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REVIEW ARTICLE

Green Extraction of Bioactive Compounds From Marine Constituents

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Abstract

Marine organisms house diverse bioactive compounds, making them a prime focus in marine pharmacology. This abstract explores eco-friendly extraction methods for isolating bioactive marine constituents and peptides from marine sources, underscoring their sustainability and environmental responsibility. Green extraction technologies include supercritical fluid extraction (SFE), pressurised solvent extraction (PSE) and enzyme extraction using microwaves and ultrasounds. Since there is less chemical interference, these newer, greener technologies would be safer. The extraction, isolation and characterisation of these marine constituents can lead to the identification of novel constituents from marine sources. Marine components and bioactive peptides made by marine species have a wide range of pharmacological capabilities, such as antioxidant, anti-inflammatory, antibacterial and anticancer activity. These attributes position marine-derived constituents as promising candidates for drug development and the creation of functional foods and nutraceuticals. Application of sustainable extraction methods aligns with responsible marine resource management principles; particularly important as marine ecosystems face increasing challenges from overexploitation and environmental stressors. Green extraction harmonises scientific exploration with ecological preservation within the area of marine pharmacology, promising advancements and responsible utilisation of marine resources.

Key words: Marine biology; Pharmacology; Phytochemicals; Ultrasonics; Ultrasound-assisted enzyme extraction; Chromatography, supercritical fluid; Solvent; SFE; PSE; Green extraction technology.

Introduction

The diverse number of phyla and aquatic settings, which make up around 70 % of the earth, have been shown to exhibit great biodiversity.[1] Due to recent advances in the field of marine research and development, pharmaceuticals today incorporate a wide range of marine substances.[2] The primary as well as secondary metabolites found in seaweeds such as terpenoids, carotenoids, tocopherols, phytosterols, polyphenols, pigments, minerals and vitamins are known to have cytotoxic, antifungal, antiviral, antihelminthic and antibacterial activities.[3, 4]

The usage of various extraction procedures, like liquid-liquid extraction, Soxhlet extraction, rapid solvent extraction and solid-phase extraction, is rising in a variety of sectors.[5] These processes make use of volatile organic compounds (VOCs) as organic phase solvents, which are poisonous, combustible and environmentally hazardous.[6] To

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address these difficulties, the principles of green chemistry and green analytical chemistry (GAC) emphasise the importance of using sustainable solvents.[7] The fifth principle of green chemistry highlights the avoidance of solvent release agents and substitutes with non-harmful alternatives.[8] This traditional extraction approach has various drawbacks, such as long-term extraction time, contamination by other chemicals and an enormous amount of one or more organic solvents, all of which contaminate the environment.[9] Therefore, this review discusses the latest and most promising technologies for the extraction of marine chemicals. In addition, the opportunities and limitations associated with the industrialisation these technologies are discussed.

The extraction, isolation and characterisation of these marine constituents can lead to the identification of novel constituents from marine sources.[10] Pharmacological properties are attributed to these marine constituents, especially antioxidant, immunostimulant and antitumor activities.[11] Various species of the *Phylum Porifera*, algae including diatoms, *Chlorophyta*, *Euglenophyta*, *Dinoflagellata*, *Chrysophyta*, *Cyanobacteria*, *Rhodophyta* and *Phaeophyta*, bacteria, fungi and weeds have been utilised by mankind. The conventional approach to isolate constituents from marine sources requires many solvents and is time-consuming.[12] Green extraction techniques restrict the amount of solvents required and waste generated throughout the process. Furthermore, the interaction with solvents and their mists can be reduced by using automated present-day procedures.[13] The development of environmentally eco-friendly and sustainable techniques for extracting natural bioactive compounds is a popular subject of study in the interdisciplinary fields of applied chemistry, biology and technology at current times.

