainability
Technology readiness level
Societal readiness level

ABSTRACT

Brown algae (Phaeophyceae) are an important source of bioactive compounds with promising applications in many sectors. However, traditional extraction methods are often resource-intensive, solvent-demanding, and environmentally burdensome, with limitations in selectivity and process efficiency. This review examines recent studies (2014–2025) on emerging extraction methods for brown algae, including pulsed electric field-assisted extraction (PEF-AE), pressurized liquid extraction (PLE), microwave-assisted extraction (MAE), ultrasound-assisted extraction (UAE), subcritical water extraction (SWE), supercritical carbon dioxide extraction ($SCCO_2$), enzyme-assisted extraction (EAE), and natural deep eutectic solvents (NADES). A central contribution of this review is the implementation of a tailored rubric to assess technology readiness level (TRL) and societal readiness level (SRL) across these extraction platforms. These methods are critically evaluated in terms of extraction performance, technical advantages, limitations, and their economic and environmental implications. Finally, future research directions are discussed to optimize these methods, overcome current challenges, and fully realize the industrial potential of brown algae-derived bioactive compounds.

1. Introduction

Across cultures and centuries, marine algae have served as both sustenance and medicine, with brown algae (Phaeophyceae) among the most biologically versatile and therapeutically valuable groups. In East Asia, iodine-rich species such as *Undaria pinnatifida* and some *Sargassum* were traditionally used to manage iodine-deficiency disorders, including goiter [1]. Māori communities in New Zealand used brown algae as laxatives, intestinal dewormers, and remedies for scabies, eczema, and burns [2,3]. In Chile, the Mapuche used *Durvillaea antarctica* to treat mumps and digestive conditions such as gastritis, ulcers, and colitis [3]. In Europe, *Fucus* and *Laminaria* species were employed to reduce glandular inflammation, manage obesity, and alleviate rheumatic pain [3,4].

Building on traditional uses, modern research has identified various bioactive compounds in brown algae, including polysaccharides (alginate, fucoidan, laminarin), polyphenols (phlorotannins), and carotenoids (fucoxanthin), as well as other metabolites. Due to their diverse bioactivities, these compounds hold significant potential in pharmaceuticals, cosmetics, nutraceuticals, and food preservation, as well as in functional foods, agriculture (as biopesticides and growth enhancers), biomaterials, and environmental remediation [5–7]. Realizing this potential requires efficient, selective, and sustainable extraction methods that can overcome the multiple limitations of traditional approaches.

Conventional extraction methods, including solvent extraction, maceration, and Soxhlet extraction, have been widely used to isolate bioactive compounds. While effective, these methods rely heavily on organic solvents, leading to environmental concerns, waste management challenges, and potential toxic residues in the final extracts [8]. Many of these solvents are volatile organic compounds (VOCs), which

Abbreviations: CAPEX, Capital expenditure; DES, Deep eutectic solvents; DPPH, 2,2-Diphenyl-1-picrylhydrazyl; DW, Dry weight; EAE, Enzyme-assisted extraction; FRAP, Ferric reducing antioxidant power; GAE, Gallic acid equivalents; GE, Glucose equivalents; GHG, Greenhouse gas; IC_{50}, Half-maximal inhibitory concentration; LCA, Life cycle assessment; MAE, Microwave-assisted extraction; NADES, Natural deep eutectic solvents; OPEX, Operating expenditure; PEF-AE, Pulsed electric field-assisted extraction; PGE, Phloroglucinol equivalent; PLE, Pressurized liquid extraction; $SCCO_2$, Supercritical carbon dioxide extraction; SMEs, Small- and medium-sized enterprises; SRL, Societal readiness level; SWE, Subcritical water extraction; TE, Trolox equivalents; TEA, Techno-economic analysis; TFC, Total flavonoid content; TPC, Total phenolic content; TRL, Technology readiness level; UAE, Ultrasound-assisted extraction; VOC, Volatile organic compound.

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https://doi.org/10.1016/j.seppur.2026.137731
Received 15 December 2025; Received in revised form 6 March 2026; Accepted 23 March 2026
Available online 28 March 2026
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readily evaporate, contributing to air pollution and ground-level ozone formation, while posing harmful effects on human health and ecosystems even at low concentrations [9,10]. Persistent exposure to VOCs can also lead to solvent accumulation in indoor environments, increasing fire and explosion hazards in industrial settings. Moreover, improper disposal or accidental leaks of these solvents can cause severe water and soil contamination. These methods also consume substantial resources, generate hazardous waste, and often deliver modest yields [11]. Beyond environmental concerns, these methods also face practical limitations. The high temperatures involved in these methods can degrade heat-sensitive compounds like fucoxanthin, compromising their efficacy and bioavailability. In addition, their low selectivity produces crude extracts that require further purification, increasing costs and complexity. Furthermore, the overall resource-intensive and time-consuming nature of these processes limits scalability, especially for industries prioritizing sustainability and high-throughput production [12]. These limitations underscore the need for greener, more efficient extraction methods that balance industrial feasibility and environmental responsibility.

To address these challenges, various innovative extraction methods have emerged, including pulsed electric field-assisted extraction (PEF-AE), pressurized liquid extraction (PLE), microwave-assisted extraction (MAE), ultrasound-assisted extraction (UAE), subcritical water extraction (SWE), supercritical carbon dioxide extraction ($SCCO_2$), enzyme-assisted extraction (EAE), and natural deep eutectic solvents (NADES). These advanced methods improve extraction efficiency, preserve bioactive compound integrity, and align with sustainability goals.

Recently, interest in brown algae bioactives and their extraction using emerging methods has grown (Fig. 1). However, despite increasing attention and advancements in extraction methods, critical gaps remain in the literature. As summarized in Table 1, many reviews discuss emerging extraction methods but often lack specificity and depth. Key issues include a broad focus on algae rather than brown algae, omission of critical extraction methods, and an overemphasis on select compounds, such as polysaccharides, while neglecting other bioactives. Furthermore, most fail to assess the technological and societal

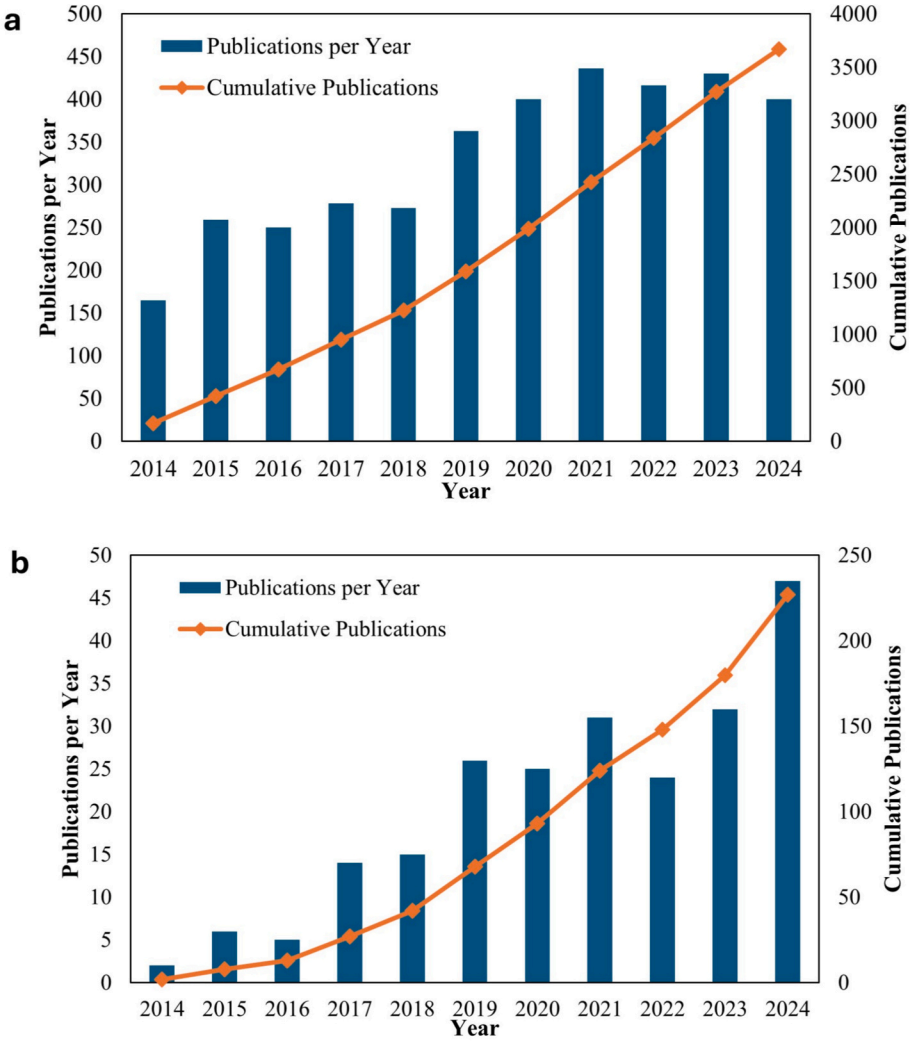


Fig. 1. Trends in publications on (a) bioactive compounds in brown algae and (b) emerging extraction methods used to extract these compounds. The graph presents the annual and cumulative number of publications, illustrating the growth in research activity from 2014 to 2024. Data were retrieved from Scopus using the following search queries: (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
(a) Publications on bioactive compounds in brown algae: TITLE-ABS-KEY ("brown algae" OR "Phaeophyceae" OR "brown seaweed") AND TITLE-ABS-KEY ("bioactive compounds" OR "bioactives" OR "fucoidan" OR "laminarin" OR "fucoxanthin" OR "phlorotannins" OR "phenolics" OR "fucosterol" OR "fatty acids" OR "alginate")
(b) Publications on emerging extraction methods for bioactive compounds from brown algae: TITLE-ABS-KEY ("brown algae" OR "Phaeophyceae" OR "brown seaweed") AND ("pulsed electric field" OR "PEF-AE" OR "pressurized liquid extraction" OR "PLE" OR "microwave-assisted extraction" OR "MAE" OR "ultrasound-assisted extraction" OR "UAE" OR "subcritical water extraction" OR "SWE" OR "supercritical CO_2 extraction" OR "$SCCO_2$" OR "enzyme-assisted extraction" OR "EAE" OR "natural deep eutectic solvents" OR "NADES") AND ("extraction" OR "bioactive compounds").

Table 1
Comparative evaluation of review articles on emerging extraction methods for bioactive compounds from algae, highlighting their contributions, gaps, and relevance to brown algae.

Review highlights	Review gaps	Ref.
Provides an in-depth analysis of advanced extraction methods for algae, identifying technical and economic challenges.	Focuses on algae broadly, not specifically on brown algae and their unique bioactives. Omits several relevant methods. Lacks analysis of technical and societal readiness. Excludes environmental and economic assessments.	[13]
Discusses various modern extraction methods, extractable compounds, and their bioactivity. Evaluates the advantages and disadvantages of these methods.	Excludes key methods, such as pulsed electric field-assisted extraction and pressurized liquid extraction. Lacks analysis of the methods' readiness for broader adoption and their technical limitations.	[14]
Compares conventional and modern extraction methods for bioactive compounds from algae, providing information on bioactivity.	Covers only four extraction methods, omitting many others. Focuses on algae generally, not specifically brown algae.	[15]
Analyzes the advantages and disadvantages of various extraction methods and suggests their suitability based on target compounds.	Focuses on three extraction methods, omitting several relevant methods. Lacks analysis of technical and societal readiness. Applies to algae broadly, not specifically to brown algae.	[16]
Provides detailed insights into each method's principles, extraction parameters, and impact on extract quality. Also discusses the fundamentals of green technologies.	Examines only three extraction methods in detail. Omits major compounds like laminarin and alginate. Lacks information on technological development and social acceptance.	[17]
Reviews advanced methods for extracting bioactives from brown algae. Discusses key extraction parameters for each method.	Limits scope to polysaccharides, excluding other bioactive categories. Lacks discussion on societal impact and technology readiness. Excludes environmental and economic assessments.	[18]

readiness of these methods, as well as their economic viability and environmental impacts. Addressing these gaps will clarify which methods best unlock brown algae's potential sustainably and at scale.

2. Bioactive compounds in brown algae

Brown algae produce diverse bioactives with applications in pharmaceuticals, nutraceuticals, and industrial biotechnology (Table 2). Sulfated polysaccharides such as fucoidan exhibit antioxidant, anti-inflammatory, antitumor, and anticoagulant properties [19–21]. Laminarin, a storage polysaccharide, provides anti-obesity, prebiotic, antioxidant, and anticancer benefits, while alginates—renowned for their gelling and stabilizing properties—also function as prebiotics and immune modulators [22–24]. Phlorotannins contribute to their defense mechanisms and stress resilience while offering strong antidiabetic, antioxidant, and anti-inflammatory activities [25–27]. Phenolic acids and flavonoids further enhance their medicinal potential [28]. Additionally, the carotenoid fucoxanthin stands out for its antioxidant, anti-obesity, and anticancer properties [29,30]. Brown algae are also a significant source of polyunsaturated fatty acids, especially eicosapentaenoic acid and docosahexaenoic acid, which support cardiovascular and brain health [7,31]. Additionally, fucosterol, a phytosterol, provides cholesterol-lowering, anti-inflammatory, and anticancer benefits [32–34]. The structural and functional diversity of these metabolites reflects the adaptations of brown algae to demanding marine environments and expands opportunities for biotechnological and therapeutic innovation.

Beyond these compounds, brown algae contain proteins yielding bioactive peptides with antihypertensive and anticancer activities, along with a diverse array of vitamins (A, B-complex, C, D, and E) and minerals (calcium, iodine, iron, and magnesium) [35–37]. These micronutrients often exceed the concentrations found in terrestrial plants, positioning brown algae as a superior source for functional foods and dietary supplements. For a more comprehensive discussion of these bioactives, their bioactivities, and applications, please refer to our recent review [38].

3. Conventional extraction methods

Conventional extraction dates to early maceration, infusion, and decoction practices used to recover bioactives from natural materials; ancient Egyptian preparations already relied on choosing water or alcohol to match solubility [60,61]. Distillation was later refined by medieval alchemists, with Avicenna often credited with improving distillation apparatus and advancing the production of rose water, thereby helping to lay the groundwork for later essential oil production [62]. In the 19th century, organic chemistry introduced defined solvents (e.g., ether, chloroform, hexane) and standardized protocols, and Soxhlet's (1879) reflux apparatus improved reproducibility for lipids and other organics [63,64]. These time-honored approaches remain common for brown algae bioactives (Table 3).

However, conventional methods face persistent sustainability and performance trade-offs. They often require large volumes of solvent, sometimes hazardous, which increases recovery and disposal burdens. In addition, long extraction times and elevated temperatures can degrade thermolabile compounds and increase energy demand at scale. Their limited selectivity further increases co-extraction and downstream purification requirements [63,64]. Consequently, greener extraction platforms are increasingly pursued to reduce hazardous solvent use and energy intensity while improving yield, selectivity, and scalability for bioactive recovery [65].

4. Emerging methods for the extraction of brown algae compounds

From early alchemist distillation to modern solvent-based extractions, the process of isolating bioactive compounds has evolved alongside advancements in science and technology. Many gains in efficiency, selectivity, and purity, however, have depended on organic solvents and energy-intensive operations, raising sustainability concerns. As awareness of the environmental impact of conventional methods grows, extraction science is shifting toward a new era—one that prioritizes greener technologies without sacrificing performance.

Today, the convergence of green chemistry and process engineering is driving a paradigm shift in sustainable extraction, where efficiency and environmental responsibility are no longer competing forces but complementary objectives. Accordingly, a suite of emerging methods—including PEF-AE, PLE, MAE, UAE, SWE, $SCCO_2$, EAE, and NADES—has been developed. These methods leverage advancements in green chemistry to improve extraction yields, reduce processing times, and minimize environmental impact, aligning with global sustainability initiatives.

While these methods present challenges, their advantages (e.g., higher efficiency, reduced ecological footprint, and improved bioactive compound recovery) make them transformative for sustainable bioprocessing (Table 4). These methods, while having some mechanistic overlap, are categorized by their primary mechanism of action. For instance, UAE and MAE are classified as “physical methods” due to their reliance on ultrasound waves and microwave radiation, respectively, despite the potential contribution of thermal effects. Table 5 summarizes studies that apply these methods to extract bioactives from brown algae, detailing key parameters such as optimal extraction conditions, targeted compounds, and resulting yields. Together, Tables 4 and 5 provide a comprehensive assessment of the advantages, disadvantages, and performance of these emerging extraction methods.

Table 2
Bioactive compounds in brown algae: polarity, bioactivity, applications, and market value.

Compound category	Key compounds	Polarity	Bioactivity	Applications	Market value	Ref.
Polysaccharides	Fucoidans Laminarin Alginate	Polar	Antioxidant Anti-inflammatory Antitumor Antibacterial Anticoagulant Prebiotic	Pharmaceuticals Nutraceuticals Cosmetics (alginate: Stabilizers and gelling agents) Biotechnology	Fucoidan: Emerging market with rapid growth Laminarin: Emerging market with high growth potential Alginate: High market value with stable growth	[20–24,39–41]
Phenolic compounds	Phlorotannins Phenolic acids Flavonoids	Polar to moderately polar	Antioxidant Antimicrobial Anti-inflammatory Anticancer Antidiabetic Anti-aging	Functional foods Cosmetics Pharmaceuticals Nutraceuticals	High market value with stable growth	[25,26,28,42–44]
Lipids	Polyunsaturated fatty acids Fucosterol	Nonpolar	Anticoagulant anti-inflammatory antioxidant Antidiabetic Neuroprotective Cholesterol-lowering	Pharmaceuticals Nutraceuticals Cosmetics Functional foods	Moderate market value with stable growth	[31,32,34,45–48]
Pigments	Fucoxanthin	Semi-polar; lipid-soluble	Antioxidant Anti-inflammatory Anti-obesity Neuroprotective Antidiabetic Anticoagulant	Food colorants Nutraceuticals Pharmaceuticals Cosmetics Aquaculture and animal feed	Moderate market value with stable growth	[29,49–53]
Proteins	Bioactive peptides	Varies (depends on amino acid composition and structure)	Antioxidant Anti-inflammatory Antihypertensive Antidiabetic Anticancer	Functional foods Nutraceuticals Pharmaceuticals	Moderate market value with stable growth	[35,54–56]
Micronutrients	Vitamins (A, B-complex, C, D, E) Minerals (calcium, copper, sodium, phosphorus, potassium, iron, zinc, cobalt, magnesium, manganese, and iodine)	Varies	Essential for nutrition and overall health Antioxidant Immune support Anti-inflammatory Neuroprotective	Nutraceuticals Functional foods Pharmaceuticals Cosmetics Agricultural and animal feed	Varies	[36,37,57–59]

4.1. Physical methods

4.1.1. Pulsed electric field-assisted extraction (PEF-AE)

PEF-AE is a non-thermal extraction method that enhances the release of bioactive compounds by applying high-voltage electric pulses that induce electroporation, creating temporary or permanent pores in cell membranes, thereby accelerating diffusion of intracellular compounds into the surrounding solvent [81]. The efficiency of PEF-AE depends on electric field strength, pulse duration, solvent composition, and matrix properties [136]. Typically, batch systems employ 100–300 $V \cdot cm^{-1}$ electric field strengths, whereas continuous-flow systems operate at higher intensities, often between 20 and 80 $kV \cdot cm^{-1}$ [81]. PEF-AE is advantageous for extracting heat-sensitive compounds, as it significantly reduces thermal degradation compared to conventional thermal methods. Its primary mechanism, electroporation, enhances mass transfer without requiring high temperatures, and the short pulse durations combined with localized electric fields minimize Joule heating [137,138]. Additional advantages include faster extraction times, reduced solvent use, and good energy efficiency compared with conventional extractional thermal extractions [81]. These characteristics make PEF-AE an appealing option for sustainable bioprocessing, particularly where the preservation of bioactivity is a priority.

