UNIVERSIDADE ESTADUAL PAULISTA – UNESP

CENTRO DE AQUICULTURA DA UNESP

SUSTENTABILIDADE DO CULTIVO DE MACROALGAS NO MAR E EM TERRA SOB AS PERSPECTIVAS DA SÍNTESE EMERGÉTICA E ECONOMIA NEOCLÁSSICA

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Jaboticabal, São Paulo

2023

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DEDICATÓRIA

Dedico o presente trabalho às comunidades tradicionais que viveram e vivem do cultivo de macroalgas marinhas, às comunidades caiçaras que sentem os efeitos das mudanças climáticas, aos produtores que se preocupam com o desenvolvimento sustentável e principalmente às gerações futuras. Desejo que o presente trabalho contribua para discussões capazes de ajudar minimamente diferentes setores da sociedade para um futuro melhor.

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A presente tese é fruto de um conjunto de acontecimentos do universo que associados conspiraram para que o trabalho fosse realizado da maneira como aqui é apresentado. Desse modo, é importante agradecer a cada um que colaborou para que esse trabalho fosse concluído.

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APOIO FINANCEIRO E INSTITUCIONAL

Agradeço ao Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) pela bolsa de doutorado (PROJETO:402202/2019-8; Processo: 142364/2019-3). Esse estudo é parte integrante da Rede de Sustentabilidade na Aquicultura. O presente trabalho foi realizado com apoio do Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) (processos nº. 562820/2010-8; 406069/ 2012-3 e 306361/2014-0) e à Financiadora de Estudos e Projetos (FINEP) (convênio nº. 01.10.0578.00/10). Também recebemos recursos da Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) (processo nº. 10/ 52212-3). Agradeço também ao projeto AQUAVITAE (EU project 818173) financiado pelo programa Horizon 2020 (Call H2020-BG-2018-2) pelo financiamento do intercâmbio estudantil para a complementação da formação profissional. Agradeço à Empresa Brasileira de Pesquisa Agropecuária (Embrapa) e ao Centro de Aquicultura da Unesp (Caunesp) pelo apoio institucional oferecido durante o desenvolvimento dessa tese.

ATIVIDADES EXTRAS REALIZADAS DURANTE O DOUTORADO

Além das atividades obrigatórias para a obtenção do título de doutora em aquicultura, como a presente tese, créditos cursados em disciplinas e estágio docência, a discente também desenvolveu as seguintes atividades no período de 4 anos:

1. Participação projeto AQUAVITAE (EU project 818173) financiado pelo programa Horizon 2020 (Call H2020-BG-2018-2).
2. Projeto “Viabilidade técnica e econômica e sustentabilidade do cultivo orgânico integrado do camarão-branco-do-pacífico com macroalgas e ostras” - CNPq (PROJETO:402202/2019-8 - Formação empreendedora de doutorandos para aumento da competitividade de empresas por meio da inovação científica empresarial)
3. Palestra “Algicultura” como parte da programação da disciplina "Aquicultura", ofertada ao discentes matriculados no Curso de Graduação (Bacharelado) em Ciências Biológicas, do Instituto de Biociências do Câmpus do Litoral Paulista (UNESP - IB/CLP).
4. Palestra “O Brasil e a infodemia do cultivo de algas”, como parte integrante da disciplina “Sistema de Produção”, aos alunos do programa de Pós-Graduação em Aquicultura da Unesp, do Centro de Aquicultura da Unesp-Caunesp.
5. Projeto de extensão “Implementação do cultivo de macroalgas na fazenda Synbiaqua” – Fundunesp (Processo nº: 3161/2021)
6. Projeto de extensão “Teste do cultivo de espécies nativas de macroalgas na Reserva Extrativista Marinha de Corumbau (RESEX Corumbau), Cumuruxatiba, Prado – Bahia.” – Funep (Processo nº 1.136/2022)
7. Intercâmbio estudantil para a complementação da formação profissional no Centro Interdisciplinar de Investigação Marinha e Ambiental (CIIMAR) – Aquavitae (EU project 818173)

UTILIDADE DA TESE

A presente tese apresenta uma análise biofísica associada a uma análise neoclássica do cultivo de macroalgas no mar e na terra, abordando a sustentabilidade que atenda aos interesses ecossistêmicos e econômicos. Os dados apresentados neste trabalho servirão para o avanço do conhecimento em algicultura, possibilitando futuros estudos e subsidiando políticas públicas e tomadores de decisão, como investidores, aquicultores e órgãos governamentais.

RESUMO

Existe elevado interesse sobre as macroalgas no cenário aquícola devido ao valor da biomassa e também pela possibilidade de integração das algas a outros sistemas para mitigação de impactos e/ou melhoria na qualidade do ambiente aquático. No entanto, há necessidade de análises que possibilitem o desenvolvimento sustentável da algicultura. A contabilidade ambiental permite avaliar os sistemas de produção de modo holístico, demonstrando a demanda por recursos naturais, eficiência, capacidade de renovação, carga ambiental e sustentabilidade. A análise econômica neoclássica fornece informações sobre a viabilidade econômica, lucratividade e resiliência econômica dos sistemas. Desse modo, realizamos a síntese emergética e análise da viabilidade econômica do cultivo das macroalgas no mar e em terra, avaliando diferentes mercados. Para o cultivo no mar o Índice Emergético de Sustentabilidade foi de 30,36, 29,17 e 0,31 para os mercados de carragena, consumo humano e extrato glicólico, respectivamente. Porém, o cultivo no mar foi economicamente viável apenas para os cenários de consumo humano e extrato glicólico, que tiveram Valor Presente Líquido de US$1.097.389,91 e US$1.099.824,30, respectivamente. O cultivo de macroalgas em terra apresentou Índice Emergético de 0,22 para todos os mercados analisados, devido à alta dependência dos recursos da economia nesse sistema produtivo. Porém, o cultivo em terra é viável para todos os mercados, com Valor Presente Líquido superior a US$929.898.74, sendo o bioestimulante e consumo humano os mais atrativos. O presente trabalho nos permite identificar as diferenças e semelhanças entre sistemas de cultivo de macroalgas, para propor melhorias em ambos os sistemas para alcançar a sustentabilidade. As informações aqui apresentadas servirão de base para futuros estudos, tomadas de decisões e formulações de políticas públicas.

Palavras-chave: Aquicultura; Algas marinhas; Sustentabilidade; Economia ambiental

ABSTRACT

There is a high interest in seaweed aquaculture due to its biomass value and the potential for integration with other systems to mitigate impacts and improve the quality of the aquatic environment. Complementary analyses are needed to enable the sustainable development of seaweed farming. Emergy synthesis enables a holistic evaluation of production systems, including the assessment of natural resource demand, efficiency, renewal capacity, environmental impact, and sustainability. Neoclassical economic analysis provides information on the economic feasibility, profitability, and resilience of the system. We conducted an analysis of both sea-based and land-based seaweed farming using emergy synthesis and economic feasibility, evaluating different markets. The Emergy Sustainability Index for sea-based farming of carrageenan, human consumption, and glycolic extract markets was 30.36, 29.17, and 0.31, respectively. However, sea-based farming was economically viable only for human consumption and glycolic extract markets, with a Net Present Value of US$1,097,389.91 and US$1,099,824.30, respectively. Land-based seaweed farming had an Emergy Index of 0.22 for all analyzed markets, indicating low sustainability due to its dependence on economic resources. However, land-based farming was economically feasible for all market scenarios, with a Net Present Value of over US$929,898.74. Biostimulant and human consumption markets were the most attractive options. This study identifies the differences and similarities between seaweed farming scenarios and proposes improvements for both systems. The information presented here will serve as a foundation for future studies, decision-making processes, and the formulation of public policies.

Keywords: Aquiculture; Marine algae; Sustainability; Environmental economy

INTRODUÇÃO GERAL

O cultivo de macroalgas marinhas tem sido um "*hot topic*" no cenário internacional e nacional na última década. Dados apresentados pela FAO (2022) mostram que essa atividade cresceu nas últimas duas décadas, com o aumento da produção mundial de ~10.6 milhões de toneladas produzidas em 2000 para 35.1 milhões de toneladas em 2020. Em 2018 a produção de macroalgas representou 51.3% da produção da maricultura mundial (Chopin e Tacon, 2020). Esse cenário acompanha o aumento do interesse comercial sobre as algas marinhas. As macroalgas têm diferentes usos e aplicações, como alimento humano, hidrocolóides, cosméticos, alimentação animal, fertilizante, entre outros FAO (2018). Dessa extensa lista, o comércio das macroalgas como alimento é de maior volume e valor, e está associado aos países asiáticos (FAO, 2018). O uso das macroalgas para a extração de hidrocolóides, apesar de ocupar um mercado mundial, representa menor volume e valor quando comparado ao mercado de alimentos (FAO, 2018). Além disso, estudos apontam que a produção de macroalgas para o mercado de hidrocolóides pode não ser economicamente viável e atrativo (Ladner et al., 2018; Nogueira e Henriques, 2020; Pereira et al., 2020).

Desse modo, apesar de o uso das macroalgas como alimento direto para o ser humano ser tradicional e milenar na culinária oriental (Mouritsen et al., 2019), esse tem se mostrado um "novo" mercado potencial e atrativo para o ocidente (FAO, 2021; Mouritsen et al., 2019). As macroalgas apresentam grande variedade de aplicação para composição de produtos, ingredientes ou suplementos de base natural e elevado valor com funções bioativas, antivirais, farmacêuticas, nutracêuticas e antioxidantes (FAO, 2018). As macroalgas apresentam várias propriedades de interesse para a indústria de cosméticos como funções emoliente, antiinflamatória e antioxidante (Hitton et al., 2007; Nurjanah et al., 2016). Além disso, o interesse crescente dos consumidores em produtos naturais, veganos, e "*cruelty-free*" tem feito crescer o uso de macroalgas na indústria cosmética (Mazarrasa et al., 2014). Outro mercado de crescente interesse é o de biofertilizantes. Os extratos das macroalgas apresentam características de melhorar a produtividade das plantações, assim como de atender ao nicho da agricultura orgânica (Mukherjee e Patel, 2020; Prakash et al., 2018; Zafar et al., 2022). Somado a isso, a situação de guerra entre

Ucrânia e Rússia gerou o desabastecimento e instabilidade em relação à disponibilidade de fertilizantes no cenário brasileiro. Essa questão fez com que houvesse uma grande mobilização governamental no Brasil para aprovação do cultivo de macroalgas ao longo da costa brasileira. Até 2020 algicultura no Brasil não apresentava dados de produção declarados sendo previsto uma mudança para esse cenário em 2021, devido à solicitação de permissões áreas aquícolas (MAPA, 2021).

Essa expansão da atividade aquícola vem acompanhada da preocupação de que ela ocorra de maneira organizada e sustentável (FAO, 2020). Alguns trabalhos apontam as macroalgas como promotoras socioambientais (Chopin, 2012; Edwards, 2015; FAO, 2013; Kim and Yarish, 2014; Marinho-Soriano et al., 2009; Msuya, 2014; Powell et al., 2014; Radulovich et al., 2015; Rebours et al., 2014; Visch et al., 2020; Wood et al., 2017; Yang et al., 2015). Uma das principais características de interesse das algas é serem organismos fotosintéticos que, portanto, sequestram carbono (Duarte et al., 2017; Gouvêa et al., 2020; Mashoreng et al., 2019), além de remover os compostos inorgânicos da água reduzindo a eutrofização (Chopin, 2014; Edwards, 2015). No entanto, o nível de impacto de serviços como o sequestro de carbono e a promoção das algas como a grande solução para o aquecimento global têm sido questionados (Troell et al., 2022). Além disso, a viabilidade econômica dos cultivos é questionável, podendo variar de acordo com mercados direcionados, região do cultivo e flutuações da produção (Ladner et al. 2018; Nogueira e Henriques 2020; Pereira, Kimpara, e Valenti 2020; Valderrama et al. 2015). Artigos recentes abordam a sustentabilidade das macroalgas de modo quantitativo e de acordo com aspectos ambientais, sociais e econômicos. Pereira et al. (2021) apontam a sustentabilidade do cultivo da *Hypnea pseudomusciformis* em região tropical visando o nicho de mercado para consumo humano direto, com baixo risco da espécie utilizada e eficiência no uso dos recursos como energia e nutrientes. Collins et al. (2022) avaliaram a viabilidade econômica e sustentabilidade através da análise do ciclo de vida do cultivo de *Alaria esculenta* no Atlântico Norte e observaram absorção de carbono e viabilidade econômica. Apesar do potencial para contribuir com o desenvolvimento sustentável, a produção necessita de regulamentação apropriada e mitigações para evitar resultados negativos indesejados (Spillias et al., 2022). Desse modo, são necessários estudos que avaliem a sustentabilidade geral

dos sistemas produtivos de diferentes maneiras para uma melhor compreensão de suas características positivas e negativos, identificando pontos chave para aumentar a sustentabilidade.

Existe uma série de metodologias utilizadas para avaliar a sustentabilidade de sistemas aquícolas como Conjunto de Indicadores (Valenti et al., 2018), Análise do Ciclo de Vida (Ciambrone, 1997), Pegada Ecológica (Wackernagel e Rees, 1996), e Síntese em Emergia (Odum 1996). Conjunto de Indicadores é uma ferramenta completa e prática que avalia a sustentabilidade considerando os aspectos ambientais sociais e econômicos através de uma abordagem neoclássica que considera os serviços ecossistêmicos como externalidades positivas e negativas que são adicionadas na análise de custo-retorno do sistema (Valenti et al., 2018). A Análise do Ciclo de Vida (ACV) é uma metodologia padronizada que avalia potenciais impactos ambientais associados a um produto considerando todos os estágios de seu ciclo de vida, desde a extração da matéria-prima até o descarte dos resíduos e embalagens (Ciambrone, 1997). A ACV é uma ferramenta muito aceita por stakeholders, porém tem uma abordagem mais ambiental e econômica do que social, além de necessitar de software pago e/ou banco de dados pago ou restrito, dificultando sua ampla aplicação. A Pegada Ecológica mede a sustentabilidade através da área requerida para manter os padrões de um sistema considerando a produção de todos os insumos utilizados e o processamento dos resíduos gerados (Wackernagel e Rees, 1996), essa é uma ferramenta simples de viés mais ambiental. A emergia com “m” é uma contabilidade ambiental baseada na ciência para representar valores ambientais, econômicos e sociais em uma mesma medida (Odum, 1996). Essa metodologia avalia, por meio da energia direta e indireta utilizadas, os trabalhos da natureza e do homem para gerar um produto ou serviço. A síntese emergética mostra a demanda pelos recursos naturais, eficiência, capacidade de renovação, carga ambiental e sustentabilidade gerados pelo sistema produtivo (Odum, 1996). Assim, a emergética proporciona uma visão holística do sistema de cultivo de macroalgas e *insights* sobre a sustentabilidade desses sistemas, porém com o viés biofísico. A sociedade funciona de acordo com a economia neoclássica, de modo que é necessário a associação das análises de sustentabilidade com indicadores de viabilidade econômica.

Desse modo, propomos com a presente tese avaliar a sustentabilidade do cultivo de macroalgas no mar e em terra usando as ferramentas síntese emergética e análise econômica para diferentes sistemas de produção considerando diferentes mercados e simulando diferentes cenários estratégicos. O objetivo principal é avaliar a sustentabilidade dos sistemas de produção considerando os princípios ecossistêmico da biofísica e econômico neoclássico. Como objetivos específicos temos a identificação dos itens chave para redução da sustentabilidade, aspectos gerais dos sistemas, fatores econômicos dos sistemas, e sugestão de alternativas para o desenvolvimento em acordo com os objetivos do desenvolvimento sustentável (ODS) da ONU (United Nations, 2015). A perspectiva é que os resultados gerados no presente estudo sirvam de suporte para a gestão pública e para os tomadores de decisão contribuído para o avanço da Economia Azul sustentável.

O cultivo de macroalgas na costa Brasileira ainda é incipiente, apresentando estágio inicial de desenvolvimento e poucos cultivos comerciais (Valenti et al.,2020). A *Hypnea pseudomusciformis* está entre as espécies nativas cultivadas que apresentam grande potencial de viabilidade produtiva e econômica com potencial sustentável (Pereira et al., 2021; Valenti et al., 2020). Já a *Kappaphycus alvarezii* é uma espécie introduzida para cultivo na costa Brasileira (Valenti et al., 2020) e que tem tido o cultivo amplamente disseminado ao longo da costa no último ano. O primeiro capítulo “Sustainability of the seaweed *Hypnea pseudomusciformis* sea-based farming for different markets in South Atlantic: An emergy and economic approach” avalia o cultivo no mar da espécie nativa para os mercados de extração de carragena, consumo humano direto ou extrato glicólico para cosméticos. O segundo capítulo “The sustainability of the seaweed *Kappaphycus alvarezii* land-based farming for different markets: An emergy and economic approach” avalia a sustentabilidade do cultivo desta espécie para venda de carragena, alimento humano e biofertilizante, cultivada em canais de abastecimento de carcinicultura. Todos os resultados obtidos na presente tese serão disponibilizados no portfólio de resultados da Rede de Pesquisa em Sustentabilidade na Aquicultura.

CAPITULO 1 – Sustainability of the seaweed *Hypnea pseudomusciformis* sea-based farming for different markets in South Atlantic: An emergy and neoclassic approach

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Abstract

Seaweeds are highly sought-after products in mariculture. Seaweed farming is often associated with sustainability due to its autotrophic characteristics. However, there is a lack of scientific studies on the impacts of this aquaculture system. Therefore, we evaluated *Hypnea pseudomusciformis* farming, taking into account environmental accounting and economic feasibility when selling the products in the following markets: carrageenan (C), human direct consumption (HC), and glycolic extract (GE). Emergy analysis is a viable tool for measuring the sustainability of aquaculture and identifying necessary improvements in the production system. Additionally, the emergy associated with economic analysis can provide more substantial information for decision-making. The main inputs of the system were identified, and different production scenarios were simulated. The most significant items included labor, services, and plastic, along with liquid glycerin for the glycolic extract market. Natural resources constituted the majority of inputs for the carrageenan and human consumption markets, accounting for 83% of the total, while financial resources represented 80% of the total for the glycolic extract market. To evaluate sustainability indexes considering both biophysical and neoclassical economic approaches, we simulated various scenarios. These strategic scenarios involved using less and recycled plastic, shortening the farming time cycle, utilizing more renewable solvents, and combining all these strategies. For the carrageenan market, the Emergy Sustainability Index (ESI) ranged from 30.4 (base scenario) to 31.3 (plastic reduction), and the net present value (NPV) was negative for all scenarios. In the case of the HC market, the ESI ranged from 29.2 (base scenario) to 30.0 (plastic reduction), and the NPV ranged from US$1,070,464 to US$1,428,363, with the lowest NPV observed for reducing plastic and the highest NPV for reducing the farm cycle length. Regarding the GE market, the ESI ranged from 0.3 to 0.6, and the NPV varied from US$ -458,730,648 to US$ 1,508,171. The NPV was negative for solvent replacement strategies and higher for reducing time cycle. Seaweed farming for carrageenan showed no economic feasibility and, therefore, is considered unsustainable from a neoclassical economic perspective. However, for human consumption, when combining different strategies, the production system demonstrated sustainability from both emergy and economic perspectives. As for the glycolic extract market, emergy analysis sustainability was highest for scenarios involving renewable solvents, while for the neoclassic analysis it was non-sustainable. These results suggest that combining emergy synthesis with economic analysis provides a useful tool for decision-making, ensuring the sustainability of production processes.

Keywords: environmental accounting; bioeconomy; macroalgae; sustainability

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1. Introduction

The highlight of the blue economy in the last decade has promoted the development of blue activities such as mariculture (FAO, 2022). In this scenario, seaweed farms are one of the most expanding mariculture activities. Seaweed culture has shown high interest and growth, as global production has tripled, from 10.6 million tonnes in 2000 to 35.1 million tonnes in 2020 (FAO, 2022). Seaweed cultivation contributed to nearly 30% of the global aquaculture production in 2019 (FAO, 2021). Seaweeds are interesting due to their multiple uses and applications in food and non-food industries (FAO, 2018, 2003), and the demand for novel foods and nutraceutical seaweed-based products has risen (FAO, 2021; Pacheco et al., 2021). This increasing interest in seaweeds is expected to continue to grow, expanding farming in the following decades.

Despite being an activity that is still little known, red macroalgae were the second most cultivated group of aquatic organisms in the world in 2018 (FAO, 2020a). Despite being a very representative activity in terms of volume, the seaweed species diversity with cultivable techniques is relatively low compared to animal aquaculture species. However, there is extensive seaweed biodiversity. The Rhodophyta pool still represents unexplored biodiversity in several areas with just a few cultivable species (Pacheco et al., 2021). This scenario makes testing and developing new species' farming techniques necessary.

Among this huge biodiversity to be explored by aquaculture to supply many markets, there is the species *Hypnea pseudomusciformis.* The *H. pseudomusciformis* is an economic-value and novel cultivable red seaweed species for aquaculture in tropical regions. In the past, there was the exploitation of *H. pseudomusciformis* by the carrageenan industry in Brazil (Marinho-Soriano, 2017), and a few studies tried without success to farm this species (Berchez et al., 1993; Camacho and Montaña-Fernández, 2012; Castelar et al., 2016; Ganesan et al., 2006; Neto, 1987). Recent work shows the technical feasibility of *H. pseudomusciformis* farming, describing a patented technology to culture this macroalga (Pereira et al., 2020a). This technology brings an alternative species for developing seaweed culture in tropical countries.

