Algal Research 29 (2018) 80–91

Contents lists available at ScienceDirect

Algal Research

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

Process and economic feasibility for the production of functional food from the brown alga *Ecklonia radiata*

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ARTICLE INFO

Keywords:
Bioprocess
Economic assessment
Phlorotannin
Polysaccharide
Process simulation
Seaweed

ABSTRACT

This article provides a case-study for the simulated industrial-scale production of high-value functional food products from the brown seaweed *Ecklonia radiata*. Three process scenarios at a batch processing scale of 2000 kg seaweed were assessed for their economic feasibility: Scenario 1: Enzyme-assisted production of a crude seaweed extract; Scenario 2: Scenario 1, followed by fractionation based on different molecular weights (MW); Scenario 3: Ethanolic extraction, followed by enzyme-assisted extraction and separation into high and low MW fractions. Scenario 2 demonstrated greater profitability, with a payback time of 1.6 years and a net present value (NPV) twice that of Scenario 1 (2.1 years and US$ 45.03M). Scenario 3 was not economically feasible, with a negative NPV and payback time that was three times longer than Scenario 1. To improve profitability, Scenario 4 was assessed, which integrated Scenario 1 (at the batch processing scale of 500 kg seaweed) with formulation of the extract as a functional ingredient into a juice-based beverage. This process was more profitable than Scenario 1, with a payback time and NPV of 1.1 years and US$ 89.43M, respectively.

1. Introduction

Brown seaweeds (Phaeophyceae), in general, are considered important sources of bioactive compounds with a range of biological activities [1]. Brown seaweed-derived, bioactive ingredients include: polysaccharides (e.g., fucoidans, alginates and laminarins), polyphenols (phlorotannins) and carotenoids (fucoxanthins). In addition, they also contain polyunsaturated fatty acids (PUFAs), including omega-3 fatty acids, proteins and bioactive peptides [2]. These compounds are of increasing interest for their broad range of bioactivities, in particular antioxidant, prebiotic, neuro-protective, anti-bacterial, anti-inflammatory, immune modulation, anti-diabetic, anti-cancer and anti-coagulant properties [3,4,5], all with potential applications in the functional food and nutraceutical industries. The brown seaweed *Ecklonia radiata* was chosen in this study as it is one of the most abundant seaweed species in South Australia, with significant quantity and potential for commercial exploitation. Despite this natural abundance, most brown seaweeds harvested locally are underutilised and processed primarily into fertilisers and animal feeds [6].

The efficient extraction of polysaccharides and other bioactive compounds from seaweeds can be impeded by the high degree of structural complexity of their cell walls [7]. Our previous study [8] demonstrated that enzyme-assisted extraction intensified with microwave heating was a more effective means of increasing the recovery of phlorotannins from *E. radiata*, when compared with conventional acidic extraction. The seaweed extracts obtained showed high potential for use as functional food ingredients with reported antioxidant activities of 740 μmol Trolox equivalents (TE)/g DW. This activity is comparable to green and black tea (761 μmol TE/g DW) [9], and greater than that of some fruits, vegetables, and medicinal plants commonly recognised as high antioxidant sources (e.g., 100–500 μmol TE/g DW) [10,11,12,13].

Aside from increasing the recovery of phlorotannins and antioxidant compounds, we also demonstrated enzymatic extraction to be an effective technique for producing brown seaweed polysaccharides with prebiotic potential [14]. Currently, the low efficiency of biomass utilisation and the large volumes of waste by-products are problems generally associated with the industrial processing of seaweed. In order to

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https://doi.org/10.1016/j.algal.2017.11.022
Received 31 July 2017; Received in revised form 18 November 2017; Accepted 18 November 2017
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alleviate these problems and improve economic viability, integrated biorefinery processes have been proposed for the production of multiple products through the comprehensive utilisation of seaweed biomass [15,16,17,18,19,20,21,22]. In our research, a sequential extraction process, based on the biorefinery concept, was developed to produce different fractions enriched with different bioactive compounds from *E. radiata*. The process involved ethanolic extraction of a phlorotannin-enriched fraction, followed by the use of carbohydrate-hydrolytic enzymes and the fractionation of the extract according to molecular weight (MW). One of the products was a high MW polysaccharide-enriched fraction, which was observed to be resistant to human digestive enzymes, but readily fermentable by gut bacteria, resulting in the production of beneficial short chain fatty acids (SCFA), including butyric acid. Meanwhile, the phlorotannin-enriched fraction was also shown to influence the gut microbiota through the inhibition of the growth of potentially pathogenic bacteria in vitro [23]. During in vivo studies, rats fed with the high MW polysaccharide-supplemented diet showed significant improvements in their cecal digesta weight (1.4 vs control 0.6 g/100 g body weight), total SCFA (209 vs control 160 μmol) and an abundance of the key butyric acid producer *Faecalibacterium prausnitzii*, accompanied by a decrease in potentially toxic phenol and *p*-cresol in the cecum [24]. These results suggested that the high MW polysaccharide components could potentially be consumed by humans as dietary fibres and prebiotics.