Recent studies highlight PEF-AE's potential for extracting bioactive compounds from brown algae, achieving promising yields of polyphenols, carbohydrates, and pigments with enhanced antioxidant properties. For instance, PEF-treated *Alaria esculenta* extracts achieved the highest phenolic and carbohydrate yields with potent antioxidant properties [109]. Similarly, another study reported polyphenol yields of 4.0 ± 1.6 mg GAE $\times$ 100 g^{-1} DW and carbohydrate yields of 2.6 ± 2.9 mg GE $\times$ g^{-1} DW, with a supernatant yield of $70 \pm 15\%$ and an extraction yield of $15 \pm 8\%$, all achieved with minimal heat generation [110]. Moreover, PEF-AE has shown significant promise in the cosmeceutical sector. For instance, PEF-AE-produced extracts from Icelandic macroalgae, particularly *Alaria esculenta*, outperformed conventional hot water extractions in polyphenol, flavonoid, and antioxidant content [111]. These extracts exhibited potent inhibitory activity against enzymes such as collagenase, elastase, tyrosinase, and hyaluronidase, demonstrating potential for use in skin whitening and anti-aging formulations. Collectively, these studies indicate that PEF-AE can improve the recovery of selected bioactives from brown algae while preserving functional properties.

4.1.1.1. Limitations, reproducibility constraints, and unresolved scale-up barriers. Despite these advantages, PEF-AE does not consistently deliver the same extraction benefit across all systems, because its performance remains highly sensitive to matrix conductivity, ionic strength, chamber configuration, and electric-field distribution [81,136]. For example, a study on bell pepper tissue reported that increasing PEF intensity up to 10 $kJ \cdot kg^{-1}$ caused a nearly 13% reduction in total polyphenol content, together with clear decreases in antioxidant activity, indicating that excessive treatment can compromise bioactive quality rather than improve recovery [139]. In grape vinification, PEF markedly improved polyphenol release in one cultivar but produced only a minor effect in another despite measurable membrane permeabilization, indicating that electroporation does not necessarily

Table 3
Summary of studies employing conventional extraction methods for isolating bioactive compounds from brown algae.

Extraction methods	Algal species	Target compound(s)	Findings	Optimal extraction conditions	Ref.
Maceration	*Nizamuddinia zanardinii*	Phenolic compounds	Maceration yielded the highest flavonoid content but lower overall extraction efficiency than microwave-assisted extraction.	EtOH 50%; 10:1; 30 °C; 24 h; 400 rpm	[66]
	Fucus vesiculosus, Fucus distichus, Fucus serratus, and Ascophyllum nodosum	Fucoidan	Dynamic maceration resulted in fucoidan extracts with higher antioxidant and anticancer activities compared to ultrasound-assisted extraction.	EtOH 5%; 10:1; pH: 4; 60 °C; 200 rpm	[67]
	Sargassum polycystum, Sargassum cristaefolium, Sargassum aquifolium, Turbinaria ornata	Crude extract	Maceration yielded similar flavonoid levels but lower phenolics, antioxidant activity, and cytotoxicity than ultrasonic-assisted extraction.	EtOH 96%; 10:1; room temp.; 72 h (3 × 24 h)	[68]
Hydrodistillation	*Taonia atomaria, Padina pavonica*	Volatile and semi-volatile organic compounds	Hydrodistillation captured distinct, species-specific volatiles.	H_2O; ≈100 °C; dynamic hydrodistillation; 2 h	[69]
	Sargassum natans I, Sargassum natans VIII, Sargassum fluitans	Volatile organic compounds	Hydrolates of *S. fluitans* and *S. natans VIII* contained phenylpropanoids (chavicol and m-eugenol) that deterred oviposition and caused contact irritancy in *Aedes aegypti*.	H_2O; ≈100 °C; 1:1; 1 h	[70]
	Fucus virsoides J. Agardh	Volatile organic compounds	Hydrodistillation revealed a terpene-dominated volatile profile.	H_2O; ≈100 °C; 2 h	[71]
Percolation	*Fucus vesiculosus*	Fucoidan	Crude fucoidan (10 ± 2% yield) was bacteriostatic against *E. coli, S. aureus, S. epidermidis, and B. licheniformis*; higher efficacy than purified fraction.	5% EtOH; pH: 4;	[72]
	Padina tetrastromatica, Stoechospermum marginatum	Crude extract	Methanolic percolation extract of *P. Tetrastromatica* showed significant antibacterial activity (9–11 mm inhibition zones at 500 μg/disk) against *Bacillus pumilus* and *Pseudomonas vesicularis*.	MeOH 90%; room temp., 2–3 percolations	[73]
	Fucus vesiculosus	Fucoidan	Percolation yielded 95.6 ± 0.7% pure fucoidan and a 2.4-fold higher yield than maceration.	EtOH 10%; 20 °C; 12 h	[74]
Decoction	*Fucus vesiculosus*	Phlorotannins and peptide derivatives	Decoction increased antioxidant, acetylcholinesterase-inhibitory, and cholesterol-lowering activities of *F. vesiculosus* extracts, particularly in ocean-harvested samples rich in phlorotannins and peptides.	H_2O; 20:1; ≈100 °C; 30 min	[75]
	Dictyota dichotoma, Padina gymnospora, Sargassum wightii, Turbinaria conoides	Fucoxanthin	Decoction of *D. dichotoma* showed the strongest antioxidant, anti-hyaluronidase, and anticancer effects, linked to its high fucoxanthin content.	H_2O; 66.7:1; ≈100 °C; 5 min	[76]
	Kjellmaniella crassifolia	Alginate	Decoction extracted mannuronic acid-rich alginate from *K. Crassifolia*, while guluronic acid-rich fractions remained in the residue and required alkali extraction.	H_2O; 20:1; ≈100 °C; 6 h	[77]
Soxhlet	*Undaria pinnatifida*	Fucoxanthin	Soxhlet yielded 50 $\mu g \cdot g^{-1}$ fucoxanthin, substantially lower than liquefied DME (390 $\mu g \cdot g^{-1}$) and supercritical CO_2 with ethanol (994.53 $\mu g \cdot g^{-1}$), likely due to thermal degradation and absence of pretreatment.	EtOH (HPLC-grade); 33:1; 78 °C; 12 h	[78]
	Undaria pinnatifida	Lipids (polyunsaturated fatty acids)	Ethanolic Soxhlet extract showed significant antibacterial and antioxidant activities.	EtOH (absolute); 20:1; 78 °C; 8 h	[79]
	Colpomenia sinuosa	Phenolics and terpenoids	Methanolic Soxhlet extract induced cytotoxicity and apoptosis in colorectal cancer cells by generating reactive oxygen species, demonstrating anticancer potential.	MeOH; 10:1; 60 °C; 8 h	[80]

translate into comparable extraction gains across biological matrices [140]. This lack of transferability has also been observed during larger-scale validation. In virgin olive oil extraction, a pilot- and industrial-scale study found that the effect of PEF remained strongly cultivar-dependent. Although phenolic enrichment was confirmed for Manzanilla, no positive effect was observed for Hojiblanca, and the authors also noted substantial discrepancies among previously reported laboratory-scale studies, indicating that benefits observed at small scale do not necessarily translate robustly across larger-scale processing conditions and raw materials [141].

PEF-AE can also be limited by equipment-related failure modes that affect long-term operability and product quality. In particular, electrode corrosion may occur at the electrode–liquid interface, releasing metal species into the treated medium. In a stainless-steel PEF system, repeated treatment of an aqueous sodium chloride solution resulted in detectable dissolution of Fe, Cr, Ni, and Mn, highlighting that pulse conditions and chamber design can influence contamination risk and food-safety performance [142,143]. Such effects are especially relevant for saline or conductive feedstocks, where electrochemical interactions may be intensified. In macroalgal processing, a key unresolved scale-up barrier for PEF is the limited transfer of batch-based laboratory protocols to continuous industrial operation; in a continuous-process study on *Ulva* sp., the authors noted that most previous macroalgal PEF studies had been conducted in batch systems and that industrial application requires continuous processing, highlighting reactor design and process-mode transfer as major scale-up constraints [144]. Overall, the major unresolved challenge in PEF-AE is not only to increase mass transfer, but also to establish robust operating windows that remain reproducible across feedstocks and reactor configurations while avoiding over-treatment and preserving chamber stability.

4.1.2. Pressurized liquid extraction (PLE)

PLE, also known as accelerated solvent extraction, uses elevated temperatures and pressures (35–200 bar) to enhance compound extraction from solid or semi-solid matrices [85]. By operating at temperatures above a solvent's typical boiling point while maintaining it in a liquid state, PLE increases solubility, diffusion, and mass transfer rates. This method efficiently recovers polyphenols, fatty acids, and polysaccharides while potentially minimizing thermal degradation compared to conventional methods involving prolonged heating

Table 4
Advantages and disadvantages of various emerging extraction methods.

Extraction methods	Advantages	Disadvantages	Ref.
Physical methods			
Pulsed electric field-assisted extraction (PEF-AE)	-preserves heat-sensitive bioactive compounds -higher extraction yield and purity -faster than conventional methods -reduces solvent use -adaptable to continuous-flow systems -energy-efficient and eco-friendly	-high initial investment and operational costs -requires precise control of electric field strength, pulse duration, and treatment time -extraction efficiency depends on the material's electrical conductivity and composition -regular maintenance is needed to prevent electrode fouling and wear -potential degradation of specific bioactives	[81–83]
Pressurized liquid extraction (PLE)	-faster extraction with less solvent -high yields due to enhanced solubility and mass transfer at elevated temperatures and pressures -suitable for extracting polar and nonpolar compounds -effective across a broad range of matrices -eco-friendly, mainly when ethanol or ethanol–water mixtures are used	-high initial costs -potential degradation of thermolabile compounds at high temperatures -some common solvents are not compatible with this technology -complex solvent recovery -extraction parameters must be optimized for each sample type -requires high-pressure equipment and safety measures -scaling up is challenging	[84–86]
Microwave-assisted extraction (MAE)	-faster extraction with reduced solvent consumption -higher yields due to efficient heating and mass transfer -selective heating of polar molecules -energy-efficient; heats only the sample -solvent-free options available for specific applications -reduced thermal degradation of heat-sensitive compounds -more diluted acids can be used compared to conventional extraction -available for industrial-scale applications -eco-friendly	-high initial cost; expensive equipment -closed systems may require high-pressure conditions -risk of uneven heating, reducing reproducibility -requires solvents with microwave-absorbing properties -effective only for small particle sizes -excessive microwave power can degrade sensitive compounds	[87–90]
Ultrasound-assisted extraction (UAE)	-higher yield and faster extraction -Low energy and solvent consumption -reduces extraction temperature -improves solvent penetration and diffusion -preserves heat-sensitive compounds -can be adapted for industrial use -eco-friendly	-high initial costs -risk of bioactive degradation at high power -free radicals generated during sonication can degrade some compounds -achieving uniform cavitation and energy distribution can be difficult at an industrial scale -extraction efficiency varies with material type and structure	[91–93]
Thermal methods			
Subcritical water extraction (SWE)	-uses water as a solvent, avoiding harmful chemicals -enhances mass transfer and solubility -allows class-selective extractions via tunable polarity -preserves bioactivity of sensitive compounds -faster than conventional methods -cost-effective -eco-friendly	-high initial setup costs -energy-intensive -potential thermal degradation of bioactive compounds -requires precise parameter optimization -equipment corrosion risk -challenges scaling while maintaining consistency	[94–97]
Supercritical fluid methods			
Supercritical carbon dioxide extraction ($SCCO_2$)	-uses CO_2, which is non-toxic, nonflammable, and considered a "green" solvent -highly tunable for selective extractions -can extract thermally labile or easily oxidizable compounds under mild conditions, preserving bioactivity -produces solvent-free, high-purity extracts -extracts are typically microorganism-free	-expensive equipment and operational costs -energy-intensive -requires optimization of multiple parameters (pressure, temperature, co-solvents, particle size, etc.) -CO_2 alone is ineffective for highly polar compounds (requires co-solvents like ethanol) -high-pressure handling requires specialized safety measures -complex solubility prediction and process modeling due to variations in matrix-solute interactions and multi-component systems	[98–101]
Biochemical methods			
Enzyme-assisted extraction (EAE)	-improves cell disruption and yield -high selectivity -mild processing conditions, preserving bioactivity -reduces solvent use -can be combined with other extraction methods -sustainable and eco-friendly	-high enzyme cost -enzyme activity decreases over time -requires precise control of pH, temperature, substrate size, and enzyme loading to maintain enzyme activity -high enzyme load can extract unwanted compounds - limited industrial adoption	[102–104]
Solvent-based methods			

(*continued on next page*)

Table 4 (*continued*)

Extraction methods	Advantages	Disadvantages	Ref.
Natural deep eutectic solvents (NADES)	-generally non-toxic to humans and suitable for food, pharmaceuticals, and cosmetics -enhances antioxidant activity of extracts -highly customizable properties (e.g., polarity, viscosity, and thermal stability) -cost-effective compared to synthetic alternatives -easy to prepare -eco-friendly and sustainable	-high viscosity hinders mass transfer -their viscosity may accelerate equipment wear and tear - scaling up is challenging - some NADES can react with sensitive biomolecules - stability may decline with prolonged storage	[105–108]

[145,146]. However, careful optimization of temperature and solvent selection is necessary to preserve heat-sensitive bioactive compounds.

In brown algae, PLE is particularly attractive because of its high efficiency, short processing times, broad applicability to both polar and nonpolar compounds, and reduced solvent use [147]. A study on *Saccharina japonica* showed that PLE effectively extracted fucoidan, with the highest crude fucoidan yield (8.23%) obtained using 0.1% sodium hydroxide at 140 °C and 50 bar [113]. The extracted fucoidan, rich in fucose, exhibited antioxidant and emulsion-stabilizing properties, making it valuable for food and pharmaceutical applications. Similarly, PLE was used to extract unsaturated fatty acids and phenolic compounds from *Laminaria ochroleuca*. Ethanol and ethyl acetate produced lipid extracts with high content of unsaturated fatty acids (up to 55% of total fatty acids), with ethanol extracts showing the most nutritionally favorable profile (omega-6 to omega-3 fatty acid ratio of 4.4, atherogenic index of 0.74, and thrombogenic index of 1.05) [112]. Moreover, PLE efficiently extracted bioactive compounds from *Fucus vesiculosus*, yielding extracts with potent antioxidant and antibacterial activity against *Escherichia coli* and *Staphylococcus aureus* [148]. Together, these studies indicate that PLE is a versatile and efficient extraction method for brown algae and can generate bioactive-rich extracts with applications across pharmaceutical, nutraceutical, and food industries.

4.1.2.1. Limitations, reproducibility constraints, and unresolved scale-up barriers. Despite these advantages, the benefits of PLE are not always preserved at the product level, particularly in seaweed systems, where higher extraction severity can promote the co-extraction of non-target compounds. This can reduce selectivity and increase the burden of additional downstream purification. For example, in a food-grade PLE study on brown seaweeds (*Durvillaea incurvata*, *Lessonia spicata*), mannitol, an abundant and highly co-extractable seaweed carbohydrate, accounted for up to ~50% of the dry extract mass, with the authors noting that mannitol can interfere with antioxidant and phenolic assays and affect tolerability in people with irritable bowel syndrome [149]. More broadly, a recent review also noted that PLE commonly co-extracts interfering compounds, often making further purification necessary [150]. Thus, although PLE can improve extraction efficiency, its practical advantage may be offset when higher yields are accompanied by lower selectivity. In addition, PLE is not consistently superior to conventional extraction in macroalgae. In a comparative study of four Irish macroalgae, the elevated temperature and pressure used in PLE did not improve antioxidant activity relative to conventional solid–liquid extraction [151]. In *Fucus serratus*, cold-water solid–liquid extraction also produced a higher total phenolic content than the corresponding PLE extract. This indicates that elevated temperature and pressure do not necessarily translate into better functional recovery in seaweed matrices. In addition, PLE is strongly condition-dependent, and the extraction window that maximizes one target is not always optimal for another. For instance, a study on *Fucus vesiculosus* used low-polarity water PLE and showed that yield and total phenolic content increased with temperature, but the different targets peaked under different temperature windows (e.g., highest alginate at 140 °C and highest crude fucoidan at 160 °C) [114]. These results show that PLE optimization is often target-specific rather than broadly transferable, which limits reproducibility across different feedstocks, objectives, and process settings. Finally, pilot-scale evidence has shown that larger PLE systems can suffer from uneven heating, channeling, continued extraction during cooling, fouling and eventual clogging of heat exchangers, declining flow performance, and high energy demand, all of which complicate process control and may reduce economic viability [152]. In summary, although PLE can accelerate extraction and reduce solvent use, its industrial value in seaweed biorefineries remains constrained by limited selectivity, target-specific optimization, and scale-up-related operability challenges.

4.1.3. Microwave-assisted extraction (MAE)

MAE is an advanced method that isolates bioactives by using microwave energy to heat the solvent and sample, accelerating extraction. Microwaves induce oscillations in polar molecules, generating localized heating that disrupts cellular structures, enhances solvent penetration, and facilitates compound release [153]. Key factors influencing MAE efficiency include solvent type (e.g., ethanol, methanol, acetone, or mixtures), power (300–1000 W), time (seconds to minutes), and solvent-to-solid ratio, all of which must be carefully optimized to improve extraction performance while minimizing the thermal degradation of sensitive compounds. In the context of brown algae valorization, MAE is appealing because it combines rapid heating with relatively low solvent demand and can often outperform conventional techniques such as maceration or Soxhlet extraction [154]. In addition, its compatibility with water, ethanol, and their mixtures supports its use as a more sustainable extraction strategy [89]. These features have made MAE a widely investigated intensified technique for recovering bioactive compounds from natural matrices.

Several recent studies underscore MAE's potential for extracting bioactive compounds from brown algae. For instance, MAE at 110 °C for 15 min significantly outperformed conventional methods in extracting phenolic compounds from four brown algae species, yielding higher crude content, increased phenolic content, and enhanced bioactivity [155]. Similarly, MAE efficiently extracted phlorotannins from *Fucus vesiculosus*, exhibiting significant α-glucosidase inhibitory activity and again outperforming conventional methods [118]. Furthermore, a recent study highlighted the ability of this technology to sequentially extract proteins and fucoidan from *U. pinnatifida* waste [156]. Continuous MAE yielded proteins with angiotensin-converting enzyme inhibitory activity and fucoidan, with optimal protein extraction at 100–120 °C and maximum fucoidan yield (12.3%) at 150 °C for 30 min. These findings underscore that this technology not only enhances bioactive compound yields but also preserves their biological activity, reinforcing its role as a sustainable and efficient method for extracting functional ingredients from brown algae.

4.1.3.1. Limitations, reproducibility constraints, and unresolved scale-up barriers. Although MAE is often promoted as a more efficient alternative to conventional extraction, this advantage is not universal. In lemon myrtle leaves, MAE did not significantly improve the recovery of total polyphenols, flavonoids, or proanthocyanidins relative to conventional shaking water bath extraction [157]. Moreover, the conventional extract showed superior antioxidant performance in several assays, indicating that faster microwave processing did not translate into better functional extract quality. Similar limitations have also been reported in macroalgal systems. In a comparative study of macroalgal polysaccharide extraction, MAE reduced processing time substantially, but for

Table 5
Optimal extraction conditions of emerging methods for bioactive compound recovery from brown algae.