Sustainable development is a concern in all production sectors, including aquaculture and seaweed farming. Global aquaculture prioritization is the aquatic ecosystem's sustainable management and the responsible use of resources (FAO, 2020b). Seaweed farms are frequently associated with sustainability (Duarte et al., 2017; Kim and Yarish, 2014; Radulovich et al., 2015; Rebours et al., 2014). However, this concept is often based on

general organism characteristics and not on in-depth analysis of the aquaculture system and its impacts. One study that used sustainability indicators to evaluate seaweed farming for the human consumption market attested sustainability and ecosystem services provision (Pereira et al., 2021). Despite the indicators being an easily applicable and interpretable tool (Valenti et al., 2018), it still has neoclassical economic biases and it is difficult to compare different production systems considering an ecosystem approach.

Therefore, additional sustainability evaluations that analyze seaweed cultivation with different and extensive approaches are essential. Besides sustainability indicators, there are other methods to evaluate sustainability in aquaculture systems, such as Life Cycle Assessment, Ecological Footprint, and Emergy Synthesis (Valenti et al., 2018). The emergy with "m" is an environmental accounting based on science to represent environmental, social, and economic values in the same measure (Odum, 1996). This method evaluates nature and man works for product and services generation accounting for the total energy used directly and indirectly. Some studies applied this methodology with success to aquaculture systems such as tilapia (David et al., 2021b, 2018; Garcia et al., 2014), lambari (Fonseca et al., 2022), oysters (Williamson et al., 2015), and aquaponic systems (David et al., 2022). The Emergy Synthesis shows the natural resources demanded, efficiency, renewability capacity, environmental load, and sustainability that systems may generate (Odum, 1996). So, Emergy Synthesis may provide seaweed farming sustainability insights from a holistic and ecosystemic perspective. Thus, the present study aims to evaluate *H. pseudomusciformis* farming to generate products sold in different markets using the environmental accounting tool combined with a neoclassical economic analysis to evaluate sustainability key factors in both perspectives, to identify possible improvement actions and decision making towards sustainability.

2. Material and methods

2.1. Study area and data collection

We evaluated data from a pilot culture conducted at facilities of "Associação de Produtores de Algas de Flecheiras e Guajiru" (APAFG) (Association of Algae Producers of Flecheiras and Guajiru), which is a traditional coastal community practicing seaweed farming and ecotourism in Flecheiras Beach, Trairi municipality of Ceará Northeastern Brazil, for

more than 25 years. Associated with seaweed farming, APAFG also participates in tourism and collaborates with schools and universities to facilitate technical and educational visits. Additionally, there is a restaurant called "Barraca das Algas," owned by some associates, which specializes in serving dishes made with seaweed utilizing the farmed biomass.

We simulated a 7.51 ha with 7,500 liner meters seaweed farm using longlines with substrates in the sea, based on a pilot farming of 30 linear meters. The longline structure is modular, where each module of 1 m is composed by a polypropylene braided rope with a 1 cm diameter thickness and substrates spaced 30 cm from each other (Fig. 1). The ~25 g seedlings are tied at the substrates and are farmed for 45 days. There is no need for any industrial inputs during farming. The seaweed farming management is based on replacement of lost seedlings, checking farming structures, and cleaning seaweeds weekly to avoid fouling. It is done by shaking the structures to remove sand, organisms, and accumulated particles. After 45 days, a manual harvesting occurs, by pulling seaweeds from the substrates. The farmers obtain new seedlings by vegetative growth. The seedling's production uses the harvested seaweed's apical parts. Therefore, the farm has 7.5 km of longlines and 8 production cycles of 45 days per year. After 45 farming days, we obtain 0,96kg per long-line meter. Of the total harvested biomass, about 8% is for seedlings production to start a new farming cycle The technology farm for *H. pseudomusciformis* biomass culture is described in detail by (Pereira et al., 2020a) and patented on a Brazilian patent basis (#BR 10 2019 027,248 1; 19 December 2019).

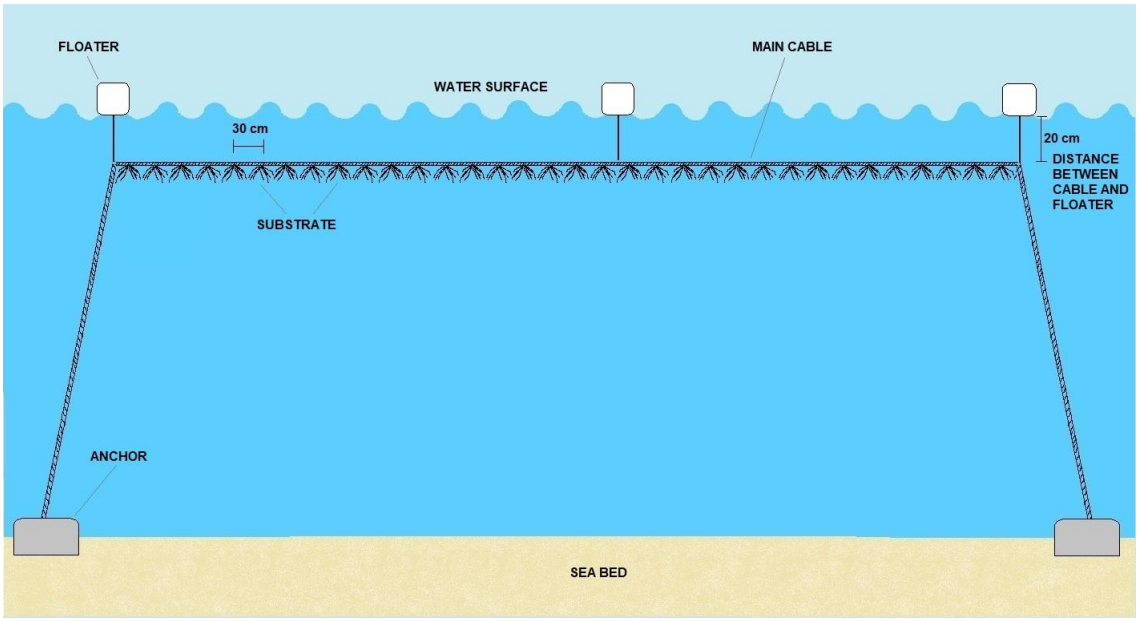

Figure 1. Longline with substrates scheme used in the sea-based *H. pseudomusciformis* farming.

We obtained the data of environmental and economic inputs associated with seaweed farming via in situ visits to the production system at the stocking, middle of farming cycle, and harvest periods. Water, sediment, and organisms were sampled during field activities. Other information about nature, economy and social inputs of seaweed farming were obtained through a semi-structured survey applied to the associated farmers. The questionnaire focused on the accounting of the materials, equipment, and purchased infrastructure, as well as labor, taxes, and depreciation. All inputs were accounted for in units/hectare and correspond to one year of the farm operation.

2.2. Market scenarios

We simulated three different market scenarios for seaweed farming. The first one is selling bleached and dry seaweed for the carrageenan industry (C), the second one is dehydrated seaweed for human consumption (HC), and the third one is non-industrial production of glycolic extract on-site for the cosmetic industry (GE) (Figure 2). In this study, the system boundaries were the marine surface occupied by farming. The monetary values were acquired in the Brazilian market in the third quarter of 2022 and converted to US$ dollars (US$1.00 = R$5.38). All input values correspond to one year of farm operations on a one-hectare farm basis.

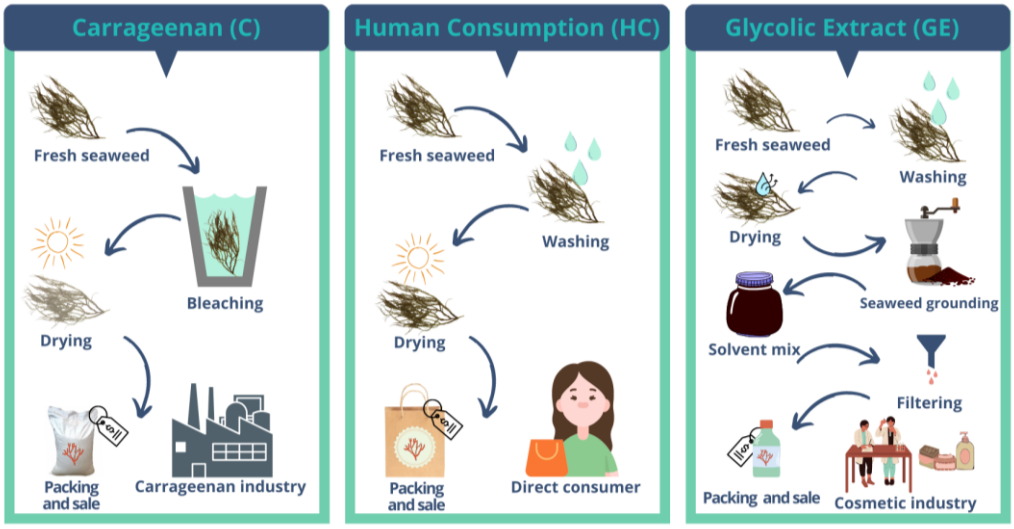

Figure 2. Seaweed processing scheme for the different market scenarios: carrageenan (C); Human Consumption (HC); and Glycolic Extract (GE).

2.2.1. Carrageenan industry (C)

The carrageenan industry scenario corresponds to the sale of bleached and dry seaweed biomass directly to the industry. The harvested seaweed is bleached by washing and soaking the biomass into freshwater to remove impurities and seaweed pigments. Afterwards, the biomass is sun dried until reaching 15% humidity. The commercialization occurs in raffia bags of 25 kg. The different strategy scenarios are described below:

2.2.1.1.Carrageenan industry using less and recycled plastic (C_{pr})

This scenario considers a reduction of the standard cultivation length from 45 to 40 days, allowing nine cycles per year instead of eight, in the base scenario. It yields 11,070.00 kg of bleached and dry seaweed per year.

2.2.1.2.Carrageenan industry with farming cycle length reduction (C_{cr})

This scenario considers a reduction of the standard cultivation length from 45 to 40 days. In this scenario, we have nine cycles per year (one more than base scenario) and a total production of 11,070.00 kg of bleached and dry seaweed per year.

2.2.1.3.Carrageenan industry using less and recycled plastic and farm cycle length reduction (C_T)

This scenario merges all scenarios tested above to analyze if the strategy combinations optimize and improve sustainability.

2.2.2. Human Consumption (HC)

The dehydrated seaweed biomass is sold directly to tourists and visitors of Barraca das Algas, restaurants, and other interested clients.. The harvested seaweed biomass is washed in freshwater to remove impurities. Afterwards, the seaweed is sun dried until 15% humidity. The commercialization occurs in paper bags of 100 g or 1 kg. The different strategy scenarios are described below:

2.2.2.1.Human Consumption using less and recycled plastic (HC_{pr})

This scenario considers the reduction of plastic materials to increase Renewability. We changed the plastic ribbon to attach the seedlings on the longlines for cotton yarn. We also consider the longline ropes made of 0 to 80% recycled material. This material is 1.5 times more expensive than non-recycled plastic.

2.2.2.2.Human Consumption with farming cycle length reduction (HC_{cr})

This scenario considers a reduction of the standard cultivation length from 45 to 40 days. In this scenario, we have nine cycles per year and a total production of 11,070.00 kg of dry seaweed per year.

2.2.2.3.Human Consumption using less and recycled plastic and farming cycle length reduction (HC_T)

This scenario merges all scenarios tested above to analyze if the strategy combinations optimize and improve sustainability.

2.2.3. Glycolic Extract (GE)

The harvested seaweed biomass undergoes several processing steps. First, it is washed in freshwater to remove other organisms and impurities. Then, the biomass is dried in the shade

and ground. A recycled amber glass container covered with aluminum foil is used to mix the ground biomass, liquid glycerin, and grain alcohol. The amber glass bottle is sealed and kept in a dark place for 1 to 2 weeks, with homogenization performed twice a day. After this process, the liquid is filtered using a paper filter and bottled in plastic containers ranging from 100 mL to 1 L in size. These products are intended for sale to small cosmetic manufacturers and industries. Below are descriptions of different strategy scenarios:

2.2.3.1.Glycolic Extract using less and recycled plastic (GE_{pr})

This scenario considers the reduction of plastic materials to increase Renewability. We changed the plastic ribbon to attach the seedlings on the longlines for cotton yarn. We also consider the longline ropes made of 0 to 80% recycled material. This material has a price 1.5 times higher than traditional plastic.

2.2.3.2.Glycolic Extract with farming cycle length reduction (GE_{cr})

This scenario considers a reduction of the standard length of cultivation from 45 to 40 days. In this scenario, we have nine cycles per year and a total production of 11,070.00 kg of dry seaweed per year.

2.2.3.3.Glycolic Extract using plant-based extract solvent (GE_{sr})

This scenario considers the replacement of the traditional liquid glycerin solvent for a plant-based glycerin, which has higher Renewability, equal to 31%.

2.2.3.4.Glycolic Extract using less and recycled plastic, farming cycle length reduction, and plant-based solvent (GE_T)

This scenario merges all scenarios tested above to analyze if the strategy combinations optimize and improve sustainability.

Table 1. Farming strategy scenarios tested for the different markets: less and recycled plastic (pr); farming cycle reduction (cr); plant-based solvent (sr) and all scenarios combination (T). * The plant-based solvent applies to the glycolic extract market only.

Scenario	Abbreviation	Description
Reducing use of plastic and increasing its renewability	pr	Plastic ribbon replacement for cotton yarn and cables made from 80% renewable and recycled material
Farming cycle reduction	cr	Cycle time was reduced from 45 to 40 days, with an increase of one cycle per year and a yield of 1.02 kg per long-line meter
*Renewable plant-based solvent	sr	Considers the use of vegetable liquid glycerin with renewability of 31%
All scenarios merged	T	Combination of all strategic scenarios

2.3. Emergy synthesis

The Emergy Synthesis considered all the directly and indirectly energy used to generate a product or a service (Odum, 1996). It is also called Environmental Accounting and is a biophysical approach to establishing a value for natural resources that considers a holistic view, recognizing all natural efforts to make a product. The Emergy Synthesis procedure covers the following three main steps: (1) build an energy diagram to define the system boundaries and organize all inputs and outputs components and their relationships (Figure 3); (2) create the emergy table with the quantitative flows and choose suitable Unit Emergy Values (UEVs); (3) calculate the emergy indexes.

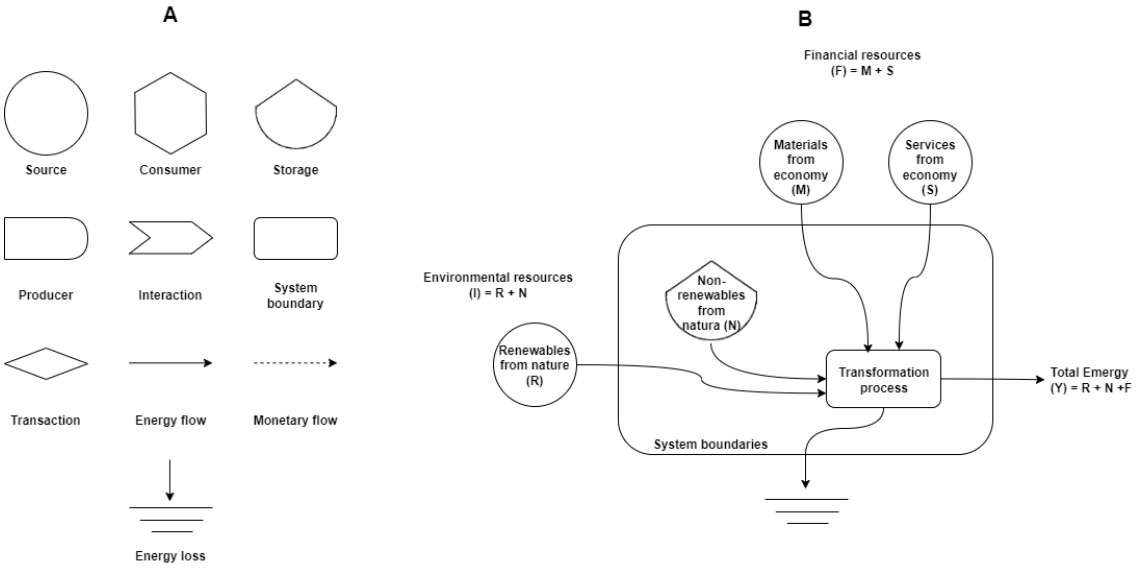

Figure 3. (A) Most commonly used symbols in energy systems diagrams (Odum, 1995). (B) Generic energy diagram with symbols and acronyms used in Emergy Synthesis to calculate the emergy indexes. R = renewable resources from nature; N = non-renewable resources from nature. Modified from Fonseca et al. (2022).

In the first step of the assessment, it is necessary to draw a diagram. The energy flow diagram uses a systemic perspective to identify all energy input sources of the system, the internal processes that occur, and all the system outputs. This diagram allows a holistic view of the system and how it works (Odum, 1996). In the second step of the analysis, an energy inputs inventory is created with a table where the items are classified and organized as the source type as natural renewable resources (R), natural local non-renewable resources (N), or purchase resources from the economy (F). Input resources were accounted for in mass (g), energy (J), or money (US$) units. All resources must be in the same unit to calculate the Emergy Synthesis, which is the solar emjoules (sej). So, we multiplied the quantified input resource flows by their respective UEVs. The UEVs were obtained in scientific literature and at the Emergy Evaluation Folios published by the Center of Environmental Policy from the University of Florida. The present work used the global baseline of 1.20E+25 sej/yr (Brown and Ulgiati, 2016). In this inventory table, the input quantity is multiplied by their respective UEVs, resulting in energy flows in solar emjoules (sej) and quantifying the system's outputs. All system outputs are considered as co-products, and are composed of all emergy demanded by the system for calculating their UEVs. The exception of this is seaweed seedlings, which accounted for only a proportion of inputs applied in seaweed farming, excluding the

processing phase, as it re-enters the system instead of being processed and sold. The third step consists of emergy indexes calculation and interpretation (Table 2).

Table 2. Emergy indicators used in the present study.

Indicator	Abbreviation	Formula	Description
Unit Emergy Value	UEV	UEV = Y/E	Ratio of the total emergy demanded by value UEV = Y / E the unity output. Example of units are sej/J, sej/kg and sej/$.
Renewability[a]	R%	m-R%=100 (R+Mr+Sr)/Y	Ratio of the nature and economy's renewable fraction by the total emergy demanded to produce dry seaweeds or seaweeds glycolic extract.
Environmental Loading Ratio [a]	ELR	m-ELR=(N+Mn+Sn)/(R+Mr+Sr)	Ratio of the total non-renewable loading ratio of resources by the total renewable resources.
Emergy Yield Ratio	EYR	EYR = Y/F	Ratio of the total emergy demanded to produce dry seaweeds or seaweeds glycolic extract by the resources from the economy.
Emergy Investment Ratio	EIR	EIR = F/(R+N)	Ratio of the resources from the economy by nature renewable and non-renewable resources.
Emergy Exchange Ratio	EER	EER = Y/[($) x (sej/$)]	Ratio between the emergy contained in the product and the emergy contained in the money received by its sale. These indices express the exchange ratio of one or more exchange partnerships and is a measure of the relative advantage that is established between the exchange partners.
Emergy Sustainability Index	ESI	ESI = EYR/m-ELR	Ratio between the emergy yield ratio by the environmental loading ratio.

Indicators developed by Odum (1996); [a] Modified according to (Agostinho et al., 2018). Y = total emergy; E = product/service total quantity; R = renewable from nature; N = non-renewable from nature; F = resources from economy; M = materials; S = services; r = renewable fraction; n = non-renewable fraction; m = modified considering partial renewability.

The Unit Emergy Value (UEV) measures the environmental cost of the product or service; it indicates the system efficiency when compared to others of the same hierarchical level. The Renewability (R%) indicates the renewability fraction of the total emergy demanded delivering the product or service. This study considered the partial Renewability of each input for emergy indicators, according to Agostinho et al. (2018). The partial Renewability application is appropriate when the materials and services used are from the local economy. The resources Renewability values were considered when available in the literature, as suggested by Agostinho et al. (2019). The Environmental Loading Ratio (ELR) indicates the pressure of a production system over the natural ecosystems. ELR values lower than 2 indicate low pressure, from 2 to 10 indicate moderate pressure, and higher than 10 indicate high pressure (Brown and Ulgiati, 2004). The Emergy Yield Ratio (EYR) indicates the system's net contribution to the economy beyond its operation. EYR values lower than 2 show a high dependence on purchased resources and a low contribution to the larger economy (Brown and Ulgiati, 2004). The Emergy Investment Ratio (EIR) evaluates the process efficiency in emergy invested use compared with alternatives. If the EIR is higher than other similar systems, it does not compete economically (Brown and Ulgiati, 2004). The Emergy Exchange Ratio (EER) indicates the relation between the product emergy and the money emergy by its sale. The EER equal to or lower than one shows a payment of the emergy spent on the offered product or service (Brown and Ulgiati, 2004). The Emergy Sustainability Index (ESI) indicates the system's contribution to the economy by environmental pressure. The ESI values lower than 1 indicate unsustainability, values ranging from 1 to 5 indicate short-term sustainability, and values higher than 5 indicate long-term sustainability (Brown and Ulgiati, 2004).

