I3-4-Seaweed

Connecting the European Seaweed Industry

Postharvest Processes And Key Technologies Of Seaweed



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I3-4 SEAWEED

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POSTHARVEST PROCESSES AND KEY TECHNOLOGIES OF SEAWEED

In order to unlock the vast potential of algae as a source of diverse high-value bioactive metabolites, there is a clear need to develop appropriate, fast, cost-effective and environmentally friendly extraction processes that align with sustainability goals (Irianto et al., 2024). Conventional extraction methodologies necessitate elevated levels of energy consumption in conjunction with the utilisation of environmentally detrimental solvents. The utilisation of environmentally detrimental solvents has become increasingly obsolete in recent years, with green extraction technologies being favoured due to their inherent sustainability and environmental benefits (Hong-Wei et al., 2015). Consequently, a major challenge of biotechnological processes is achieving economic viability through the production of commercially valuable compounds. Most of these compounds are accumulated inside the cells, requiring efficient technologies for their extraction, recovery and purification. (Corrêa et al., 2020).

The process commences with a pivotal step: the handling of seaweed post-harvest. This stage primarily impacts the quality of the final product (Zhu et al., 2021). Seaweed is a perishable product due to its high moisture content (approximately 75–85% of its total weight). Therefore, a series of postharvest handling processes are required to transform the product into a broad range of formats (e.g. dried, powder, salted, flakes, liquid extracts or combinations with other biomass) for further processing.

BIOMASS PREPARATION AND PRESERVATION

CLEANING METHODS

It is a common pretreatment to remove impurities such as salt, sand and fauna. This process can be done partly or completely with seawater. Sometimes at least a final freshwater rinsing is required to remove salt. During or after washing, seaweed can be cut or milled depending on requirements. However, some water-soluble compounds may also be removed during washing. For instance, it has been reported that oven drying of Laminaria digitate lead to laminarin degradation, resulting in an approximately 10-fold increase in glucose concentrations compared to freeze-dried algae (Adams et al. 2015).

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SOAKING TECHNOLOGIES

The choice of soaking methods mainly depends upon seaweed species and intended use. Soaking can reduce potentially undesirable compounds in seaweed (e.g. iodine), although it also affected the content of bioactive compounds, still preserved Palmaria palmata at 4°C for 15 days in artificial seawater and reported a more favourable aroma compared with its frozen counterpart. Seaweed can also be soaked in media with osmotic properties, with organic and mineral acids for dehydration (LePape et al. 2002, Gallagher et al. 2017; Stévant et al. 2018)

BLANCHING TECHNOLOGIES

Blanching is a common cooking process or preservation technique used in the food industry, whereby food is immersed in boiling water or steam for a set amount of time. Blanching is adopted to prevent or relieve natural degradation by expelling air inside the tissue, inactivating the enzymes and killing foodborne pathogens (Wang et al. 2018).

However, a considerable amount of nutrients, such as saccharides, proteins and water-soluble minerals, may leach out because of the direct exposure to the heating media (water or steam). Furthermore, hot water blanching and steam blanching consume high energy inputs and generate polluted liquid waste during processing. Therefore, novel blanching technologies such as high-humidity hot air impingement blanching (HHAIB), microwave blanching, infrared blanching, ohmic heating, and blanching assisted by ultrasonic pretreatment and high-pressure treatment have been studied widely. Although novel blanching technologies may perform better than conventional methods in energy efficiency and processing time, there are still some drawbacks, for example, the high industrial cost of the infrastructure and the potential mass cell wall ruptures in addition to the appearance of unwanted structural changes.

DRYING AND DEHYDRATION

Drying seaweeds can extend their shelf life, enable distribution across different regions, and facilitate storage and transportation (Santhoshkumar et al., 2023). However, the process can cause significant quality changes and accounts for 20–30% of total biomass production costs. The main objectives should be to improve the efficiency of recovering valuable components from algal biomass, reduce operational and maintenance expenses, and minimize environmental impacts (Fahrina et al., 2024; Vatanpour et al., 2024).

No single drying procedure can be considered consistently superior for all seaweed species or target compounds. The most suitable technique should be selected and optimized for each species, considering its specific characteristics and the intended end-use.

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The following section describes the conventional drying methods pros and cons (Table 1). Figure 1 summarizes the energy requirements, physical principles, and effect.