Extraction methods	Algal species	Target compound(s)	Extraction conditions	Outcome	Ref.
Physical methods					
Pulsed electric field-assisted extraction (PEF-AE)	*Alaria esculenta*	Polyphenols, carbohydrates, and fucoxanthin	H_2O + EtOH 60%; 7.5 kV × cm^{-1}; 0.96 μs; 1.2 Hz; 720 pulses; 0.7 ms	Polyphenols: 10.47 mg GAE·g^{-1} DW; carbohydrates: 21.4 mg GE·g^{-1} DW; Fucoxanthin: 73 mg·100 g^{-1} DW	[109]
	Laminaria digitata	Polyphenols, carbohydrates	H_2O; 7.5 kV × cm^{-1} (exponential decay); 0.96 μs; 1.2 Hz; 140 pulses; 30 °C	Yield: 15% DW; TPC: 4.0 mg GAE·100 g^{-1} DW; carbohydrates: 2.6 mg GE·g^{-1} DW	[110]
	Alaria esculenta	Phenolic compounds, flavonoids, and carbohydrates	H_2O; 8 kV × cm^{-1} (exponential decay); 0.96 μs; 1.2 Hz; 22 °C; 10 min	TPC: 8869.7 μg GAE·g^{-1} DW; flavonoids: 12,098.7 μg QE·g^{-1} DW; DPPH: >90%; carbohydrates: 44.8 mg GE·g^{-1} DW	[111]
Pressurized liquid extraction (PLE)	*Laminaria ochroleuca*	Fatty acids, phenols	EtOH:H_2O (1:1); 20 mL; 160 °C; 100 bar; 10 min	Yield: 52% DW; TPC: 173.65 mg GAE·g^{-1} DW	[112]
	Saccharina japonica	Fucoidan	0.1% NaOH; 140 °C; 50 bar; 5 min	Yield: 8.23% DW; DPPH: 41.88%	[113]
	Fucus vesiculosus	Fatty acids	Ethyl acetate + EtOH:H_2O (50:50); 160 °C; 100 bar; 10 min	Yield: 571.9 mg·g^{-1} DW	
	Fucus vesiculosus	Alginate, fucoidan	Low polarity H_2O; 10 bar; 140 °C (alginate); 160 °C (fucoidan); 200 °C (TPC); 5 min	Yield: Alginates: 2.13% DW; fucoidans: 22.3% DW; DPPH: IC_{50} 0.14 mg·mL^{-1}	[114]
Microwave-assisted extraction (MAE)	*Sargassum vestitum*	Phenolic compounds	EtOH 70% (*v*/v); 50:1; 960 W; 75 s	TPC: 60.74 mg GAE·g^{-1} DW; DPPH: 121.68 mg TE·g^{-1} DW; FRAP: 72.29 mg TE·g^{-1} DW	[115]
	Nizimuddinia zanardini	Sodium alginate	HCl; 29:1; 400 W; 19 min; pH: 1.0; 67 °C	Yield: 31.39% (*w*/w); uronic acid: 62.33% of sodium alginate	[116]
	Ascophyllum nodosum	Fucoidan	0.1 M HCl; 15 min; 120 °C	Yield: 16.08% DW; sulfate content: 14.71% of fucoidan	[117]
	Fucus vesiculosus	Phlorotannins	EtOH 57% (v/v); 400 W; 75 °C; 5 min	Yield: 3.16 PGE × g^{-1} DW	[118]
Ultrasound-assisted extraction (UAE)	*Ascophyllum nodosum*	Total phenolics, fucose, and uronic acid	0.03 M HCl; 10:1; 750 W; 114 μm; 20 kHz; 25 min	TPC: 143.12 mg GAE × g^{-1} DW; fucose: 87.06 mg × g^{-1} DW; uronic acid:128.54 mg × g^{-1} DW	[119]
	Sargassum carpophyllum	Phenolic compounds	EtOH 50%; 30:1; 280 W; 25 °C; 20–25 kHz; 40 min	Yield: 80.39 mg extract·g^{-1} algae; TPC: 3.665 mg PHG·g^{-1} algae	[120]
	Sargassum angustifolium and *Cystoseira indica*	Fucoxanthin	MeOH/acetone (7:3) (*S. angustifolium*); MeOH (*C. indica*); 30:1; 150 W; 37 °C; 15 min	Yield: 0.79 mg·g^{-1} DW (*S. angustifolium*); 0.81 mg·g^{-1} DW (*C. indica*)	[121]
	Sargassum muticum	Alginate	H_2O; 20:1; 150 W; 40 Hz; 1.5 A; 25 °C; 30 min	Yield: 15% DW	[122]
Thermal methods					
Subcritical water extraction (SWE)	*Ecklonia maxima*	Phenolic compounds	H_2O; 30:1; 180 °C; 40 bar; 23.75 min	Yield: 76.02% DW; TPC: 41.20 mg GAE × g^{-1} DW; antioxidant activity: 1.81 mmol TE × g^{-1} DW	[123]
		Polysaccharides	H_2O; 30:1; 120 °C; 40 bar; 5 min	Yield: 58.25% DW; sulfate content: 48.53 mg SO_4^{2-} g^{-1}; alginates: 15.65% DW	
	Nizimuddinia zanardinii	Fucoidan	H_2O; 21:1; 150 °C; 7.5 bar; 29 min; 425 rpm	Yield: 25.98% DW	[124]
	Undaria pinnatifida	Phlorotannins	H_2O; 100:1; 210 °C; 20 min	Yield: 0.99 mg PGE × g^{-1} DW	[125]
		Fucoidan	H_2O; 50:1; 120 °C; 5 min	Yield: 46 mg × g^{-1} DW	
Supercritical methods					
Supercritical carbon dioxide extraction ($SCCO_2$)	*Saccharina japonica, Sargassum horneri*	Fucoxanthin	CO_2 + EtOH; 27 g × min^{-1}; 250 bar; 45 °C; 2 h	Yield: 0.41 mg × g^{-1} DW (*S. japonica*); 0.77 mg × g^{-1} DW (*S. Horneri*)	[126]
	Undaria pinnatifida	Fucoxanthin	CO_2 + EtOH; 4 mL × min^{-1}; 50 °C; 6000 psi (413.7 bar); 4 h; 100 μm	Yield: 22.09 mg × g^{-1} extract; TFC: 32.15 mg × g^{-1} extract	[127]
	Saccharina japonica	Fucoxanthin, phlorotannins, and carotenoids	CO_2 + 2% sunflower oil (fucoxanthin, carotenoids) and 2% H_2O (phlorotannins); 27 g × min^{-1}; 300 bar; 50.62 °C (fucoxanthin, carotenoids); 48.98 °C (phlorotannins); 30–60 min (phlorotannins); 60–120 min (fucoxanthin, carotenoids)	Fucoxanthin: 1.421 mg × g^{-1} DW; phlorotannins: 0.927 mg × g^{-1} DW; Total carotenoids: 2.391 mg × g^{-1} DW	[101]
	Sargassum muticum	Lipids	CO_2; 10 kg × h^{-1}; 290 bar; 45 °C; 2 h	Total lipids: 0.8% DW; glycolipids: 82.2%; neutral: 13.7%; phospholipids: 4.1%	[128]
Biochemical methods					
Enzyme-assisted extraction (EAE)	*Fucus distichus subsp. evanescens*	Fucoidan	Cellic®CTec2 5% (*v*/*w*) + SALy 0.35% (*w*/w); pH 6.0; 40 °C; 24 h	Yield: 40% DW	[129]
	Hizikia fusiforme	Sulfated polysaccharides	Celluclast® 5% (*v*/*w*); distilled H_2O; pH 4.5; 50 °C; 24 h	Yield: 29.35% DW; IC_{50}: (DPPH: 0.81, alkyl: 0.25, hydroxyl 0.21 mg × mL^{-1})	[130]
	Sargassum horneri	Fucoidan	Celluclast® 1% (v/w); distilled H_2O; pH 4.5; 50 °C; 24 h	Fucose: 48.69%; galactose: 31.13%; sulfate: 22.05%	[131]
Solvent-based methods					

(*continued on next page*)

Table 5 (*continued*)

Extraction methods	Algal species	Target compound(s)	Extraction conditions	Outcome	Ref.
Natural deep eutectic solvents (NADES)	*Fucus vesiculosus, Ascophyllum nodosum*	Phlorotannins	Choline chloride + lactic acid or choline chloride + malic acid (50–70% H_2O); 5:1; maceration; 50 °C; 2 h	Phlorotannins: ≈69% (*F. vesiculosus*); ≈72% (*A. nodosum*) of total	[132]
	Fucus vesiculosus	Phlorotannins	Lactic acid:Choline chloride 3:1 (30% H_2O); 12:1; UAE; 23 min	Yield: 137.3 mg PGE × g^{-1} DW	[133]
	Fucus vesiculosus	Phlorotannins and fucoxanthin	Lactic acid:Choline chloride; (30% H_2O); 10:1; UAE; 25 °C; 1 h	Phlorotannins: 28.7 mg PGE × g^{-1} DW; fucoxanthin: 0.45 mg × g^{-1} DW	[134]
	Sargassum muticum	Phenolic compounds	L-lactic acid:Fructose 5:1 (25% H_2O); 3:1; maceration; room temperature; 2 h	TPC: 6.30 mg GAE × g^{-1} DW; DPPH: 27%; FRAP: 30 μM $FeSO_4$	[135]

Note: The table includes units and acronyms to describe extraction methods, conditions, and outcomes for bioactive compounds from brown algae. These terms are defined below for clarity.

DPPH: 2,2-Diphenyl-1-picrylhydrazyl; FRAP: Ferric reducing antioxidant power; IC_{50}: Half-maximal inhibitory concentration; TFC: Total flavonoid content; TPC: Total phenolic content.

% DW: percentage of dry weight. mg GAE·g^{-1} DW: milligrams of gallic acid equivalents per gram of dry weight. mg GE·g^{-1} DW: milligrams of glucose equivalents per gram of dry weight. mg PGE·g^{-1} DW: milligrams of phloroglucinol equivalents per gram of dry weight. mg QE·g^{-1} DW: milligrams of quercetin equivalents per gram of dry weight. mg TE·g^{-1}: milligrams of trolox equivalents per gram. mg·g^{-1} DW: milligrams per gram of dry weight.

Sargassum muticum it produced a lower alginate yield than the conventional method (33.67 vs 38.38 g), shifted the main molecular-weight fraction downward (83 vs 157 kDa), and weakened anti-adhesion performance against bacteria, indicating that faster microwave processing can compromise polymer integrity and functional quality rather than improve them [158].

A further limitation is that MAE is highly sensitive to heating uniformity and energy delivery. Even at laboratory scale, the efficacy of MAE can be limited by non-uniform heating and localized overheating. For example, a study on carrot-peel extraction demonstrated that while continuous MAE offers rapid processing, it often yields lower carotenoid recovery than conventional methods because the high-intensity radiation required for extraction simultaneously triggers the thermal degradation of sensitive compounds like β-carotene [159]; accordingly, intermittent microwave operation was required to extend treatment without excessive overheating. Such findings indicate that successful MAE depends not only on faster heating, but also on precise control of temperature evolution during the process. Scale-up introduces an additional challenge because nominal microwave power is not directly transferable across systems or reactor sizes. Consequently, processes developed in one system cannot be reliably reproduced in another unless they are reformulated in terms of absorbed power and energy input rather than applied power alone [160]. This lack of direct transferability complicates process standardization and makes reactor-dependent effects a major unresolved barrier to industrial implementation. Overall, the principal challenge for MAE is not only to accelerate extraction, but also to ensure uniform energy distribution, avoid local overheating, and establish scale-independent operating parameters that preserve both yield and product quality.

4.1.4. Ultrasound-assisted extraction (UAE)

UAE, or sonication, is an innovative method that employs high-frequency sound waves (20–100 kHz) to generate cavitation bubbles in a solvent [161]. These sound waves induce alternating compression and rarefaction cycles in a liquid medium, leading to the formation and collapse of microscopic bubbles [91]. The implosion of these bubbles generates localized high temperatures and pressures that can disrupt cell walls and membranes and facilitate the release of intracellular compounds into the solvent. This process can enhance mass transfer and solubility, making UAE faster and more efficient than conventional methods [162].

In brown algae, UAE is particularly attractive because it can help overcome mass-transfer limitations associated with alginate-rich cell-wall structures. Brown algae are rich in alginate, an anionic polysaccharide that can form Ca^{2+}-crosslinked gel networks described by the "egg-box" model; these gel-like, viscous domains can restrict solvent penetration and solute diffusion, thereby increasing mass-transfer resistance during extraction, especially for high-molecular-weight compounds [163–165]. UAE can partially overcome this barrier because acoustic cavitation disrupts the "egg-box" junction zones of calcium-alginate hydrogels by exerting transient mechanical forces that temporarily displace divalent Ca^{2+} cations from their coordination sites within the guluronic acid (G-block) cavities. This process results in a reversible loss of network integrity and a reduction in elastic modulus [166]. Concurrently, the resulting turbulence, particle collisions, and liquid-jet effects at the solid–liquid interface physically loosen the gel network. This combined action—the molecular displacement of ions and the mechanical disturbance of pores—effectively thins boundary layers and shortens diffusion pathways, facilitating the rapid release of solutes from the algal matrix [167]. Thus, UAE may relieve the transport constraints associated with egg-box-type structuring mainly through physical disruption and improved interfacial mass transfer, rather than through demonstrated direct or permanent rupture of Ca^{2+}-mediated junctions. Moreover, UAE also allows precise extraction process control by adjusting factors such as frequency, amplitude, and power, making it a versatile method [92]. It is also compatible with both polar and nonpolar solvents and can be integrated with other green extraction methods, aligning with sustainability goals [91,168].

In brown algae, recent studies have shown that UAE can improve the recovery of several classes of bioactive compounds. For instance, it significantly improved the extraction of total phenolics (143.12 mg GAE × g^{-1}), fucose (87.06 mg × g^{-1}), and uronic acid (128.54 mg × g^{-1}) from *Ascophyllum nodosum* [119]. Similarly, UAE optimized the extraction of phenolics with potent antioxidant activity from *Sargassum carpophyllum*, with ethanol concentration and ultrasonic power identified as critical factors influencing yield and bioactivity [120]. However, excessive power or solid-liquid ratios reduced bioactivity by extracting non-phenolic components, highlighting the need for optimized parameters. UAE has also been successfully employed to extract fucoxanthin from *Sargassum angustifolium* and *Cystoseira indica* and to improve the yield of alginate [121,167]. These findings highlight UAE as a versatile, eco-friendly, and efficient approach for harnessing high-value compounds from brown algae.

4.1.4.1. Limitations, reproducibility constraints, and unresolved scale-up barriers. Although UAE is effective at laboratory scale, its practical implementation remains constrained by cavitation-related equipment wear, contamination risks, and operability problems under prolonged or intensified processing. A systematic erosion study showed that continuous sonication at 18–20 kHz produced clear probe pitting within 7.5 h, generated metallic micron-sized particles, and increased dissolved Fe and Ti in water, indicating that transducer wear can become a food-safety and equipment-integrity concern under prolonged operation [169]. The same study also reported that when they attempted to run an

80 kHz, 220 W ultrasonic system in 16 L tanks, the welds in the treatment vessel eroded through on three occasions and the vessel drained overnight within 24 h. This is a clear scale-up and operability concern for prolonged or continuous processing.

A second limitation is that UAE can induce sonochemical depolymerisation of polymers. Although this can be beneficial for tailored low-molecular-weight products, it becomes a drawback when polymer integrity is required to preserve viscosity, gelling behavior, or bioactivity. For example, one study found that ultrasound treatment reduced fucoidan molecular weight, and that the extent of depolymerisation was highly sensitive to ultrasonic intensity, temperature, and concentration [170]. This implies that modest variations in biomass solids, salinity, or medium viscocity may alter the extent of polymer breakdown and thus contribute to batch-to-batch variability.

Finally, scale-up presents an additional unresolved barrier because acoustic fields are inherently non-uniform and strongly dependent on reactor geometry. A pilot-scale tubular flow reactor required substantially higher specific ultrasonic power (2.5-fold) to reproduce the extraction yield obtained in the smaller laboratory reactor [171]. More broadly, cavitational activity is spatially heterogeneous, probe intensity decays sharply with distance from the emitting surface, and both transducer design and reactor geometry determine how acoustic energy is distributed within the extraction volume [172]. Consequently, power or amplitude settings cannot be directly transferred between systems with the expectation of equivalent extraction performance. In summary, the main challenge for UAE is not only to intensify mass transfer, but also to control cavitation uniformly, avoid equipment degradation, and preserve product integrity across scales.

4.2. Thermal methods

4.2.1. Subcritical water extraction (SWE)

SWE, or pressurized hot water extraction, uses water at 100–374 °C under high pressure to maintain its liquid state [94]. Its efficiency stems from water's changing properties at elevated temperatures; as temperature increases, water's dielectric constant decreases, reducing its polarity and allowing it to behave more like an organic solvent. This shift broadens its solvation capacity and enables the extraction of compounds across a wide ploarity range, including hydrophobic substances. The efficiency of SWE depends mainly on temperature, pressure, residence time, solvent-to-solid ratio, and matrix composition, and its use of water as the extraction medium, reduces reliance on hazardous organic solvents while allowing selective recovery of different compound classes by adjusting operating conditions [94,96]. These features make SWE a promising option for sustainable processing of marine biomass.

Several studies have demonstrated the potential of SWE for extracting valuable compounds from brown algae. When applied to *Sargassum thunbergii*, *Undaria pinnatifida*, and *Saccharina japonica*, it yielded hydrolysates with a total phlorotannin content of up to 38.82 ± 0.17 mg PGE × g^{-1} and antioxidant activity reaching 124.77 ± 2.47 mg TE × g^{-1} [173]. These extracts also exhibited antihypertensive, α-glucosidase inhibitory, and antibacterial properties against foodborne pathogens. Moreover, a study on *Ecklonia maxima* optimized SWE conditions using response surface methodology, revealing that extraction temperature significantly influences yield and bioactivity [123]. The highest phenolic content and antioxidant activity were achieved at 180 °C for 23.75 min with a solvent-to-solid ratio of 30 mL × g^{-1}, while polysaccharide extraction peaked at 120 °C for 5 min under the same ratio, both at 40 bar. SWE was also effective in extracting fucoidan from *Nizamuddinia zanardinii*, achieving a yield of 25.98% under optimal conditions (150 °C, 29 min, 21 g × mL^{-1}), significantly surpassing the yield of conventional methods (5.2%) [124]. The resulting fucoidan exhibited potent antioxidant, anticancer, and immunomodulatory activities, with a well-defined monosaccharide profile and a molecular weight of 694 kDa. Furthermore, SWE has been successfully applied to beach-cast brown algae, supporting the valorization of low-value or waste biomass streams [174]. Collectively, these studies indicate that SWE is a versatile and sustainable platform for recovering high-value bioactive compounds from brown algae.

4.2.1.1. Limitations, reproducibility constraints, and unresolved scale-up barriers. A major limitation of SWE, particularly in carbohydrate-rich seaweeds, is that it is not purely an extractive process but also a chemically reactive one. Under subcritical-water conditions, Maillard, caramelisation, and thermoxidation pathways can generate neoformed antioxidant species; accordingly, increases in measured antioxidant capacity do not necessarily indicate improved recovery of native bioactives [175]. This was illustrated in a study of algae and plant matrices, where *Undaria pinnatifida* showed a marked increase in antioxidant capacity as extraction temperature increased from 100 to 200 °C, with the increase attributed to newly formed reaction products rather than simply greater extraction of native antioxidants [176]. The same thermal reactivity can also promote the formation of undesirable degradation products such as 5-hydroxymethylfurfural under more severe SWE conditions, whose concentration has been shown to increase sharply with temperature and residence time in SWE-treated food by-product matrices [177]. These findings indicate that SWE outcomes are governed not only by solubility effects, but also by concurrent thermal reactions that can alter extract composition and complicate interpretation of bioactivity results.