2.3.1. Ecosystem services

This study accounted for Ecosystem Services (ES) as a co-products of aquaculture production in sustainability assessments, according to David et al. (2022). The Ecosystem Services provided by *H. pseudomusciformis* sea-based farming are identified based on previously published data by Pereira et al. (2021). The Ecosystem Services are positive feedback to society, and we classified them in the emergy table as a system’s outputs, as "Legal Reserve" area and "Ecotourism". The “native vegetation conservation” considered was the preserved area in the land used for the harvest processing and multiplied by the value of the intact forest preservation. However, as there is no restinga emergy studies available in the

literature, we considered the average global value of tidal marsh Ecosystem Services (Costanza et al., 1997). The "Ecotourism" is calculated based on how much consumers paid for this service, multiplied by the number of people who attended the tours. All values of emergy services were calculated by multiplying the energy flow by the monetary transformity.

2.4.Bioeconomic analysis

All costs and prices were obtained in the Brazilian market in the fourth quarter of 2022 and converted to US$ dollars (US$1.00 = R$5.38). We used the sale prices published by Pereira et al. (2020b) for all the market scenarios updating the value according to inflation.

Fixed Costs (FC) included employee salaries, vehicle property tax, maintenance of equipment and facilities, depreciation of assets, and opportunity costs. The depreciation was calculated by the straight-line method (Engle, 2010). Opportunity costs were the interests of the fixed capital and remuneration of the entrepreneur. Variable Costs (VC) consisted of expenses with plastic raffia ribbon, cotton yarn, fuel, plastic raffia bag, manual labor, and taxes. The VC for producing the glycolic extract included liquid glycerin, grain alcohol, plastic bottles, and paper filters. Cost and revenue data were used to determine Gross Revenue (GR), Net Revenue (NR), and Profit (P) as described below:

$$GR = Production\ x\ Selling\ price \quad (1)$$

$$NR = Gross\ revenue - Total\ costs \quad (2)$$

$$P = Net\ revenue - Opportunity\ costs \quad (3)$$

The cash flow analysis considered 20 years of operation. Year zero included the initial investments and working capital. Production was assumed to be 40 and 20% lower than the predicted values for the first and second years, respectively, to compensate for potential difficulties at the beginning of the venture such as technological adjustments, personnel training, and insertion of the product into markets.

Internal Rate of Return (IRR), Net Present Value (NPV), Benefit-Cost Ratio (BCR), and Discounted Payback Period (DPP) were used to determine the financial feasibility. The four indicators were determined based on annual inputs and outputs according to calculations described in Engle (2010), Jolly and Clonts (1993) and Shang (1990):

$$\sum_{t=1}^{n} \frac{NCF_t}{(1+IRR)^t - NCF_0} = 0 \quad (4)$$

$$NPV = \sum_{t=1}^{n} \frac{NCF_t}{(1+i)^t - NCF_0} \quad (5)$$

$$BCR = \sum_{t=1}^{n} (NCF_t/(1+i)^t)/NCF_0 \quad (6)$$

DPP is the time t discounted at a given Minimum Attractive Rate of Return (MARR), where:

$$\sum_{t=0}^{n} NCF^{MARR} = 0 \quad (7)$$

NCF is the net cash flow; i is the discount rate; n is the number of years in operation (0, 1, 2, 3…n) and t is the year. The MARR and the discount rate were 13.75% per year, which was the interest on initial capital in Brazil in the first quarter of 2023.

3. Results

We present a systematic view of the emergy synthesis for *H. pseudomusciformis* sea-based farming, which is commercialized for three distinct markets. All scenarios depict the same energy flow diagram to the farm (Figure 4), while the energy flow diagrams for processing the seaweed biomass to the final product vary across different market scenarios (Figure 5).

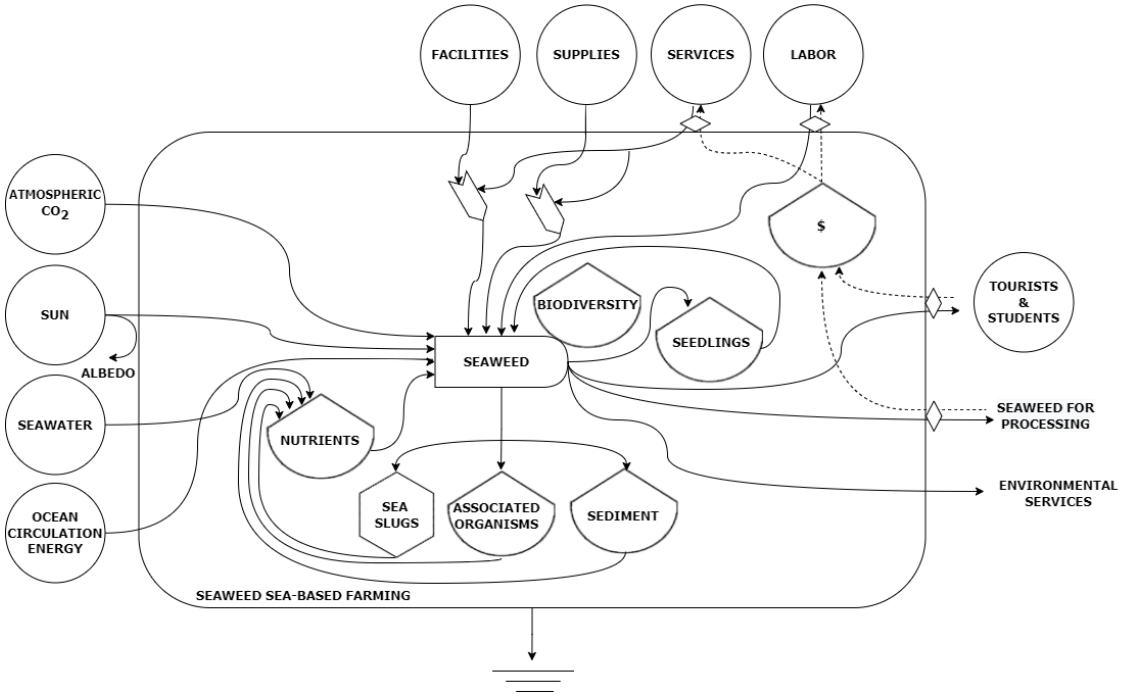

Figure 4. Energy diagram of the seaweed *H. pseudomusciformis* sea-based farming.

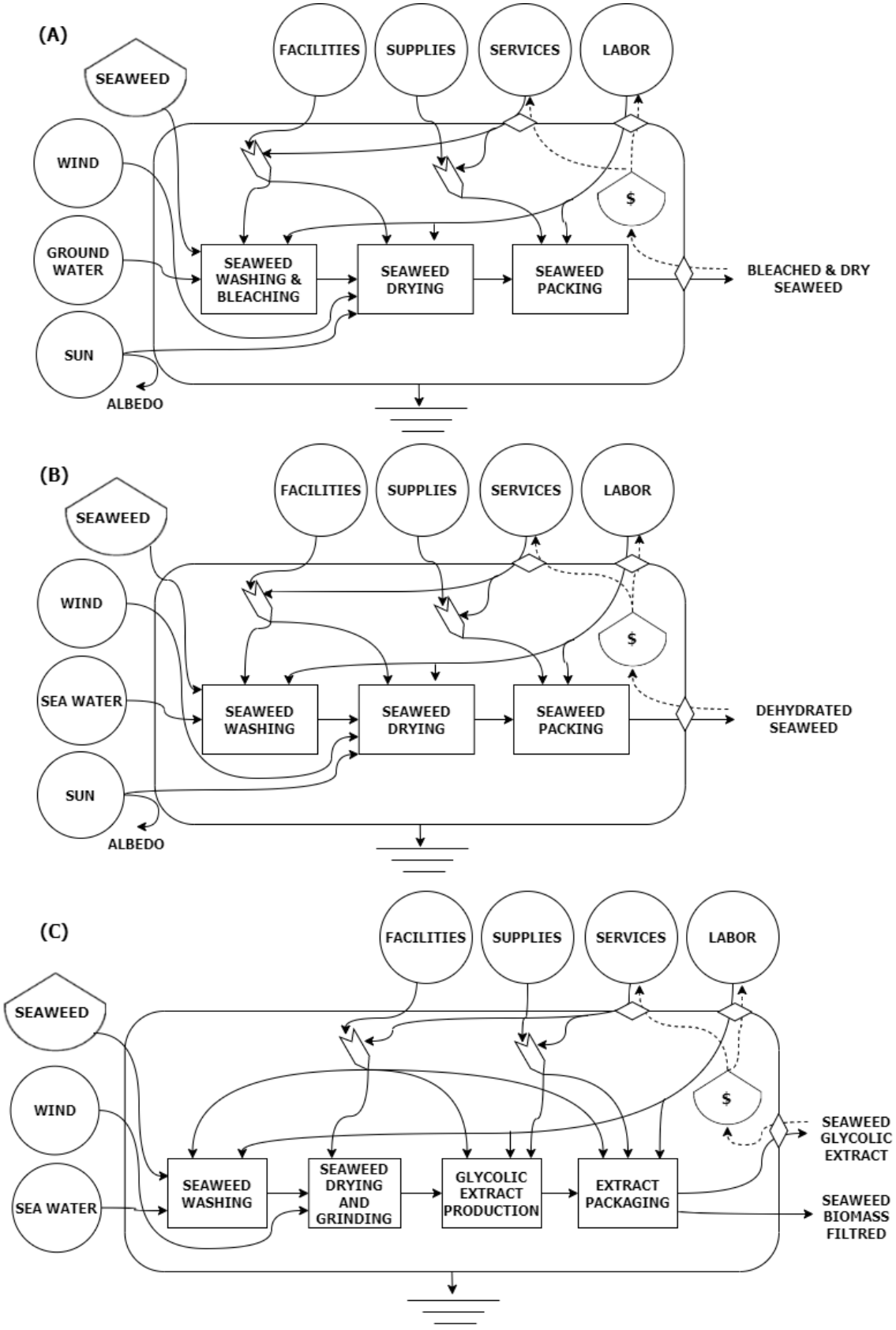

Figure 5. Processing of seaweed biomass to the final product occurs as follows for each market: (A) Carrageenan, (B) Human consumption, and (C) Glycolic extract.

Renewable resources from nature (R) represents ~83% of energy flow to carrageenan and human consumption scenarios. The renewable resources from nature corresponds to ~20% of the energy flow in the glycolic extract scenario. Non-renewable resources from nature (N) represents less than 0.01% of all three analyzed market scenarios. The resources from economy (F) accounts for ~17% of carrageenan and human consumption and ~80% of the glycolic extract. For carrageenan and human consumption, human labor is the highest emergy input representing 89% of total, followed by services with 8%, and carbon with 2%. For the glycolic extract, liquid glycerin represents 82% of the flow, followed by labor (11%), services (6%), and plastic (0.7%).

Table 4. Emergy table of sea-based *H. pseudomusciformis* farming for carrageenan market base scenario (C).

Note	Item	Unit	Amount (unit/ha/year)	UEV (sej/unit)	UEV Reference	Emergy E12 sej/ha/year	Emergy (%)
Renewable nature resources (R)							
1	Sun	J	1.81E+12	1.00E+00	Odum (2000)	1.81E+00	0.0
2	Wind	J	3.11E+07	1.28E+03	Giannetti et al. (2019)	3.97E-02	0.0
3	Ocean circulation	J	1.46E+08	3.68E+04	Giannetti et al. (2019)	5.38E+00	0.0
4	Seawater	J	1.93E+07	1.98E+05	Odum and Arding (1991)	3.81E+00	0.0
5	Nitrogen	g	3.78E+04	1.14E+09	Odum and Arding (1991)	4.32E+01	0.1
6	Carbon	g	3.60E+05	2.59E+09	Kim and Lee (2011)	9.33E+02	1.7
7	Phosphate	g	2.40E+03	1.03E+10	Odum and Arding (1991)	2.47E+01	0.0
8	Switchgrass	g	5.67E+00	2.51E+08	Felix and Tilley (2009)	1.07E-02	0.0
Non-renewable nature resources (N)							
9	Ground water	J	1.04E+07	7.67E+04	Giannetti et al. (2019)	8.01E-01	0.0
10	Switchgrass	g	9.05E+01	2.51E+08	Felix and Tilley (2009)	2.27E-02	0.0
Resources from the larger economy (F)							
	Renewable materials (Mr)						
11	Cotton	g	1.61E+03	1.45E+09	Blatt and Almeida (2017)	2.34E+00	0.0
	Non-renewable materials (Mn)						
12	Plastic	J	5.11E+08	1.92E+05	Giannetti et al. (2019)	9.82E+01	0.2
13	Cotton	g	1.61E+03	1.45E+09	Blatt and Almeida (2017)	2.34E+00	0.0
14	Fuel (gasoline)	J	1.30E+08	4.16E+04	Giannetti et al. (2019)	5.42E+00	0.0
	Renewable infrastruture (Ifr)						
15	Steel	g	2.26E+01	2.29E+09	Brown and Bardi (2001)	5.16E-02	0.0
	Non-renewable infrastruture (Ifn)						
16	Plastic	J	2.95E+08	1.92E+05	Giannetti et al. (2019)	5.67E+01	0.1
17	Iron	g	6.49E+04	4.15E+09	Oliveira et al. (2018)	2.70E+02	0.5
18	Steel	g	5.01E+02	2.29E+09	Brown and Bardi (2001)	1.15E+00	0.0
19	Aluminum ingot	g	1.11E+03	1.49E+10	Buranakan (1998)	1.65E+01	0.0
20	Rubber	g	1.13E+01	5.47E+09	Buranakan (1998)	6.19E-02	0.00
21	Wood	J	3.30E+08	2.85E+05	Buranakan (1998)	9.40E+01	0.2

22	Concrete	g	2.80E+04	1.83E+09	Buranakan (1998)	5.12E+01	0.1
	Renewable services (Sr)						
23	Human labor	J	4.40E+16	8.72E+06	Bonilla et al. (2010)	4.40E+04	80.4
24	Services	$	6.33E+14	5.61E+12	Giannetti et al. (2018)	6.33E+02	1.2
	Non-renewable services (Sn)						
25	Human labor	J	4.89E+15	8.72E+06	Bonilla et al. (2010)	4.89E+03	8.9
26	Services	$	3.59E+15	5.61E+12	Giannetti et al. (2018)	3.59E+03	6.5
	Total Emergy (Y)					**5.48E+04**	**100.0**
	Total renewable resources from nature (R)					***4.57E+04***	***83.4***
	Total non-renewable resources from nature (N)					***8.23E-01***	***0.0***
	Total resources from large economy (F)					***9.07E+03***	***16.6***
	Outputs						
	Products						
27	Bleached and dry seaweed	g	1.10E+06	4.97E+10	Present study	5.48E+04	
	Ecosystem Services						
	Legal Reserve Area: native						
28	Vegetation	$	3.00E+01	1.82E+15	Present study	5.48E+04	
29	Ecotourism	$	1.12E+02	4.90E+14	Present study	5.48E+04	

Table 5. Emergy table of sea-based *H. pseudomusciformis* farming for human consumption market base scenario.

Note	Item	Unit	Amount (unit/ha/year)	UEV (sej/unit)	UEV Reference	Emergy E12 sej/ha/year	Emergy (%)
Renewable nature resources (R)							
1	Sun	J	1.81E+12	1.00E+00	Odum (2000)	1.81E+00	0.0
2	Wind	J	3.11E+07	1.28E+03	Giannetti et al. (2019)	3.97E-02	0.0
3	Ocean circulation	J	1.46E+08	3.68E+04	Giannetti et al. (2019)	5.38E+00	0.0
4	Seawater	J	1.93E+07	1.98E+05	Odum and Arding (1991)	3.81E+00	0.0
5	Nitrogen	g	3.78E+04	1.14E+09	Odum and Arding (1991)	4.32E+01	0.1
6	Carbon	g	3.60E+05	2.59E+09	Kim and Lee (2011)	9.33E+02	1.7
7	Phosphate	g	2.40E+03	1.03E+10	Odum and Arding (1991)	2.47E+01	0.0
8	Switchgrass	g	4.26E+01	2.51E+08	Felix and Tilley (2009)	1.07E-02	0.0
Non-renewable nature resources (N)							
9	Switchgrass	g	9.05E+01	2.51E+08	Felix and Tilley (2009)	2.27E-02	0.0
Resources from the larger economy (F)							
	Renewable materials (Mr)						
10	Cotton	g	1.61E+03	1.45E+09	Blatt and Almeida (2017)	2.34E+00	0.0
11	Paper	g	1.40E+03	2.95E+09	Corcelli et al. (2018)	4.12E+00	0.0
	Non-renewable materials (Mn)						
12	Plastic	J	5.11E+08	1.92E+05	Giannetti et al. (2019)	9.82E+01	0.2
13	Cotton	g	3.18E+03	1.45E+09	Blatt and Almeida (2017)	4.61E+00	0.0
14	Fuel (gasoline)	J	1.30E+08	4.16E+04	Giannetti et al. (2019)	5.42E+00	0.0
15	Paper	g	2.60E+03	2.95E+09	Corcelli et al. (2018)	7.67E+00	0.0
	Renewable infrastruture (Ifr)						
16	Steel	g	2.26E+01	2.29E+09	Brown and Bardi (2001)	5.16E-02	0.0
	Non-renewable infrastruture (Ifn)						
17	Plastic	J	2.95E+08	1.92E+05	Giannetti et al. (2019)	5.67E+01	0.1
18	Iron	g	6.49E+04	4.15E+09	Oliveira et al. (2018)	2.70E+02	0.5
19	Steel	g	5.01E+02	2.29E+09	Brown and Bardi (2001)	1.15E+00	0.0
20	Aluminum ingot	g	1.11E+03	1.49E+10	Buranakan (1998)	1.65E+01	0.0

21	Rubber	g	1.13E+02	5.47E+09	Buranakan (1998)	6.19E-01	0.0
22	Wood	J	3.30E+08	2.85E+05	Buranakan (1998)	9.40E+01	0.2
23	Concrete	g	2.80E+04	1.83E+09	Buranakan (1998)	5.12E+01	0.1
	Services (Sr)						
24	Human labor	J	5.05E+09	8.72E+06	Bonilla et al. (2010)	4.40E+04	80.1
25	Services	$	1.19E+02	5.61E+12	Giannetti et al. (2018)	6.68E+02	1.2
	Services (Sn)						
26	Human labor	J	5.61E+08	8.72E+06	Bonilla et al. (2010)	4.89E+03	8.9
27	Services	$	6.75E+02	5.61E+12	Giannetti et al. (2018)	3.79E+03	6.9
	Total Emergy (Y)					**5.50E+04**	**100.0**
	Total renewable resources from nature (R)					***4.57E+04***	***83.1***
	Total non-renewable resources from nature (N)					***2.27E-02***	***0.0***
	Total resources from large economy (F)					***9.29E+03***	***16.9***
	Outputs						
	Products						
28	Dehydrated seaweed	J	1.20E+07	4.57E+09	Present study	5.50E+04	
	Ecosystem Services						
29	Legal reserve area: native vegetation	$	3.00E+01	1.83E+15	Present study	5.50E+04	
30	Ecotourism	$	1.12E+02	4.92E+14	Present study	5.50E+04	

Table 6. Emergy table of sea-based *H. pseudomusciformis* farming for glycolic extract market base scenario.