Table 1. Drying methods applied to seaweeds: methodological principles, main observations, and reported species. Based on: Santhoshkumar et al. (2023), Charles et al. (2020), Mohana et al. (2020), Silva et al. (2019), Thunyawanichnondh et al. (2020), Zhu et al. (2021), Badmus et al. (2019), and Mayol et al. (2015).

Drying method	Method description	Key observations / remarks
Sun drying	Direct exposure of harvested algae to sunlight under ambient conditions, without mechanical control of temperature, airflow, or humidity.	Very low cost and simple, but highly dependent on weather conditions. Leads to losses of nutrients, color, and flavor; risk of environmental contamination and poor hygiene; low reproducibility and limited process control.
Solar drying	Use of solar radiation within simple or semi-mechanical drying structures to improve efficiency compared with open sun drying.	Cost-effective and widely used in tropical regions with high solar irradiance; significantly longer drying times than most mechanical methods; performance strongly depends on dryer design and climatic conditions.
Tray drying / hot air oven drying	Convective drying using heated air circulated by fans in a controlled chamber; temperature and airflow are mechanically regulated.	Final moisture contents of 2–10% achieved. Better recovery of pigments and bioactives than solar drying; however, higher temperatures and prolonged exposure reduce chlorophyll, phenolics, and flavonoids. High temperatures can enhance texture (crispness).
Vacuum oven drying	Dehydration under reduced pressure and moderate temperatures, lowering the boiling point of water and limiting oxidation and thermal degradation.	Suitable for heat- and oxygen-sensitive compounds; improved quality retention compared with hot air drying; higher energy demand and longer processing times.
Freeze drying (lyophilization)	Material is frozen and water is removed by sublimation under low pressure.	Excellent preservation of heat-sensitive and bioactive compounds; lowest reported moisture contents (~0.97%); high capital and operating costs limit large-scale application.
Heat pump drying	Closed-loop system in which moist air is dehumidified below the dew point and reheated via a heat pump cycle before recirculation.	More energy-efficient than conventional hot air drying; gentle drying conditions; still insufficiently studied for seaweeds and requires process optimization.
Fluidized bed drying	High-velocity upward air flow suspends and agitates particles, enhancing heat and mass transfer.	Rapid and uniform drying; air velocity must exceed particle terminal velocity; best suited for fragmented or particulate seaweed biomass.
Microwave drying	Electromagnetic radiation induces volumetric heating of water molecules, enabling rapid moisture removal.	Very short drying times; final moisture comparable to freeze-dried products; reduced contamination and oxidation. High energy demand and scale-up challenges keep it largely at the research stage.