This chemical sensitivity becomes especially important during scale-up, because the extent of reaction is governed not only by nominal extraction conditions but also by the heating profile and residence history, which are more difficult to reproduce across reactor sizes. A recent review noted that most studies remain at bench scale, that dynamic systems can suffer from plumbing blockage, and that industrial scale-up is still an unresolved development step [94]. Consistent with this, a pilot-scale study showed that matching nominal extraction conditions did not guarantee identical product profiles across scales. Although bulk oligomer and protein recoveries were broadly similar, heating rate still affected monosaccharide and phenolic release, demonstrating that compositional selectivity remained scale-dependent even when overall yields appeared transferable [178]. Thus, reproducibility in SWE depends not only on nominal temperature and pressure, but also on how rapidly and uniformly those conditions are reached and maintained throughout the system. For marine biomasses, these scale-up challenges are compounded by materials-compatibility challenges. Seaweed-derived chloride, sulfur, and ash can increase the corrosive and fouling burden on hydrothermal equipment, raising additional concerns for long-term operability and maintenance [97,179]. Overall, the main unresolved challenge for SWE is not only to maximize extraction efficiency, but also to control reaction severity, preserve compositional selectivity, and ensure stable operation under the thermally and chemically demanding conditions required for scale-up.

4.3. Supercritical fluid methods

4.3.1. Supercritical carbon dioxide extraction ($SCCO_2$)

$SCCO_2$ is widely regardes as a selective, eco-friendly method for isolating bioactive compounds from natural sources. $SCCO_2$ leverages the unique properties of CO_2 in its supercritical state, achieved at temperatures above 31.1 °C and pressures exceeding 73.8 bar, where it combines gas-like diffusivity with liquid-like density, enabling rapid penetration of solids and efficient solvation of target compounds [180]. A major strength of $SCCO_2$ is that its solvating power can be finely tuned through pressure and temperature, allowing selective recovery of different compound classes. In practice, extraction efficiency is governed not only by pressure and temperature, but also by extraction time, CO_2 flow rate, particle size, and the presence of co-solvents [181]. In addition, the use of CO_2 as a non-toxic, nonflammable, and readily removable solvent makes $SCCO_2$ particularly suitable for extracting

heat- and oxidation-sensitive compounds under mild conditions, while often producing high-purity extracts free of solvent residues [99].

Several studies have demonstrated the potential of $SCCO_2$ for recovering valuable compounds from brown algae. In one study, $SCCO_2$ with ethanol as a co-solvent at 250 bar and 45 °C achieved fucoxanthin yields of up to 0.77 mg × g^{-1} from *Saccharina japonica* and *Sargassum horneri* [126]. In *Sargassum muticum*, ethanol-modified $SCCO_2$ significantly enhanced fucoxanthin, phenolic, and lipid yields versus pure $SCCO_2$ [53]. Adding 10% ethanol increased overall extraction yields by up to threefold and fucoxanthin yields by 90-fold, while also moderately enhancing phenolic content and antioxidant activity. Furthermore, using sunflower oil as a co-solvent optimized carotenoid and fucoxanthin extraction from *Saccharina japonica* at 50.62 °C, 300 bar, and 2.00% co-solvent concentration, while water performed best for phlorotannins under comparable conditions [101]. Collectively, these findings highlight $SCCO_2$'s tunable selectivity for isolating bioactives, positioning it as a promising method for nutraceutical and pharmaceutical applications.

4.3.1.1. Limitations, reproducibility constraints, and unresolved scale-up barriers. A recurrent limitation of $SCCO_2$ is the polarity mismatch between supercritical CO_2 and many target compounds. Because CO_2 is intrinsically non-polar, its ability to recover polar antioxidants such as phlorotannins is inherently limited unless co-solvents are added. This weakens the "solvent-free" advantage often associated with $SCCO_2$ and can increase downstream separation requirements [101]. This limitation is clearly illustrated in a direct comparison using *Sargassum serratifolium*, where $SCCO_2$ with ethanol as co-solvent produced the lowest extraction yield and the poorest recovery of phenolics and antioxidant activity among the tested methods, performing worse than both methanolic extraction and PLE [182]. The authors attributed this underperformance to the intrinsically low polarity of CO_2. Additional reported process limitations include thermal non-uniformity within the packed bed and depressurization-induced recovery problems. In packed-bed $SCCO_2$ extraction, internal temperature gradients can shift the cumulative extraction curve, showing that the apparent extraction kinetics may be influenced by local non-isothermal conditions, not solely by the intrinsic mass-transfer behavior of the solute [183]. Consequently, laboratory extraction curves obtained under nominal set-point conditions may not always reflect purely intrinsic extraction behavior, because part of the observed profile can arise from temperature heterogeneity within the bed rather than from the extraction mechanism itself. Likewise, during pressure release, throttling effects and even dry-ice formation may disrupt stable product collection, meaning that extraction performance inside the vessel does not necessarily translate into equally reliable downstream recovery [184]. These effects complicate reproducibility and make process interpretation more difficult, especially when extraction and separation stages are closely coupled.

Scale-up introduces an additional layer of complexity. Even when an explicit scale-up rule is applied, pilot-scale $SCCO_2$ performance may still diverge from laboratory predictions. For example, in the scale-up of *Phyllanthus niruri* extraction using ethanol–water-modified CO_2, the predicted and validation extraction curves were not fully superimposable; the main extraction stage occured approximately 30 min later at the larger scale [185]. The authors attributed this delay to the use of larger particles to reduce channeling, as well as to void spaces in the larger vessel, both of which slowed mass transfer. More broadly, a major unresolved barrier in $SCCO_2$ scale-up is the lack of universally reliable transport models. In particular, mass-transfer correlations developed for conventional fluid systems cannot be directly applied to supercritical systems, and under supercritical conditions, natural convection can interfere with forced mass transfer, further complicating process prediction and scale-up [181]. Overall, the principal challenge for $SCCO_2$ is not only to achieve selective extraction, but also to maintain reliable mass transfer, stable product recovery, and predictive scale-up across reactor sizes and operating conditions.

4.4. Biochemical methods

4.4.1. Enzyme-assisted extraction (EAE)

EAE is an extraction method that enhances the release of intracellular compounds by using enzymes to degrade cell walls and membranes, thereby facilitating compound diffusion into the extraction medium [186]. Its efficiency depends mainly on enzyme type, enzyme loading, pH, temperature, reaction time, and substrate composition [104,187]. Because different enzymes target different matrix components, EAE can be tailored to the selective recovery of specific compound classes. Common enzymes used in EAE include polysaccharide-degrading enzymes such as agarase, amylase (e.g., Termamyl®), arabinase, carrageenanase, cellulase (e.g., Celluclast®), glucanase, glucoamylase, hemicellulase (e.g., Viscozyme®), pectinase, and xylanase as well as proteolytic enzymes such as Alcalase®, Flavourzyme®, Kojizyme™, Neutrase®, papain, and Umamizyme™. Multifunctional blends such as Ultraflo® target fibers and complex substrates, further enhancing extraction efficiency [188–190].

In brown algae, EAE is particularly relevant because enzymatic treatment can reduce matrix resistance by loosening the alginate-rich cell-wall network, thereby improving porosity and diffusion. Targeted EAE systems utilizing alginate lyases, frequently in synergy with cellulases, degrades the cell wall matrix by cleaving complex polysaccharides. This structural breakdown enhances accessibility to the cellular interior, facilitating the high-yield recovery of bioactive compounds like fucoidans [191]. Because EAE generally operates under mild conditions, with relatively low temperatures and limited solvent input, it can help preserve compound integrity while reducing extraction severity [192]. Compared to conventional extraction techniques, EAE offers greater biochemical selectivity, improved yields, and compatibility with other extraction methods for enhanced performance.

Recent studies highlight EAE's effectiveness in enhancing both yield and bioactivity of brown algae extracts. For instance, enzymatic extraction of seven brown algae species using carbohydrases and proteases markedly improved antioxidant and antimicrobial activities [193]. Viscozyme® and Alcalase® produced extracts with high antioxidant activity, whereas Flavourzyme® yielded those with the highest antimicrobial activity, although overall antimicrobial activity was generally low. In another study, a combination of cellulase (Cellic® CTec2) and alginate lyase was applied to isolate fucoidans from *Fucus distichus* subsp. *evanescens* and *Saccharina latissima* [129]. Conducted at pH 6.0 and 40 °C, the process involved calcium ion precipitation to remove non-fucoidan polysaccharides, ethanol precipitation for crude fucoidan recovery, and ion-exchange chromatography for purification. The resulting fucoidans (400–800 kDa in *F. evanescens*; 300–800 kDa in *S. latissima*) achieved yields comparable to chemical extraction, while retaining their native structures. Similarly, in *Hizikia fusiforme*, Celluclast-assisted hydrolysis followed by ethanol precipitation yielded polysaccharides with potent in vitro and in vivo antioxidant activity [130]. Collectively, these findings reinforce EAE as a sustainable and effective extraction strategy that preserves compound integrity and enhances the biological potential of brown algae.

4.4.1.1. Limitations, reproducibility constraints, and unresolved scale-up barriers. EAE in seaweed systems is attractive because it can be biochemically selective, yet it is often operationally fragile and difficult to standarize at scale because its performance depends on enzyme–matrix compatibility and tight process windows. Enzyme choice and operating conditions can alter both yield and co-extraction. This was demonstrated in an ulvan EAE study where different commercial cellulases and proteases, applied under distinct pH and temperature buffers and residence times, produced substantial differences in ulvan recovery and in co-extracted components such as protein carryover [194]. This sensitivity creates a practical irreproducibility ceiling, since modest shifts in biomass composition or enzyme formulation can alter cell-wall

disruption and the balance between solubilization and hydrolysis.

Product quality is further complicated by co-extracted matrix components and extraction-induced compositional changes that persist even in targeted workflows. For instance, a fucoidan protocol combining a commercial cellulase blend (Cellic® CTec2) with an alginate lyase (SALy) required a 24 h reaction at 40 °C (pH 6.0) and still produced crude fucoidans containing low-molecular-weight alginate even after $CaCl_2$ precipitation, requiring anion-exchange chromatography and subsequent desalting by membrane filtration to obtain purified fucoidan [129]. Notably, the fucoidan yields were comparable to mild acid extraction. This shows that the selectivity advantage of EAE does not necessarily eliminate downstream purification burdens and that enzymatic specificity alone may be insufficient to guarantee a clean product stream.

At larger scales, the main barriers are often dominated by process engineering rather than enzymatic chemistry alone. A techno-economic biorefinery analysis for *Saccharina latissima* modeled EAE in stirred tanks and reported that high dilution was needed to manage the very high viscosities caused by solubilized alginate, increasing working volumes and tank sizing costs [195]. The study also identified the EAE step as a throughput bottleneck in one simulated process because of the long reactor time (17.5 h). These operational limits are further amplified by biochemical failure modes that couple feedstock variability to performance, including phenolic inhibition, since phenolics can complex with proteins and reduce hydrolysis by limiting enzyme access at the substrate surface, an effect likely relevant for phlorotannin-rich brown seaweeds and expected to vary seasonally [196,197]. Limited enzyme stability and reusability also remain common operational failure modes, with progressive loss of catalytic potency upon reuse reported for immobilized β-glucosidase systems [198,199]. Overall, the main unresolved challenge for EAE is not only to achieve selective matrix disruption, but also to develop robust enzyme–matrix systems that remain reproducible, scalable, and economically viable across heterogeneous feedstocks [189].

4.5. Solvent-based methods

4.5.1. Natural deep eutectic solvents (NADES)

Deep eutectic solvents (DES) are eco-friendly solvents formed by combining a hydrogen-bond acceptor and a hydrogen-bond donor, creating a eutectic mixture with a melting point lower than that of its components, often remaining liquid at room temperature [200]. A subset, NADES, comprises natural compounds such as sugars, organic acids, polyols, and amino acids, making them highly biocompatible [201]. NADES are readily prepared by heating and stirring their components into a homogeneous liquid without requiring additional solvents or purification steps. NADES exhibit low volatility, toxicity, and flammability, as well as high thermal stability, and extraction efficiencies comparable to conventional solvents. Their tunable physicochemical properties, particularly polarity and viscosity, enhance their ability to solvate a wide range of compounds, including both polar and nonpolar substances [202]. Furthermore, NADES are energy-efficient to produce, decompose without generating harmful by-products, and are reusable due to their nonvolatility, positioning them as sustainable alternatives to conventional solvents [202,203]. These features have driven growing interest in their use for the recovery of bioactive compounds from natural matrices.

Recent studies have demonstrated the potential of NADES for extracting bioactive compounds from brown algae. For instance, a lactic acid–choline chloride (3:1) NADES efficiently extracted phlorotannins from *Fucus vesiculosus*, yielding 137.3 mg PGE × g^{-1} DW with antioxidant activity comparable to ethanol-based methods [133]. Similarly, another study evaluated ten NADES formulations using combinations of choline chloride, lactic acid, betaine, and glucose to extract phlorotannins from *Fucus vesiculosus* and *Ascophyllum nodosum* [132]. The extractions, performed through maceration (50 °C for 120 min), achieved phlorotannin recoveries of 60–72% of the total biomass content. The most efficient NADES consisted of aqueous mixtures (50–70% water) of choline chloride with lactic or malic acid, exhibiting extraction efficiencies comparable to acetone and ethanol. Similarly, NADES have been used to extract fucoxanthin from *Fucus vesiculosus*, producing extracts with high antioxidant activity and stability compared to conventional methods [134]. Collectively, these studies indicate that NADES are promising alternative solvents for recovering brown algal bioactives.

4.5.1.1. Limitations, reproducibility constraints, and unresolved scale-up barriers. Despite their promise as "green" and tunable solvents, NADES face several practical limitations that can undermine reproducibility, downstream process simplicity, and large-scale implementation. A persistent technical constraint is their often high viscosity, which suppresses diffusion and makes extraction efficiency strongly dependent on temperature, mixing, and especially water content [202]. This creates a reproducibility problem because even small compositional shifts can markedly change rheology and solvation behavior. Crucially, this sensitivity is strongly influenced by hydration. A large-scale analysis of reported NADES formulations highlights that water is a delicate control variable because, although hydration can reduce viscosity, excessive water can compete with the hydrogen-bond network and destabilize the eutectic structure [204]. In that study, only hydrophilic NADES commonly accommodated water as a third component, with typical reported formulations containing up to ~40% water on a mole-ratio basis, whereas higher water contents were suggested to yield stable systems only if additional stabilizing forces operate, implying that dilution strategies can erode NADES-specific behavior and reproducibility. This represents a significant industrial hurdle when processing inherently moist biomass like seaweed, where uncontrolled dilution can inadvertently alter the solvent's chemical identity.

Another major limitation is downstream purification and solvent regeneration. Because NADES generally exhibit negligible vapor pressure, evaporation-based solvent removal is impractical. Therefore, product recovery often relies on non-evaporative approaches, including water (or hydroalcoholic) addition to decrease viscosity and disrupt the hydrogen-bond network, liquid–liquid partitioning with pH-assisted back-extraction for ionizable targets, and capture on macroporous adsorption resins followed by elution with a suitable solvent [205,206]. These operations can increase secondary solvent and water consumption, add unit operations, and change the composition of the recycled NADES. This can offset part of the presumed green advantage of the solvent system. For example, recovery of phenolics from NADES has been reported to require 10-fold water dilution followed by liquid–liquid extraction with 2-methyltetrahydrofuran, and in some cases even more complex multi-solvent sequences, thereby introducing additional solvent burdens and process complexity [207]. Even where solvent recycling is attempted, solvent performance can degrade across reuse cycles. In a choline cloride:glycerol NADES system regenerated by vacuum-assisted evaporation (2 h at 90 °C), rutin extraction efficiency declined to 92%, 87%, and 81% of the fresh solvent after one, two, and three reuse cycles, respectively, indicating that solvent make-up and quality control may become important scale-up cost drivers [208].

Additional concerns arise from solvent-dependent co-extraction and safety assessment. In seaweed systems, metal co-extraction must be evaluated case by case because macroalgae can contain hazardous inorganic arsenic and cadmium, and solvent choice can materially influence their mobilization [209]. Although some NADES may co-extract fewer trace metals than water or acetone, this advantage is formulation-dependent and cannot be generalized. Moreover, despite being composed of "natural" constituents, NADES do not exhibit uniformly low toxicity. Cytotoxicity has been shown to depend strongly on solvent composition and component ratio, with several choline-chloride-based NADES displaying measurable toxicity in mammalian cell assays [210]. Collectively, these limitations indicate that NADES deployment is

frequently constrained by viscosity-driven mass-transfer and handling limits, the need for dilution or thermal conditioning that can alter solvent behavior, and the non-trivial burden of solvent recovery and quality control, all of which can erode the presumed advantages over conventional hydroalcoholic systems [211,212].

5. Technology readiness level (TRL) and societal readiness level (SRL)

The technology readiness level (TRL) is a systematic framework developed by NASA in the 1970s to assess the maturity of technologies throughout their development lifecycle [213]. It ranges from TRL 1, where fundamental principles are observed, to TRL 9, which signifies validation through successful operational deployment (Fig. 2). The TRL scale provides a structured pathway for transitioning technologies from research to real-world applications, supporting strategic decision-making on investments and implementation.

Complementing TRL, the societal readiness level (SRL) framework, introduced by Innovation Fund Denmark, evaluates a technology's readiness for societal adoption. It considers user uptake, public acceptance, and societal impact, focusing on the social dimensions of innovation [214]. Like TRL, SRL follows a nine-level scale, from SRL 1 (identifying societal needs and challenges) to SRL 9 (full societal integration and widespread acceptance) (Fig. 3). Initially conceived to expand TRL's scope, SRL has since been adopted to assess the societal impact of EU-funded research and innovation projects, particularly within public services during the 2021–2027 programming period. Together, TRL and SRL provide a holistic assessment framework that balances technical feasibility with societal relevance.

While SRL often focuses on public perception and consumer acceptance, its advancement also depends on industrial stakeholders, regulators, and policymakers. Industry determines whether technologies can be scaled and commercialized, while policy and regulation shape pathways for social adoption. Moreover, societal readiness is inherently context dependent and multi-actor. In regions prioritizing sustainability, supportive policies and consumer expectations may accelerate SRL progression, whereas in markets driven by efficiency, profitability, or rapid market deployment, adoption may depend more on industrial uptake and market demand. Moreover, in sectors governed by strict health and safety regulations, public health concerns may limit adoption regardless of industrial interest or high technical maturity. Thus, SRL should be viewed as a dynamic framework influenced by technical feasibility, stakeholder engagement and acceptance, policy/regulatory conditions, and market adoption pathways.

TRL and SRL capture different dimensions of progress, and they do not always advance in parallel. A technology with a high TRL may still face societal resistance, while strong societal demand alone does not ensure technical feasibility. Therefore, a combined TRL–SRL analysis enables a comprehensive evaluation, identifying gaps in technical maturity or societal readiness. The case of hexane extraction in vegetable oil production illustrates this divergence. Hexane extraction, a mature and well-established process that has been employed for decades as the principal method for producing most of the world's vegetable oil, has achieved a very high TRL. It recovers nearly all available oil from seeds at low cost and remains the industry standard for large-scale production [215]. However, its SRL is uneven, particularly in Europe, due to environmental and occupational health concerns. Hexane, a VOC, contributes to photochemical smog and ozone formation and is linked to neurotoxicity and other adverse health effects [216]. These risks have intensified consumer demand for clean-label products and heightened sensitivity to potential solvent residues in foods—trends especially visible in Europe, Australasia, and North America [217]. Consequently, European regulatory authorities have adopted stricter policies on hexane use, reinforcing these societal concerns and accelerating the search for safer and more sustainable extraction technologies.