Note	Item	Unit	Amount (unit/ha/year)	UEV (sej/unit)	UEV Reference	Emergy E12 sej/ha/year	Emergy (%)
Renewable nature resources (R)							
1	Sun	J	1.81E+12	1.00E+00	Odum (2000)	1.81E+00	0.00
2	Wind	J	3.11E+07	1.28E+03	Giannetti et al. (2019)	3.97E-02	0.00
3	Ocean circulation	J	1.46E+08	3.68E+04	Giannetti et al. (2019)	5.38E+00	0.00
4	Seawater	J	1.93E+07	1.98E+05	Odum and Arding (1991)	3.81E+00	0.00
5	Nitrogen	g	3.78E+04	1.14E+09	Odum and Arding (1991)	4.32E+01	0.01
6	Carbon	g	3.60E+05	2.59E+09	Kim and Lee (2011)	9.33E+02	0.18
7	Phosphate	g	2.40E+03	1.03E+10	Odum and Arding (1991)	2.47E+01	0.00
8	Switchgrass	g	4.26E+01	2.51E+08	Felix and Tilley (2009)	1.07E-02	0.00
Non-renewable nature resources (N)							
9	Switchgrass	g	9.05E+01	2.51E+08	Felix and Tilley (2009)	2.27E-02	0.00
Resources from the larger economy (F)							
	Renewable materials (Mr)						
10	Cotton	g	1.61E+03	1.45E+09	Blatt and Almeida (2017)	2.34E+00	0.00
11	Paper	g	1.40E+02	2.95E+09	Corcelli et al. (2018)	4.12E-01	0.00
12	Liquid glycerin	g	4.71E+05	9.17E+10	Fahd et al. (2012)	4.32E+04	8.49
13	Grain alcohol	J	9.94E+08	1.24E+05	Dong et al. (2008)	1.23E+02	0.02
	Non-renewable materials (Mn)						
14	Plastic	J	1.76E+10	1.92E+05	Giannetti et al. (2019)	3.39E+03	0.67
15	Cotton	g	3.18E+03	1.45E+09	Blatt and Almeida (2017)	4.61E+00	0.00
16	Fuel (gasoline)	J	1.30E+08	4.16E+04	Giannetti et al. (2019)	5.42E+00	0.00
17	Paper	g	2.60E+02	2.95E+09	Corcelli et al. (2018)	7.67E-01	0.00
18	Liquid glycerin	g	4.06E+06	9.17E+10	Fahd et al. (2012)	3.72E+05	73.18
19	Grain alcohol	J	7.79E+09	1.24E+05	Dong et al. (2008)	9.67E+02	0.19
	Renewable infrastruture (Ifr)						
20	Steel	g	2.26E+01	2.29E+09	Brown and Bardi (2001)	5.16E-02	0.00
21	Glass	g	7.86E+00	3.03E+09	Almeida et al. (2017)	2.38E-02	0.00

	Non-renewable infrastruture (Ifn)						
22	Plastic	J	2.96E+08	1.92E+05	Giannetti et al. (2019)	5.68E+01	0.01
23	Iron	g	6.51E+04	4.15E+09	Oliveira et al. (2018)	2.70E+02	0.05
24	Steel	g	5.01E+02	2.29E+09	Brown and Bardi (2001)	1.15E+00	0.00
25	Aluminum ingot	g	1.11E+03	1.49E+10	Buranakan (1998)	1.65E+01	0.00
26	Rubber	g	1.13E+02	5.47E+09	Buranakan (1998)	6.19E-01	0.00
27	Wood	J	3.30E+08	2.85E+05	Buranakan (1998)	9.40E+01	0.02
28	Concrete	g	2.80E+04	1.83E+09	Buranakan (1998)	5.12E+01	0.01
29	Glass	g	1.56E+03	3.03E+09	Almeida et al. (2017)	4.74E+00	0.00
	Services (Sr)						
30	Human labor	J	5.89E+09	8.72E+06	Bonilla et al. (2010)	5.14E+04	10.10
31	Services	$	8.07E+02	5.61E+12	Giannetti et al. (2018)	4.53E+03	0.89
	Services (Sn)						
32	Human labor	J	6.55E+08	8.72E+06	Bonilla et al. (2010)	5.71E+03	1.12
33	Services	$	4.57E+03	5.61E+12	Giannetti et al. (2018)	2.57E+04	5.04
	Total Emergy (Y)					**5.09E+05**	**100.0**
	Total renewable resources from nature (R)					***5.69E+04***	***19.7***
	Total non-renewable resources from nature (N)					***2.27E-02***	***0.0***
	Total resources from large economy (F)					***3.52E+04***	***80.3***
	Outputs						
	Products						
34	Seaweed glycolic extract	J	2.24E+11	2.27E+06	Present study	5.09E+05	
	Ecosystem Services						
35	Legal reserve area: native vegetation	$	3.00E+01	1.69E+16	Present study	5.09E+05	
36	Ecotourism	$	1.12E+02	4.55E+15	Present study	5.09E+05	

The seaweed farming for the carrageenan industry has total emergy of 5.48E+16 sej/ha/year, in which 4.57E+16 sej/ha/year correspond to emergy of renewable from nature, 8.23E+11 sej/ha/year to non-renewable from nature, and 9.07E+15 sej/ha/year to economy resources (Table 4). The Unit Emergy Value (UEV) ranged between 4.04E+10 and 4.97E+10 sej/g for the bleached and dry seaweed, from 1.82E+15 to 1.84E+15 sej/$ for legal reserve area (native vegetation) and 4.88E+14 to 4.93E+14 sej/$ for Ecotourism (Table 7). Emergy indicators of seaweed farming to the carrageenan industry are in Table 8. This scenario product displays a Renewability (R%) ranging from 83.3 to 83.7% and an Environmental Loading Ratio (ELR) equals to 0.20. The Emergy Yield Ratio (EYR) ranges from 5.99 to 6.12, the Emergy Investment Ratio (EIR) from 0.20, an Emergy Exchange Ratio (EER) from 1.48 to 1.80, and an Emergy Sustainability Index (ESI) from 29.84 to 31.28.

Table 7. Unit Emergy Value (UEV) for the seaweed *H. pseudomusciformis* sea-based farming for the carrageenan industry considering different strategies scenarios. Carrageenan base scenario (C); Carrageenan using less and recycled plastic (C_{pr}); Carrageenan with farming cycle length reduction (C_{cr}); Carrageenan using less and recycled plastic and farming cycle length reduction (C_T).

UEV	C	C_{pr}	C_{rt}	C_T
Bleached and dry seaweeds (sej/J)	4.96E+09	4.95E+09	4.05E+09	4.04E+09
Bleached and dry seaweeds $_{ws}$ (sej/J)	1.46E+08	1.38E+08	1.36E+08	1.28E+08
Bleached and dry seaweeds (sej/g)	4.97E+10	4.95E+10	4.05E+10	4.04E+10
Bleached and dry seaweeds $_{ws}$ (sej/g)	1.46E+09	1.38E+09	1.36E+09	1.28E+09
Legal reserve area: native vegetation (sej/$)	1.82E+15	1.82E+15	1.84E+15	1.83E+15
Legal reserve area: native vegetation $_{ws}$ (sej/$)	5.37E+13	5.07E+13	6.16E+13	5.81E+13
Ecotourism (sej/$)	4.90E+14	4.88E+14	4.93E+14	4.92E+14
Ecotourism $_{ws}$ (sej/$)	1.44E+13	1.36E+13	1.65E+13	1.56E+13

ws = without monetary services

Table 8. Emergy indicators for the seaweed *H. pseudomusciformis* sea-based farming for the carrageenan industry considering different scenarios. Carrageenan base scenario (C); Carrageenan using less and recycled plastic (Cpr); Carrageenan with farming cycle length reduction (Ccr); Carrageenan using less and recycled plastic and farming cycle length reduction (CT).

Indicator	Abbreviation	C	C_{pr}	C_{cr}	C_T
Renewability [a]	R%	83.42	83.65	83.29	83.49
Renewability [a] $_{ws}$	R% $_{ws}$	62.89	68.30	66.88	72.26
Environmental Loading Ratio [a]	ELR	0.20	0.20	0.20	0.20
Emergy Yield Ratio	EYR	6.03	6.12	5.99	6.06
Emergy Investment Ratio	EIR	0.20	0.20	0.20	0.20
Emergy Exchange Ratio	EER	1.80	1.80	1.49	1.48
Emergy Sustainability Index	ESI	30.36	31.28	29.84	30.65

[a] Modified according to Agostinho et al. (2018).

The initial investment costs for seaweed farming in the carrageenan market scenario ranged from US$25,188 to US$31,069 (Table 9). The production costs ranged from US$31,297 to US$34,667. However, the annual profit was negative for all farm strategies, and the cash flow analysis indicated a lack of liquidity throughout the project lifetime. The indicators of financial feasibility were negative, with no Internal Rate of Return (IRR) observed for any of the strategies, and a negative Net Present Value (NPV). Additionally, there was no Benefit-Cost Ratio (BCR) or return on invested capital. The plot illustrating the relationship between ESI and NPV can be seen in Figure 6.

Table 9. Cost-return analysis and indicators of the financial feasibility of seaweed farming to carrageenan industry for different hypothetical farm strategies. Carrageenan base scenario (C); Carrageenan using less and recycled plastic (C_{pr}); Carrageenan with farming cycle length reduction (C_{cr}); Carrageenan using less and recycled plastic and farming cycle length reduction (C_T).

Item	C	C_{pr}	C_{rt}	C_T
Selling price (US$/kg)	0.60	0.60	0.60	0.60
Production yield (kg/year)	9,000	9,000	11,070	11,070
Production cost (US$/year)	31,297	32,769	33,543	34,667
Initial investment (US$/ha)	25,188	31,069	25,188	31,069
Gross revenue (US$)	5,400	5,400	8,081	6,642
Net revenue (US$)	-18,468	-19,539	-17,889	-20,073
Break-even price (US$/kg)	3.48	3.64	3.03	3.13
Profit (US$)	-25,897	-27,369	-25,462	-28,025
IRR (%/aa)	-	-	-	-
NPV (US$)	-392,170	-419,096	382,348	-430,365
BCR (US$)	-2.69	-2.31	-2.62	-2.37
DPP (years)	-	-	-	-

IRR: internal rate of return; NPV: net present value; BCR: benefit-cost ratio; PP: pay-back period

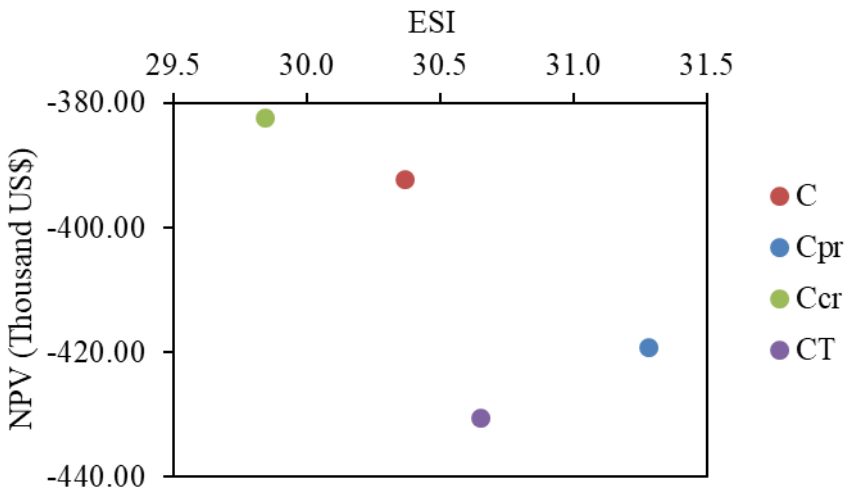

Figura 6. Emergy Sustainability Index (ESI) and Net Present Value (NPV) of seaweed farming for the carrageenan market. Comparison of the base scenario and different management strategies. Carrageenan base scenario (C); Carrageenan using less and recycled plastic (C_{pr}); Carrageenan with farming cycle length reduction (C_{cr}); Carrageenan using less and recycled plastic and farming cycle length reduction (C_T).

The seaweed farming for the human consumption has total emergy of 5.50E+16 sej/ha/year, in which 4.57E+16 sej/ha/year corresponds to renewable emergy from nature, 2.27E+10 sej/ha/year to non-renewable from nature, and 9.29E+15 sej/ha/year to economy resources (Table 5). The Unit Emergy Value (UEV) ranged from 3.70E+10 and 4.57 E+10 sej/g for the dehydrated seaweed, from 1.83E+15 to 1.84E+15 sej/$ for legal reserve area (native vegetation) and 4.91 E+14 to 4.94E+14 sej/$ for Ecotourism (Table 10). Emergy indicators of seaweed farming for human consumption are present in Table 11. This scenario product displays a Renewability (R%) ranging from 83.1 to 83.3% and an Environmental Loading Ratio (ELR) of 0.20. The Emergy Yield Ratio (EYR) ranges from 5.92 to 6.06, the Emergy Investment Ratio (EIR) of 0.20, an Emergy Exchange Ratio (EER) from 0.06 to 0.07, and an Emergy Sustainability Index (ESI) from 29.15 to 30.93.

Table 10. Unit Emergy Value (UEV) for the seaweed *H. pseudomusciformis* sea-based farming for human consumption considering different strategies scenarios. Human consumption base scenario (HC); Human consumption using less and recycled plastic (HC_{pr}); Human consumption with farming cycle length reduction (HC_{cr}); Human consumption using less and recycled plastic and farming cycle length reduction tion (HC_T).

UEV	HC	HC_{pr}	HC_{rt}	HC_T
Dehydrated seaweeds (sej/J)	4.57E+09	4.56E+09	3.70E+09	3.69E+09
Dehydrated seaweeds $_{ws}$ (sej/J)	1.35E+08	1.27E+08	1.25E+08	1.18E+08
Dehydrated seaweeds (sej/g)	4.57E+10	4.56E+10	3.70E+10	3.70E+10
Dehydrated seaweeds $_{ws}$ (sej/g)	1.35E+09	1.27E+09	1.25E+09	1.18E+09
Legal reserve area: native vegetation (sej/$)	1.83E+15	1.83E+15	1.84E+15	1.84E+15
Legal reserve area: native vegetation ws (sej/$)	5.41E+13	5.10E+13	6.20E+13	5.85E+13
Ecotourism (sej/$)	4.92E+14	4.91E+14	4.94E+14	4.93E+14
Ecotourism $_{ws}$ (sej/$)	1.45E+13	1.37E+13	1.66E+13	1.57E+13

Table 11. Emergy indicators for the seaweed *H. pseudomusciformis* sea-based farming for the human consumption industry considering different scenarios. Human consumption base scenario (HC); Human consumption using less and recycled plastic (HC_{pr}); Human consumption with farming cycle length reduction (HC_{cr}); Human consumption using less and recycled plastic and farming cycle length reduction tion (HC_T).

Indicator	Abbreviation	HC	HC_{pr}	HC_{cr}	HC_T
Renewability [a]	R%	83.12	83.34	83.12	83.32
Renewability [a] $_{ws}$	R% $_{ws}$	62.72	68.08	66.69	72.02
Environmental Loading Ratio [a]	ELR	0.20	0.20	0.20	0.20
Emergy Yield Ratio	EYR	5.92	6.00	5.92	5.99
Emergy Investment Ratio	EIR	0.20	0.20	0.20	0.20
Emergy Exchange Ratio	EER	0.07	0.07	0.06	0.06
Emergy Sustainability Index	ESI	29.17	30.02	29.15	29.93

Initial investment costs for seaweed farming to the human consumption market scenario ranged from US$25,188 to US$31,069 (Table 12). The production costs ranged from US$58,730 to US$68,410. The annual profit ranged from US$49,601 to US$68,100, and the cash flow analysis showed liquidity over the project lifetime with a Discounted Payback Period of ~1.6 years. The Internal Rate of Return (IRR) ranged from 97.8% to 138.3%, and the Net Present Value (NPV) was between 1,070,464 and 1,428,363. The Benefit-cost Ratio (BCR) was between US$6.63 and US$10.77 per dollar invested. The plot of the relationship between ESI and NPV is in Figure 7.

Table 12. Cost-return analysis and indicators of the financial feasibility of sea-based seaweed farming to human consumption for different hypothetical farm strategies. Human consumption base scenario (HC); Human consumption using less and recycled plastic (HC_{pr}); Human consumption with farming cycle length reduction (HC_{cr}); Human consumption using less and recycled plastic and farming cycle length reduction tion (HC_T).

Item	HC	HC_{pr}	HC_{rt}	HC_T
Selling price (US$/kg)	12.20	12.20	12.20	12.20
Production yield (kg/year)	9,000	9,000	11,070	11,070
Production cost (US$/year)	58,730	60,202	66,958	68,410
Initial investment (US$/ha)	25,188	31,069	25,188	31,069
Gross revenue (US$)	109,803	109,803	135,058	135,058
Net revenue (US$)	60,266	59,195	77,822	76,770
Break-even price (US$/kg)	6.53	6.69	6.05	6.18
Profit (US$)	51,073	49,601	68,100	66,648
IRR (%/aa)	112.4	97.9	138.3	120.7
NPV (US$)	1,097,390	1,070,464	1,428,363	1,401,807
BCR (US$)	8.33	6.63	10.77	8.61
DPP (years)	1.59	1.71	1.46	1.55

IRR: internal rate of return; NPV: net present value; BCR: benefit-cost ratio; PP: pay-back period

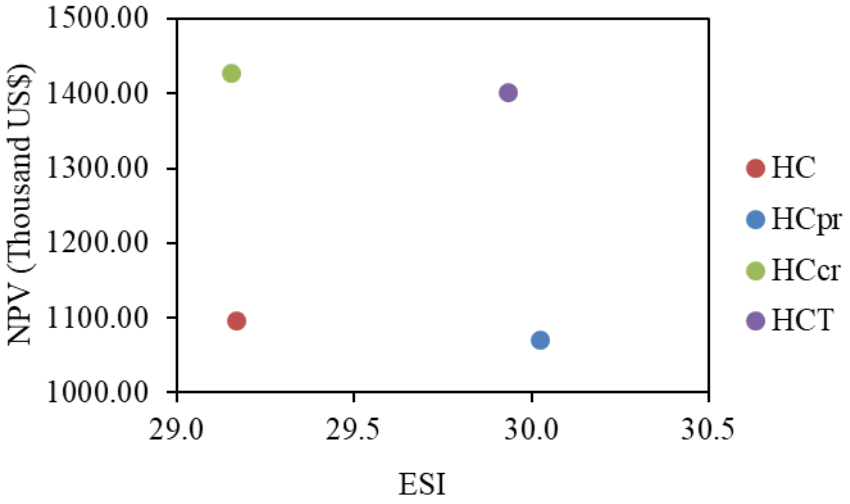

Figura 8. Emergy Sustainability Index (ESI) and Net Present Value (NPV) of sea-based seaweed farming for the human consumption market. Comparison of the base scenario and different management strategies. Human consumption base scenario (HC); Human consumption using less and recycled plastic (HC_{pr}); Human consumption with farming cycle length reduction (HC_{cr}); Human consumption using less and recycled plastic and farming cycle length reduction tion (HC_T).

The seaweed farming for the glycolic extract has total emergy of 5.09E+17 sej/ha/year, in which 1.00E+17 sej/ha/year correspond to renewable emergy from nature, 2.27E+10 sej/ha/year to non-renewable from nature, and 4.09+17 sej/ha/year to economy

resources (Table 6). The Unit Emergy Value (UEV) ranged from 8.15E+10 and 1.05E+14 sej/g for the glycolic extract, from 1.69E+16 to 2.17E+19 sej/$ for legal reserve area (native vegetation) and 4.55E+15 to 5.81E+18 sej/$ for Ecotourism (Table 13). Emergy indicators of seaweed farming to the glycolic extract are present in Table 14. This scenario product displays a Renewability (R%) ranging from 18.8 to 30.7% and an Environmental Loading Ratio (ELR) ranging from 2.26 to 4.31. The Emergy Yield Ratio (EYR) ranges from 1.23to 1.44, the Emergy Investment Ratio (EIR) from 2.26 to 4.31, an Emergy Exchange Ratio (EER) from 0.14 to 173.64, and an Emergy Sustainability Index (ESI) from 0.29 to 0.64.m 18.8 to 30.7% and an Environmental Loading Ratio (ELR) ranging from 2.26 to 4.31. The Emergy Yield Ratio (EYR) ranges from 1.23to 1.44, the Emergy Investment Ratio (EIR) from 2.26 to 4.31, an Emergy Exchange Ratio (EER) from 0.14 to 173.64, and an Emergy Sustainability Index (ESI) from 0.29 to 0.64.

Table 13. Unit Emergy Value (UEV) for the seaweed *H. pseudomusciformis* sea-based farming for the glycolic extract considering different strategies scenarios. Glycolic extract base scenario (GE); Glycolic extract using less and recycled plastic (GE_{pr}); Glycolic extract with farming cycle length reduction (GE_{cr}); Glycolic extract with more renewable solvent (GE_{sr}); Glycolic extract using less and recycled plastic farming cycle length reduction, and plant-based solvent (GE_T).

UEV	GE	GE_{pr}	GE_{rt}	GE_{sr}	GE_T
Seaweed Glycolic Extract (sej/J)	2.27E+06	2.27E+06	2.01E+06	2.58E+09	2.31E+09
Seaweed Glycolic Extract $_{ws}$ (sej/J)	1.88E+06	1.88E+06	1.68E+06	2.58E+09	2.31E+09
Seaweed Glycolic Extract (sej/g)	9.23E+10	9.23E+10	8.15E+10	1.05E+14	9.39E+13
Seaweed Glycolic Extract $_{ws}$ (sej/g)	7.64E+10	7.64E+10	6.85E+10	1.05E+14	9.39E+13
Legal reserve area: native vegetation (sej/$)	1.69E+16	1.69E+16	1.88E+16	1.92E+19	2.17E+19
Legal reserve area: native vegetation ws (sej/$)	1.40E+16	1.40E+16	1.58E+16	1.92E+19	2.16E+19
Ecotourism (sej/$)	4.55E+15	4.55E+15	5.05E+15	5.17E+18	5.81E+18
Ecotourism $_{ws}$ (sej/$)	3.77E+15	3.77E+15	4.24E+15	5.17E+18	5.81E+18

Table 14. Emergy indicators for the seaweed *H. pseudomusciformis* sea-based farming for the glycolic extract industry considering different scenarios. Glycolic extract base scenario (GE); Glycolic extract using less and recycled plastic (GE_{pr}); Glycolic extract with farming cycle length reduction (GE_{cr}); Glycolic extract with more renewable solvent (GE_{sr}); Glycolic extract using less and recycled plastic farming cycle length reduction, and plant-based solvent (GE_T).

Indicator	Abbreviation	GE	GE_{pr}	GE_{cr}	GE_{sr}	GE_T
Renewability [a]	R%	19.70	19.70	18.83	30.70	30.70
Renewability [a] ws	R% ws	10.51	10.52	10.53	30.70	30.70
Environmental Loading Ratio [a]	ELR	4.08	4.08	4.31	2.26	2.26
Emergy Yield Ratio	EYR	1.25	1.25	1.23	1.44	1.44
Emergy Investment Ratio	EIR	4.08	4.08	4.31	2.26	2.26
Emergy Exchange Ratio	EER	0.15	0.15	0.14	173.64	155.51
Emergy Sustainability Index	ESI	0.31	0.31	0.29	0.64	0.64

Initial investment costs for seaweed farming for the glycolic extract market scenario ranged from US$26,299 to US$32,180 (Table 15). The production costs ranged from US$502,302 to US$713,753. There was no annual profit for GEsr and GET, but it ranged from US$34,261 to US$53,388 in the other scenarios. The cash flow analysis showed no liquidity over the project lifetime for GEsr and GET. The discounted payback time was ~5.5 years, except for GEsr and GET. Also, there was no IRR for the GEsr and GET, despite it ranging from 21.1 to 25.4% in the other scenarios. The NPV was between -US$458,730,004 and US$1,508,171. There was no benefit-cost ratio GEsr and GET, and it was between US$6.75 and US$11.33 per dollar invested. The plot of the relationship between ESI and NPV is in Figure 10.