In this study, in order to understand the economic feasibility of such production processes at an industrial scale, a widely used industry process simulation software SuperPro Designer was used to assess and compare four possible seaweed value-added processes based on our previous studies. This approach has been used to assess the feasibility of biofuel and succinic acid production from seaweeds [25,26,27,28], functional food ingredients from fish protein hydrolysates [29], and production of bioactive compounds from other plant materials such as grape bagasse, turmeric, and ginseng [30,31,32,33,34]. However, there have been no reports on a techno-economic feasibility for the production of seaweed-derived bioactive compounds and functional food products. Therefore, the aim of this study was to conduct a comparative economic assessment of industrial-scale production processes for high value bioactive compounds and functional food products from the brown seaweed *E. radiata* as a case study. However, the outcomes of this assessment are likely to have much wider applicability, with potential to inform the economic feasibility of many other processes for the isolation and use of bioactive ingredients from other seaweeds that are increasingly seen as important sources of functional foods and nutraceuticals. The results from this study should help bring about the informed use and expansion of new platforms that enable seaweed utilisation for the growing demand of higher-value food and health products and thereby also support economic development.

2. Materials and methods

2.1. Simulation description

The simulations were all performed using the software SuperPro Designer 8.0® (Intelligen Inc., Scotch Plains, USA). All of the models used batch processes, with the baseline processing capacity of 2000 kg of dried seaweed per batch for three extraction processes. Taking into account the limiting factor of the size of the functional juice market and the ability of the market to absorb the new product at the starting period, production scale was reduced to 500 kg of dried seaweed per batch for the process that incorporated seaweed extract into the production of a model beverage product. The annual operating time of 7920 h per year was employed, which corresponds to 330 days per year of continuous 24 h per day shifts. The currency is in $US. *Ecklonia radiata* was selected as the raw material in this study based on our previous experimental studies [6,8,14,23,24]. It was assumed that seaweed used in all simulations was commercial dried Australian beach-cast seaweed for human consumption. The change of seaweed compositions due to different seasons was not taken into account in this study. The seaweed was rinsed in fresh water to remove any visible surface contaminants, and placed on mesh racks to dry. Then it was dried at 45–50 °C to obtain a moisture content of approximately 10%.

2.2. Proposed industrial process scenarios

Three different process scenarios were designed and considered for the production of different high-value seaweed fractions as ingredients. Scenario 1: A single enzyme-assisted extraction step to produce a "Crude extract Fraction (CF)", as well as a "Fibre-enriched Fraction 1 (FF1)", which corresponded to that biomass remaining after the enzymatic extraction; Scenario 2: The same process as Scenario 1, but with the CF subsequently being separated into two fractions based on their MWs, a "High MW Polysaccharide and Phlorotannin-enriched Fraction (HPPF)" and a "Low MW Polysaccharide and Phlorotannin-enriched Fraction (LPPF)". Scenario 3: a sequential extraction process consisting of two steps: the first used ethanol to extract a "Phlorotannin-enriched Fraction (PF)", with the residual material then being subjected to enzyme-assisted extraction to produce an extract that was separated into a "High MW Polysaccharide-enriched Fraction (HPF)" and a "Low MW Polysaccharide-enriched Fraction (LPF)". Another product, the: "Fibre-enriched Fraction 2 (FF2)", corresponded to the biomass that remained after the enzymatic extraction. To further improve the profitability of Scenario 1, Scenario 4 represented the same process as Scenario 1, but with the liquid CF being incorporated into a "Fruit Juice-based Beverage (FJB)", as a functional ingredient, at 2% w/w (based on DW of CF).

2.2.1. Single extraction

The process layouts proposed for Scenarios 1 and 2 are presented in Fig. 1a, b.

2.2.1.1. CF. The dried and ground seaweed was dispersed in pH-adjusted tap water in the ratio 1:10 (w/v). The pH of the water was adjusted to 4.5 using 1 M HCl prior to the addition of the seaweed, to achieve the optimum pH for Viscozyme® L (major activity: beta-glucanase, including the activity of xylanase, cellulase, and hemicellulase). The enzyme solution was added at 10% (v/w), and the enzymatic hydrolysis was performed at the optimal temperature of 50 °C for 3 h under continuous mixing. The enzyme was then inactivated by boiling the sample at 100 °C for 10 min. The extract was cooled and transferred through a plate and frame filter to separate the residual biomass. The filtrate was collected, adjusted to pH 7.0 using 1 M NaOH, spray dried, and packed into aluminium bags (1 kg/bag) and carton boxes (24 bags/box). Adjuvants such as maltodextrin and glucose syrup may be used to assist in the drying process of CF and also other products (HPPF, LPPF, PF, HPF, and LPF) if required. In this simulation, these adjuvants or additives were not considered, to simplify the simulation.

2.2.1.2. FF1. The residue remaining after filtration was drum dried and packed into plastic bags (10 kg/bag).

2.2.1.3. HPPF and LPPF. The liquid CF derived from the single extraction was subjected to ultrafiltration using a 30 kDa molecular weight cut-off (MWCO) membrane with a filtrate flux rate of 20 L/m^2.h. Three ultrafiltration units, each with a membrane area of 70 m^2, were required to complete the process within 5 h to separate the HPPF and LPPF. Both fractions were then spray dried and packed into aluminium bags (1 kg/bag) and carton boxes (24 bags/box).

2.2.2. Sequential extraction

The process layout proposed for the sequential extraction process, Scenario 3, is presented in Fig. 2.

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