Green extraction is based on rational techniques that consume low energy, allow the use of different diluents and environmentally friendly natural resources and provide an extract or product that is better and safer.[14] Observations made in this literature review include extraction with supercritical fluids, extraction with pressurised solvents, extraction with microwaves, extraction with ultrasound, extraction with pulsed electric fields and extraction of marine constituents using enzymes. According to our review, using environmentally friendly solvents in the extraction process necessitates a greater understanding of various factors such as cytotoxicity, temperature, time and solid-liquid ratio; external factors include temperature, viscosity, solubility and pH; and intrinsic solvent effects include polarity, viscosity and pH. This will lead to better environmental compatibility.[15] A systematic selection of green solvents, novel extraction and purification procedures will allow a better yield of phytoconstituents with fewer solvent residues and an environmentally friendly approach. However, further research is needed on green or smart solvents with higher yield, lower operating costs and excellent specificity for phytochemicals. The continued development of environmentally friendly technologies and the consumption of renewable raw resources have become essential elements of environmentally friendly operations.[16] A research and development policy that is applicable to traditional solid-liquid extraction (SLE) methods would be valuable.

Marine phytoconstituents

Marine alkaloids are naturally occurring alkaline compounds with significant biological activity. Their chemical structures comprise complex carbon backbone rings and amine nitrogen functional groups.[17] Pyrido-acridine alkaloids have been discovered from a variety of marine species, including porifera, sea squirts and tunicates.[18] Various indole alkaloids are claimed to be produced by molluscs, algae, sponges and sea squirts.[19] Marine indole alkaloids are a diverse category of naturally occurring substances that show promise as potential new therapeutic targets for a range of psychiatric disorders as well as for a better understanding of serotonin receptor function.[20] Carotenoids are important pigments essential for photosynthesis. More than 250 types of carotenoids have been isolated from marine sources.[21] Phlorotannins exhibit various biological effects, including antidiabetic, antioxidant, antiproliferative, anti-HIV, skin-protective, radioprotective and antiallergic properties.[22]

Solvents

The most crucial step in the extraction procedure is selecting a suitable solvent.[5] When selecting a solvent, it is important to consider selectivity, solubility, cost and safety. Solvents for extracting biomolecules from marine sources are selected based on the polarity of the target solution.[23] A substance that dissolves efficiently in a solvent with the same polarity as the solute. Phytoconstituents from a marine source can be entirely extracted using successive solvent extraction.[24] Environmentally safe solvents for extracting elements from marine sources include ionised liquids, deep eutectic solvents, super critical fluids, switchable solvents, liquid polymers and renewable solvents.[25]

Researchers have long struggled in extracting marine components.[9] An extraction of marine constituents depends primarily on the solubility of these constituents in the solvents and the surface permeability of the solvents.[26] In the case of poorly water-soluble pharmaceuticals, their water solubility has been improved by various methods. One of these is hydrotropic solubilisation.[27] Hydrotropes are the substances used to increase the solubility of marine components many times over under normal circumstances.[28] Hydrotropic solutions are currently in high demand in the industry due to their distinctive characteristics, including ease of availability, good retrievability, non-flammability, factors that do not interfere with solute emulsification and environmental friendliness.[29, 30] Increasing the water solubility of phytoconstituents is the biggest challenge in extraction today, as over 70 % of recently found phytoconstituents have poor water solubility.[31] Hydrotropic compounds increase the solubility of weaker water-soluble molecules by means of weak van der Waals interactions such π-π or attractive dipole-dipole interactions.[32] Hydrotropes such as sodium butyl monoglycol sulphate and sodium alkylbenzene sulfonates have been used to preferentially extract water-insoluble or nonpolar components following permeabilising the cells.[33]

Green extraction

Alternative green solvents, energy recovery, the use of cutting-edge technologies, safe operations, reduce waste and the pursuit of non-denatured, contaminant-free extracts are all aspects of green extraction. Pharmaceuticals are being extracted from natural matrices more frequently now, taking advantage of green extraction methods that focus on converting biomass into profitable lead compounds for drug discovery.[34] The use of green solvent during extraction of marine sources will reduce the risk of solvent residue final product. Traditional methods for extraction like maceration, percolation and hot continuous extraction are more tedious, require high temperatures and higher volumes of solvent and use expensive equipment, which leads to environmental pollution, health dangers, degradation of isolated chemicals and high cost. Several eco-friendly processes, such as pressurised solvent extraction and microwave-assisted extraction and preparative thin-layer chromatography, can extract pure constituents in larger quantities without using harmful organic solvents. Furthermore, they operate at lower temperatures, making them appropriate for extracting thermolabile components from marine sources.[35]