Table 15. Cost-return analysis and indicators of the financial feasibility of sea-based seaweed farming to glycolic extract for different hypothetical farm strategies. Glycolic extract base scenario (GE); Glycolic extract using less and recycled plastic (GE_{pr}); Glycolic extract with farming cycle length reduction (GE_{cr}); Glycolic extract with more renewable solvent (GE_{sr}); Glycolic extract using less and recycled plastic farming cycle length reduction, and plant-based solvent (GE_T).

Item	GE	GE_{pr}	GE_{rt}	GE_{sr}	GE_T
Selling price (US$/kg)	11.96	11.96	11.96	11.96	11.96
Production yield (kg/year)	45,000	45,000	55,350	45,000	55,350
Production cost (US$/year)	502,302	503,774	608,394	586,779	713,753
Initial investment (US$/ha)	26,299	32,180	26,299	26,299	32,180
Gross revenue (US$)	538,035	538,035	661,783	538,035	661,783
Net revenue (US$)	73,526	72,455	98,006	-5,517	-269
Break-even price (US$/kg)	11.16	11.19	10.99	13.04	12.90
Profit (US$)	35,733	34,261	53,388	-48,744	-51,971
IRR (%/aa)	21.9	21.1	25.4	-13.8	-10.2
NPV (US$)	1,099,824	1,072,898	1,508,171	-458,730	-435,367
BCR (US$)	8.41	6.75	11.33	-2.53	-1.87
DPP (years)	6.59	6.72	5.24	-1.86	-3.28

IRR: internal rate of return; NPV: net present value; BCR: benefit-cost ratio; PP: pay-back period

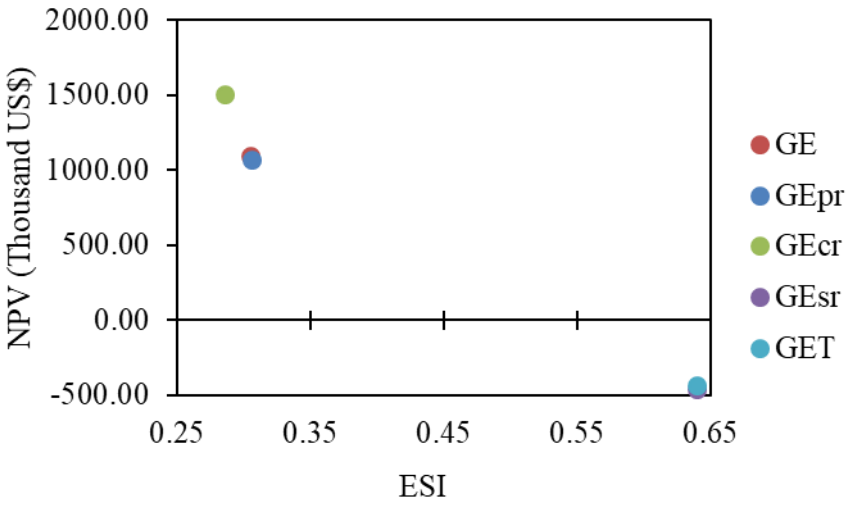

Figura 8. Emergy Sustainability Index (ESI) and net present value (NPV) of sea-based seaweed farming for the glycolic extract market. Comparison of the base scenario and different management strategies. Glycolic extract base scenario (GE); Glycolic extract using less and recycled plastic (GE_{pr}); Glycolic extract with farming cycle length reduction (GE_{cr}); Glycolic extract with more renewable solvent (GE_{sr}); Glycolic extract using less and recycled plastic farming cycle length reduction, and plant-based solvent (GE_T).

4. Discussion

The sea-based seaweed farming presented similar product transformities for carrageenan and direct human consumption market scenarios ranges from 3.69E+09 to 4.96E+09 sej/J. Only seaweed glycolic extract had slightly lower transformity ranging from 2.01+06 to 2.58E+09 sej/J, despite consuming more economic resources in its processing as a higher emergy product. The farming system studied involves the monoculture of a low trophic level that requires minimal technological input. Other mariculture products such as fish present transformity around 1.32E+06sej/J (Vassallo et al., 2007) and oysters approximately to 1.31E+07 sej/J (Williamson et al., 2015). The farming system model analyzed in the present study is similar to other sea-based tropical seaweed farming models described in previous studies (Bindu and Levine, 2011; Kim et al., 2017). Sea-based seaweed farming relies heavily on natural resources, including sunlight, atmospheric CO_2, nutrients such as nitrogen and phosphate, and the energy of ocean circulation.. The ocean circulation energy is essential for carrying the nutrients and seaweed development as it helps seaweed cleaning. During farming there is no addition of any economic input but labor. Labor is the main sea-based seaweed farming input (Pereira et al., 2020b), which was confirmed by the present study. The combination of these characteristics may differentiate tropical sea-based seaweed farming from temperate sea-based seaweed farming in terms of emergy. Tropical seaweed farming tends to rely more on natural resources and less on technological inputs compared to temperate seaweed farming, which is often associated with greater technological involvement (Burg et al., 2016; Kim et al., 2017). Despite the similar emergy between the different markets analyzed, there was a difference in economic feasibility among them. Emergy Synthesis considers the biophysical account of nature and human services, while neoclassical economics evaluates the economic resilience of a project over the years according to the capitalist economy. Therefore, these methods complement each other for decision-making. In addition to profit, enterprises need to ensure sustainability. Thus, from the entrepreneur's perspective, the most sustainable scenario would be to produce seaweed for direct human consumption, followed by the production of glycolic extract. Despite being sustainable from an Emergy Synthesis perspective, seaweed farming intended for sale to the carrageenan industry is economically unfeasible.

The seaweed biomass processing to the carrageenan and human consumption markets are very similar in inputs required. One difference between them is groundwater use for bleaching seaweed for carrageenan extraction, instead of using filtered seawater for washing seaweeds

for human consumption. Another difference is the packaging of plastic raffia bags to carrageenan and paper bags for human consumption. The glycolic extract market biomass process is different from the others, in which seaweed is washed in filtered seawater, dried in the shade, ground, mixed with solvent, and packaged in plastic bottles. For carrageenan and human consumption, the emergy demand was very similar for renewable resources from nature (~83%), non-renewable from nature (<0.01), and resources from the economy (~17%). The most representative items for carrageenan and human consumption were labor from traditional communities followed by services, carbon, iron from the anchors, plastic from the longlines, and plastic raffia ribbon. In the present study, we considered a high labor Renewability of 90% once the workforce used in the farming process comes from local and familiar workers organized in an association, according to Agostinho et al. (2019). A previous sustainability study suggests that labor demand may indicate a more socially sustainable system (Valenti et al., 2018). The other items present low or no Renewability. For the glycolic extract, liquid glycerin was the most representative input, followed by labor and services. The liquid glycerin is an economic resource with low Renewability. Hence, the simulated scenarios for each market aim to replace low-renewability inputs or compensate for them through cultivation strategies to assess their impact on emergy synthesis and neoclassical economy.

The bleached and dry seaweed UEVs was 4.96E+09 sej/J for the carrageenan base scenario. The seaweed production for the carrageenan market shows a Renewability of 83.4%. The Renewability value represents an average of the system renewal capacity. The labor was the most representative input in C scenario, and it is a high renewable input, with 90% Renewability. The renewability increases to 83.7 and 83.5% with the plastic reduction and strategy combinations, respectively. The cycle length reduction reduces the system's renewability to 83.3%. The carrageenan Environmental Loading Ratio of 0.20 and the Emergy Yield Ratio of 6.03 indicates low pressure in the ecosystems and low dependence on resources from the economy with high contribution to the larger economy. The carrageenan scenario displays an Emergy Investment Ratio of 0.20, indicating a potential product economic competition. The C scenario Emergy Exchange Ratio of 1.80 displays that the value paid for the seaweed in the neoclassic economy is almost two times lower than its emergy value. It corroborates with the neoclassical bioeconomic analysis that showed no economic feasibility for this market strategy. This scenario exhibits a long-term sustainability, with the Emergy Sustainability Index of 30.36.

The simulated strategic scenarios showed that it is possible to improve some emergy system indexes. The plastic items replacement and the combined strategies of plastic and cycle reduction may slightly improve the system sustainability. There are no other environmental accounting studies using emergy synthesis available in the literature on seaweeds for carrageenan extraction or other similar products. The neoclassical analysis showed no economic feasibility for all scenarios to extract carrageenan. This non-feasibility is due to the value paid for the product, which is lower than the operating costs. The occidental seaweed production cost is higher than the market sale price, according to Pereira et al. (2020b). The carrageenan is a commodity, and the Asian production of carrageenan from Kappaphycus and Euchema seaweed species production highly influences the price of it, which is lower than the production of carrageenan from other species in countries outside Asia. Even with the cycle length reduction, the productivity increase did not decrease production costs. Thus, despite being able to present short-term sustainability from the emergy synthesis perspective, the carrageenan market does not display economic feasibility. Therefore, this market strategy is not a sustainable option for the seaweed farmer.

The human consumption base scenario market shows the UEVs of 4.57E+09 sej/J for the dehydrated seaweeds and a high Renewability of ~83.1%. Seaweed as a vegetable presents a higher Renewability when compared to similar products such as aquaculture and traditional vegetables. For example, organic soybean has a 78% Renewability (Albino and Callado, 2012), and aquaponic vegetables range from 33 to 38% (David et al., 2022). Seaweed Renewability may be even higher than terrestrial vegetables as leaf and mixed vegetables, with Renewability of 12 and 13%, respectively (Albino and Callado, 2012). Terrestrial vegetable systems present low Renewability because of the large amounts of energy invested in irrigation, fertilizers, and fuels (Albino and Callado, 2012). Instead of terrestrial vegetables, sea-based seaweed farming did not require fertilizers and feed, the major economic inputs in other systems (Pereira et al., 2021), being potentially more renewable vegetable sources. Furthermore, traditional agriculture usually occupies soil that generates an emergy input of soil loss through erosion. The human consumption market shows low pressure on ecosystems, with an ELR of 0.20, and low dependence on resources from the economy with an EYR of 5.92 with high contribution to the larger economy. The seaweed human consumption EIR of 0.20 shows higher economic competition than other similar products such as aquaponic vegetables with 1.7 and 2.1 (David et al., 2022) and organic soybean, which is 1.40 (Albino and Callado, 2012). Seaweeds also are more economically competitive than leaf and mixed vegetables, which shows an EIR ranging from 4.68 to 5.26 (Albino and Callado, 2012). The

seaweed vegetable value paid by the neoclassical economy is higher than its emergy value, with an EER of 0.07. The seaweed for human consumption farming displayed a long-term sustainability system with an ESI of 29.17. Seaweed vegetable sustainability is higher than products such as aquaponic vegetables, of which ESI is 0.50-0.60 (David et al., 2022). These results corroborate with previous sustainable analyses using the indicators of sustainability to assess aquaculture systems showed that *H. pseudomusciformis* sea-based farming presents a high sustainability level (Pereira et al., 2021). However, the indicators approach is based on a neoclassical perspective and does not consider the materials characteristics and origins as emergy synthesis does. Sea-based seaweed farming for human consumption may be a more sustainable and competitive product than other terrestrial and aquaponic vegetables for human consumption. Furthermore, seaweed is a healthy, nutritional, and functional food (FAO, 2021; Mouritsen et al., 2019). These characteristics may make seaweed a healthy and sustainable option to complement and improve the human diet.

The farming time reduction slightly reduces the emergy indexes. However, using less and recycled plastic combined with cycle length reduction slightly improved human consumption sustainability indicators, resulting in ESI 29.93 for the strategies merged scenario. These two practices are feasible for the farmer to attend to and may improve the seaweed vegetable sustainability. Studies suggest the human feed market is a promising niche for seaweed aquaculture activity (Buschmann et al., 2017; FAO, 2021). The economic analysis showed feasibility for all the scenarios evaluated, with TIRs above 97.9%, NPVs above US$1,070,464, and a discounted payback of fewer than two years. The analysis of ESI versus NPV indicates that the merged strategies scenario is better for the farmer to make the enterprise profitable and the seaweed product sustainable.

The seaweed glycolic extract transformity was 2.27E+06 sej/J. This system to produce the seaweed glycolic extract showed a Renewability of ~19.7%. The production of glycolic extract utilizes petroleum-derived glycerin as a solvent, which has a renewability of 10%. On the other hand, plant-based glycerin derived from soy exhibits a renewability of 30.7%. Therefore, we simulated the glycolic extract manufacturing process using soy glycerin to assess the variation in emergetic indicators based on the solvent source. This value is higher than traditional liquid glycerin, which has a Renewability of 10% (Fahd et al., 2012) and lower than glycerin from soybean biodiesel, which presents an index of 30.7% (Cavalett and Ortega, 2010). The glycolic extract Environmental Loading Ratio of 4.08 and the Emergy Yield Ratio of 1.25 show moderate pressure on the ecosystems and high dependence on economic resources because of its high utilization of inputs such as liquid glycerin. The GE

market showed moderate performance in the emergy use with an Emergy Investment Ratio of 4.08 and an Emergy Exchange Ratio of 0.15, indicating that the value paid for the seaweed extract is higher than its emergy value for producing it. The seaweed glycolic extract also presents an Emergy Sustainability Index of 0.31, which is low. The seaweed extract has higher ESI than traditional liquid glycerin, which has an ESI of 0.13 (Fahd et al., 2012). So, seaweed glycolic extract is a sustainable choice for cosmetics production comparing to traditional liquid glycerin. The scenario with plastic reduction did not change the emergy indexes, and farming time reduction slightly reduces it. Traditional liquid glycerin replacement for soybean biodiesel glycerin improves emergy indexes performance as ESI increased to 0.64. The soybean biodiesel glycerin is a more natural and renewable solvent because it comes from a plant-based source (Cavalett and Ortega, 2010). However, the economic analysis shows that the scenarios with soybean biodiesel glycerin are not feasible, because this input is more expensive than traditional glycerin, increasing the production costs. The economic feasibility of glycolic extract utilizing plant-based glycerin is only realized when the final product is sold for a minimum price of 13 US$/kg. The other scenarios presented a TIR above 21.1%, NPV above 1,072,898 and a discounted payback between 7 and 11 years. These results suggest that a plastic and cycle length reduction combination may be the best strategy to attend emergy sustainability and economic feasibility for the glycolic extract market.

A positive aspect pointed out by the present study is the set of ecosystem services of seaweed farming as native vegetation preservation and ecotourism. According to Brazil Law nº 12.651/2012, Restinga areas are considered permanent protection areas, and the suppression of vegetation may be authorized only in public utility cases. The seaweed farming presence in the Restinga areas is a way to protect this ecosystem from the pressure of real estate expansion in the region, which is of high tourist and economic interest. Other studies classify the seaweed culture as an ecosystem services provider (Cabral et al., 2016; Chopin and Tacon, 2020; Hasselström et al., 2018; Kim et al., 2017; Pereira et al., 2021; Soares et al., 2018). In the Emergy Synthesis, nature ecosystem services are intrinsic in the system diagram, and only economic and social ecosystem services are outputs of the system as products. Economy ecosystem services are accounted for as the system outputs, differently from other sustainability evaluation methods, such as the indicators which classify the ecosystem services as externalities (Valenti, 2018). The seaweed farming ecosystem services may motivate government incentives for the activity. Aquaculture ecotourism may promote responsible recreational fishing, local cultures, biodiversity conservation, and employment

alternatives for young people in coastal communities (FAO, 2020b). Future studies on emergy analysis are needed to account for other environmental ecosystem services from seaweed farming, such as atmospheric regulation, and eutrophication regulation.

Fonseca et al. (2022) suggest that the emergy indexes low performance is related to key factors that generate considerable emergy input or low productivity. However, the productivity increases by the seaweed farming length reduction alone did not result in improvement in emergy indexes performance and it was not enough to increase productivity at significant levels to improve farm sustainability. The Hypnea farming technique analyzed in this present study is a novel technology, and its further enhancements have the potential to optimize the system and management, leading to improved productivity outcomes. Farming efforts should be done to increase productivity per longline, such as the increase of seedlings per meter. The sea-based seaweed farming is a simple system that depends on only a few inputs, mainly labor, which is higher renewable. Its aspect makessea-based community farms highly sustainable from the Emergy Synthesis perspective. This result strengthens previous works that affirm sea-based seaweed farms as a socioeconomic developer to developing countries. Generally, plastic reduction is one of the most important mitigation measures for ocean pollution (Rhodes, 2018). In the present study, we observe the plastic low impact on the Emergy Synthesis indicators. However, plastic replacement is possible by changing the plastic raffia ribbon for cotton yarn and plastic ropes and cables of longlines for materials that use recycled PET without turns system economic unfeasible. The biophysical perspective in Emergy Synthesis does not consider taxes as a neoclassical economy. However, they are essential for the neoclassical economy and may interfere in enterprise feasibility. The interest in sustainable aquaculture development (FAO, 2020b) combined with the Sustainable Development Goals (SDG) effort to "Climate action (SDG13)", and "Life below water (SDG 14)" (United Nations, 2015) may justify the seaweed farming incentives. Government incentives for seaweed production are already taking place in other countries (FAO, 2010; Valderrama et al., 2015). So, the tax reduction for seaweed farming activity may improve the economic dimension of sustainability of the system.

The classification of tropical seaweed farming as a simple low-technology system is frequent. The present study obtained a systems emergy demand between 5.48E+16 and 5.09E+17sej/ha/year. Compared with other marine aquaculture systems, such as fish farming that are ~6.67E+17 sej/ha/year (Vassallo et al., 2007), seaweed may demands low emergy. However, seaweed presents a higher emergy demand compared with oyster farming demand that ranges from 9.55E+08 to 3.80E+09 sej/ha/year (Lu et al., 2022). There is a difference

among emergy studies for inputs accounting inventory. Nevertheless, the Environmental Load Ratio of seaweed farming system ranging between 0.20 and 4.08 displays a low environmental pressure when compared with fish systems with an ELR of 5.00 (Vassallo et al., 2007) and oyster with an ESI of 0.20 to 8.43 (Lu et al., 2022). Regardless, it is difficult to compare the Emergy Synthesis of aquaculture systems because there is no standardization for the items that must be accounted for in the aquaculture systems analysis (Morales et al., 2022). An example supporting this statement is water, which is often overlooked in farming practices but is actually the most crucial input in aquaculture systems. Many studies fail to adequately consider the input of water in these systems. A recent publication (Morales et al., 2022) discusses the importance of water use in emergy synthesis accounting and how it may influence the results of analyses. Also, David et al. (2021a) present a review of aquaculture studies applying Emergy Synthesis. These publications attempt to standardize the Emergy synthesis applications in aquaculture, which is essential to develop emergy analysis inputs standardization for different aquaculture systems.

Results show that the Emergy Sustainability Index and the other emergy indicators calculated in this study reveal differences comparing sustainability measured using a set of indicators such as Valenti et al. (2018), as published in Pereira et al. (2021). The Emergy Synthesis makes it possible to identify the system renewability capacity and the source of the resources, such as polluting materials such as plastic. The indicators of Valenti et al. (2018) enable identifying the risk of invasive species, which is not possible with Emergy Synthesis. These differences may be due to environmental and economic approaches used in both methodologies. The base of Emergy Synthesis is nature contribution to production systems using energy inputs, their transformities, and a biophysical approach, providing a holistic and integrated view without dividing sustainability into dimensions (Odum, 1996). On the other hand, the set of indicators uses a meristic approach, dividing the systems into the three dimensions of sustainability and an individualized measure of the elements that make up each dimension (Valenti et al., 2018); the economic dimension considers the contribution of nature to production systems through the concept of externalities (Pigou, 2005). This present study result indicates that Emergy Synthesis may be an efficient tool to identify the system fragilities from a holistic perspective. However, it should not be used alone for decision-making. Aquaculture Emergy Synthesis studies groups have been formed over the last few years, and the new emergy studies allow improving analysis making it more understandable and robust (Morales et al., 2022). The combination of Emergy Synthesis and economic

analysis in the present study was complementary to ensure a broader analysis of production systems and guarantee the best decision-making towards sustainability.

5. Conclusion

The present study demonstrates that Emergy Synthesis is a feasible tool for assessing the sustainability of seaweed farming, as it provides a comprehensive view of the entire system and identifies areas for improvement. However, it is recommended to complement this analysis with another method that meets the requirements of neoclassical economics for decision-making purposes. Emergy Synthesis allows for comparisons of sustainability among similar products, which can be important information for farmers seeking financing and clients interested in sustainable products. It enabled us to compare different scenarios and identify ways to enhance the system's sustainability without compromising economic feasibility.