A similar TRL–SRL mismatch is evident in genetically modified organisms. Technologically, engineered varieties, such as Bt corn and glyphosate-resistant soybeans, have reached a high TRL [218]. In

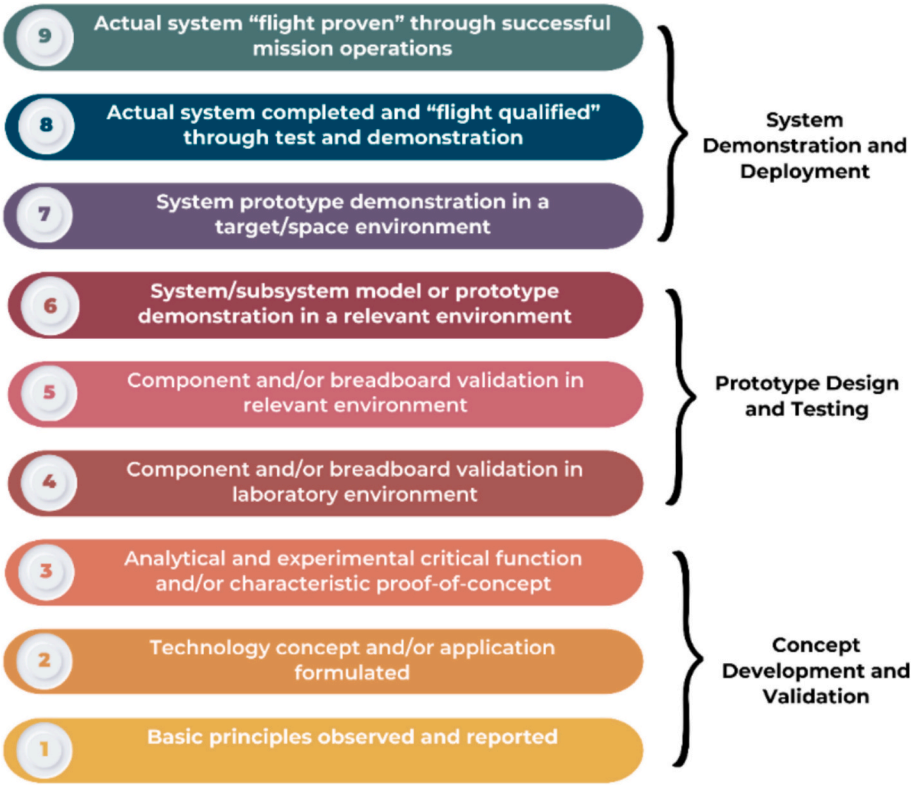


Fig. 2. Technology readiness level (TRL) scale developed by NASA to evaluate a technology's maturity and readiness for deployment.

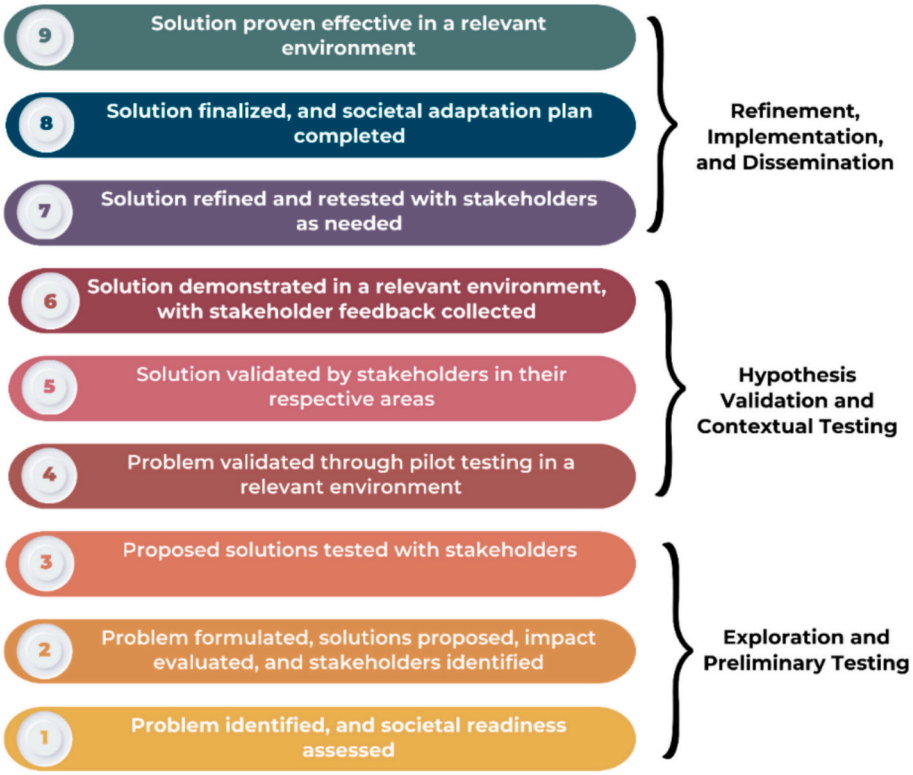


Fig. 3. Societal readiness level (SRL) scale developed by Innovation Fund Denmark to evaluate a technology's readiness for societal adoption.

countries such as the United States, Brazil, and Argentina, genetically modified crops account for a significant proportion of agricultural production [219,220]. Notably, in Argentina, virtually all major crops are genetically engineered, with 100% of soybean, 99% of corn, and 100% of cotton plantations being transgenic [220]. However, societal readiness remains regionally uneven. In Europe, public skepticism, ethical debates, and stringent regulations have restricted their use despite demonstrated technical maturity [221]. Multiple concerns related to food safety, environmental impact, and the role of multinational corporations in agriculture continue to hinder societal acceptance.

Comparable patterns are observed in lab-grown (cultivated) meat, a technology that has reached an advanced stage of development, with multiple companies operating pilot-scale facilities worldwide (e.g., Aleph Farms, Believer Meats, and BioTech Foods). However, societal acceptance remains limited due to high production costs and persistent consumer skepticism concerning safety and naturalness [222]. Together, these examples illustrate how high technical maturity does not necessarily guarantee societal acceptance, reinforcing the importance of a combined TRL–SRL perspective when assessing extraction technologies for bioactive compounds.

To improve transparency, reproducibility, and comparability, this review introduces extraction-specific scoring rubrics that operationalize the established NASA TRL scale and the Innovation Fund Denmark SRL framework for the assessment of extraction technologies (Tables 6 and 7). These rubrics do not replace the underlying TRL and SRL frameworks; rather, they translate each level into explicit, extraction-relevant minimum qualifying evidence.

The TRL rubric was designed to translate generic readiness levels into criteria that are directly interpretable for extraction systems. In this context, level assignment depends not only on whether extraction is possible, but on whether the process has been demonstrated with sufficient technical depth, integration, robustness, and operational control to justify progression to the next stage. For example, the rubric distinguishes between early laboratory proof of concept, broader laboratory validation across operating conditions, bench-scale integration with at least one primary separation step, pilot-scale operation with evidence of recovery and reuse, and higher stages involving process-line integration, compliance readiness, and repeated operational use.

The SRL rubric was designed to reflect the fact that societal readiness is not determined solely by public perception, but also by the interaction of market demand, stakeholder confidence, regulatory compatibility, and the practical conditions required for adoption. Accordingly, the rubric captures progression from early problem definition and value framing, through stakeholder consultation and structured acceptance evidence, toward pilot validation with users, early market uptake, repeated adoption across contexts, and eventual integration into routine sectoral practice. This allows the societal dimension of readiness to be assessed more systematically and with greater consistency across technologies.

TRL scores were assigned according to the highest level supported by the available technical evidence, including peer-reviewed studies, pilot- or industrial-scale reports, technical white papers, company documentation, and commercial evidence. SRL scores were assigned according to the highest level supported by the available societal and market evidence, including stakeholder-related evidence, studies of social perception and acceptance, regulatory acceptance, adoption signals, and evidence of market or sector uptake. All assessments were interpreted specifically in the context of extraction technologies for bioactive compounds and were conducted by author consensus using the predefined TRL and SRL rubrics. A given TRL or SRL level was assigned only when the minimum qualifying evidence defined in the corresponding rubric was judged to be sufficiently supported by the available literature. Where evidence for the next level was partial, inconsistent, or limited in scope, the assessment was not advanced. The evaluation was qualitative and rubric-based rather than numerically weighted, and the same decision logic was applied consistently across all technologies. Isolated reports of advanced deployment were not treated as sufficient to define overall readiness unless they were supported by evidence of repeatability, process relevance, or broader implementation consistent with the rubric criteria.

Table 6
Extraction-specific rubric used in this review to assign technology readiness level (TRL) scores to extraction technologies.

TRL	Level description	Minimum qualifying evidence
1	Basic principles observed	Plausible extraction mechanism defined (e.g., mass transfer, solvation, cell disruption); key operating variables identified (e.g., temperature, pressure, time, solvent or working fluid composition, solvent-to-feed ratio).
2	Concept formulated	Intended application defined (e.g., target compound, matrix, intended quality attributes); conceptual process flow described (e.g., principal unit operations, solvent or working fluid, and primary recovery steps).
3	Lab proof-of-concept	Target compound or fraction confirmed and quantified; core performance metrics reported consistently (e.g., yield, selectivity, productivity); basic repeatability demonstrated ($\geq$2 independent runs).
4	Lab validation	Performance validated across a defined operating window ($\geq$2 conditions); preliminary mass balance reported, including impurity or co-extractive characterization; boundary conditions and key process sensitivities identified from observed limitations (e.g., thermal degradation, interfacial instability, fouling); solvent-matrix compatibility across the relevant polarity range established.
5	Bench prototype	Bench-scale demonstration completed, including extraction and $\geq$ 1 primary downstream separation step(s); evidence of solvent or working fluid chemical stability obtained over $\geq$3–5 recycle loops; process robustness demonstrated against relevant feedstock variability (e.g., moisture content, particle size distribution, composition); primary techno-economic drivers identified qualitatively (e.g., major equipment class, utilities, solvent recovery burden).
6	Pilot demonstrated	Pilot-scale operation demonstrated over sustained runs sufficient to reach stable operation and reveal drift or instability; basic operating procedures and control approach documented; solvent or working fluid recovery and reuse demonstrated at proof-of-feasibility level (accounting for $\geq$90–95% of solvent, where applicable).
7	Demonstrated in operational environment	System demonstrated in an operationally relevant environment at pilot-scale throughput; product consistently meeting defined specifications; integration with a realistic process line demonstrated (e.g., utilities, safety systems, hygiene or cleanability requirements); sanitary design and cleanability procedures validated, where applicable; operational safety and environmental compliance confirmed via formal hazard assessment and established effluent management systems.
8	System complete and qualified	Pre-commercial or commercial-scale unit demonstrated to be reliable and maintainable through repeated operation with planned maintenance; full technical readiness for regulatory certification and formal compliance pathway finalized or in late-stage progression for the intended sector (e.g., GMP/ATEX/ISO, operating permits).
9	Operational deployment	Technology proven through sustained commercial operation and multi-site deployment, where relevant; high operational availability verified over extended operating periods; ongoing regulatory compliance, safety performance, and process consistency documented under standard industrial conditions.

Table 7
Extraction-specific rubric used in this review to assign societal readiness level (SRL) scores to extraction technologies.

SRL	Level description	Minimum qualifying evidence
1	Societal/market need defined	Clear problem and intended benefit defined (e.g., safer solvent, clean-label, lower energy); primary stakeholders identified.
2	Value proposition and adoption barriers framed	Clear value proposition defined relative to current practice; initial adoption barriers identified (e.g., cost, safety, consumer perception, regulatory burden).
3	Early stakeholder engagement	Documented engagement with at least one relevant stakeholder group (e.g., industry user, regulator, community group, researchers); stakeholder feedback and concerns summarized; initial sector acceptance requirements identified (e.g., compliance expectations, quality expectations, operational constraints).
4	Acceptance explored in relevant context	Structured acceptance evidence obtained (e.g., interviews, surveys); applicable rules, standards, and likely compliance hurdles identified; market/user acceptance criteria for products made using the technology defined (e.g., safety, purity, residual-solvent limits, labeling expectations); downstream requirements with potential adoption implications identified.
5	Adoption feasibility validated	Evidence of potential user willingness to trial obtained (e.g., pilot partner, funded trial, procurement interest); key safety and quality requirements for the intended market identified; preliminary procurement and business constraints identified (e.g., CAPEX/OPEX drivers, vendor/service availability, supply-chain dependencies).
6	Demonstration with stakeholders	Documented pilot or field-relevant use-case showing both benefits and operational constraints; required product safety and quality checks underway or preliminary limits met; stakeholder expectations for handling residuals, solvent management, waste, or co-products defined; likely compliance route for the intended sector identified and judged feasible.
7	Early market uptake	Evidence of initial uptake beyond a one-off pilot obtained (e.g., paid trials, repeat trials, procurement commitment, licensing discussions); at least one intended user willing to adopt under realistic conditions; practical evidence of conformity with relevant sector acceptance and compliance expectations in the intended application.
8	Established adoption across contexts	Repeated adoption across multiple users, sites, product types, or regulatory contexts; sector-appropriate quality assurance and documentation practices operating in a verifiable manner; supporting supply, service, or operational infrastructure sufficiently reliable to enable continued use; stable stakeholder acceptance demonstrated beyond pilot-dependent conditions.
9	Full societal integration	Routine use in the target sector(s); stable acceptance across relevant stakeholder groups, regulatory expectations, and operational settings; recognition as an established extraction option rather than a novel exception; sector-appropriate governance, quality systems, and supplier/service ecosystems mature and durable; public and professional perception broadly stable and favorable.

Because this was a literature-based comparative assessment rather than a direct audit of each platform, scores were assigned conservatively as ranges rather than fixed single-point values to avoid overstating precision. Accordingly, TRL and SRL were expressed as bounded intervals (e.g., TRL 3–4 or SRL 4–5) that reflect both the most defensible level supported by the available evidence and a margin of uncertainty around the exact position of the technology within that stage of development. This approach recognizes that readiness progression is often gradual rather than strictly discrete, particularly when technologies are transitioning between adjacent phases such as conceptual validation, laboratory demonstration, bench development, pilot translation, or early adoption. In this interpretation, the lower bound represents the level securely supported by the available evidence, whereas the upper bound represents the nearest subsequent level that appears plausible but cannot yet be assigned with full confidence because the evidence remains incomplete, heterogeneous, context dependent, or limited in scale. Applying ranges consistently across all technologies therefore provides a more transparent and cautious basis for comparison.

Because direct industrial deployments for extracting bioactives from brown seaweed remain limited, evidence from analogous applications (e.g., bioactive extraction from other botanicals or marine matrices) was also considered where process principles and equipment were reasonably transferable. Because several TRL and SRL estimates draw partly on deployments in other food sectors (e.g., olive oil, juice, botanicals), seaweed-specific validation is needed before assuming equivalent performance for marine macroalgae. Brown-algal slurries are typically saline and may be highly viscous due to alginates and other hydrocolloids, which can accelerate corrosion and scaling, promote electrode fouling, and affect energy delivery. For example, in PEF systems, high salinity and suspended solids can increase the risk of electrode corrosion and deposit formation, affecting field uniformity and operational stability [143]. In UAE, cavitation efficacy depends strongly on the medium; increased viscosity changes bubble formation and collapse behavior and can require higher acoustic intensities [223]. Therefore, TRL and SRL levels inferred from non-marine applications are best interpreted as evidence of platform maturity and transferability potential, with final readiness for seaweed bioprocessing requiring confirmation under representative marine-biomass conditions.

While this approach provides a structured overview of readiness across technologies, it has inherent limitations. The TRL assessment remains partly dependent on the interpretation of available technical evidence, particularly because reporting quality and validation depth vary across studies. Similarly, SRL assessment remains context dependent, as societal readiness can vary across regions, regulatory systems, industries, and user groups. Additionally, the relative absence of long-term field studies and commercial case studies for many emerging extraction methods further limits the comprehensiveness of these evaluations. Therefore, this analysis should be viewed as a structured and evidence-based comparative assessment rather than as a definitive or universally fixed classification. Applying this combined framework, Table 8 summarizes the TRL and SRL levels assigned in this review for the emerging extraction methods discussed, based on the evidence base described above and anchored to the extraction-specific rubrics provided in Tables 6 and 7.

Strengthening TRL–SRL assessment frameworks is essential for fair evaluation, but successful industrial diffusion also requires strategies that bridge the gap between technical validation and societal acceptance. Adoption of emerging extraction technologies, therefore, depends on integrated efforts combining technological maturity, social trust, and regulatory support. Evidence from organic markets shows how initially less-efficient practices gained global traction through certifications, public incentives, and communication campaigns emphasizing health and sustainability, shifting consumer preferences [224–226]. By analogy, emerging extraction technologies can become attractive

Table 8
Technology readiness level (TRL) and societal readiness level (SRL) assessment of various emerging extraction methods for bioactive compounds. Color coding: red (1–3), yellow (4–6), green (7–9).

Extraction Method	TRL	SRL	Assessment Summary
Physical Methods			
Pulsed electric field-assisted extraction (PEF-AE)	7–8	6–7	Multiple pilots and early industrial integrations (juices/olive, botanicals) show repeatable gains and manufacturing-readiness; however, case-specific design, electrode fouling, and high acquisition costs temper diffusion.
Pressurized liquid extraction (PLE)	7–8	6–7	Reproducible lab-to-pilot performance and recognized protocols attest to technical maturity, while specialized expertise and equipment qualification requirements limit broad adoption.
Microwave-assisted extraction (MAE)	7–8	7–8	Proven efficacy with pilots and some industrial lines (cannabis, cosmetics) and strong time/solvent savings; however, scale-up physics and high unit costs limit ubiquity.
Ultrasound-assisted extraction (UAE)	7–8	7–8	Pilots and niche industrial lines (olive oil, seaweeds) validate throughput and energy/yield benefits; however, reactor scale-up uniformity, horn erosion/metal shedding validation, and standardization remain hurdles.
Thermal Methods			
Subcritical water extraction (SWE)	7–8	7–8	Pilots and niche deployments show maturity; however, thermal degradation risks, corrosion control, and costly high-pressure infrastructure slow adoption.
Supercritical Fluid Methods			
Supercritical CO_2 extraction ($SCCO_2$)	8–9	8–9	Longstanding full-scale use (coffee, hops, botanicals) and solvent-free, tunable operation underpin strong technical and societal readiness despite high capital/safety requirements.
Biochemical Methods			
Enzyme-assisted extraction (EAE)	7–8	7–8	Pilot/industrial demonstrations show selective, mild extraction; however, maturity is constrained by enzyme cost/stability, matrix variability, and tight process control.
Solvent-based Methods			
Natural deep eutectic solvents (NADES)	**3–4**	4–5	Compelling lab-scale performance and green credentials drive interest; however, viscosity/recovery challenges, inconsistent toxicological evidence, and scarce pilot demonstrations restrain adoption.

alternatives to conventional methods if their development is paired with a structured adoption strategy that links innovation to market readiness. Such a strategy should include, among other measures, (i) pilot-scale trials that validate laboratory findings under real conditions and reduce regulatory or investment risks; (ii) public incentives (e.g., grants, tax credits, procurement programs) that lower adoption costs; (iii) clear communication and labeling to convey safety, health, and sustainability benefits; (iv) cross-sector alliances between producers (e.g., seaweed producers) and end-user industries (e.g., nutraceuticals and cosmetics) to ensure stable supply and credibility; and (v) recognized standards or certifications that help differentiate and validate new technologies in the marketplace.

Moreover, the role of emerging digital trends should not be overlooked as additional catalysts to accelerate both TRL and SRL. Digital twins allow virtual modeling and simulation of extraction processes, reducing experimental trials and optimizing resources before scale-up [227]. Similarly, artificial-intelligence-assisted process optimization (e.g., machine learning, chemometrics) can rapidly identify operating conditions that maximize yield while minimizing energy and solvent consumption, with successful applications already reported for bioactive extraction using $SCCO_2$ and hybrid "green" methods [228,229]. These tools can accelerate TRL by shortening iteration cycles and strengthen SRL by producing robust, transparent evidence for regulators, consumers, and investors. Together, these strategies form a strong foundation for bridging technical innovation with industrial and societal adoption.