Ultrasound-enzyme assisted extraction

One of the innovative and relatively inexpensive methods for extracting marine components is ultrasound-assisted extraction.[36] Alginate, carrageenans, fucoxanthin, phenolic compounds and β-carotene are the main substances that are extracted using this method. The efficiency of the extraction is determined by the number of sequences used in the extraction phase, temperature, solvent properties, sample quantity, solvent properties, frequency and ultrasound intensity.[37] The UP200St ultrasonicator was used for the isolation of uronic acid and polysaccharides from microalgae (*Vischeria punctata*).[38] *Fucus virsoides* and *Cystoseira barbata* are two species from which polysaccharides are extracted using ultrasound-assisted extraction.[39] Lipids from the biomass of *Nannochloropsis oculata* were isolated using a solvent-free, continuous and environmentally friendly method.[40] Studies showed that enzymatic pretreatment and pressurised liquid extraction (PLE) with ultrasound-assisted extraction improved the extraction yield. Ultrasonic-assisted enzymatic pretreatment of *Nannochloropsis gaditana* gave the highest glycolipid yield (44.54 %).[40] There are reports of pretreatments and the use of enzymes to extract proteins from the microalgae *Chlorella vulgaris* using this method.[41] The ultrasonic device is more affordable and easier to use than other innovative extraction techniques such as microwave-assisted extraction.[42] Isolation of phycobiliproteins from macroalgae in conjunction with sonication and other conventional methods improved the percentage yield of the product.[43] It has been reported that astaxanthin from *Haematococcus pluvialis* can be extracted with the aid of enzymes.[44]

Microwave-assisted extraction

Microwave-assisted extraction is typically used to extract terpenes, alkaloids and glycosides from natural products because it offers significant time savings, better selectivity and less solvent consumption while also having an extraction efficiency that is higher or equivalent to traditional solvent extractions.[45] The frequency range utilised in microwave extraction for marine phytoconstituents is 300 MHz to 300 GHz. By heating the tissue and solvent in a microwave during the extraction process, the kinetics of extraction are improved. The polar molecules are directly affected by the microwaves that heat the sample.[46] Dipolar rotations are utilised in the conversion of microwaves into thermal energy. The dielectric constants of the solvents are directly correlated with the heating.[47] The substrate's cell walls are ruptured by the high vapor pressure produced by heating, enabling the contents to flee into the solvent and evaporating the moisture. Solvents with high dielectric constants and considerable microwave energy absorption capacities are used in the majority of MAE processes. Nonetheless, the choice of extraction method and the medium's capacity to react with microwaves can also be controlled by combining different solvents. The yield of extracts typically rises with longer extraction times. Even at low temperatures or low operating power, however, if the secondary metabolites are exposed to microwave radiation for an extended length of time, they will undeniably suffer thermal damage.[48] One of the novel extraction techniques that has been developed and used recently is microwave-assisted extraction with ionic liquids. Proteins from the biomass of *Nannochloropsis oceanica* were successfully extracted with a microwave-assisted technique using ionic liquids, achieving the highest yield compared to conventional methods.[49]

Elution-extrusion counter-current chromatography (EECCC)