The novel red seaweed species, *H. pseudomusciformis*, has potential for three markets: carrageenan, human consumption, and glycolic extract. While the carrageenan market has the potential to be sustainable, the seaweed sale price to the carrageenan industry needs to be higher to make it economically feasible. For the human consumption market, seaweed may be a more sustainable choice compared to similar products, and improvements in farming practices, such as reducing the use of plastic and optimizing farming length, can further enhance its sustainability. Seaweed for human consumption may also offer more attractive economic prospects for producers.

In the cosmetic industry, using seaweed glycolic extract instead of traditional liquid glycerin can be a sustainable option. Employing a more renewable solvent in extract production can improve the sustainability level of glycolic extract from an Emergy Synthesis perspective. Increasing seaweed farming yield alone is not the key factor for improving the sustainability of the system at the tested level.

The present study contributes to the development of *H. pseudomusciformis* and other sea-based seaweed aquaculture activities by demonstrating how to enhance production efficiency for mariculture. Furthermore, this analysis provides information on system characteristics and sustainability aspects that will support stakeholders such as farmers, governments, investors, and others. The findings align with the UN Sustainable Development Goals and promote the development of seaweed farming activities.

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Supplementary Materials

Article: Sustainability of the seaweed *Hypnea pseudomusciformis* sea-based farming for different markets in South Atlantic: An emergy and economic approach

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Table 1. List of Unit Emergy Values (UEVs) actualized to the baseline 1.20E+25 sej/year according to Brown et al. (2016).

	Itens	Unit	Reference UEV (sej/unit)	UEV updated (sej/unit)	Reference Baseline (sej/yr)	Reference UEV
1	Sun	J	1.00E+00	1.00E+00	9.44E+24	Odum (2000)
2	Wind	J	1.28E+03	1.28E+03	1.20E+25	Giannetti et al. (2019)
3	Ocean circulation	J	3.68E+04	3.68E+04	1.20E+25	Giannetti et al. (2019)
4	Seawater	J	1.55E+05	1.98E+05	9.44E+24	Odum and Arding (1991)
5	Dissolved Nitrogen	g	9.00E+08	1.14E+09	9.44E+24	Odum and Arding (1991)
6	Dissolved Carbon	g	3.42E+09	2.59E+09	1.58E+25	Kim and Lee (2011)
7	Dissolved Phosphate	g	8.10E+09	1.03E+10	9.44E+24	Odum and Arding (1991)
8	Ground water	J	7.67E+04	7.67E+04	1.20E+25	Giannetti et al. (2019)
9	Switchgrass	g	3.31E+08	2.51E+08	1.58E+25	Felix and Tilley (2009)
10	Plastic	J	1.92E+05	1.92E+05	1.20E+25	Giannetti et al. (2019)
11	Cotton	g	1.45E+09	1.45E+09	1.20E+25	Blatt and Almeida (2017)
12	Gasoline	J	4.16E+04	4.16E+04	1.20E+25	Giannetti et al. (2019)
13	Paper	g	2.95E+09	2.95E+09	1.20E+25	Corcelli et al. (2018)
14	Glycerin	g	1.21E+11	9.17E+10	1.58E+25	Fahd et al. (2012)
15	Grain-ethanol	J	1.24E+05	1.24E+05	1.20E+25	Dong et al. (2008)
16	Human Labor	J	1.15E+07	8.72E+06	1.58E+25	Bonilla et al. (2010)
17	Iron	g	4.15E+09	4.15E+09	1.20E+25	Oliveira et al. (2018)
18	Steel	g	1.80E+09	2.29E+09	9.44E+24	Brown and Bardi (2001)
19	Aluminum ingot	g	1.17E+10	1.49E+10	9.44E+24	Buranakan (1998)
20	Rubber	g	4.30E+09	5.47E+09	9.44E+24	Buranakan (1998)
21	Wood	J	2.24E+05	2.85E+05	9.44E+24	Buranakan (1998)
22	Concrete	g	1.44E+09	1.83E+09	9.44E+24	Buranakan (1998)
23	Glass	g	3.03E+09	3.03E+09	1.20E+25	Almeida et al. (2017)
24	Monetary (EmDollar Brazil)	$	5.61E+12	5.61E+12	1.20E+25	Giannetti et al. (2018)
25	Glycerin from soybean biodisel	g	1.68E+14	1.28E+14	1.58E+25	Cavalett and Ortega (2010)

Table 2. Calculations for the seaweed sea-based farming to produce and sell for the carrageenan industry (7.51 ha).

Note	Item	Value	Unit	Reference
	Inputs			
1	**Sun**			
	Insolation	2.22E+12	J/ha/year	FUNCEME (2011)
	Solar transmittance coefficient	81.60	%	Sangpradit (2014)
	Annual flow	1.81E+12	J/ha/year	
	UEV	1.00E+00	sej/J	By definition
	Emergy	1.81E+12	sej/ha/year	
	Sun = (2.22E+12 J/ha/year)(0.8 absorbed)*(1.00E+00) = 1.81E+12 sej/ha/year*			
2	**Wind**			
	Density of air	1.20E+00	kg/m³	
	Wind velocity	2.41E+00	m/s	Hersbach et al. (2019)
	Time	3.15E+07	s	
	Drying area	8.00E+00	m²	
	Annual flow	3.11E+07	J/ha/year	
	UEV	1.28E+03	sej/J	Giannetti et al. (2019)
	Emergy	3.97E+10	sej/ha/year	
	Wind = ((((0.5)(1.20)*(8)*(2.41^3))/1000*24 hours)*(3.60E+06 J/kWh)*(5days)*(8 cycles))/(7.51 productive area)*(1.28E+03)=3.97E+10 sej/ha/year*			
3	**Ocean Circulation**			
	Ocean circulation velocity	4.00E-01	m/s	Signorini and Miranda (1983)
	Farming seawater volume	3.75E+04	m³	
	Seawater density	1.00E+03	kg/m³	
	Farming water mass	3.76E+07	kg	
	Currents kinetic energy	3.01E+06	J	
	Annual flow	1.46E+08	J/ha/year	
	UEV	3.68E+04	sej/J	Giannetti et al. (2019)
	Emergy	5.38E+12	sej/ha/year	
	Ocean Circulation = (((3.76E+07)(4^2)/2)/(7.51productive area))/(365 days)*(3.68E+04)= 5.38E+12 sej/ha/year*			
4	**Seawater**			
	Seaweed biomass water	84.27	%	
	Seaweed annual biomass	5.74E+04	kg	
	Seawater density	1.00E+03	kg/m³	
	Seaweed biomass water	6.42E+00	m³/ha/year	
	Transformation	3.00E+06	J/m³	Odum andArding (1991)
	Annual flow	1.93E+07	J/ha/year	
	UEV	1.98E+05	sej/J	Odum and Arding (1991)
	Emergy	3.81E+12	sej/ha/year	
	*Seawater = (((0.84*5.74E+04)/1.00E+03))/(7.51productive area)*(1.98E+05) = 3.81 sej/ha/year*			
5	**Nitrogen**			
	Nutrient concentration	3.14E+01	g/kg	
	Seaweed annual dried biomass	1.20E+03	kg/ha/year	
	Annual flow	3.78E+04	g/ha/year	
	UEV	1.14E+09	sej/g	Odum and Arding (1991)
	Emergy	4.32E+13	sej/g/year	
	*Nitrogen = 3.14E+01*1.20E+03*1.14E+09 = 4.32E+13 sej/ha/year*			

6	**Carbon**			
	Nutrient concentration	2.99E+02	g/kg	
	Seaweed annual dried biomass	1.20E+03	kg/ha/year	
	Annual flow	3.60E+05	g/ha/year	
	UEV	2.59E+09	sej/g	Kim and Lee (2011)
	Emergy	9.33E+14	sej/g/year	
	*Carbon = 2.99E+02*1.20E+03*2.59E+09 = 9.33E+14 sej/ha/year*			
7	**Phosphate**			
	Nutrient concentration	2.00E+00	g/kg	
	Seaweed annual dried biomass	1.20E+03	kg/ha/year	
	Annual flow	2.40E+03	g/ha/year	
	UEV	1.03E+10	sej/g	Odum and Arding (1991)
	Emergy	2.47E+13	sej/g/year	
	*Phosphate = 2.00E+00*1.20E+03*1.03E+10 = 2.47E+13 sej/ha/year*			
8	**Switchgrass**			
	Quantity	1.00E+03	g	
	Renewable fraction	32.00	%	Felix and Tilley (2009)
	Annual flow	1.77E+01	g/ha/year	
	UEV	2.51E+08	sej/g	Felix and Tilley (2009)
	Emergy	1.07E+10	sej/g/year	
	*Switchgrass = (1.00E+03/(7.51productive area))*0.32*2.51E+08 = 1.07 sej/g/year*			
9	**Ground water**			
	Quantity	16	m^3	
	Transformation	4.90E+06	J/m^3	
	Annual flow	1.04E+07	J/ha/year	
	UEV	7.67E+04	sej/J	Giannetti et al. (2019)
	Emergy	8.01E+05	sej/ha/year	
	*Ground water = ((16*4.90E+06)/(7.51productive area))*7.67E+04 = 8.01E+05 sej/ha/year*			
10	**Switchgrass**			
	Quantity	1.00E+03	g	
	Non-renewable fraction	68.00	%	Felix and Tilley (2009)
	Annual flow	1.33E+02	g/ha/year	
	UEV	2.51E+08	sej/g	Felix and Tilley (2009)
	Emergy	2.27E+10	sej/g/year	
	*Switchgrass = (1.00E+03/(7.51productive area))*0.68*2.51E+08 = 2.27E+10sej/g/year*			
11	**Cotton**			
	Quantity	3.60E+04	g	
	Renewable fraction	33.69	%	Blatt and Almeida (2017)
	Annual flow	4.79E+03	g/ha/year	
	UEV	1.45E+09	sej/g	Blatt and Almeida (2017)
	Emergy	2.34E+12	sej/ha/year	
	*Cotton = (3.60E+04/(7.51productive area))*0.34*1.45E+09 = 2.34E+12 sej/ha/year*			
12	**Plastic (Materials)**			
	Quantity	3.84E+09	J	
	Annual flow	5.11E+08	J/ha/year	
	UEV	1.92E+05	sej/J	Giannetti et al. (2019)
	Emergy	9.82E+13	sej/ha/year	
	*Plastic (Materials) = (3.84E+09/(7.51productive area))*1.92E+05 = 9.82E+13 sej/ha/year*			
13	**Cotton**			
	Quantity	3.60E+04	g	

	Non-renewable fraction	66.31	%	Blatt and Almeida (2017)
	Annual flow	4.79E+03	g/ha/year	
	UEV	1.45E+09	sej/g	Blatt and Almeida (2017)
	Emergy	4.61E+12	sej/ha/year	
	*Cotton = (3.60E+04/(7.51productive area))*0.66*1.45E+09 = 4.61E+12 sej/ha/year*			
14	**Fuel (gasoline)**			
	Quantity	9.79E+08	J	
	Annual flow	1.30E+08	J/ha/year	
	UEV	4.16E+04	sej/J	Giannetti et al. (2019)
	Emergy	5.42E+12	sej/ha/year	
	*Fuel = (9.79E+08/(7.51productive area))*4.16E+04 = 5.42E+12 sej/ha/year*			
15	**Steel**			
	Quantity	3.93E+04	g	
	Renewable fraction	4.31	%	Pan et al. (2016)
	Depreciation	10	years	
	Annual flow	2.26E+01	g/ha/year	
	UEV	2.29E+09	sej/g	Brown and Bardi (2001)
	Emergy	5.16E+10	sej/ha/year	
	*Steel = ((3.93E+04/(7.51productive area))/10)*0.04*2.29E+09 = 5.16E+10 sej/ha/year*			
16	**Plastic (Equipments and Infrastructure)**			
	Quantity	1.11E+10	J	
	Depreciation	5	years	
	Annual flow	2.95E+08	J/ha/year	
	UEV	1.92E+05	sej/J	Giannetti et al. (2019)
	Emergy	5.67E+13	sej/ha/year	
	*Plastic = ((1.11E+10/(7.51productive area))/5)*1.92E+05 = 5.67E+13 sej/ha/year*			
17	**Iron**			
	Quantity	2.44E+06	g	
	Depreciation	5	years	
	Annual flow	6.49E+04	g/ha/year	
	UEV	4.15E+09	sej/g	Oliveira et al. (2018)
	Emergy	2.70E+14	sej/ha/year	
	*Iron = ((2.44E+06/(7.51productive area))/5)*4.15E+09 = 2.70E+14 sej/ha/year*			
18	**Steel**			
	Quantity	3.93E+04	g	
	Non-renewable fraction	95.69	%	Pan et al. (2016)
	Depreciation	10	years	
	Annual flow	5.01E+02	g/ha/year	
	UEV	2.29E+09	sej/g	Brown and Bardi (2001)
	Emergy	1.15E+12	sej/ha/year	
	*Steel = ((3.93E+04/(7.51productive area))/10)*0.96*2.29E+09 = 1.15E+12 sej/ha/year*			
19	**Aluminum ingot**			
	Quantity	8.32E+04	g	
	Depreciation	10	years	
	Annual flow	1.11E+03	g/ha/year	
	UEV	1.49E+10	sej/g	Buranakan (1998)
	Emergy	1.65E+13	sej/ha/year	
	*Aluminum ingot = ((8.32E+04/(7.51productive area))/10)*1.49E+10 = 1.65E+13 sej/ha/year*			
20	**Rubber**			
	Quantity	8.50E+03	g	

	Depreciation	10	years	
	Annual flow	1.13E+02	g/ha/year	
	UEV	5.47E+09	sej/g	Buranakan (1998)
	Emergy	6.19E+11	sej/ha/year	
	*Rubber = ((8.50E+03/(7.51productive area))/10)*5.47E+09 = 6.19E+11 sej/ha/year*			
21	**Wood**			
	Quantity	1.19E+06	g	
	Transformation	2.09E+04	J/g	
	Depreciation	10	years	
	Annual flow	3.30E+08	J/ha/year	
	UEV	2.85E+05	sej/J	Buranakan (1998)
	Emergy	9.40E+13	sej/ha/year	
	*Wood = ((1.19E+06 * 2.09E+04 /(7.51productive area))/10)*2.85E+05 = 9.40E+13 sej/ha/year*			
22	**Concrete**			
	Quantity	2.10E+06	g	
	Depreciation	10	years	
	Annual flow	2.80E+04	g/ha/year	
	UEV	1.83E+09	sej/g	Buranakan (1998)
	Emergy	5.12E+13	sej/ha/year	
	*Concrete = ((2.10E+06/(7.51productive area))/10)*1.83E+09 =5.12E+13 sej/ha/year*			
23	**Human labor**			
	Man-works	12	persons	
	Calories	2.92E+02	kcal/hour	
	Work-hour	8	hours/day	
	Days	360	days/year	
	Annual work	1.01E+07	kcal/year	
	Conversion to J	4.18E+03	J/kcal	
	Renewable fraction	90.00	%	Agostinho et al. (2019)
	Annual flow	5.05E+09	J/ha/year	
	UEV	8.72E+06	sej/J	Bonilla et al. (2010)
	Emergy	4.40E+16	sej/year	
	*Human labor = ((12*2.92E+02*8*360/(7.51productive area)))*4.18E+03*0.9*8.72E+06 = 4.40E+16 sej/ha/year*			
24	**Services**			
	Quantity	5.65E+03	$	
	Renewable fraction	15.00	%	Giannetti et al. (2018)
	Annual flow	1.13E+02	$/ha/year	
	UEV	5.61E+12	sej/$	Giannetti et al. (2018)
	Emergy	6.33E+14	sej/ha/year	
	*Services = (5.65E+03 / (7.51productive area))*0.15*5.61E+12 = 6.33E+14 sej/ha/year*			
25	**Human labor**			
	Man-works	12	persons	
	Calories	292	kcal/hour	
	Work-hour	8	hours/day	
	Days	360	days/year	
	Annual work	1.01E+07	kcal/year	
	Conversion to J	4.18E+03	J/kcal	
	Non-renewable fraction	10	%	Bonilla et al. (2010)
	Annual flow	5.61E+08	J/ha/year	
	UEV	8.72E+06	sej/J	Odum and Arding (1991)

	Emergy	4.89E+15	sej/year	

*Human labor = ((12*2.92E+02*8*360/(7.51productive area)))*4.18E+03*0.1*8.72E+06 = 4.89E+15 sej/ha/year*

26	**Services**			
	Quantity	5.65E+03	$	
	Non-renewable fraction	85.00	%	Giannetti et al. (2018)
	Annual flow	6.39E+02	$/ha/year	
	UEV	5.61E+12	sej/$	Corcelli et al. (2018)
	Emergy	3.59E+15	sej/ha/year	

*Services = (5.65E+03 / (7.51productive area))*0.85*5.61E+12 = 3.59E+15 sej/ha/year*

	Outputs			
27	**Bleached and dry seaweed**			
	Harvest biomass	8.28E+06	g/year	
	Annual flow	1.10E+06	g/ha/year	
	Self-consumption	0.00	%	
	UEV	4.97E+10	sej/g	Present study
	Emergy	5.48E+16	sej/ha/year	

*Bleached and dry seaweed = (8.28E+06 / (7.51productive area))*4.97E+10 = 5.48E+16 sej/ha/year*

	Ecosystem Services			
28	**Legal reserve area: native vegetation**			
	Quantity	1.30E-02	ha	
	Estimated value	1.74E+04	$/ha/year	Costanza et al., 1997
	Annual flow	3.00E+01	$/ha/year	
	UEV	1.82E+15	sej/$	Present study
	Emergy	5.48E+16	sej/ha/year	

*Native vegetation = (1.30E-02 / (7.51productive area))*1.82E+15 = 5.48E+16 sej/ha/year*

29	**Ecotourism**			
	Quantity	1.40E+02	Unit	
	Price	6.00E+00	$/unit	
	Annual flow	1.12E+02	$/ha/year	
	UEV	4.90E+14	sej/$	Present study
	Emergy	5.48E+16	sej/ha/year	

*Ecotourism = (1.40E+02 / (7.51productive area))*4.90E+14 = 5.48E+16 sej/ha/year*

Table 3. The initial investments cost to the seaweed sea-based farming for carrageen in different scenarios. Carrageenan base scenario (C); Carrageenan using less and recycled plastic (C_{pr}); Carrageenan with farming cycle length reduction (C_{cr}); Carrageenan using less and recycled plastic and farming cycle length reduction (C_T). (US$1.00 = R$ 5.38).

Items	**C; C_{cr}**		**C_{pr};C_T**	
	R$	**%**	**R$**	**%**
Longline †	12,543.68	49.80	17,700.28	56.97
Braided rope †	782.06	3.10	1,173.09	3.78
Anchor †	5,130.11	20.37	5,130.11	16.51
Buoy †	780.67	3.10	780.67	2.51
Waterbox ‡	85.50	0.34	85.50	0.28
Commercial Scale †	52.04	0.21	52.04	0.17
Knife ‡	687.73	2.73	687.73	2.21
Boat ‡	483.27	1.92	483.27	1.56
Motor ‡	33.46	0.13	33.46	0.11
Life Jacket ‡	6.51	0.03	6.51	0.02
Shed §	487.92	1.94	487.92	1.57
Handling table †	331.78	1.32	331.78	1.07
Drying table ‡	487.73	1.94	487.73	1.57
Vehicle ‡	1,869.89	7.42	1,869.89	6.02
Project cost	1,425.74	5.66	1,758.60	5.66
Total	**25,188.10**	**100.00**	**31,068.59**	**100**
Total (R$/ha)	**3,353.94**		**4,136.96**	

† Useful life estimated at 5 years; ‡ Useful life estimated at 10 years; § Useful life estimated at 15 years.

Table 4. Annual costs (US$) and the percentage (%) of operating costs for sale to seaweed sea-based farming for carrageen in different scenarios. Carrageenan base scenario (C); Carrageenan using less and recycled plastic (C_{pr}); Carrageenan with farming cycle length reduction (C_{cr}); Carrageenan using less and recycled plastic and farming cycle length reduction (C_T). (US$1.00 = R$ 5.38).

Itens description	**Unit**	**Price/Unit**	**C**			**C_{pr}**			**C_{cr}**			**C_T**		
		(US$)	**Quantity**	**Total Cost**	**%**	**Quantity**	**Total Cost**	**%**	**Quantity**	**Total Cost**	**%**	**Quantity**	**Total Cost**	**%**
Variable cost				**14,656**			**13,159**			**13,159**			**14,934.92**	
Ribbon	kg	2.97	120.00	357	1.8	0.00	0.00	0.0	135.00	401	1.9	0	0.00	0.0
Cotton yarn	kg	5.95	36.00	214	1.1	72.00	428.25	2.2	40.50	241	1.1	81	482	2.3
Eventual labor	daily	13.01	832.00	10,825	55.2	832.00	10,825.28	55.3	936.00	12,178	56.1	936	12,178	57.1
Fuel	L	0.93	96.00	89	0.5	96.00	89.22	0.5	108.00	100	0.5	108	100	0.5
Raffia bag	unit	0.52	180.00	93	0.5	180.00	93	0.5	221.4	115	0.5	221	115	0.5
Rural Social Security Special Contribution[a]				124	0.6		124	0.6		186	0.9		153	0.7
Tax on the sale of the product[b]				972	5.0		972	5.0		1,455	6.7		1,196	5.6
General costs[c]				634	3.2		627	3.2		734	3.4		711	3.3
Fixed cost				**6,290**			**6,401**			**6,290**			**19,732**	
Vehicle property tax[d]				37	0.2		37	0.2		37	0.2		37	0.2
Fixed labor	annual wage	5,776.93	1	5,777	29.5	1.00	5,777	29.5		5,777	26.6	1	5,777	27.1
Maintenance [e]				475	2.4		586	3.0		475	2.2		586	2.7
Annual depreciation				4,270			5,380			6,290			5,380	
Interest on working capital [f]				1,347			1,345			1,492			1,467	
Remuneration on fixed capital [g]				1,732			2,136			1,732			2,136	
Remunerations of the entrepreneur				4,349			4,349			4,349			4,349	
Total Production Cost (TPC)				**31,297**			**32,769**			**33,543**			**34,667**	

[a] 2,3% of gross revenue; [b] 18% of gross revenue; [c] 5% of variable cost; [d] 4% of vehicle value;[e] 2% of investments; [f] 13.75% a.a. on haf of the effective operational cost; [g] 13.75% on haf fixed investments

Table 5. Calculations for the seaweed sea-based farming to produce and sale for direct human consumption industry (7.51ha).