5.1. Physical methods

5.1.1. Pulsed electric field-assisted extraction (PEF-AE)

PEF-AE has evolved from a laboratory concept into a near-commercial technology, with numerous pilot trials and growing industrial demonstrations confirming its potential as a fast, energy-efficient, and non-thermal extraction method [83,230–232]. For instance, a pilot-scale countercurrent system operating at 600 V × cm^{-1} for 10–50 ms significantly improved inulin extraction from chicory roots, achieving yields at 60 °C comparable to conventional extraction at 80 °C while maintaining juice purity above 87% [231]. Similarly, a pilot-scale trial found that applying PEF to olive paste (2 kV × cm^{-1}; ≈11.25 kJ·kg^{-1}) increased extraction yield by 13.3% versus control and elevated bioactives (total phenolics +11.5%, phytosterols +9.9%, tocopherols +15.0%) without adverse sensory effects [232]. Additionally, PEF is used industrially for juice and milk pasteurization, with continuous platforms (e.g., OptiCept) integrated into industrial lines, indicating the manufacturing readiness of the core technology [233,234].

Despite these promising demonstrations, several technical barriers limit PEF-AE from broader adoption. Extraction efficiency depends on the raw material's electrical conductivity and cell wall structure, often requiring case-specific tuning or pretreatments [83]. Moreover, during high-field treatment, electrochemical reactions and electrode corrosion can occur in the treatment chamber, impacting equipment life and potentially product quality unless carefully mitigated (e.g., using inert electrodes, pulse shapes, cleaning in place) [143]. Although PEF can reduce energy use versus thermal processes, its high capital cost and localized heating limit broad applicability, particularly for thermolabile compounds [235]. Based on the above evidence, PEF-AE can be rated as TRL 7–8, reflecting multiple pilot-scale demonstrations and early industrial integration.

Beyond technical maturity, the successful industrial adoption of PEF-AE also depends on its SRL. PEF-AE aligns with clean-label and sustainability expectations by lowering energy demand, shortening processing times, and reducing reliance on chemical additives [236]. Moreover, its ability to extract natural compounds with limited thermal degradation also fits market trends for natural and sustainable ingredients. Notably, a pilot cost-benefit analysis in an olive oil mill found that integrating PEF reduced malaxation time by 33% (45 → 30 min) without degrading quality, i.e., the oil remained "extra-virgin" under EU legal standards, signaling regulatory compatibility [232]. Moreover, at 5 t·h^{-1} throughput with equipment valued at ≈EUR 450,000, the analysis projected an annual return on investment (ROI) of approximately 20%, indicating attractive economics for medium-to-large plants. Notably, the modular and flexible nature of PEF systems facilitates integration into diverse industrial and bioprocessing contexts, supporting broader societal adoption [237,238]. Moreover, growing industrial engagement from equipment developers such as Pulsemaster (The Netherlands) and ScandiNova (Sweden), who are scaling PEF systems from laboratory to industrial settings, suggests progress toward broader industrial implementation [239,240]. Public perception of PEF is generally favorable when benefits are clearly communicated [241]. Consistent with this trajectory, the PEF market size was valued at USD 300 million in 2024, and it is expected to reach USD 750 million by 2033, indicating rising interest among industry and policy stakeholders and a corresponding increase in SRL [242].

However, significant socio-economic hurdles remain, including high up-front capital costs (USD 100,000–500,000), limited accessibility for small- and medium-sized enterprises (SMEs), the need for adaptive regulatory frameworks, and the absence of comprehensive financial comparisons with conventional methods [81,242,243]. Laboratory and pilot-scale PEF systems (1–4 kW) cost ≈USD 6500–9800 on the secondary market, while industrial-scale systems (≈200 kW) reach ≈USD 300,000–500,000, excluding ancillary equipment, underscoring steep scale-related costs [244,245]. Moreover, consumer acceptance of PEF technology and products depends strongly on clear benefit communication and familiar terminology; when unfamiliar, consumers perceive higher risk and show lower purchase intent, whereas transparent messaging improves acceptance [246]. From this perspective, PEF-AE can be rated at SRL 6–7, having been validated in relevant environments with growing stakeholder interest, but still requiring cost reductions, clearer standards, and targeted communication strategies to achieve broader societal uptake. Current efforts emphasize scaling the technology and addressing practical adoption barriers, such as cost and operational usability, exemplifying refinement driven by stakeholder engagement, consistent with SRL 6–7 [231,247].

5.1.2. Pressurized liquid extraction (PLE)

PLE is a green and efficient method increasingly used at pilot scale to recover bioactive compounds from diverse biomass sources [248–252]. Across pilots, laboratory parameters have been transferred to larger vessels with minimal performance loss when using aqueous ethanol at elevated temperature and pressure to accelerate mass transfer. For instance, intermittent PLE of passion-fruit leaves successfully transferred lab-scale parameters (70% ethanol, 80 °C, 5 × 6 min static steps with 100% solvent renewal) from 34 mL to 2 L, maintaining comparable extraction-curve profiles and achieving 35.6 ± 1.5% total solids from ≈3.8 L of extract [250]. Similarly, a 10 L pilot using mung-bean seed-coat by-products (160 °C, 9 MPa, 50:50 ethanol–water *v*/v) achieved lab-comparable performance while preserving the extract's composition and quality [253]. This consistency across scales highlights its robust mass-transfer behavior and practical scale-up potential [250]. PLE is considered an automated technique capable of in-cell cleanup and in-line analytical coupling, which reduces downstream processing and enables real-time monitoring [254]. This integration has been demonstrated at pilot scale for açaí pulp by coupling PLE with in-line solid-phase purification and on-line high-performance liquid chromatography detection, enabling real-time process monitoring and yielding extracts approximately fivefold more concentrated than extraction alone [255].

However, PLE systems are prone to pressure faults and blockages when matrices are fine, wet, viscous, or poorly dispersed [256]. In practice, liquid or slurry samples must be pre-blended with an adsorbent (e.g., diatomaceous earth) or dried to a controlled residual moisture to preserve permeability and stable back-pressure during extraction [257]. PLE is also unsuitable for heat- or pressure-sensitive compounds, and its

broad solvation range may lead to co-extraction of unwanted substances, increasing purification steps [258,259]. Based on the evidence, PLE for bioactive extraction is best rated TRL 7–8, supported by robust laboratory validation and multiple pilot-scale demonstrations with successful parameter transfer.

From a societal readiness standpoint, PLE aligns well with green chemistry and sustainability goals. Its reduced solvent use, lower energy demand, and shorter extraction times have gained broad acceptance among research and industrial stakeholders [84,260]. Notably, PLE has achieved full validation and regulatory acceptance in environmental and analytical contexts (U.S. EPA Method 3545 A) for extracting semi-VOCs, including pesticides and hydrocarbons, from soils, sediments, and sludges [261]. Moreover, its reliability is reflected in widespread laboratory adoption of commercial systems such as Thermo-Fisher's ASE and Büchi's SpeedExtractor since the mid-2000s [262,263]. However, the need for high-pressure equipment (often up to 100 bar) raises capital costs and complicates adoption, particularly for SMEs [174]. Typical lab systems fall in the USD 15,000–80,000 range, with specific models (e.g., Thermo Dionex ASE 350) publicly listed new at USD 25,000 [264,265]. In addition, recurrent maintenance, consumables, and specialized operator training add operating costs that further disincentivize adoption despite demonstrated technical advantages [266]. Finally, public familiarity is limited because PLE is marketed as an analytical tool rather than a consumer-facing technology, and fragmented nomenclature (PLE/ASE/PFE) further obscures visibility [267]. Considering limited full-scale deployments in the target sectors, moderate stakeholder familiarity, and capital barriers, PLE is best assessed at SRL 6–7, reflecting validation in relevant environments but incomplete diffusion into production contexts.

5.1.3. Microwave-assisted extraction (MAE)

MAE is a mature green technology widely validated at laboratory, pilot, and industrial scales for recovering diverse bioactives, including lipids, phenolics, alkaloids, and essential oils while reducing solvent use, shortening extraction times, and often improving yields and bioactive integrity versus conventional methods [268–270]. For example, pilot-scale demonstrations report solvent-free MAE of essential oils (e.g., rosemary, white thyme, and curcuma) in minutes rather than 2–4.5 h for hydrodistillation, achieving comparable or greater yields with improved antioxidant and antimicrobial activity [271–273]. At the industrial scale, a continuous-flow 915 MHz MAP™ system has processed cannabis slurries at throughputs up to 30 kg $\times$ h^{-1} using 360 L $\times$ h^{-1} ethanol, achieving ≈93% THC recovery and 55–61% extract purity [274].

Despite its maturity, MAE faces several scale-up challenges. Maintaining uniform electromagnetic fields in large reactors is challenging, resulting in hot spots and efficiency losses [275]. Therefore, reactor design must control power reflection, mode patterns, and load matching to protect equipment and performance [276,277]. Extraction performance also depends on the solvent type, solvent-to-solid ratio, microwave power, temperature, and biomass properties, complicating standardization across feedstocks. Overall, based on robust laboratory performance, multiple pilot-scale demonstrations, and early industrial deployments supported by an emerging supplier base, MAE is appropriately rated TRL 7–8 for bioactive extraction.

From a societal readiness perspective, MAE aligns with sustainability and clean-label priorities through reduced energy and solvent inputs as well as shorter processing times. MAE also benefits from broad consumer familiarity with microwaves, which enhances perceived safety, especially when benefits such as solvent-free extraction and minimal nutrient loss are clearly communicated [278]. These attributes support uptake in markets where “clean processing” is a key differentiator (e.g., natural colorants, herbal supplements, cannabis oils) [279,280]. Moreover, companies like Radient Technologies (Canada) and Croda (United Kingdom) show strong stakeholder confidence in MAE's commercial feasibility, while the presence of MAE-derived compounds in cosmetics, food, and herbal supplements indicates growing acceptance within regulated markets [281,282]. For instance, Radient Technologies operates the world's largest MAE facility, using its patented MAP™ platform to process up to five metric tons of biomass per day, and recovers lipids, alkaloids, and phenolics for cosmetics, food, nutraceuticals, pharmaceuticals, and biofuels [274,281]. Similarly, Croda applies MAE industrially to produce high-value plant extracts for personal care, and systems from Ferrite Microwave Technologies (USA) and SAIREM (France) further confirm integration across food, pharmaceutical, and cosmetic sectors [282–284]. This industrial confidence is reflected in the global MAE unit market, estimated at USD 585 million in 2024 and projected to reach USD 1.2 billion by 2033 [285].

However, high capital investment costs pose economic barriers to broader adoption, especially for SMEs [286]. New microwave digestion/extraction systems generally cost USD 15,000–100,000, depending on capacity, automation, and performance features, while used units typically cost USD 8000–50,000, depending on condition and brand [287]. Industrial MAE systems are bespoke and sold by quotation. Moreover, misconceptions about microwave safety persist, including unfounded fears of nutrient degradation or radiation risk, which may influence consumer acceptance [288]. Interestingly, simply describing the process as “dielectric heating” improves acceptance compared with “microwaves”, underscoring the role of language in shaping public trust [289]. Finally, large-scale economic assessments remain scarce, forcing companies to rely on case-specific ROI analyses [290]. Taken together, these factors position MAE at SRL 7–8, reflecting established societal awareness and growing market confidence, but still short of full societal readiness due to persistent misconceptions, high capital costs, and limited large-scale economic validation.

5.1.4. Ultrasound-assisted extraction (UAE)

UAE is a green, non-thermal extraction method that promotes solvent penetration and cell disruption, yielding shorter extraction times, reduced energy demand, higher yields, greater purity, and superior retention of thermolabile constituents [91,291]. Its efficiency has been shown at pilot and industrial scales [91,292–294]. For example, a pilot-scale circulatory UAE of *U. pinnatifida* sporophyll using a 20 L system (960 W, 20 kHz, 30 °C, 3 h) achieved ≈53% extract yield, outperforming a conventional process (24.7%) and lab horn-UAE (33%), while also recovering fucoxanthin (≈3%) and low-molecular-weight polysaccharides [292]. The resulting extracts exhibited higher antioxidant capacity and anti-inflammatory effects, supporting technical feasibility and bioactivity at pilot scale. At an industrial scale, UAE has replaced malaxation in virgin olive oil production via a continuous sono-heat-exchanger system operating at 30 kHz, 15–18 kJ·kg^{-1}, and 23–27 °C, improving oil yield by 2% and extractability by 10% [294].

Despite these strengths, scale-up can produce uneven acoustic energy distribution in large reactors, compromising cavitation and extraction efficiency [91,295]. Probe-type ultrasound systems are more suitable for scale-up but still require flow-through systems or multiple probes to ensure uniform cavitation and avoid “dead zones” [296,297]. Moreover, real-time monitoring remains a bottleneck, though recent advances in near-infrared spectroscopy, piezoelectric sensors, and imaging techniques are improving process control [298,299]. Reliability is further reduced by equipment wear and fouling, particularly when processing viscous or particulate-rich materials. Collectively, the available evidence supports a TRL of 7–8 for UAE, with olive oil applications at TRL 8 and trending toward TRL 9 [294].

From a societal readiness perspective, UAE aligns strongly with sustainability and clean-label preferences by shortening processes and often reducing solvent and energy use, though water or food-grade solvents (e.g., ethanol) are commonly employed rather than true solvent-free operation [291]. In a comparative life cycle assessment (LCA) on polyphenol recovery from chicory grounds, water-UAE lowered average impacts by ≈20% across multiple categories versus the baseline, whereas switching to ethanol increased several impacts despite yield gains—underscoring context-dependent “green” outcomes [300].

Industrial adoption is evidenced by companies such as Natac (Spain) and Eden Ecosystem (France), which apply UAE to obtain high-quality botanical extracts while reducing energy use and processing times [301,302]. Major equipment vendors include Hielscher Ultrasonics (Germany), Industrial Sonomechanics (USA), and Sonics & Materials (USA), known for their scalable, high-performance systems used in pharmaceuticals, botanicals, and food industries [303–305]. These companies supply a full spectrum of equipment, ranging from research-scale units (hundreds of watts, $<10\ L{\cdot}h^{-1}$) to high-throughput industrial systems (several kilowatts operating in continuous flow, processing hundreds to thousands of liters per hour). Furthermore, reported estimates for the ultrasonic-extraction machinery segment indicate a value of ≈USD 150 million in 2024 with projections to ≈USD 300 million by 2033, signaling growing vendor participation and capital deployment [306].

Nonetheless, the high capital investment required for industrial-scale UAE—covering transducers, power units, and control systems—together with ongoing maintenance and energy costs, is prohibitive for many SMEs [307]. Up-front acquisition of laboratory ultrasound extraction systems typically ranges from ≈USD 2000–8000 for 200–550 W probe units (e.g., Hielscher UP200St/UP400St, Branson SFX550), while pilot/industrial sonicators (1–4 kW) are priced by quotation; for example, an Industrial Sonomechanics ISP-3600 W (3.6 kW) continuous processor lists for ≈USD 66,066–78,233 [308–310]. Furthermore, consumer skepticism and reluctance to pay a premium for UAE-derived products persist, reflecting limited familiarity with the technology and limited benefit communication [311,312]. Collectively, the evidence supports an SRL of 7–8 for UAE.

5.2. Thermal methods

5.2.1. Subcritical water extraction (SWE)

SWE is a mature green technology for extracting bioactives and valuable chemicals from diverse feedstocks. Studies report successful scale-up from lab to pilot and industrial scales with consistent yields and reproducibility [178,313–315]. For example, pilot-scale reactors up to 25 L have demonstrated robust process control and reliability at industry-relevant scales [314]. A lab-to-pilot system on brewer's spent grain (170 °C, 22 min) achieved 56% carbohydrate release, 78% pentose yield, and notable recovery of proteins and phenolics with low inhibitor levels, maintaining reproducibility upon scale-up [178]. A pilot study on turmeric achieved 13.58% curcuminoids at 135 °C for 5 min using a 50:50 water–ethanol mixture, demonstrating faster and more efficient recovery than conventional atmospheric ethanol extraction [315]. Comprehensive techno-economic analyses (TEAs) further indicate that SWE is competitive with, or superior to, conventional extraction, offering higher net present value, lower manufacturing costs, shorter payback periods, and better environmental performance than ethanol extraction [316]. Economic evaluations further support industrial viability, particularly when integrated with biorefinery approaches [317,318]. Moreover, companies such as Nikken Foods (Japan) and Exinnov (France) already use SWE for the selective extraction of high-value compounds [319,320].

Despite these advances, unresolved technical limitations remain. A significant concern is the thermal degradation of heat-sensitive compounds at the high operating temperatures typically used. Moreover, selectivity–degradation trade-offs are intrinsic to high-temperature water; during SWE, sugars and amino acids can dehydrate and undergo Maillard reactions, forming 5-hydroxymethylfurfural and browning products that alter color and flavor, complicating food compliance [177,321]. SWE is also less effective for poorly water-soluble compounds, often requiring co-solvents like ethanol or surfactants to improve extraction efficiency [322]. Moreover, at larger scales, corrosion from hot, pressurized, reactive water can damage metal components and increase maintenance costs [94,97]. Considering its proven scalability, economic competitiveness, and existing industrial applications—yet acknowledging thermal, solubility, corrosion, and scale-up challenges—SWE is most appropriately rated at TRL 7–8, reflecting near-industrial maturity but not full commercialization across all sectors.

Societally, SWE aligns strongly with green chemistry principles, avoiding organic solvents, enabling circular economy valorization of by-products, and lowering solvent burden in downstream purification [95,96]. Using water instead of organic solvents makes SWE particularly attractive for food, pharmaceutical, and nutraceutical applications, supporting consumer safety and regulatory compliance. Water is nonflammable, non-toxic, and inexpensive, all of which contribute to lower health and environmental risks compared to conventional solvents [96]. These advantages make SWE not only technically viable but also highly compatible with evolving societal expectations for sustainable and health-conscious production methods.

However, widespread adoption is limited by the high up-front cost of specialized high-pressure and high-temperature reactors and pumps [96]. Lab-scale SWE units cost ≈USD 3300–20,000 per system (model and volume dependent) [323,324]. Moreover, an industrial TEA reported the purchase cost of major equipment at NZD 1.35 million [316]. Moreover, because extraction methods are generally not required on consumer labels, the visibility of SWE remains low, limiting its recognition and societal acceptance. In addition, while standardized extraction protocols are essential for ensuring market readiness and industrial adoption, matrix-specific variation makes universal procedures difficult to implement [96]. Altogether, SWE aligns with green chemistry and circularity goals and is supported by credible pilot and techno-economic evidence, yet broader societal normalization and market-facing recognition are still evolving, consistent with SRL 7–8.

5.3. Supercritical fluid methods

5.3.1. Supercritical carbon dioxide extraction ($SCCO_2$)

$SCCO_2$ is a mature, commercially established technology for coffee decaffeination and hop extraction, with broad adoption across natural product processing [325–329]. Key advantages include tunable selectivity, low-temperature operation that preserves thermolabile compounds, rapid solvent removal yielding residue-free extracts, and use of a nonflammable, low-toxicity solvent [330]. These benefits have been repeatedly demonstrated at pilot scale, supporting its extension to diverse natural matrices. For instance, a 2-L system produced high-quality Moringa seed oil with up to 75.27% yield at 35 MPa and 30 °C, with composition comparable to conventional methods and selective enrichment of oleic acid, tocopherols, and sterols at lower pressures [328]. Similarly, a study on safflower seed oil extraction demonstrated successful scale-up from a 0.5 L bench system processing 100 g of seeds to a 260 L pilot unit handling 46.5 kg per run. The experimental results closely aligned with model predictions, and the resulting oil exhibited superior quality compared to conventional methods [331].

Despite these strengths, several technical limitations remain. $SCCO_2$ systems operate at high pressures, demanding robust safety systems and specialized infrastructure (pressure vessels, seals, and pumps), complicating large-scale implementation and elevating capital costs [332]. Moreover, the apolarity of CO_2 limits its solubility for polar compounds, often requiring the use of co-solvents or higher operating pressures to improve performance, adding separation steps and design complexity [99]. Moreover, small temperature and pressure variations can strongly influence CO_2 density and mass transfer, extending optimization time. Overall, evidence of technical maturity, proven scalability, and widespread industrial use supports rating $SCCO_2$ at TRL 8–9.