A liquid chromatographic method called ECCC is used to stop solutes from irreversibly adhering to the stationary phase. This method separates the hydrophobic solutes from the stationary phase by extrusion with a liquid stationary phase after counter-current chromatography.[50] The combination of LCMS and ECCC can be used for the isolation of minor components, which may be new biomolecules from the complex mixture.[51] Since ECCC allows separation in normal and reversed phase modes, it can be used for the separation of polar and non-polar components from complex biological samples. It is efficient, has better solute resolution and recovery, high yield of separated compounds, high purity and the flexibility to change the polarity of the solvent during separation compared to conventional techniques. It is used for metabolomic fingerprinting studies.[52] The isolation of fucoxanthin from brown algae is performed using the EECCC technique.[53] Phytol, fucosterol and saringosterol were isolated from the brown alga *Sargassum horneri* using HSCCC. Conventional LLC is an affordable and ecofriendly isolation technique because it uses ionic liquids in liquid-liquid chromatography.[54]

Supercritical fluid extraction (SFE)

Natural products are complex matrices often contain molecules with considerable structural similarities and important components in low concentrations.[55, 56] A liquid enters the supercritical phase when its critical point is exceeded by temperature and pressure.[57] The CO_2 pressure is 74 bar, while the critical temperature is 31 °C (304 K). In this state, CO_2 behaves like a gas, easily penetrates solids and similarly dissolves materials. SFE is frequently used to extract different minerals and compounds from different by-products of food processing, such as polyunsaturated fatty acids from fish by-products, carotenoids from plant waste and marine microalgae.[58] Thermosensitive substances can be extracted faster with SFE with less solvent residue than with other standard methods. It has been reported that *Scenedesmus almeriensis* microalgae can yield carotenoids and lutein through supercritical fluid extraction.[59] The main disadvantages are that the equipment is expensive and the extraction requires a trained person.[60] Supercritical fluid extraction is used to isolated β-carotene and fatty acids (FAs) from the microalgae *Dunaliella salina*.[61]

Pressurised solvent extraction (PSE)

PSE is an extraction method where the target compounds are extracted at pressures and temperatures between 35 and 200 bar (50 and 20 °C). PSE is the process of extracting analytes from solid and semi-solid sample media under elevated pressure and temperature for a brief period of time (5–10 min).[60] It is also referred to as accelerated solvent extraction (ASE), pressurised liquid extraction (PLE), high-pressure solvent extraction (HPSE), high pressure high-temperature solvent extraction (HPHTSE), pressurised hot solvent extraction (PHSE) and subcritical solvent extraction (SSE). The solvents are heated above their regular boiling point due to the high pressure, which increases the solubility and mass transfer rate of the solvents while reducing their viscosity and surface tension. The most recent study describes the use of PLE to extract polysaccharides, carotenoids and phenolic chemicals from a range of algal species.[62] Twelve structurally diverse, bioactive natural products were reported from five marine sponges using pressurised solvent extraction.[63] The SWE process has demonstrated a number of advantages of over conventional extraction techniques because of its high output, efficiency, short extraction duration, affordability and environmental stewardship.[64, 65]

Green electro-membrane extraction (EME)

A tiny supported liquid membrane (SLM) that is managed to keep within the wall of a porous hollow fibre is subjected to an electric field during an EME photonic excitation. Polypropylene (PP) is the preferred material for the majority of EME processes. Biopolymers such as agarose are a sustainable and environmentally friendly extraction and have recently gained considerable importance in EME as a green technique.[66, 67] The advantages include that they are bioresorbable, accessible, non-toxic, flexible, etc. However, there are also some disadvantages, such as the fragile nature of the agarose film, which should only be used once.[68] Parabens and three fluoroquinolones were extracted using a green electro-membrane extraction method with a biopolymeric chitosan membrane as a substrate.[69]

Electroporation

Electroporation is an environmentally friendly, solvent-free and non-destructive extraction of marine components. The use of solvents and waste management are the two main issues with extraction. Short, high-voltage electrical pulses were used in electroporation to increase the cell's permeability.[66] However, the duration and intensity of the pulse are chosen so that the cell retains its integrity and vitality.[70] Since electroporation is reusable, there is less waste and environmental pollution as the microbe can revive after extraction. Unlike other extraction techniques, it produces a product that is affordable, safe and of excellent quality without solvent contamination. Furthermore, the marine elements to be extracted can be selected by fine-tuning the pulse.[71] The fact that less extract is obtained with this method than with other conventional approaches is a disadvantage. *Chlorella vulgaris* proteins and lipids have been separated via electroporation.[72] Combined treatment with pulsed electric fields and temperature is used for the isolation of carbohydrates from *Chlorella vulgaris*.[73] Pulsed electric fields at medium temperature are used for the extraction of lutein from *Chlorella vulgaris*.[74] Pulsed electric fields have been used to extract pigments and phenolic compounds from the microalgae *Nannochloropsis* spp.