Note	Item	Value	Unit	Reference
	Inputs			
1	**Sun**			
	Insolation	2.22E+12	J/ha/year	Funceme (2011)
	Solar transmittance coefficient	81.60	%	Sangpradit (2014)
	Annual flow	1.81E+12	J/ha/year	
	UEV	1.00E+00	sej/J	By definition
	Emergy	1.81E+12	sej/ha/year	
	Sun = (2.22E+12 J/ha/year)(0.8 absorbed)*(1.00E+00) = 1.81E+12 sej/ha/year*			
2	**Wind**			
	Density of air	1.20E+00	kg/m³	
	Wind velocity	2.41E+00	m/s	Hersbach et al. (2019)
	Time	3.15E+07	s	
	Drying area	8.00E+00	m²	
	Annual flow	3.11E+07	J/ha/year	
	UEV	1.28E+03	sej/J	Giannetti et al. (2019)
	Emergy	3.97E+10	sej/ha/year	
	Wind = ((((0.5)(1.20)*(8)*(2.41^3))/1000*24 hours)*(3.60E+06 J/kWh)*(5days)*(8 cycles))/(7.51 productive area)*(1.28E+03)=3.97E+10 sej/ha/year*			
3	**Ocean Circulation**			
	Ocean circulation velocity	4.00E-01	m/s	Signorini and Miranda (1983)
	Farming seawater volume	3.75E+04	m³	
	Seawater density	1.00E+03	kg/m³	
	Farming water mass	3.76E+07	kg	
	Currents kinetic energy	3.01E+06	J	
	Annual flow	1.46E+08	J/ha/year	
	UEV	3.68E+04	sej/J	Giannetti et al. (2019)
	Emergy	5.38E+12	sej/ha/year	
	Ocean Circulation = (((3.76E+07)(4^2)/2)/(7.51productive area))/(365 days)*(3.68E+04)= 5.38E+12 sej/ha/year*			
4	**Seawater**			
	Seaweed biomass water	84.27	%	
	Seaweed annual biomass	5.74E+04	kg	
	Seawater density	1.00E+03	kg/m³	
	Seaweed biomass water	6.42E+00	m³/ha/ano	
	Transformation	3.00E+06	J/m³	Odum andArding (1991)
	Annual flow	1.93E+07	J/ha/year	
	UEV	1.98E+05	sej/J	
	Emergy	3.81E+12	sej/ha/year	
	*Seawater = (((0.84*5.74E+04)/1.00E+03))/(7.51productive area)*(1.98E+05) = 3.81 sej/ha/year*			
5	**Nitrogen**			
	Nutrient concentration	3.14E+01	g/kg	
	Seaweed annual dried biomass	1.20E+03	kg/ha/year	
	Annual flow	3.78E+04	g/ha/year	
	UEV	1.14E+09	sej/g	Odum and Arding (1991)
	Emergy	4.32E+13	sej/g/year	

*Nitrogen = 3.14E+01*1.20E+03*1.14E+09 = 4.32E+13 sej/ha/year*

6	**Carbon**			
	Nutrient concentration	2.99E+02	g/kg	
	Seaweed annual dried biomass	1.20E+03	kg/ha/year	
	Annual flow	3.60E+05	g/ha/year	
	UEV	2.59E+09	sej/g	Kim and Lee (2011)
	Emergy	9.33E+14	sej/g/year	

*Carbon = 2.99E+02*1.20E+03*2.59E+09 = 9.33E+14 sej/ha/year*

7	**Phosphate**			
	Nutrient concentration	2.00E+00	g/kg	
	Seaweed annual dried biomass	1.20E+03	kg/ha/year	
	Annual flow	2.40E+03	g/ha/year	
	UEV	1.03E+10	sej/g	Odum and Arding (1991)
	Emergy	2.47E+13	sej/g/year	

*Phosphate = 2.00E+00*1.20E+03*1.03E+10 = 2.47E+13 sej/ha/year*

8	**Switchgrass**			
	Quantity	1.00E+03	g	
	Renewable fraction	32.00	%	Felix and Tilley (2009)
	Annual flow	4.26E+01	g/ha/year	
	UEV	2.51E+08	sej/g	Felix and Tilley (2009)
	Emergy	1.07E+10	sej/g/year	

*Switchgrass = (1.00E+03/(7.51productive area))*0.32*2.51E+08 = 1.07 sej/g/year*

9	**Switchgrass**			
	Quantity	1.00E+03	g	
	Renewable fraction	68.00	%	Felix and Tilley (2009)
	Annual flow	1.33E+02	g/ha/year	
	UEV	2.51E+08	sej/g	Felix and Tilley (2009)
	Emergy	2.27E+10	sej/g/year	

*Switchgrass = (1.00E+03/(7.51productive area))*0.68*2.51E+08 = 2.27E+10sej/g/year*

10	**Cotton**			
	Quantity	3.60E+04	g	
	Renewable fraction	33.69	%	Blatt and Almeida (2017)
	Annual flow	4.79E+03	g/ha/year	
	UEV	1.45E+09	sej/g	Blatt and Almeida (2017)
	Emergy	2.34E+12	sej/ha/year	

*Cotton = (3.60E+04/(7.51productive area))*0.34*1.45E+09 = 2.34E+12 sej/ha/year*

11	**Paper**			
	Quantity	3.00E+04	g	
	Renewable fraction	34.95	%	Corcelli et al. (2018)
	Annual flow	3.99E+03	g/ha/year	
	UEV	2.95E+09	sej/g	Corcelli et al. (2018)
	Emergy	4.12E+12	sej/ha/year	

*Paper = (3.00E+04/(7.51productive area))*0.35*2.95E+09 = 4.12E+12 sej/ha/year*

12	**Plastic (Materials)**			
	Quantity	3.84E+09	J	
	Annual flow	5.11E+08	J/ha/year	
	UEV	1.92E+05	sej/J	Giannetti et al. (2019)
	Emergy	9.82E+13	sej/ha/year	

*Plastic (Materials) = (3.84E+09/(7.51productive area))*1.92E+05 = 9.82E+13 sej/ha/year*

13	**Cotton**			

	Quantity	3.60E+04	g	
	Non-renewable fraction	66.31	%	Blatt and Almeida (2017)
	Annual flow	4.79E+03	g/ha/year	
	UEV	1.45E+09	sej/g	Blatt and Almeida (2017)
	Emergy	4.61E+12	sej/ha/year	
	*Cotton = (3.60E+04/(7.51productive area))*0.66*1.45E+09 = 4.61E+12 sej/ha/year*			
14	**Fuel (gasoline)**			
	Quantity	9.79E+08	J	
	Annual flow	1.30E+08	J/ha/year	
	UEV	4.16E+04	sej/J	Giannetti et al. (2019)
	Emergy	5.42E+12	sej/ha/year	
	*Fuel = (9.79E+08/(7.51productive area))*4.16E+04 = 5.42E+12 sej/ha/year*			
15	**Paper**			
	Quantity	3.00E+04	g	
	Non-renewable fraction	65.05	%	Corcelli et al. (2018)
	Annual flow	3.99E+03	g/ha/year	
	UEV	2.95E+09	sej/g	Corcelli et al. (2018)
	Emergy	7.67E+12	sej/ha/year	
	*Paper = (3.00E+04/(7.51productive area))*0.65*2.95E+09 = 7.67E+12 sej/ha/year*			
16	**Steel**			
	Quantity	3.93E+04	g	
	Renewable fraction	4.31	%	Pan et al. (2016)
	Depreciation	10.00	years	
	Annual flow	2.26E+01	g/ha/year	
	UEV	2.29E+09	sej/g	Brown and Bardi (2001)
	Emergy	5.16E+10	sej/ha/year	
	*Steel = ((3.93E+04/(7.51productive area))/10)*0.04*2.29E+09 = 5.16E+10 sej/ha/year*			
17	**Plastic (Equipments and Infrastructure)**			
	Quantity	1.11E+10	J	
	Depreciation	5.00	years	
	Annual flow	2.95E+08	J/ha/year	
	UEV	1.92E+05	sej/J	Giannetti et al. (2019)
	Emergy	5.67E+13	sej/ha/year	
	*Plastic = ((1.11E+10/(7.51productive area))/5)*1.92E+05 = 5.67E+13 sej/ha/year*			
18	**Iron**			
	Quantity	2.44E+06	g	
	Depreciation	5	years	
	Annual flow	6.49E+04	g/ha/year	
	UEV	4.15E+09	sej/g	Oliveira et al. (2018)
	Emergy	2.70E+14	sej/ha/year	
	*Iron = ((2.44E+06/(7.51productive area))/5)*4.15E+09 = 2.70E+147 sej/ha/year*			
19	**Steel**			
	Quantity	3.93E+04	g	
	Non-renewable fraction	95.69	%	Pan et al. (2016)
	Depreciation	10	years	
	Annual flow	5.01E+02	g/ha/year	
	UEV	2.29E+09	sej/g	Brown and Bardi (2001)
	Emergy	1.15E+12	sej/ha/year	
	*Steel = ((3.93E+04/(7.51productive area))/10)*0.96*2.29E+09 = 1.15E+12 sej/ha/year*			
20	**Aluminum ingot**			

	Quantity	8.32E+04	g	
	Depreciation	10	years	
	Annual flow	1.11E+03	g/ha/year	
	UEV	1.49E+10	sej/g	Buranakan (1998)
	Emergy	1.65E+13	sej/ha/year	

*Aluminum ingot = ((8.32E+04/(7.51productive area))/10)*1.49E+10 = 1.63E+13 sej/ha/year*

21	**Rubber**			
	Quantity	8.50E+03	g	
	Depreciation	10	years	
	Annual flow	1.13E+02	g/ha/year	
	UEV	5.47E+09	sej/g	Buranakan (1998)
	Emergy	6.19E+11	sej/ha/year	

*Rubber = ((8.50E+03/(7.51productive area))/10)*5.47E+09 = 6.19E+11 sej/ha/year*

22	**Wood**			
	Quantity	1.19E+06	g	
	Transformation	2.09E+04	J/g	
	Depreciation	10	years	
	Annual flow	3.30E+08	J/ha/year	
	UEV	2.85E+05	sej/J	Buranakan (1998)
	Emergy	9.40E+13	sej/ha/year	

*Wood = ((1.19E+06 * 2.09E+04 /(7.51productive area))/10)*2.85E+05 = 9.40E+13 sej/ha/year*

23	**Concrete**			
	Quantity	2.10E+06	g	
	Depreciation	10	years	
	Annual flow	2.80E+04	g/ha/year	
	UEV	1.83E+09	sej/g	Buranakan (1998)
	Emergy	5.12E+13	sej/ha/year	

*Concrete = ((2.10E+06/(7.51productive area))/10)*1.83E+09 =5.12E+13 sej/ha/year*

24	**Human labor**			
	Man-works	12	persons	
	Calories	2.92E+02	kcal/hour	
	Work-hour	8	hours/day	
	Days	360	days/year	
	Annual work	1.01E+07	kcal/year	
	Conversion to J	4.18E+03	J/kcal	
	Renewable fraction	90.00	%	Agostinho et al. (2019)
	Annual flow	5.05E+09	J/ha/year	
	UEV	8.72E+06	sej/J	Bonilla et al. (2010)
	Emergy	4.40E+16	sej/year	

*Human labor = ((12*2.92E+02*8*360/(7.51productive area)))*4.18E+03*0.9*8.72E+06 = 4.40E+16 sej/ha/year*

25	**Services**			
	Quantity	5.69E+03	$	
	Renewable fraction	15.00	%	Giannetti et al. (2018)
	Annual flow	1.14E+02	$/ha/year	
	UEV	5.61E+12	sej/$	Giannetti et al. (2018)
	Emergy	6.37E+14	sej/ha/year	

*Services = (5.69E+03 / (7.51productive area))*0.15*5.61E+12 = 6.37E+14 sej/ha/year*

26	**Human labor**		
	Man-works	12	persons

	Calories	292	kcal/hour	
	Work-hour	8	hours/day	
	Days	360	days/year	
	Annual work	1.01E+07	kcal/year	
	Conversion to J	4.18E+03	J/kcal	
	Non-renewable fraction	10	%	Agostinho et al. (2019)
	Annual flow	5.61E+08	J/ha/year	
	UEV	8.72E+06	sej/J	Bonilla et al. (2010)
	Emergy	4.89E+15	sej/year	

*Human labor = ((12*2.92E+02*8*360/(7.51productive area)))*4.18E+03*0.1*8.72E+06 = 4.89E+15 sej/ha/year*

27	**Services**			
	Quantity	5.69E+03	$	
	Non-renewable fraction	85.00	%	Giannetti et al. (2018)
	Annual flow	6.44E+02	$/ha/year	
	UEV	5.61E+12	sej/$	Corcelli et al. (2018)
	Emergy	3.61E+15	sej/ha/year	

*Services = (5.69E+03 / (7.51productive area))*0.85*5.61E+12 = 3.61E+15 sej/ha/year*

	Outputs			
28	**Dehydrated seaweed**			
	Harvest biomass	8.28E+06	g/year	
	Annual flow	1.10E+06	g/ha/year	
	Self-consumption	0.00	%	
	UEV	4.57E+10	sej/g	Present study
	Emergy	5.04E+16		

*Dehydrated seaweed = (8.28E+06 / (7.51productive area))*4.57E+10 = 5.04E+16 sej/ha/year*

	Ecosystem Services			
29	**Legal reserve area: native vegetation**			
	Quantity	1.30E-02	ha	
	Estimated value	1.74E+04	$/ha/year	
	Annual flow	3.00E+01	$/ha/year	
	UEV	1.83E+15	sej/$	Present study
	Emergy	5.50E+16	sej/ha/year	

*Native vegetation = (1.30E-02 / (7.51productive area))*1.83E+15 = 5.50E+16 sej/ha/year*

30	**Ecotourism**			
	Quantity	1.40E+02	Unit	
	Price	6.00E+00	$/unit	
	Annual flow	1.12E+02	$/ha/year	
	UEV	4.92E+14	sej/$	Present study
	Emergy	5.50E+16	sej/ha/year	

*Ecotourism = (1.40E+02 / (7.51productive area))*4.92E+14 = 5.50E+16 sej/ha/year*

Table 6. The initial investments cost to the seaweed sea-based farming for human consumption considering different strategies scenarios. Human consumption base scenario (HC); Human consumption using less and recycled plastic (HC_{pr}); Human consumption with farming cycle length reduction (HC_{cr}); Human consumption using less and recycled plastic and farming cycle length reduction (HC_T). (US$1.00 = R$ 5.38).

Items	**HC HC$_{cr}$**		**HC$_{pr}$;HC$_T$**	
	US$	**%**	**US$**	**%**
Longline †	12,543.68	49.80	17,700.28	56.97
Braided rope †	782.06	3.10	1,173.09	3.78
Anchor †	5,130.11	20.37	5,130.11	16.51
Buoy †	780.67	3.10	780.67	2.51
Waterbox ‡	85.50	0.34	85.50	0.28
Commercial Scale †	52.04	0.21	52.04	0.17
Knife ‡	687.73	2.73	687.73	2.21
Boat ‡	483.27	1.92	483.27	1.56
Motor ‡	33.46	0.13	33.46	0.11
Life Jacket ‡	6.51	0.03	6.51	0.02
Shed §	-	-	-	-
Handling table †	-	-	-	-
Drying table ‡	-	-	-	-
Vehicle ‡	487.92	1.94	487.92	1.57
Project cost	331.78	1.32	331.78	1.07
Commercial Scale †	487.73	1.94	487.73	1.57
Knife ‡	1,869.89	7.42	1,869.89	6.02
Boat ‡	1,425.74	5.66	1,758.60	5.66
Total	**25,188.10**	**100.00**	**31,068.59**	**100**
Total (R$/ha)	**3,353.94**		**4,136.96**	

† Useful life estimated at 5 years; ‡ Useful life estimated at 10 years; § Useful life estimated at 15 years.

Table 7. Annual costs (US$) and the percentage (%) of operating costs for sale to seaweed sea-based farming for human consumption considering different strategies scenarios. Human consumption base scenario (HC); Human consumption using less and recycled plastic (HC_{pr}); Human consumption with farming cycle length reduction (HC_{cr}); Human consumption using less and recycled plastic and farming cycle length reduction (HC_T). (US$1.00 = R$ 5.38).

Itens description	Unit	Price/Unit	HC			HCpr			HCcr			HCT		
		US$	Quantity	Total Cost	%	Quantity	Total Cost	%	Quantity	Total Cost	%	Quantity	Total Cost	%
Variable cost				**38,977**			**38,827**			**46,676**			**46,507**	
Ribbon	kg	2.97	120	357	0.8	0	0	0.0	120	401	0.8	0	0	0.0
Cotton yarn	kg	5.95	36	214	0.5	72	428	0.9	36	241	0.5	72	482	0.9
Eventual labor	daily	13.01	832	10,825	23.9	832	10,825	23.9	832	12,178	23.0	832	12,178	23.0
Fuel	L	0.93	96	89	0.2	96	89	0.2	96	100	0.2	96	100	0.2
Kraft paper bag	unit	0.04	90,000	3,346	7.4	90,000	3,346	7.4	98,400	4,115	7.8	98,400	4,115	7.8
Rural Social Security Special Contribution[a]				2,525	5.6		2,525	5.6		3,106	5.9		3,106	5.9
Tax on the sale of the product[b]				19,765	43.7		19,765	43.7		24,310	45.9		24,310	45.9
General costs[c]				1,856	4.1		1,849	4.1		2,223	4.2		2,215	4.2
Fixed cost				**6,290**			**6,401**			**6,290**			**6,401**	
Vehicle property tax[d]				37	0.1		37	0.1		37	0.1		37	0.1
Fixed labor	annual wage	5,776.93	1	5,777	12.8	1	5,777	12.8	1	5,777	10.9	1	5,777	10.9
Maintenance [e]				475	1.0		586	1.3		475	0.9		586	1.1
Annual depreciation				4,270			5,380			4,270			5,380	
Interest on working capital [f]				3,112			3,109			3,641			3,637	
Remuneration on fixed capital [g]				1,732			2,136			1,732			2,136	
Remunerations of the entrepreneur				4,349			4,349			4,349			4,349	
Total Production Cost (TPC)				**58,730**			**60,202**			**66,958**			**68,410**	

[a] 2,3% of gross revenue; [b] 18% of gross revenue; [c] 5% of variable cost; [d] 4% of vehicle value; [e] 2% of investments; [f] 13.75% a.a. on haf of the effective operational cost; [g] 13.75% on haf fixed investments

Table 8. Calculations for the seaweed sea-based farming to produce and sale for glycolic extract (7.51 ha).