Beyond technical maturity, $SCCO_2$'s societal readiness depends on economic feasibility, sustainability narratives, regulatory fitness, and public acceptance. Recently, $SCCO_2$ has gained significant attention due to the increasing demand for natural and organic products, as it enables the production of high-quality extracts without the use of harmful

solvents. By using CO_2, which is non-toxic, nonflammable, and indefinitely recyclable, $SCCO_2$ is widely regarded for its human health benefits and positive environmental impact [333]. From a regulatory perspective, CO_2 is already widely accepted as a processing medium in food and natural product manufacturing, and $SCCO_2$ processing typically avoids a residual-solvent compliance burden because CO_2 is removed during depressurization. Consequently, regulatory scrutiny tends to focus on extract specifications (e.g., contaminants and quality attributes) rather than on qualification or removal of a retained process solvent, which supports higher SRL compared with solvent systems that may remain in the product phase. Legalization of medicinal cannabis has further accelerated interest, as $SCCO_2$ yields high-purity cannabinoid extracts while preserving bioactivity [334,335]. $SCCO_2$ is also scalable, compatible with other extraction methods, and supports the valorization of agro-industrial and food waste, contributing to sustainability and circular economy goals [336,337]. Beyond pilot applications, $SCCO_2$ has become a standard industrial approach for extracting, fractionating, refining, and deodorizing lipids and essential oils, with extensive commercial adoption across the food and natural product sectors [333]. $SCCO_2$ is one of the most standardized and widely recognized industrial processes, particularly in the coffee and tea industries, where it operates at full commercial scale, decaffeinating over 150,000 tons of product annually across plants in the United States and Europe [329,338]. Global companies such as Phasex (USA) and Eden Labs (USA) have further demonstrated the versatility and scalability of $SCCO_2$ systems across diverse industries, with proven integration into food, nutraceutical, and cosmetic lines [338,339]. In New Zealand, Callaghan Innovation provides pilot facilities and scale-up support [340]. Likewise, companies such as Sanford Bioactives and SCENZA apply $SCCO_2$ to produce high-value natural extracts (e.g., mussel oil and plant-derived bioactives) [341,342]. Fueled by growing demand for high-purity, solvent-free products, the $SCCO_2$ market is set to grow from $1.5 billion in 2024 to $2.9 billion by 2033 [343].

Despite this maturity, adoption is often constrained by cost and infrastructure demands. Public listings indicate that pilot-scale units (5–20 L) range from USD 35,000 to 250,000, with price driven by vessel size, automation, and pressure rating [344,345]. Industrial systems typically require substantially higher up-front investment—often ranging from USD 200,000 to over USD 1 million for pressure-rated vessels, compressors, separators, automated controls, and facility modifications—which can be prohibitive for SMEs despite long-term savings from solvent recycling and improved product quality [346]. Moreover, CO_2 handling poses safety risks during operation, storage, and transfer; accidental releases or leaks are recognized occupational and environmental risks, necessitating gas detection, robust ventilation, personnel training, and confined-space protocols [347]. Additional challenges include feedstock-specific parameter optimization, consistent product quality, and clearer regulatory pathways for market entry [100]. Despite these obstacles, $SCCO_2$ remains one of the most advanced and commercially viable extraction methods available, offering a scalable, sustainable, and high-purity approach to bioactive compound extraction, justifying its high SRL of 8–9.

5.4. Biochemical methods

5.4.1. Enzyme-assisted extraction (EAE)

EAE has emerged as an efficient and environmentally sustainable method for isolating bioactive compounds. Enzymes offer high substrate specificity, operate under mild conditions, and reduce the need for harsh solvents, thereby enhancing selectivity, product quality, and energy efficiency [102]. EAE has been explored at pilot and industrial scales, particularly for oilseeds and plant biomolecules, yielding higher product recovery, improved quality, and lower environmental impact than conventional solvent extraction methods [348–351]. For example, pilot-scale EAE of grape pomace achieved high yields of phenolic acids (91.9%), flavonoids (92.4%), and anthocyanins (63.6%), comparable to sulfite-assisted extraction [348]. Similarly, a process scaled from 0.08 kg to 2 kg of extruded soybeans achieved yields of up to 99% oil, 94% protein, and 83% solids under two-stage countercurrent conditions, while reducing water use [349]. Enzymatic deproteinization of waste shrimp shells using papain and bromelain also removed 87.5% of protein with ≈24% less water than conventional routes [351].

Despite these advances, wider industrial adoption faces technical barriers, including high enzyme cost, limited reusability, and activity loss during processing [352]. Publicly listed bulk food-grade enzymes (e.g., pectinases and proteases) often sell for USD 4–15·kg^{-1} at feed grade and USD 20–60·kg^{-1} at food grade, illustrating the wide cost spread that challenges low-margin applications [353,354]. Nevertheless, pilot-scale and TEA studies indicate that EAE can be economically viable when co-products (e.g., proteins and fibers) are valorized [355]. Moreover, emerging industry initiatives—such as BASF's 2024 computer-assisted regression model with the Austrian Research Centre of Industrial Biotechnology and the University of Graz to accelerate biocatalyst performance and scale-up—further demonstrate industry commitment to lowering development costs and time-to-market [356]. EAE performance also depends on strict control of time, pH, temperature, and substrate ratio; slight deviations can reduce activity or cause denaturation of enzymes, making scale-up dependent on precise monitoring and control strategies [189,192,357]. Furthermore, the heterogeneity and complexity of plant cell walls and proteins further complicate standardization, as conditions and enzyme blends must be optimized for each substrate [352]. Enzymes must also be deactivated after extraction—typically by thermal treatment (80–90 °C) or by process adjustments and separation—to stop hydrolysis and meet safety regulations, adding extra cost and control requirements [358]. However, recent innovations such as enzyme immobilization and hybrid systems integrating EAE with other extraction technologies (e.g., supercritical fluids or ultrasound) are being developed to enhance industrial feasibility and reduce costs [102,359]. These technological advancements and market signals position EAE at a TRL of 7–8.

From a societal perspective, the long history of enzyme use in multiple sectors—ranging from food processing to pharmaceuticals, cosmetics, animal feed, textiles, paper, bioethanol, and detergents—has established their reputation as safe, efficient, and eco-friendly, fostering social normalization and public trust [360,361]. Reflecting this confidence, investments in enzyme technology research surpassed USD 500 million in 2023, catalyzing efforts to boost efficiency and expand industrial applications [362]. Further supporting its commercial viability and industrial potential, companies like Novozymes® (Denmark), Symrise AG® (Germany), and BASF (Germany), have actively developed and commercialized enzyme-based extraction solutions [363–365]. Fueled by the demand for more sustainable processes, the global enzyme market was valued at USD 9.84 billion in 2023 and is expected to reach USD 27.51 billion by 2035 [362].

Nonetheless, public and regulatory acceptance remains uneven. While enzymes used in traditional food processes are widely accepted due to familiarity, their use in modern industrial applications can sometimes raise ethical and regulatory concerns, particularly when derived from genetically modified organisms [366]. Moreover, limited public awareness of their sustainability benefits also dampens consumer support [367]. Allergenicity is another consideration: while consumer risk is typically low when enzymes are inactivated or removed, enzymes are recognized occupational sensitizers, necessitating exposure controls and verification of deactivation [368]. Rare but documented reactions—especially to plant cysteine proteases such as papain and bromelain, which can trigger anaphylaxis or occupational asthma—underscore residual risks for sensitized individuals [369]. Considering these factors, EAE's SRL is best characterized as 7–8, with further gains contingent on cost reductions, more transparent market communication, and continued stakeholder engagement.

5.5. Solvent-based methods

5.5.1. Natural deep eutectic solvents (NADES)

NADES are rapidly gaining traction as sustainable alternatives to conventional solvents due to their biocompatibility, non-toxicity, and strong extraction efficiency [106,107]. Most current research remains at the laboratory scale, where NADES have proven effective and sustainable for extracting diverse bioactive compounds from plants, food products, and environmental samples [132–135,370]. For instance, a lab-scale study demonstrated that a choline chloride–citric acid (1:1, 30%) NADES enabled efficient extraction of isoflavones from soy products, achieving enrichment factors of up to 598 and recoveries of 64.7–99.2% [370]. Similarly, a choline chloride–oxalic acid NADES combined with UAE yielded the highest levels of ellagic acid (3.21 ± 0.09 mg $\times$ g^{-1}) from *Geum japonicum*, outperforming conventional solvents such as methanol, ethanol, and acetone [371]. These studies highlight the potential of NADES to replace petroleum-based solvents in bioactive compound extraction. To date, scale-up has reached volumes of 300–500 mL, yielding promising but yet pre-pilot results [372,373].

Despite these advantages, NADES face technical challenges that hinder large-scale adoption. Many NADES exhibit high viscosity at room temperature, hindering solvent flow, diffusion, mixing, and pumping [205]. Although viscosity can be reduced by heat or water addition, water also alters polarity and solubility [374]. Because NADES cannot be readily stripped by evaporation, product recovery must instead rely on phase transfer or fractionation steps, such as dilution and precipitation, liquid–liquid partitioning with pH-assisted back-extraction for ionizable targets, adsorption and desorption on resins, or membrane separations; consequently, downstream processing becomes more unit-operation intensive, often raising water and solvent use and making stable solvent recycling more difficult [205,375,376]. As a result, demonstrating consistent and validated removal of NADES components, impurities, and degradation by-products becomes a critical requirement for food and pharmaceutical applications, where residual solvent limits, toxicological acceptability, and product purity must be substantiated. This downstream separation challenge remains one of the main factors constraining the SRL of NADES-based extraction systems. Moreover, sugar- and choline-based NADES can degrade or promote Maillard reactions at elevated temperatures, risking product modification unless processing conditions are carefully controlled [377,378]. These challenges highlight the need for further optimization before industrial-scale adoption. Based on current evidence, DES/NADES for bioactive compound extraction can be positioned at TRL 3–4, reflecting validation at laboratory and small bench scales, with early steps toward prototyping but not yet pilot scale.

While technical development remains at early stages, societal readiness is progressing in parallel. From a societal readiness perspective, NADES are increasingly recognized in research and industry for their sustainability, safety, and versatility, though the evidence is mixed. On the positive side, NADES support low-VOC, “green” process narratives, deliver strong extraction performance, and are often derived from benign, bio-based components. Their negligible vapor pressure reduces air emissions, and in some cases, their efficiency can reduce overall solvent use and promote safer operations [379]. However, several practical and environmental caveats counterbalance these strengths. High viscosity and mass-transfer limits complicate continuous processes, frequently requiring dilution, heat, or process aids (e.g., ultrasound or microwaves), measures that can erode their “green” advantage unless credible recovery and recycling strategies are demonstrated [380]. In addition, LCAs indicate that not all DES/NADES outperform conventional solvents; for example, cradle-to-gate impacts of choline chloride–urea (“reline”) exceed those of methanol and ethanol, challenging general claims of environmental superiority [211].

Safety considerations also temper societal readiness. While many NADES are assembled from pharmaceutically acceptable ingredients or components individually regarded as safe for food or pharmaceutical use, mixture-level toxicity is composition-dependent; thus, the safety profile of the individual components does not guarantee the safety of the final formulation. For example, pairing choline chloride with different hydrogen-bond donors caused significant cytotoxicity shifts: choline chloride–oxalic acid mixtures proved far more toxic to fish and human cell lines than choline chloride–glycerol, demonstrating that mixture toxicity depends on the specific pairings rather than the presumed safety of the individual components [381]. Furthermore, comprehensive human and environmental safety datasets remain limited, creating uncertainty for their approval in food and pharmaceutical applications [381]. Therefore, the toxicity of many DES/NADES components—and particularly their interactions with cellular membranes—still requires much more detailed investigation [382]. Accordingly, unlike $SCCO_2$ (where the solvent is already broadly accepted and is not typically a residue-limiting contaminant), NADES face formulation-specific regulatory hurdles. Even when individual constituents are pharmaceutically acceptable or individually recognized as safe for food or pharmaceutical use, the mixture can exhibit distinct toxicological behavior and may require mixture-level safety substantiation, impurity profiling, and validated downstream removal. This formulation-dependent regulatory burden can constrain SRL for novel NADES systems until standardized safety and purification frameworks are demonstrated at scale.

Public awareness of NADES also remains limited due to their technical nature and lack of mainstream exposure, which can slow social acceptance [374]. Nevertheless, companies such as Des Solutio (Portugal) and NADES Design (Croatia) are developing NADES-based solutions, signaling growing commercial interest [383,384]. One example is ImproVITA, a NADES-based formulation developed by Des Solutio made entirely from natural compounds and designed to replace chemical preservatives in fresh-cut fruits and vegetables [385]. Reflecting this momentum, the DES market (with NADES understood as a subset of DES) was valued at USD 166.5 million in 2024 and is projected to reach USD 374.2 million by 2030, underscoring its accelerating transition from research to application [386]. Based on these developments, NADES currently align with SRL 4–5, as their adoption beyond research settings is still in progress.

6. Environmental and economic assessment

Sustainability concerns are driving adoption of extraction methods that reduce energy consumption, solvent hazards, and waste while maintaining or impriving process efficiency. Conventional extraction methods, although foundational to the field, often rely on energy-intensive processes and toxic solvents, leading to significant environmental degradation [63]. In contrast, emerging methods grounded in green chemistry principles can recover bioactives from natural sources while promoting economic profitability, minimizing environmental impact, and actively supporting the United Nations' sustainable development goals on responsible production and climate action. Large-scale deployment, however, demands more than just environmental gains; it requires clear evidence of cost efficiency, scalability, and profitability. Accordingly, this section provides a comparative analysis of various emerging extraction methods, assessing key performance metrics such as solvent use, energy consumption, environmental impact, capital expenditure (CAPEX), operating expenditure (OPEX), and profitability (Table 9).

It is important to acknowledge the limitations of this analysis. Economic viability must be assessed with a specific purpose, as costs and benefits vary depending on the target compounds, raw materials, and intended applications. Additionally, factors such as implementation scale, regional energy prices, and infrastructure availability directly influence operational costs and environmental impact. Given the complexity of comparing different methods across various settings, the findings presented here should be considered guidelines rather than absolute conclusions.

As shown in Table 9, emerging extraction methods differ markedly in

Table 9
Comparative analysis of emerging extraction methods: performance metrics on solvent use, energy consumption, environmental impact, capital expenditure (CAPEX), operating expenditure (OPEX), and long-term cost efficiency.

Extraction method	Solvent use	Energy consumption	Environmental impact	CAPEX	OPEX	Long-term cost efficiency	Ref.
Physical methods							
Pulsed electric field-assisted extraction (PEF-AE)	Low	Low	Low	High	Low–moderate	Moderate–high	[81,82,136,247,387]
Pressurized liquid extraction (PLE)	Moderate	Moderate–high	Low–moderate	Moderate–high	Moderate	High	[84–86,148,150,388]
Microwave-assisted extraction (MAE)	Low–moderate	Low–moderate	Moderate	Moderate–high	Low–moderate	High	[153,270,389,390]
Ultrasound-assisted extraction (UAE)	Low	Low–moderate	Low	Low–moderate	Low–moderate	Moderate	[291,391–393]
Thermal methods							
Subcritical water extraction (SWE)	Low	Moderate–high	Low–moderate	Moderate–high	Moderate–high	Moderate	[94–96,174,391,394]
Supercritical methods							
Supercritical carbon dioxide extraction ($SCCO_2$)	Low	Moderate–high	Low–moderate	High	Low–moderate	Moderate–high	[95,394–397]
Biochemical methods							
Enzyme-assisted extraction (EAE)	Low	Low	Low	Low–moderate	Moderate–high	Moderate	[186,189,195,398]
Solvent-based methods							
Natural deep eutectic solvents extraction (NADES)	Low	Low–moderate	Low–moderate	Low–moderate	Moderate–high*	High*	[106,107,202,399]

Note: The terms "Low", "Moderate", and "High" for each category are defined as follows:
Solvent Use:
Low: Minimal use of solvents, use of green solvents (e.g., water, CO_2).
Moderate: Controlled use of moderately hazardous solvents (e.g., ethanol).
High: High use of organic solvents or hazardous chemicals (e.g., hexane, chloroform).
Energy Consumption:
Low: Minimal energy use, fast extraction typically requiring simple equipment or mild conditions.
Moderate: Moderate energy use for processing or heating.
High: Intensive energy input and long extraction times.
Environmental Impact:
Low: Environmentally friendly practices, use of green solvents (e.g., water or CO_2), minimal waste generation, and non-toxic by-products.
Moderate: Moderate waste production and solvent disposal concerns.
High: High waste production, hazardous chemical residues, excessive resource use (e.g., energy, water, or other resources).
CAPEX:
Low: Low-cost, widely available equipment; no high-pressure or high-voltage systems; minimal safety infrastructure.
Moderate: Specialized equipment required but standard industrial availability; moderate compliance and safety systems.
High: High-pressure/high-voltage/high-spec equipment and materials; significant installation, certification, and safety costs.
OPEX:
Low: Low utilities (electricity, heat, cooling) and consumables; minimal solvent make-up; limited waste handling; low maintenance burden.
Moderate: Moderate utilities and/or consumables (e.g., ethanol make-up, moderate maintenance); routine waste handling.
High: High utilities (heat duty, compression, cooling, water handling) and/or expensive consumables (e.g., enzymes, large solvent make-up, frequent membranes/resins/electrodes/seals replacement); significant waste treatment and maintenance burden.
Long-term Cost Efficiency:
Low: High operational costs over time outweigh the initial investment, with minimal return on investment.
Moderate: Reasonable operational costs and return on investment, with savings in some areas offset by expenses in others.
High: Significant long-term savings due to low operational costs, reduced waste, and optimized resource use.
* For NADES, OPEX and long-term cost efficiency are highly sensitive to solvent make-up costs, achievable recycle rates, and downstream recovery requirements.

solvent use, energy consumption, environmental impact, and cost efficiency. At a broad level, PEF-AE, UAE, EAE, and many NADES-based systems tend to reduce reliance on conventional organic solvents and can operate under relatively mild extraction conditions, whereas MAE, SWE, and $SCCO_2$ often require higher instantaneous energy or more specialized equipment but may compensate through shorter processing times, higher selectivity, or improved product quality.

However, these broad comparisons should be interpreted cautiously. Reported environmental and economic outcomes for the same extraction platform vary widely across the literature, and this variability does not necessarily indicate inconsistency in the underlying technology. Rather, in most cases it reflects differences in study design, including system boundaries (e.g., gate-to-gate vs. cradle-to-gate), functional units (e.g., per kg extract, per kg target compound, or per kg biomass processed), process scale, feedstock composition and moisture, local electricity mix, assumptions regarding solvent recovery and heat integration, and the extent to which downstream operations such as filtration, concentration, drying, purification, and solvent removal are included. Consequently, the environmental or economic performance of any extraction method should be interpreted as configuration-dependent, not as a fixed intrinsic property of the platform itself.

PEF-AE shows notable economic and environmental advantages over

conventional thermal or solvent-based extraction methods. A TEA on grape pomace reported a positive ROI at extract selling prices of USD 200–300·kg^{-1}, with profitability driven mainly by enhanced yield and shorter processing rather than by direct energy savings [400]. Similarly, one LCA reported CO_2 emissions reductions exceeding 80% (0.006 kg CO_2-eq per extraction) compared with maceration (0.073 kg CO_2-eq), UAE (0.097 kg CO_2-eq), and MAE (0.020 kg CO_2-eq) [401]. These favorable outcomes are plausible because PEF-AE is typically applied as a short pretreatment and can reduce extraction severity in subsequent steps. However, these gains depend strongly on whether the assessment credits the downstream reductions enabled by electroporation, on the scale and efficiency of the pulse generator, and on the electricity source used. In other words, PEF-AE tends to perform best when evaluated as an integrated intensification step rather than as a stand-alone electrical unit operation. Additionally, coupling PEF systems with renewable energy sources can further reduce their footprint and mitigate ecotoxicity relative to conventional extraction approaches [402].