Purification of marine constituents

Because marine extracts contain complex combinations of neutral, acidic, basic, lipophilic and amphiphilic molecules, the process of separating pure chemicals from these extracts is very time-consuming and expensive.[75, 76] Identifying the target the substances' chemical makeup and/or biological activity will help to carry out the separation process efficiently. For complete purification of marine components, we can use liquid-liquid separation or supercritical extraction techniques and for high-resolution purification, preparative chromatography.

Preparative thin-layer chromatography

Preparative TLC is used to isolate marine phytoconstituents from crude extract or from fractions. Preparative TLC is like TLC, only difference is that in preparative TLC the stationary phase thicker than normal analytical plates. The procedure is significantly more economical because the quantities of resources required, such as silica gel, solvent and compound matrix are comparatively small and less costly.[77] Preparative TLC helps to get high-purity products with a more flexible method and is less time-consuming compared to column chromatography. Preparative chromatography can be converted to more environment-friendly by using green solvents like ionic liquids, supramolecular solvents and deep eutectic solvents for separation.[78] Preparative TLC is mainly used for the isolation and separation of natural products such as constituents from plants and marine sources.[79] 1-O-palmitoyl-2-Oleoyl, 9-hexadecenoic acid, 2-O-octadecanoic acid, 3-O-β-Dgalactopyranosyl glycerol and 2,3-dihydroxypropyl ester. Using preparative thin-layer chromatography, zeaxanthin and -3-O-β-D-galactopyranosyl glycerol were extracted from *U prolifera* (marine macroalgae).[80]

Preparative gas chromatography

To separate and isolate the highly pure and therapeutically useful constituent at higher concentrations, preparative chromatography is employed. It is very simple, quick and reliable. Marine components are extracted from the mixture in the GC column by dividing the mixture into a suitable stationary phase and a mobile phase.[81] The stationary phase of the column needs to be physically and thermally stable as well as resistant to chemical reactions for the duration of the column. A fraction collector is used in preparative GC applications to collect the separated fractions.[82] PGC is a widely recognised automated system for the efficient and practical separation of marine phytoconstituents from complicated mixtures.[83] Using preparative gas chromatography, the highly unsaturated docosahexaenoic acid was extracted from cod liver.[84]

Preparative HPLC

Preparative LC is used at the lowest flow rates in the nanolitre or microlitre range when there are only small quantities of raw material available, as in the fractionation of complicated natural product combinations, which may lead to novel discoveries in the field of life sciences.[85] A few kilograms of pure product with a potential market worth of millions of dollars are produced via precise scale-up operations and closely controlled, manual fraction collection by skilled process engineers. The chromatographic resolution is of utmost importance when separating complicated materials, such as metabolites in a biological matrix. It has become commonplace to isolate and purify natural products using preparative HPLC (prep-HPLC). Most classes of marine constituents can be purified using the many modalities that are currently accessible, including normal phase, reversed phase, size exclusion and ion exchange.

