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Benefits and Drawbacks of Novel Extraction Methods for Bioactive Peptides Derived from Marine Algal Proteins: Pulsed Electric Field, Subcritical Water, and High Hydrostatic Pressure

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Due to the growing interest in the utilization of natural and sustainable functional ingredients, marine algae have become a promising source of bioactive peptides, with a wide variety of health-promoting effects, such as antioxidant, antihypertensive, antimicrobial, and anti-inflammatory activities (da Silva Matos, 2021). Nevertheless, traditional extraction and hydrolysis methods tend to have extended processing periods, high thermal loads, and the utilization of chemical solvents, which may affect the integrity of peptides and decrease their biological effect (Samarathunga, Wijesekara and Jayasinghe, 2023). In recent years, green and non-thermal technologies have made a breakthrough and introduced more efficient and environmental friendly ways of extracting valuable peptides present in marine biomasses (Wang *et al.*, 2025).

Pulsed Electric Field (PEF) treatment is one of the new methods that causes electroporation of cell membranes. This effect increases mass transfer, breaks the cell walls of algal cells, and increases the release of intracellular proteins without degrading the original structures of the proteins (Marín-Sánchez *et al.*, 2024). Pulsed Electric Field (PEF) can be used in low temperatures, which is appropriate for heat-sensitive bioactive peptides. However, it has some disadvantages, such as heterogeneity in the treatment efficacy across various algal species based on their conductivity and structural stiffness, as well as high cost and sophistication of large-scale industrial equipment (Oliveira, 2024).

Subcritical Water Extraction (SWE) is another new technology whereby high-temperature and high-pressure water are is to adjust its dielectric properties so that it can act like organic solvents (Zakaria and Kamal, 2016). SWE enables selective solubilization of proteins and controlled of proteinshydrolysis, which reduces solvents consumption and extraction time. Despite these advantages, SWE needs advanced high-pressure systems, and extended exposure to high temperatures can lead to weakening or alteration of sensitive peptides unless optimized very carefully (Chatnarin, 2025).

High Hydrostatic Pressure (HHP) has also demonstrated the possibility of enhancing peptide extraction efficiency by changing the protein structure in addition to increasing the enzyme accessibility (Zhukova, 2022). The process is non-thermal and thus nutritional and functional properties are retained, making it appealing for the production of food grade peptides. Nevertheless, the technique is constrained by the expensive high equipment costs and the need for precise optimization of pressure-time treatment to avoid undesirable protein denaturation (Amsasekar *et al.*, 2022).

Despite the distinct benefits of each technique, they all have certain drawbacks, such as operational costs, process complexity, and species-specific variability. To maximize extraction efficiency and preserve the integrity of the peptides, it is essential to optimize pressure, temperature, electric field intensity, and extraction time. Future studies ought to combine these novel technologies with downstream applications including membrane filtration, encapsulation, and targeted delivery to improve the freshness and bioavailability of extracted peptide (Basile *et al.*, 2024).

In light of the increasing imperative of sustainable development, it has become increasingly significant to consider green technologies for the extraction of compounds from algae. These novel methods are not only effective at minimizing the environmental impact of extraction processes but also at providing high-quality,

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high-purity natural products that can be used in various applications, such as pharmaceuticals, cosmetics, and the food industry. This approach not only increases the utilization of natural resources but also paves the way for the creation of specific technologies that are environmentally friendly and sustainable.

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