PLE offers a strong balance between extraction efficiency, solvent reduction, and process controllability, but its economic and environmental profile is highly sensitive to solvent choice, pressure-temperature settings, and process integration. TEA and LCA studies show that, although PLE requires a comparatively higher initial capital investment, it can compensate through substantial reductions in solvent use and extraction time, resulting in competitive production costs of approximately EUR 9–10·kg^{-1} of extract, depending on process integration and operational scale [403]. Comparative LCAs have further revealed that PLE can reduce solvent consumption by up to 90% and carbon footprint by 30–40%, although these benefits depend strongly on solvent selection and operating severity [250,403,404]. Consequently, the apparent contradiction between high CAPEX and a reduced environmental footprint is not a true inconsistency, but rather a technical trade-off. The higher CAPEX arises primarily from the need for pressure-rated equipment, whereas the environmental advantages stem from lower solvent inventories, shorter extraction times, and, in some cases, reduced downstream processing requirements. However, these environmental gains are not intrinsic under all conditions, as they remain strongly dependent on solvent selection, operating severity, and overall process integration. Ultimately, the financial justification for PLE rests on its ability to translate resource efficiency and rapid processing into lower unit costs that offset its higher up-front investment. Its competitive advantage is most pronounced at scale, where the combination of high yields and efficient solvent recycling justifies the shift toward more complex, pressure-rated infrastructure.

MAE is often presented as a cost-effective and resource-efficient alternative to conventional solvent extraction because rapid volumetric heating can shorten extraction cycles and reduce specific energy demand per unit of recovered product [290,389]. A pilot LCA on pectin extraction found that MAE had <25% of the environmental impact of traditional acid-thermal processes [389]. TEAs have estimated production costs as low as EUR 29.9·kg^{-1}, depending on feedstock and solvent [405]. Simulated industrial-scale operations for chitin and protein recovery have also reported net present values exceeding USD 50 million and payback periods below three years [406]. These outcomes are credible when microwave absorption is efficient, solvent volumes are controlled, and the process is optimized for fast heating with minimal thermal hold time. Conversely, the viability of MAE diminishes at larger scales where maintaining thermal uniformity becomes a critical challenge, or where the selection of microwave-compatible solvents is restricted. Furthermore, the logistical complexity of downstream cooling and material handling can impose significant operational complexity. Consequently, the favorable LCA and TEA outcomes often attributed to MAE should be viewed as results of successful process intensification under optimized conditions, rather than an inherent efficiency that applies across all industrial implementations.

UAE frequently achieves reductions in energy use, extraction time, greenhouse gas (GHG) emissions, and cost relative to conventional solvent extraction, largely because acoustic cavitation can enhance mass tansfer at comparatively mild temperatures. For instance, a study using UAE to recover phenolic-rich extracts from brown seaweed reported a cost of manufacturing of EUR 922·kg^{-1} at lab scale (0.01 m^3) and EUR 340–443·kg^{-1} at larger scales (0.05–0.15 m^3), versus EUR 8981·kg^{-1} for conventional solvent extraction [407]. Additionally, a LCA on chicory waste extraction found that UAE reduced energy use by 35% and GHG emissions by up to 45% [300]. These improvements are consistent with the known ability of ultrasound to shorten extraction duration and reduce solvent demand. However, UAE outcomes depend strongly on matrix properties, reactor geometry, acoustic efficiency, and scale, because cavitation performance can deteriorate in viscous, heterogeneous, or poorly transmitting media. Therefore, while UAE often performs well in comparative studies, its advantage is not universal and should be interpreted as contingent on maintaining effective cavitation and avoiding excessive energy losses during scale-up.

SWE demonstrates competitive economic viability; however, its sustainability profile strongly depends on heat recovery. The overall sustainability of the process depends on whether the energy required for heating is effectively recycled or accounted for as a direct operational burden. A TEA on New Zealand grape marc estimated a cost of manufacture of NZD 89.6·kg^{-1}, comparable to conventional solvent extraction (NZD 87.0·kg^{-1}) and lower than $SCCO_2$ (NZD 123.4·kg^{-1}) under matched assumptions [394]. This competitiveness was attributed to high yields and the elimination of organic solvent makeup and handling. However, the same study found that SWE showed higher potential environmental impacts and higher GHG emissions than conventional solvent extraction because of its greater heat duty. Conversely, another study found that, when heat recovery is implemented, SWE's reliance on water (eliminating organic solvent burdens) makes it the most sustainable route for wine-residue valorization, with drying identified as the dominant GHG hotspot across all cases [408]. These results indicate that the performance of SWE is largely determined by thermal integration. When sensible heat is not recovered, extraction with hot compressed water can impose a substantial utility burden; however, when heat recovery is implemented and the impacts associated with organic solvents are avoided, the same process can become environmentally advantageous. The difference also depends on whether drying and other upstream heat-intensive operations dominate the overall inventory. For this reason, SWE should not be characterized as inherently sustainable or unsustainable, since its environmental profile is shaped mainly by heat management and the system boundaries applied.

$SCCO_2$ is commercially attractive for nonpolar, high-value extracts because it operates at relatively low temperatures, leaves no residual organic solvent, and enables near-complete solvent recycling. An industrial TEA for patchouli oil (400 t·y^{-1} throughput) reported a manufacturing cost of ≈USD 53.9·kg^{-1} and strong profitability (ROI ≈ 27.4%, payback ≈5.4 years) [409]. In contrast, a grape marc TEA found $SCCO_2$ more costly (≈NZD 123.4·kg^{-1}) than SWE or hydroalcoholic extraction under identical assumptions [394]. This variation is reasonable because the economics of $SCCO_2$ depend strongly on throughput, extract value, target selectivity, and how effectively capital costs are spread across production volume. A process designed for a high-value essential oil does not follow the same economic logic as one targeting a lower-value polyphenol extract. The environmental evidence is similarly context dependent. One LCA reported ≈71.4 kg CO_2-eq for $SCCO_2$ vs ≈ 6.2 kg CO_2-eq for SWE under similar boundaries, attributing the gap largely to the energy required for CO_2 circulation [410]. Conversely, another study reported that replacing hexane extraction with $SCCO_2$ coupled to membrane regeneration cut the overall environmental impact of refined sunflower oil production by ≈95% (and by ≈99% relative to $SCCO_2$ without regeneration) [411]. These contrasting outcomes are best explained by differences in counterfactual and modeling assumptions. $SCCO_2$ can appear environmentally unfavorable when compared against a thermally integrated water-based process with low-carbon utilities, but highly favorable when it replaces organic solvent-

intensive conventional extraction and when solvent regeneration and avoided emissions are properly credited. Accordingly, it is more accurate to state that $SCCO_2$ can achieve low environmental burdens under appropriate energy and recovery conditions, rather than claiming universal superiority. Despite its energy demand for pressurization and heating, $SCCO_2$ is often reported to perform favorably relative to conventional organic solvent extraction [391,411,412].

EAE operates at mild temperatures, reduces organic solvent use, and suits multiproduct biorefineries. When coupled with membrane fractionation, EAE has been reported to be techno-economically attractive for high-value products such as laminarin and fucoidan (sold at ≈EUR 300·kg^{-1}), delivering a ROI of ≈66.9% (payback ≈1.5 years). Simultaneously, OPEX can be dominated by enzyme costs (≈51% of partial OPEX for carbohydrase cocktails), making profitability highly sensitive to extraction yield, biomass composition, and enzyme costs [195]. The environmental picture is more complex. Although EAE often lowers toxicity and avoids VOC emissions relative to hexane extraction, it can also increase energy use and GHG emissions because environmental burdens are shifted upstream to enzyme manufacture and downstream to pretreatment, water handling, and separation operations. For example, in soybean oil extraction, EAE showed the highest CO_2 and GHG emissions among expelling, hexane extraction, and EAE despite solvent-related benefits [413]. Similarly, an insect-protein LCA found the enzymatic route to be ≈32% more impactful overall than the chemical baseline [414]. Overall, EAE is best viewed as a context-dependent strategy rather than an inherently greener one: its strongest case arises when product value is high enough to offset enzyme costs and when downstream processing is sufficiently efficient to prevent burdens from shifting elsewhere in the process.

DES/NADES-based systems also show wide cost and environmental variability, and this variability is especially dependent on solvent formulation and recovery strategy. Reported costs range between EUR 7–100·kg^{-1} depending on solvent components, with amino-acid-based systems >20-fold pricier than sugar-based ones [415]. Because optimal composition and water content are hard to predict a priori, published databases such as DESignSolvents can help guide more cost-effective NADES selection and reduce empirical trial-and-error [416]. Environmentally, a gate-to-gate LCA of cellulose extraction from date palm biomass using a NADES–microwave process (ReCiPe 2016H and ILCD 2011 Midpoint; OpenLCA/ELCD 3.2) identified freshwater ecotoxicity as the dominant impact category, exceeding fossil resource scarcity [417]. This result is important because it challenges the simplistic assumption that all NADES are inherently "green." Their environmental profile is strongly composition-dependent and can be heavily influenced by precursor sourcing, viscosity-related mixing and pumping demands, water addition, and the burden of downstream solvent recovery or product isolation. In many cases, the extraction step itself may appear benign, but the nonvolatility of NADES shifts the process burden to additional separation and recycle operations. Therefore, the "green" credentials of NADES should be treated as conditional rather than assumed, and case-by-case assessment remains necessary [417]. Overall, NADES-based extraction can be economically and environmentally viable, but only when recycle rates, product value, energy demand, and water consumption are carefully managed [418].

Collectively, the apparent conflicts across studies arise mainly because extraction technologies are often evaluated under non-equivalent assumptions, and the dominant burden frequently shifts from the extraction step itself to utilities, solvent recovery, drying, enzyme manufacture, or other downstream operations depending on the case. Accordingly, no single extraction technology is universally superior. Methods such as UAE, EAE, and NADES can offer favorable trade-offs between process intensity, solvent reduction, and cost under suitable conditions, whereas $SCCO_2$ and MAE are often more attractive in high-value applications where selectivity, purity, or rapid processing justify higher capital intensity. More broadly, the sustainability and profitability of each technology depend less on the nominal extraction principle alone than on process integration, product value, boundary definition, and regional energy context.

To consolidate the comparative evidence discussed above into a more decision-oriented synthesis, Table 10 presents a comparative matrix for the preliminary selection of emerging extraction platforms for brown algae bioactives under practical processing constraints. Rather than summarizing individual methods in isolation, the table brings together the main selection variables that are likely to govern process choice in practice, including target compound polarity, demonstrated scale, throughput suitability, and qualitative energy, CAPEX, and downstream burdens. In this way, the matrix is intended as a high-level screening tool to help readers identify which platforms are most likely to offer a practical fit under different processing objectives and operational constraints. The categories are presented as indicative comparative benchmarks derived from the broader technical, readiness, economic, and environmental evidence reviewed in the preceding sections. They should therefore be interpreted as strategic guidance for preliminary method screening, not as absolute rankings or substitutes for case-specific process design, TEA/LCA modeling, and experimental validation.

7. Conclusions and future directions

The literature on emerging extraction platforms for brown-algae bioactives has expanded rapidly, with recent work largely focused on improving yield, shortening extraction time, and reducing solvent use relative to conventional methods. However, the key challenge is no longer simply whether extraction is feasible, but whether it can be performed selectively, reproducibly, and economically at a scale consistent with product specifications. In this context, the value of an extraction platform is better judged not by isolated performance metrics alone, but by its compatibility with robust downstream purification, stable operation, and realistic process integration.

A persistent bottleneck is the gap between extraction performance and the production of specification-compliant products. High recovery is not sufficient if residual solvents, co-extracted impurities, or batch variability prevent consistent compliance with quality and safety requirements. Future studies should therefore move beyond reporting extraction yield alone and include specification-relevant quality indicators, while also demonstrating that downstream processing can reliably deliver products that meet defined compositional and safety criteria.

Three priority research needs emerged directly from the critical gaps identified in this review. First, seaweed-specific validation must be strengthened. Scale-up expectations are often inferred from terrestrial or non-seaweed systems, even though brown algae present distinct challenges, including residual salinity and polysaccharide-driven rheological changes that can alter mass transfer, increase fouling or corrosion risk, and modify process performance. More representative studies under relevant marine-biomass conditions are therefore needed to determine how far process performance and readiness can truly be transferred from non-seaweed applications.

Second, future optimization must become more downstream-aware. For several emerging methods, apparent gains at the extraction stage may be offset by increased burden in solvent recovery, desalting, clarification, concentration, or purification. As a result, process windows that maximize yield are not necessarily those that offer the best overall industrial performance. Future studies should therefore treat downstream burden as a core outcome alongside yield and bioactivity, with greater emphasis on extract composition, separability, and integrated process performance.

Third, reporting and benchmarking must become more standardized and decision-relevant. Differences in yield basis, solvent-to-biomass ratio, process conditions, and impurity characterization currently limit cross-study comparability and weaken readiness assessment. A stronger evidence base will require clearer and more standardized reporting,

Table 10
Decision matrix for the preliminary selection of emerging extraction platforms for brown algae bioactives under practical processing constraints.

Method	Polarity fit	Scale	Throughput	Energy burden	CAPEX burden	Downstream burden	Main limiting factors	Selection guidance
Pulsed electric field-assisted extraction (PEF-AE)	Polar–moderately polar (works in aqueous/polar media; outcome solvent-driven)	Pilot/ industrial	High	Low	High	Low–moderate	Electrode/stack design; fouling; matrix conductivity dependnce	Best when high throughput and low solvent use are priorities; requires tight control of field strength/pulse protocol and matrix-specific validation.
Pressurized liquid extraction (PLE)	Solvent-tunable (polar–nonpolar depending on solvent)	Pilot/ industrial	Moderate	Moderate–high	Moderate–high	Moderate	Pressure-rated hardware: Solvent recovery; thermolabile risk at high temperature	Best when fast, high-yield extraction is needed and CAPEX/ pressure compliance is acceptable.
Microwave-assisted extraction (MAE)	Solvent-tunable (polar–mid-polar); requires microwave-absorbing media	Pilot/ industrial	Moderate	Low–moderate	Moderate–high	Moderate	Heating uniformity/ penetration at scale; equipment cost	Best for rapid extraction with reduced solvent/time; scale-up requires managing hot spots and heat-transfer limits.
Ultrasound-assisted extraction (UAE)	Solvent-tunable (often polar solvents for many targets)	Pilot/ industrial	Moderate	Low–moderate	Low–moderate	Low–moderate	Cavitation uniformity; probe erosion/ contamination control	Best as a low-temperature intensification step; scale-up hinges on power density and uniform cavitation to avoid degradation.
Subcritical water extraction (SWE)	Polar–tunable toward less polar (temperature-tunable water polarity)	Pilot/ industrial	Moderate–high	Moderate–high	Moderate–high	Low–moderate	Thermal degradation window; corrosion/fouling; pressure qualification	Best when a water-only process is desired and energy load is acceptable; selectivity comes from temperature-tuned water polarity.
Supercritical carbon dioxide extraction ($SCCO_2$)	Nonpolar–semi-polar; polar requires co-solvent	Industrial	High	Moderate–high	High	Low–moderate	High-pressure CAPEX/safety; polarity gap without co-solvent	Best for high-purity, solvent-free recovery of lipophilic/ thermolabile targets; polar recovery typically needs co-solvents and added separation steps.
Enzyme-assisted extraction (EAE)	Polar (polysaccharides/ proteins/peptides; matrix-selective)	Pilot/ industrial	Moderate	Low	Variable	Moderate–high	Enzyme cost/ stability; process time; tight control of pH/ temperature/ loading	Best when selectivity under mild conditions is critical; economics are dominated by enzyme usage and downstream clarification/ purification.
NADES extraction	Tunable (typically polar–mid-polar; hydrophobic NADES possible)	Lab/pilot	Low	Low–moderate	Low–moderate	High	High viscosity; nonvolatility; lack of systemic toxicological data for eutectic mixtures	Best for food/pharma-grade solvent design; scale-up credibility depends on demonstrating stable recycle and meeting product specifications.

Note: The terms “Lab”, “Pilot”, and “Industrial” (Scale), and “Low”, “Moderate”, and “High” (Throughput and burden categories) are defined as follows:
Scale: highest implementation level reported for the extraction platform across biomass, food, or phytochemical processing; seaweed-specific deployment may be at an earlier stage.
Lab: Bench-scale experiments and small batch trials (proof-of-concept; not validated under pilot operating logistics).
Pilot: Demonstrated in pilot equipment or pilot campaigns (representative process conditions; repeatability at intermediate scale; partial integration of utilities and safety).
Industrial: Demonstrated in industrial or near-commercial settings (continuous or large-batch operation with industrial utilities, safety systems, and routine operation practices).
Throughput: qualitative indication of capacity for high mass-processing rates and suitability for continuous or semi-continuous operation.
Low: Mainly batch and/or long residence times; throughput constrained by kinetics (e.g., hours) and/or by stepwise handling.
Moderate: Batch or semi-continuous feasible; throughput can increase via parallelization or scale-up but may be limited by heating, mixing, or mass transfer.
High: Continuous-flow operation feasible or commonly implemented; short treatment times and strong potential for high mass-processing rates.
Energy burden: qualitative indication of the total operational energy demand required to perform the extraction, including heating, cooling, compression, and process duration. (Lower burden = more favorable under energy constraints).

Low: Minimal energy use; fast extraction typically requiring simple equipment or mild conditions.
Moderate: Moderate energy use for processing or heating. May require pressurization or sustained operation but not dominated by compression/high thermal severity.
High: Intensive energy input and long extraction times. Substantial utilities demand (heating/cooling/compression).
CAPEX burden: qualitative indication of the investment required for equipment, installation, and safety infrastructure needed to implement the method at scale. (Lower burden = more favorable under capital constraints).
Low: Low-cost, widely available equipment; no high-pressure or high-voltage systems; minimal safety infrastructure.
Moderate: Specialized equipment required but standard industrial availability; moderate compliance and safety systems.
High: High-pressure/high-voltage/high-spec equipment and materials; significant installation, certification, and safety costs.
Downstream burden: qualitative indication of the complexity and intensity of post-extraction processing required to obtain a usable extract (e.g., separation, purification, solvent removal). (Lower burden = fewer and/or simpler downstream steps.)
Low: Minimal post-processing; simple clarification and/or concentration.
Moderate: Routine solvent removal and multiple processing steps; occasional fractionation.
High: Complex purification, removal of difficult solvents/media (e.g., high-boiling solvents, NADES), or intensive desalination/enzyme removal.

including dry-weight yield, solvent inputs, extraction time, and a defined quality panel linked to downstream purification requirements.

Taken together, these findings suggest that the most credible path forward is not the search for a single universally superior extraction technology, but the development of integrated, validation-driven process designs. Emerging platforms are likely to be most effective when applied where their advantages are most defensible, including as intensification steps within broader process flowsheets rather than as stand-alone replacements in all cases. Future progress will depend on coupling technical optimization with feasibility evidence, including techno-economic and environmental assessment, as well as earlier and more explicit consideration of societal readiness through regulatory compatibility, stakeholder acceptance, and validation of product safety and specification consistency. Longer-duration, pilot-relevant studies are also needed to reveal failure modes related to recycle stability, fouling, and biomass variability.

In summary, future progress is likely to depend less on identifying a single superior technology than on developing integrated, validation-driven process designs. Emphasizing seaweed-specific robustness, downstream-aware optimization, and standardized, decision-relevant reporting will help translate promising laboratory demonstrations into scalable extraction systems for brown-algae bioactives, while reducing solvent and energy use and minimizing downstream burdens that often dominate overall environmental impact.

Declaration of competing interest

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

Acknowledgments

The authors acknowledge the financial assistance provided by the University of Auckland Doctoral Scholarship.

Data availability

No data was used for the research described in the article.

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