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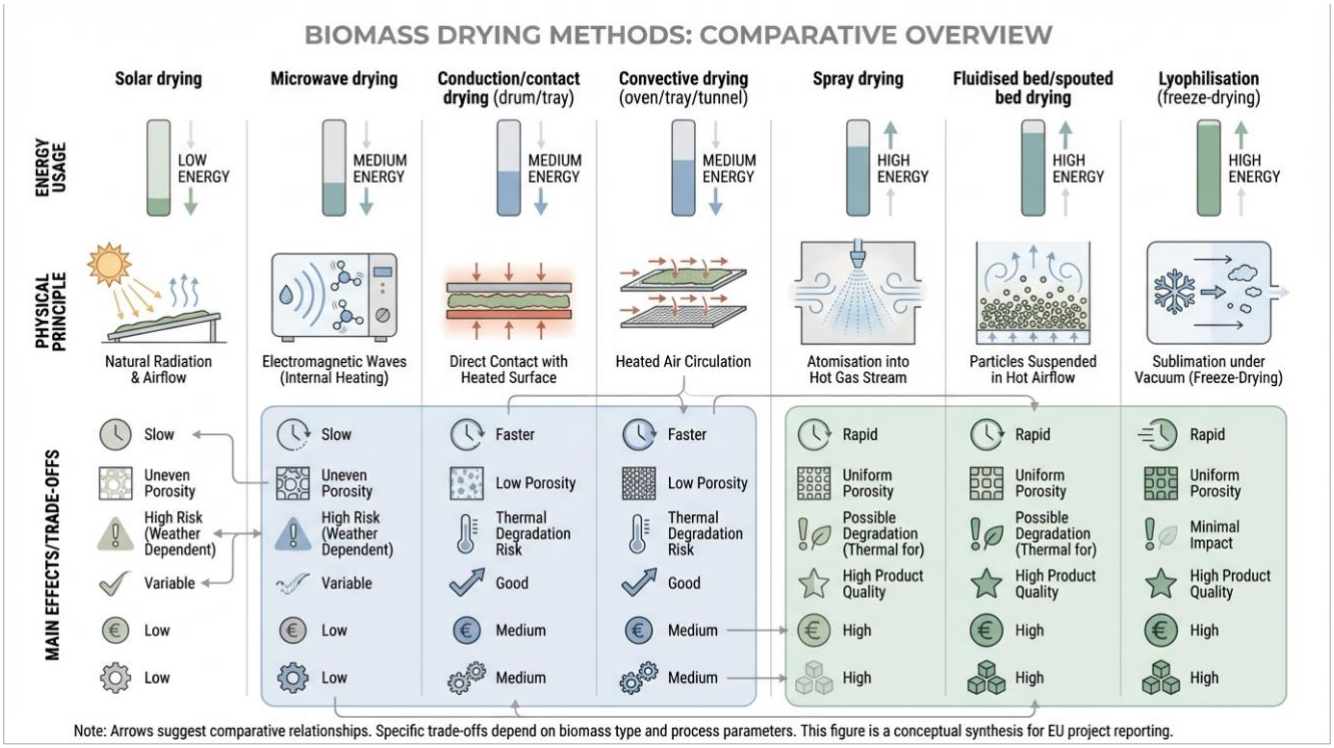

***Figure 1**. Biomass drying methods. An overview. Based in the information provided by Santhoshkumar et al. (2023) drying technologies for seaweeds, Vo et al. (2024) main parameters that control the extraction capacity of different technique, Esquivel-Hernández et al. (2016), Quitério et al. (2022) and Arias et al. (2023) reviewed the extraction technologies, Imbimbo et al. (2020) technical advances in extraction methods, Otero et al. (2021) extraction techniques for polysaccharides, and discusses their structural characterization and modification methods that may enhance their potential biological properties, Irianto et al. (2024) review the principles of green extraction, Getachew et al. (2020) extraction of marine phenolic compounds, Ali et al. (2025) extraction of bioactive, and Fatima et al., (2024) pigment extraction from algae.*

SEAWEED COMPONENTS EXTRACTION TECHNIQUES.

It is critical to select the most appropriate extraction technique based on the target bioactive compound and proposed end application (Quitério et al., 2022). Recent advancements in physicochemical treatments (e.g., supercritical fluid extraction, ultrasound-assisted extraction, pulsed electric fields, among others) and solvent-free processes aim to establish sustainable and scalable technologies aligned with the broader philosophy of green chemistry, emphasizing sustainability, resource efficiency, and the reduction of hazardous waste (Arias et al., 2023; Corrêa et al., 2020; Irianto et al., 2024).

Green extraction, an emerging influential paradigm within the chemical and pharmaceutical sciences, represents the fusion of technological innovation and environmental consciousness. This contemporary approach to the recovery of valuable compounds from natural sources, including plants, algae, and other biomass, aims to reduce the ecological impact associated with conventional extraction techniques while simultaneously enhancing process efficiency and

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improving product quality. Some key green extraction principles include: use of renewable and sustainable solvents; minimization of energy consumption; preservation of bioactive compound integrity; reduced waste generation; preservation of bioactive compound integrity; enhanced selectivity; consideration of health and safety (Irianto et al., 2024). To this end, the use of eco-friendly solvents or solvent-free methodologies has become central. Enzyme-assisted extraction (EAE), microwave-assisted extraction (MAE), ultrasonic-assisted extraction, supercritical fluid extraction (SFE), and pressurized liquid extraction (PLE) are some examples that have gained attention, as they enable reduced energy consumption and operate under milder processing conditions, thereby contributing to measurable reductions in carbon emissions (Chemat et al., 2023; Daud et al., 2022; Vo et al., 2024).