As green solvents for traditional organic eluents in the mobile phase, ethanol (EtOH), acetone, ethyl acetate, 2-propanol, glycerol and propylene carbonate (PC) are utilised.[86] Callyaerins A–F and H were isolated from *Callyspongia aerizusa* Indonesian marine sponge by semipreparative HPLC. Theonellamide G was isolated from *Theonella swinhoei* by preparative HPLC.[87] The elution power in RP stationary phases was enhanced by the combination of the anionic sodium lauryl sulphate (SLS) surfactant and the non-ionic polyoxyethylene surfactant (Brij-35) without sacrificing their separation efficiency.[88] Deoxycytidine, phenylalanine, adenosine, deoxyguanosine, adenine and thymidine were isolated from *Niphates digitalis* by semipreparative HPLC.[89] Green technique can be incorporated into HPLC by replacing organic solvents with supercritical fluid chromatography, ionic liquid, etc. This approach helps in the usage of less solvent, solvent replacement, solvent reuse methods, high degree purity etc. Ethyl methyl imidazolium dibutyl phosphate, an ionic liquid used for the separation and isolation of proteins and carbohydrates from *Ulva lactuca*.[90]

Discussion

Recent research has focused on green extraction technologies that use green solvents to improve sustainability and reduce the environmental impact of the microalgal process.[91] In order to increase extraction output and reduce energy consumption and solvent requirements, safer, more environmentally friendly and more effective extraction methods have emerged in recent years.[92] Table 1 summarises the extraction procedures that have been previously studied in relation to the comparative analysis of green extraction methods, yield and purity of bioactive compounds and their effectiveness on environmental impact.

These extraction procedures have been used to extract bioactive compounds (alkaloids, caretonoids and flavonoids) from marine sources that are present in medicinal aquatic plants, algae, fungi, and bacteria with rich biomolecules and therapeutic applications, such as antibacterial, anti-malarial, anti-tuberculosis, anti-tumour, anti-histamine, cytotoxic and antiviral activity.[93-124] While green extraction techniques offer numerous advantages for bioactive marine elements, there are still challenges and limitations associated with them. For instance, proper selectivity, extraction parameter optimisation, solvent compatibility, waste management and uniformity and consistency are some of the main challenges. Although there are challenges, green extraction approaches for bioactive marine compounds have a promising future. To overcome these restrictions, research should incorporate creative methodologies, modern technologies and interdisciplinary collaborations.

Table 1: Marine sources as compounds or molecules in medicinal aquatic plants, algae, fungi, bacteria with rich in biomolecules and therapeutic applications

Source	Active constituent	Therapeutic action	References
Indole alkaloids			
Sponge species	Manzamine A	Antimalarial, antituberculosis	93
Aplidium cyaneum	Aplicyanins A–F	Antimitotic and cytotoxic	94
Iotrochota purpurea	Matemone	Antimicrobial, cytotoxic activity	95
Dictyodendrilla sp	Dendridine A	Antibacterial and antifungal	96
Spongosorites ruetzleri	Nortopsentin A-C	Cytotoxic, anti-inflammatory, antiplasmodial, antibacterial, antifungal and insecticidal	97
Verongida rigida	Veranamine	Antidepressant	98
	5,6-dibromo-N, N-dimethyltryptamine	Antimicrobial activity, antidepressant	
	5-bromo N, N-dimethyltryptamine	Antimicrobial activity, sedative	
Quinazoline			
Aspergillus sp HNMF114	Aspertoryadins H–J	α-glucosidase inhibitory activity	99
Aspergillus sp HNMF114	6-O-demethylmonocerin	α-glucosidase inhibitory activity	100
Fusarium oxysporum	Oxysporizoline	Antibacterial activity	101
Penicamide A	Penicamide A	Cytotoxic	102
Hyrtios erectus	2-chloro-6-phenyl-8H-quinazolino [4,3-b]quinazolin-8-one	Cytotoxic	103
Piperidine alkaloids			
Haplosclerid sponges	Viscosaline	Cytotoxic, antibacterial, antitumoral and antifouling activities	104
Streptomyces chartreusis NA02069	Strepchazolin A and B	Antimicrobial activity	105
Pyrroloquinoline			
Petrosaspongia sp	Makaluvamine J	Anti-tumour	106
Carbazoles			
Xestospongia sponge	Ellipticine	Anti-tumour	107
Pyridoacridines			
Sponge *Xestospongia sp*	Neoamphimedine		108
Bis indole alkaloid			
Didemnum granulatum	Granulatimide, isogranulatimide	Cytotoxic	109
Pyrrolopyrimidine			
Eudisromu cf rigida	Rigidin A–D	Antiviral activity	110
Bromopyrrole alkaloids			
Ageles conifera	Dispacamide	Anti-histamine	111
Imidazolone alkaloid			
Calcareous sponge, *Leucetta and Clathrina*	Leucettamine B	Cytotoxicity	112
Carotenoid			
Prianos osiros	Acetylenic carotenoid	Antioxidants	113
Suberites sericeus	Isorenieratene, renieratene	Photoprotective effect	114
Diterpene glycosides			
Pseudopterogorgia elisabethae	Pseudopterosins A–D	Cosmeceuticals, anti-inflammatory and analgesic	115
Dictyota pfaffii	Dolabelladienetriol	Anti-inflammatory activity	116
Flavonoids			
Acanthophora spicifera	Tiliroside	Anti-inflammatory	117
Salicornia herbacea	Isorhamnetin-3-O-β-D-glucoside	Antioxidant	