Table 2. *Extraction methods applied to seaweeds: methodological principles, main observations, and reported species. Based on: Imbimbo et al. (2019, 2020), Lee et al. (2012, 2013), Heffernan et al. (2014), Irianto et al. (2024), Yuvarani et al. (2017), Kanda et al. (2020), Chemat et al. (2011), Kadam et al. (2014), Youssouf et al. (2017), Eghbali Babadi et al. (2020), Alboofetileh et al. (2019), Nguyen et al. (2024), Polikovsky et al. (2016), Prabhu et al. (2019), Otero et al. (2018), Jacobsen et al. (2019), Sapkale et al. (2010), Esquivel-Hernández et al. (2016), Conde et al. (2015), and Saravana et al. (2017).* ***(*)*** *Fraction selectivity is primarily governed by solvent polarity and operating conditions rather than by the physical extraction principle itself.*

Extraction method	Method description	Key observations / remarks	Predominant fraction extracted (*)	Species applied
Maceration / Solid–liquid extraction (SLE)	Traditional extraction based on soaking algal biomass in a solvent for a defined period to allow diffusion of soluble compounds into the liquid phase.	Simple, low-cost, and versatile, but time-consuming and solvent-intensive. Often limited to laboratory scale. Extraction efficiency depends on solvent polarity, temperature, time, agitation, and biomass characteristics. Higher yields do not necessarily correlate with higher bioactivity.	Both (polar and apolar)	*Fucus serratus; Laminaria digitata; Gracilaria gracilis; Codium fragile; Ecklonia cava*
Soxhlet extraction	Continuous solid–liquid extraction based on repeated solvent evaporation and condensation cycles.	Efficient for lipids and carotenoids; high solvent consumption, long extraction times, and thermal stress. Solvent type critically influences yield and selectivity.	Apolar (mainly)	*Galdieria phlegrea; Cladophora glomerata; Chaetoceros gracilis; Pleurochrysis carterae*
Ultrasound-assisted extraction (UAE)	Application of ultrasound waves (>20 kHz) to induce acoustic cavitation, enhancing cell disruption and mass transfer.	Rapid, energy-efficient, and suitable for thermo-labile compounds. Can be combined with green solvents. Already scalable at industrial level. Extraction efficiency depends on power, frequency, solvent, and temperature.	Both (polar and apolar)	*Sargassum fusiforme; Ascophyllum nodosum; Laminaria hyperborea; Ulva spp.*
Microwave-assisted extraction (MAE)	Microwave energy rapidly heats solvent and biomass, facilitating intracellular rupture and compound release.	Very fast and solvent-efficient; higher yields than conventional methods. Risk of degradation of thermo-labile compounds. Industrial scale-up still limited.	Both (polar > apolar)	*Green macroalgae; Nizamuddinia zanardinii*

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Extraction method	Method description	Key observations / remarks	Predominant fraction extracted (*)	Species applied
Enzyme-assisted extraction (EAE)	Use of carbohydrases or proteases to degrade seaweed cell walls and release intracellular compounds.	Highly selective, eco-friendly, and effective for polysaccharides and phenolics. Enzyme cost and long residence times limit industrial application.	Polar	*Padina gymnospora; Sargassum binderi; Ecklonia cava; Ulva lactuca; Fucus vesiculosus*
Pulsed electric field (PEF)	Application of short, intense electric pulses to permeabilize cell membranes and cell wall structures.	Solvent-free, non-thermal technique. Mainly applied for minerals, proteins, and polyphenols. Still emerging for polysaccharide extraction.	Polar	*Ulva ohnoi*
Pressurized liquid extraction (PLE) / Subcritical water extraction	Extraction using water or solvents at elevated temperature and pressure to maintain liquid state and enhance solubility and mass transfer.	High efficiency and reduced solvent use. Temperature is the dominant parameter. High energy demand and equipment cost limit industrial use.	Both (temperature-dependent)	*Fucus vesiculosus; Nizamuddinia zanardinii*
Supercritical fluid extraction (SFE) / SC-CO_2	Extraction using fluids above their critical point, typically CO_2, enabling tunable solvating power and rapid mass transfer.	Selective, solvent-free extracts, suitable for thermo-labile compounds. High capital cost and process complexity. Co-solvents required for polar compounds.	Apolar → Both (with co-solvent)	*Sargassum muticum; Saccharina japonica; Scenedesmus sp.; Scenedesmus obliquus*

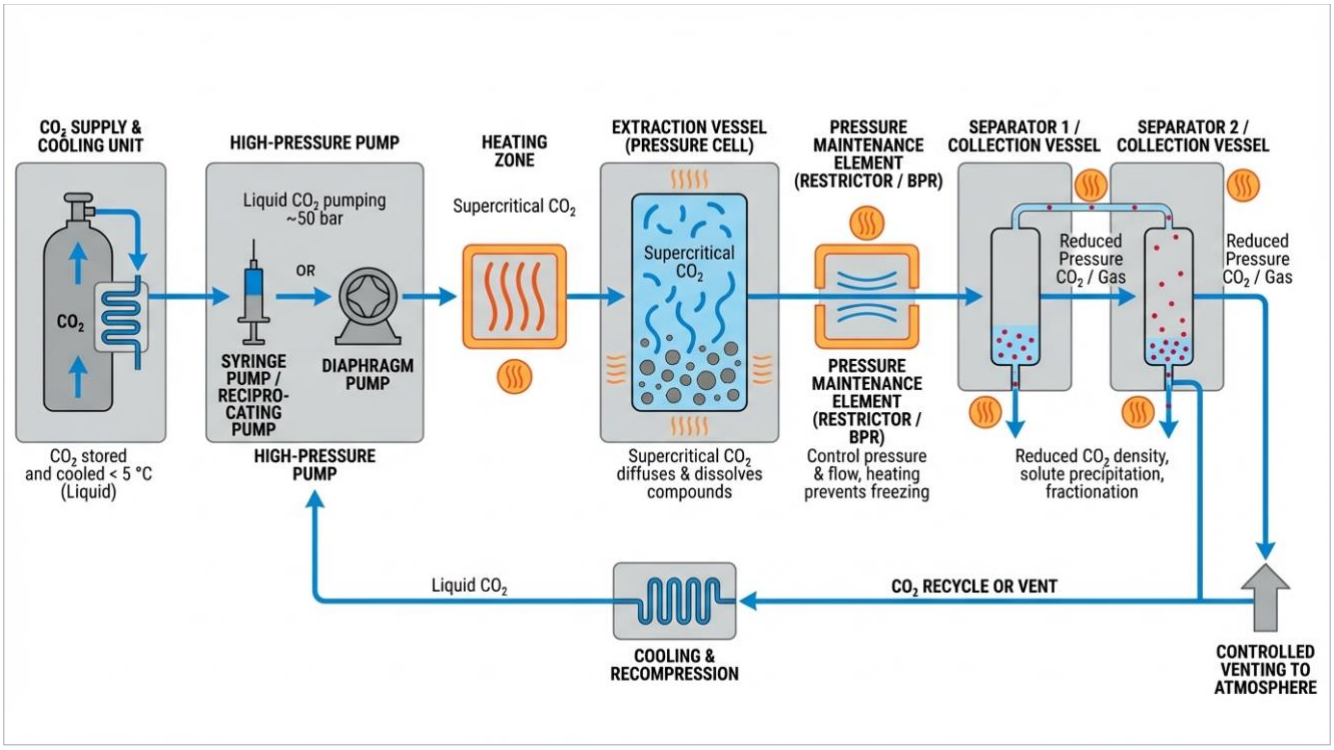

***Figure 2**. Elements and flow of a CO2-SC system as described in Sapkale et al. (2010)*

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Figure 3. *Key equipment in algae biorefinery. Industrial milling and powdering unit (pulveriser) (A); Large-scale spray dryer system (B); Freeze-dryer (lyophilizer) with temperature-controlled shelves (C); Fluid-bed encapsulator/coater for particle agglomeration (D). Images taken at the facilities of the High Technology Incubator for Blue Biotechnology and Aquaculture companies. Instituto Tecnológico de Canarias (https://www.itccanarias.org).*

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***Figure 4**. Key equipment in algae biorefinery**.** Supercritical CO_2 extraction module with high-pressure vessels, heat exchangers, and instrumentation (A); Multicolumn separation system for post-extraction fractionation and purification (B). Images taken at the facilities of the High Technology Incubator for Blue Biotechnology and Aquaculture companies. Instituto Tecnológico de Canarias (https://www.itccanarias.org).x*

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