Glycosides			
Melophlus sarasinorum	Melophlus sarasinorum	Cytotoxicity	118
Angucycline glycosides			
Streptomyces lusitanus	Grincamycin J	Cytotoxicity	119
Streptomyces lusitanus	Grincamycin I		
Dimeric diazobenzofluorene glycosides			
Micromonospora omaivitiensis	Iomaiviticins A–B	Antibiotic activity	119
Streptomyces sp ZZ446	Maculosin-O-α-L-rhamnopyranoside	Antimicrobial activity	120
Peptide-polyketide glycoside			
Streptomyces tendae HKI 0179	Cervimycins A-D	Antibiotic	121
Polyketide/alkaloid glycoside			
Sponge	Aurantoside K	Antifungal	122
Steroidal glycosides			
Eunicea laciniata	Cholestane-3β, 5α, 6β-triol	Neuroprotectant	123
Phlorotannins			
Ascophyllum nodosum	Phlorotannins	Antioxidant and UV-protective activities	124

Future research

Prospects for future developments in the sector include investigating novel green solvents, creating modular and adaptable extraction methods and integrating artificial intelligence and machine learning for process optimisation. The effective integration of green extraction techniques into a wide range of applications will also be made easier by encouraging collaboration among researchers, stakeholders from the industry and policymakers. This will ensure environmentally friendly and sustainable methods for the extraction of bioactive marine constituents.

Conclusion

A state-of-the-art review was conducted in this article to provide insight into the current technologies available for the extraction of bioactive marine constituents and peptides by using eco-friendly/green extraction technologies, such as SFE, PSE, enzyme extraction using microwaves and ultrasounds. The majority of pharmaceutical active ingredients are derived from natural products (NPs). While one-step isolation procedures are still a way off, and it is still challenging to isolate pure compounds from challenging matrices like organic matter, the time it takes to naturally purify a compound will be shortened with the application of more selective techniques for extraction, fractionation and purification. The choice of extraction methods for isolating marine phytoconstituents is primarily influenced by ease of use, cost-effectiveness, efficiency, time needed for complete extraction and economic friendliness. Additionally, they are frequently quicker, sustainable, environmentally friendly and reproducible. Pharmacological properties are attributed to these marine constituents, especially antioxidant, immunostimulant and antitumor activities. Therefore, in this review the latest and most promising technologies for the extraction of marine chemicals were discussed. However, more research is required in this field to improve the existing green extraction toques that help in the isolation and characterisation of novel phytoconstituents of marine origin. This can be achieved only by interdisciplinary research from various fields like chemistry, phytochemistry, pharmacognosy, biochemistry, materials science, etc.

Ethics

This study was a secondary analysis based on the currently existing data and did not directly involve with human participants or experimental animals. Therefore, the ethics approval was not required in this paper.

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Conflicts of interest

The authors declare that there is no conflict of interest.

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Data access

The data that support the findings of this study are available from the corresponding author upon reasonable individual request.

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