Note	Item	Value	Unit	Reference
	Inputs			
1	**Sun**			
	Insolation	2.22E+12	J/ha/year	FUNCEME (2011)
	Solar transmittance coefficient	81.60	%	Sangpradit (2014)
	Annual flow	1.81E+12	J/ha/year	
	UEV	1.00E+00	sej/J	By definition
	Emergy	1.81E+12	sej/ha/year	
	Sun = (2.22E+12 J/ha/year)(0.8 absorbed)*(1.00E+00) = 1.81E+12 sej/ha/year*			
2	**Wind**			
	Density of air	1.20E+00	kg/m³	
	Wind velocity	2.41E+00	m/s	Hersbach et al. (2019)
	Time	3.15E+07	s	
	Drying area	8.00E+00	m²	
	Annual flow	3.11E+07	J/ha/year	
	UEV	1.28E+03	sej/J	Giannetti et al. (2019)
	Emergy	3.97E+10	sej/ha/year	
	Wind = ((((0.5)(1.20)*(8)*(2.41^3))/1000*24 hours)*(3.60E+06 J/kWh)*(5days)*(8 cycles))/(7.51 productive area)*(1.28E+03)=3.97E+10 sej/ha/year*			
3	**Ocean circulation**			
	Ocean circulation velocity	4.00E-01	m/s	Signorini and Miranda (1983)
	Farming seawater volume	3.75E+04	m³	
	Seawater density	1.00E+03	kg/m³	
	Farming water mass	3.76E+07	kg	
	Currents kinetic energy	3.01E+06	J	
	Annual flow	1.46E+08	J/ha/year	
	UEV	3.68E+04	sej/J	Giannetti et al. (2019)
	Emergy	5.38E+12	sej/ha/year	
	Ocean Circulation = (((3.76E+07)(4^2)/2)/(7.51productive area))/(365 days)*(3.68E+04)= 5.38E+12 sej/ha/year*			
4	**Seawater**			
	Seaweed biomass water	84.27	%	
	Seaweed annual biomass	5.74E+04	kg	
	Seawater density	1.00E+03	kg/m³	
	Seaweed biomass water	6.42E+00	m³/ha/ano	
	Transformation	3.00E+06	J/m³	Odum andArding (1991)
	Annual flow	1.93E+07	J/ha/year	
	UEV	1.98E+05	sej/J	
	Emergy	3.81E+12	sej/ha/year	
	*Seawater = (((0.84*5.74E+04)/1.00E+03))/(7.51productive area)*(1.98E+05) = 3.81 sej/ha/year*			
5	**Nitrogen**			
	Nutrient concentration	3.14E+01	g/kg	
	Seaweed annual dried biomass	1.20E+03	kg/ha/year	
	Annual flow	3.78E+04	g/ha/year	
	UEV	1.14E+09	sej/g	Odum and Arding (1991)

	Emergy	4.32E+13	sej/g/year	
	*Nitrogen = 3.14E+01*1.20E+03*1.14E+09 = 4.32E+13 sej/ha/year*			
6	**Carbon**			
	Nutrient concentration	2.99E+02	g/kg	
	Seaweed annual dried biomass	1.20E+03	kg/ha/year	
	Annual flow	3.60E+05	g/ha/year	
	UEV	2.59E+09	sej/g	Kim and Lee (2011)
	Emergy	9.33E+14	sej/g/year	
	*Carbon = 2.99E+02*1.20E+03*2.59E+09 = 9.33E+14 sej/ha/year*			
7	**Phosphate**			
	Nutrient concentration	2.00E+00	g/kg	
	Seaweed annual dried biomass	1.20E+03	kg/ha/year	
	Annual flow	2.40E+03	g/ha/year	
	UEV	1.03E+10	sej/g	Odum and Arding (1991)
	Emergy	2.47E+13	sej/g/year	
	*Phosphate = 2.00E+00*1.20E+03*1.03E+10 = 2.47E+13 sej/ha/year*			
8	**Switchgrass**			
	Quantity	1.00E+03	g	
	Renewable fraction	32.00	%	Felix and Tilley (2009)
	Annual flow	4.26E+01	g/ha/year	
	UEV	2.51E+08	sej/g	Felix and Tilley (2009)
	Emergy	1.07E+10	sej/g/year	
	*Switchgrass = (1.00E+03/(7.51productive area))*0.32*2.51E+08 = 1.07 sej/g/year*			
9	**Switchgrass**			
	Quantity	1.00E+03	g	
	Renewable fraction	68	%	Felix and Tilley (2009)
	Annual flow	1.33E+02	g/ha/year	
	UEV	2.51E+08	sej/g	Felix and Tilley (2009)
	Emergy	2.27E+10	sej/g/year	
	*Switchgrass = (1.00E+03/(7.51productive area))*0.68*2.51E+08 = 2.27E+10sej/g/year*			
10	**Cotton**			
	Quantity	3.60E+04	g	
	Renewable fraction	33.69	%	Blatt and Almeida (2017)
	Annual flow	4.79E+03	g/ha/year	
	UEV	1.45E+09	sej/g	Blatt and Almeida (2017)
	Emergy	2.34E+12	sej/ha/year	
	*Cotton = (3.60E+04/(7.51productive area))*0.34*1.45E+09 = 2.34E+12 sej/ha/year*			
11	**Paper**			
	Quantity	3.00E+03	g	
	Renewable fraction	34.95	%	Corcelli et al. (2018)
	Annual flow	1.40E+02	g/ha/year	
	UEV	2.95E+09	sej/g	Corcelli et al. (2018)
	Emergy	4.12E+11	sej/ha/year	
	*Paper = (3.00E+04/(7.51productive area))*0.35*2.95E+09 = 4.12E+11 sej/ha/year*			
12	**Liquid glycerin**			
	Quantity	3.40E+07	g	
	Renewable fraction	10.39	%	Fahd et al. (2012)
	Annual flow	4.71E+05	g/ha/year	
	UEV	9.17E+10	sej/g	Fahd et al. (2012)
	Emergy	4.32E+16	sej/ha/year	

*Liquid glycerin = (3.40E+07/(7.51productive area))*0.10*9.17E+10 = 4.32E+16 sej/ha/year*

13	**Grain alcohol**			
	Quantity	6.60E+10	g	
	Renewable fraction	11.31	%	Dong et al. (2008)
	Annual flow	9.94E+08	g/ha/year	
	UEV	1.24E+05	sej/g	Dong et al. (2008)
	Emergy	1.23E+14	sej/ha/year	

*Grain alcohol = (6.60E+10/(7.51productive area))*0.11*1.24E+05 = 1.23E+14 sej/ha/year*

14	**Plastic (Materials)**			
	Quantity	1.32E+11	J	
	Annual flow	1.76E+10	J/ha/year	
	UEV	1.92E+05	sej/J	Giannetti et al. (2019)
	Emergy	3.39E+15	sej/ha/year	

*Plastic (Materials) = (1.32E+11/(7.51productive area))*1.92E+05 = 3.39E+15 sej/ha/year*

15	**Cotton**			
	Quantity	3.60E+04	g	
	Non-renewable fraction	66.31	%	Blatt and Almeida (2017)
	Annual flow	3.18E+03	g/ha/year	
	UEV	1.45E+09	sej/g	Blatt and Almeida (2017)
	Emergy	4.61E+12	sej/ha/year	

*Cotton = (3.60E+04/(7.51productive area))*0.66*1.45E+09 = 4.61E+12 sej/ha/year*

16	**Fuel (gasoline)**			
	Quantity	9.79E+08	J	
	Annual flow	1.30E+08	J/ha/year	
	UEV	4.16E+04	sej/J	Giannetti et al. (2019)
	Emergy	5.42E+12	sej/ha/year	

*Fuel = (9.79E+08/(7.51productive area))*4.16E+04 = 5.42E+12 sej/ha/year*

17	**Paper**			
	Quantity	3.00E+03	g	
	Non-renewable fraction	65.05	%	Corcelli et al. (2018)
	Annual flow	2.60E+02	g/ha/year	
	UEV	2.95E+09	sej/g	Corcelli et al. (2018)
	Emergy	7.67E+11	sej/ha/year	

*Paper = (3.00E+04/(7.51productive area))*0.65*2.95E+09 = 7.67E+11 sej/ha/year*

18	**Liquid glycerin**			
	Quantity	3.40E+07	g	
	Non-renewable fraction	89.61	%	Fahd et al. (2012)
	Annual flow	4.06E+06	g/ha/year	
	UEV	9.17E+10	sej/g	Fahd et al. (2012)
	Emergy	3.72E+17	sej/ha/year	

*Liquid glycerin = (3.40E+07/(7.51productive area))*0.90*9.17E+10 = 3.72E+17 sej/ha/year*

19	**Grain alcohol**			
	Quantity	6.60E+10	g	
	Non-renewable fraction	88.69	%	Dong et al. (2008)
	Annual flow	7.79E+09	g/ha/year	
	UEV	1.24E+05	sej/g	Dong et al. (2008)
	Emergy	9.67E+14	sej/ha/year	

*Grain alcohol = (6.60E+10/(7.51productive area))*0.89*1.24E+05 = 9.67E+14 sej/ha/year*

20	**Steel**			
	Quantity	3.93E+04	g	

	Renewable fraction	4.31	%	Pan et al. (2016)
	Depreciation	10	years	
	Annual flow	2.26E+01	g/ha/year	
	UEV	2.29E+09	sej/g	Brown and Bardi (2001)
	Emergy	5.16E+10	sej/ha/year	
*Steel = ((3.93E+04/(7.51productive area))/10)*0.04*2.29E+09 = 5.16E+10 sej/ha/year*				
21	**Glass**			
	Quantity	1.18E+05	g	
	Renewable fraction	0.50	%	Almeida et al. (2017)
	Depreciation	10	years	
	Annual flow	7.86E+00	g/ha/year	
	UEV	3.03E+09	sej/g	Almeida et al. (2017)
	Emergy	2.38E+10	sej/ha/year	
*Glass = ((1.18E+05/(7.51productive area))/10)*0.005*3.03E+09 = 2.38E+10 sej/ha/year*				
22	**Plastic (Equipments and Infrastructure)**			
	Quantity	1.11E+10	J	
	Depreciation	5	years	
	Annual flow	2.96E+08	J/ha/year	
	UEV	1.92E+05	sej/J	Giannetti et al. (2019)
	Emergy	5.68E+13	sej/ha/year	
*Plastic = ((1.11E+10/(7.51productive area))/5)*1.92E+05 = 5.68E+13 sej/ha/year*				
23	**Iron**			
	Quantity	2.45E+06	g	
	Depreciation	5	years	
	Annual flow	6.51E+04	g/ha/year	
	UEV	4.15E+09	sej/g	Oliveira et al. (2018)
	Emergy	2.70E+14	sej/ha/year	
*Iron = ((2.45E+06/(7.51productive area))/5)*4.15E+09 = 2.70E+14 sej/ha/year*				
24	**Steel**			
	Quantity	3.93E+04	g	
	Non-renewable fraction	95.69	%	Pan et al. (2016)
	Depreciation	10	years	
	Annual flow	5.01E+02	g/ha/year	
	UEV	2.29E+09	sej/g	Brown and Bardi (2001)
	Emergy	1.15E+12	sej/ha/year	
*Steel = ((3.93E+04/(7.51productive area))/10)*0.96*2.29E+09 = 1.15E+12 sej/ha/year*				
25	**Aluminum ingot**			
	Quantity	8.32E+04	g	
	Depreciation	10	years	
	Annual flow	1.11E+03	g/ha/year	
	UEV	1.49E+10	sej/g	Buranakan (1998)
	Emergy	1.65E+13	sej/ha/year	
*Aluminum ingot = ((8.32E+04/(7.51productive area))/10)*1.49E+10 = 1.65E+13 sej/ha/year*				
26	**Rubber**			
	Quantity	8.50E+03	g	
	Depreciation	10	years	
	Annual flow	1.13E+02	g/ha/year	
	UEV	5.47E+09	sej/g	Buranakan (1998)
	Emergy	6.19E+11	sej/ha/year	

*Rubber = ((8.50E+03/(7.51productive area))/10)*5.47E+09 = 6.19E+11 sej/ha/year*

27	**Wood**			
	Quantity	1.19E+06	g	
	Transformation	2.09E+04	J/g	
	Depreciation	10	years	
	Annual flow	3.30E+08	J/ha/year	
	UEV	2.85E+05	sej/J	Buranakan (1998)
	Emergy	9.40E+13	sej/ha/year	

*Wood = ((1.19E+06 * 2.09E+04 /(7.51productive area))/10)*2.85E+05 = 9.40E+13 sej/ha/year*

28	**Concrete**			
	Quantity	2.10E+06	g	
	Depreciation	10	years	
	Annual flow	2.80E+04	g/ha/year	
	UEV	1830508475	sej/g	Buranakan (1998)
	Emergy	5.12E+13	sej/ha/year	

*Concrete = ((2.10E+06/(7.51productive area))/10)*1.83E+09 =5.12E+13 sej/ha/year*

29	**Glass**			
	Quantity	1.18E+05	g	
	Non-renewable fraction	99.50	%	Almeida et al. (2017)
	Depreciation	10.00	years	
	Annual flow	1.56E+03	g/ha/year	
	UEV	3.03E+09	sej/g	Almeida et al. (2017)
	Emergy	4.74E+12	sej/ha/year	

*Glass = ((1.18E+05/(7.51productive area))/10)*0.995*3.03E+09 = 4.74E+12 sej/ha/year*

30	**Human labor**			
	Man-works	14	persons	
	Calories	291.5	kcal/hour	
	Work-hour	8	hours/day	
	Days	360	days/year	
	Annual work	1.18E+07	kcal/year	
	Conversion to J	4.18E+03	J/kcal	
	Renewable fraction	90	%	Agostinho et al. (2019)
	Annual flow	5.89E+09	J/ha/year	
	UEV	8.72E+06	sej/J	Bonilla et al. (2010)
	Emergy	5.14E+16	sej/year	

*Human labor = ((14*2.92E+02*8*360/(7.51productive area)))*4.18E+03*0.9*8.72E+06 = 5.14E+16 sej/ha/year*

31	**Services**			
	Quantity	3.80E+04	$	
	Renewable fraction	15.00	%	Giannetti et al. (2018)
	Annual flow	7.60E+02	$/ha/year	
	UEV	5.61E+12	sej/$	Giannetti et al. (2018)
	Emergy	4.26E+15	sej/ha/year	

*Services = (3.80E+04 / (7.51productive area))*0.15*5.61E+12 = 4.26E+15 sej/ha/year*

32	**Human labor**			
	Man-works	14	persons	
	Calories	291.5	kcal/hour	
	Work-hour	8	hours/day	
	Days	360	days/year	

	Annual work	1.18E+07	kcal/year	
	Conversion to J	4.18E+03	J/kcal	
	Non-renewable fraction	10	%	Agostinho et al. (2019)
	Annual flow	6.55E+08	J/ha/year	
	UEV	8.72E+06	sej/J	Bonilla et al. (2010)
	Emergy	5.71E+15	sej/year	

*Human labor = ((14*2.92E+02*8*360/(7.51productive area)))*4.18E+03*0.1*8.72E+06 = 5.71E+15 sej/ha/year*

33	**Services**			
	Quantity	3.80E+04	$	
	Renewable fraction	85	%	
	Annual flow	6.46E+02	$/ha/year	
	UEV	5.61E+12	sej/$	Giannetti et al. (2018)
	Emergy	3.62E+15	sej/ha/year	

*Services = (3.80E+04 / (7.51productive area))*0.85*5.61E+12 = 3.62E+15 sej/ha/year*

	Outputs			
34	**Seaweed glycolic extract**			
	Extract biomass	4.14E+07	g/year	
	Annual flow	5.51E+06	g/ha/year	
	Self-consumption	0.00E+00	%	
	UEV	9.23E+10	sej/g	Present study
	Emergy	5.09E+17		

*Seaweed glycolic extract= (4.14E+07 / (7.51productive area))*9.23E+10 = 5.09E+17 sej/ha/year*

	Ecosystem Services			
	Legal reserve area: native			
35	**vegetation**			
	Quantity	1.30E-02	ha	
	Estimated value	1.74E+04	$/ha/year	
	Annual flow	3.00E+01	$/ha/year	
	UEV	1.69E+16	sej/$	Present study
	Emergy	5.09E+17	sej/ha/year	

*Native vegetation = (1.30E-02 / (7.51productive area))*1.69E+16 = 5.09E+17 sej/ha/year*

36	**Ecotourism**			
	Quantity	1.40E+02	Unit	
	Price	6.00E+00	$/unit	
	Annual flow	1.12E+02	$/ha/year	
	UEV	4.55E+15	sej/$	Present study
	Emergy	5.09E+17	sej/ha/year	

*Ecotourism = (1.40E+02 / (7.51productive area))*4.55E+15 = 5.09E+17 sej/ha/year*

Table 9. The initial investments cost of the seaweed sea-based farming for the glycolic extract industry considering different scenarios. Glycolic extract base scenario (GE); Glycolic extract using less and recycled plastic (GE_{pr}); Glycolic extract with farming cycle length reduction (GE_{cr}); Glycolic extract using a plant-based solvent (GE_{sr}); Glycolic extract using less and recycled plastic farming cycle length reduction, and plant-based solvent (GE_T). (US$1.00 = R$ 5.38).

Items	GE; GE_{cr}		Ge_{pr}; GE_T	
	US$	**%**	**US$**	**%**
Longline †	12,543.68	47.70	17,700.28	55.00
Braided rope †	782.06	2.97	1,173.09	3.65
Anchor †	5,130.11	19.51	5,130.11	15.94
Buoy †	780.67	2.97	780.67	2.43
Waterbox ‡	85.50	0.33	85.50	0.27
Commercial Scale †	52.04	0.20	52.04	0.16
Knife ‡	687.73	2.62	687.73	2.14
Ambar gallon ‡	483.27	1.84	483.27	1.50
Cereal Mill §	33.46	0.13	33.46	0.10
Funnel ‡	6.51	0.02	6.51	0.02
Boat ‡	594.80	2.26	594.80	1.85
Motor ‡	446.10	1.70	446.10	1.39
Life Jacket ‡	7.43	0.03	7.43	0.02
Shed §	487.92	1.86	487.92	1.52
Handling table †	331.78	1.26	331.78	1.03
Drying table ‡	1,869.89	7.11	487.73	1.52
Vehicle ‡	487.73	1.85	1,869.89	5.81
Project cost	1,488.64	5.66	1,821.50	5.66
Total	**26,299**	**100.00**	**32,180**	**100.00**
Total (US$/ha)	**3,502**		**4,285**	

† Useful life estimated at 5 years; ‡ Useful life estimated at 10 years;
*** Useful life estimated at 15 years.

Table 10. Annual costs (US$) and the percentage (%) of operating costs for sale to seaweed sea-based farming for the glycolic extract industry considering different scenarios. Glycolic extract base scenario (GE); Glycolic extract using less and recycled plastic (GE_{pr}); Glycolic extract with farming cycle length reduction (GE_{cr}); Glycolic extract using a plant-based solvent (GE_{sr}); Glycolic extract using less and recycled plastic farming cycle length reduction, and plant-based solvent (GE_T). (US$1.00 = R$ 5.38).

Itens description	Unit	Price/Unit	GE			Gepr			Gecr			Gesr			GE_T		
		(US$)	Quantity	Total Cost	%	Quantity	Total Cost	%	Quantity	Total Cost	%	Quantity	Total Cost	%	Quantity	Total Cost	%
Variable cost				**436,507**			**436,358**			**535,776**			**515,550**			**632,830**	
Ribbon	kg	2.97	120	357	0.1	0	0	0.0	135	401	0.1	120	357	0.1	0	0	0.0
Cotton yarn	kg	5.95	36	214	0.0	72	428	0.1	41	241	0.0	36	214	0.0	81	482	0.1
Eventual labor	daily	13.01	736	9,576	2.1	736	9,576	2.1	828	10,773	1.9	736	9,576	1.8	828	10,773	1.6
Fuel	L	0.93	96	89	0.0	96	89	0.0	108	100	0.0	96	89	0.0	108	100	0.0
Liquid glycerin	L	3.72	40,500	150,558	32.7	40,500	150,558	32.7	49,815	185,186	33.1	40,500	225,836	41.9	49,815	277,779	42.3
Grain alcohol	L	1.71	4,500	7,695	1.7	4,500	7,695	1.7	5,535	9,465	1.7	4,500	7,695	1.4	5,535	9,465	1.4
Bottle 100mL	unit	0.28	450,000	125,465	27.3	450,000	125,465	27.3	553,500	154,322	27.6	450,000	125,465	23.3	553,500	154,322	23.5
Paper filter	unit	0.03	450,000	12,546	2.7	450,000	12,546	2.7	553,500	15,432	2.8	450,000	12,546	2.3	553,500	15,432	2.4
Rural Social Security Special Contribution[a]				12,375	2.7		12,375	2.7		15,221	2.7		12,375	2.3		15,221	2.3
Tax on the sale of the product[b]				96,846	21.0		96,846	21.0		119,121	21.3		96,846	18.0		119,121	18.1
General costs[c]				20,786	4.5		20,779	4.5		25,513	4.6		24,550	4.6		30,135	4.6
Fixed cost				**460,149**			**460,110**			**559,417**			**539,192**			**656,582**	
Vehicle property tax[d]				37	0.0		37	0.0		37	0.0		37	0.0		37	0.0
Fixed labor	annual wage	5,776.93	4	23,108	5.0	4	23,108	5.0	4	23,108	4.1	4	23,108	4.3	4	23,108	3.5
Maintenance [e]				496	0.1		607	0.1		496	0.1		496	0.1		607	0.1
Annual depreciation				4,360			5,470			4,360			4,360			5,470	
Interest on working capital [f]				31,635			31,633			38,460			37,069			45,140	
Remuneration on fixed capital [g]				1,808			2,212			1,808			1,808			2,212	
Remunerations of the entrepreneur				4,349			4,349			4,349			4,349			4,349	
Total Production Cost (TPC)				**502,302**			**503,774**			**608,394**			**586,779**			**713,753**	

[a] 2,3% of gross revenue; [b] 18% of gross revenue; [c] 5% of variable cost; [d] 4% of vehicle value;[e] 2% of investments; [f] 13.75% a.a. on haf of the effective operational cost; [g] 13.75% on haf fixed investments

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CAPÍTULO 2 – The sustainability of the seaweed *Kappaphycus alvarezii* land-based farming for different markets: An emergy and neoclassic approach

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Abstract

Seaweeds can be farmed in the sea or on land as a monoculture or as part of Integrated Multitrophic Aquaculture (IMTA). We evaluated *Kappaphycus alvarezii* monoculture land-based farming, considering emergy synthesis and neoclassical economic feasibility, taking into account three potential markets for selling the products: the carrageenan industry (C), human consumption (HC), and liquid biostimulant (LB). In the LB market, the co-product of liquid biostimulant produce is used to make bio compounds, and the biomass is bleached and dried. The Emergy Synthesis identifies the ecosystemic aspects of the system, while the neoclassical analysis focuses on economic feasibility. The combination of these analyses is crucial for generating substancial information for decision-making. In all market scenarios, the resources from the economy constituted higher inputs than those from nature, accounting for approximately 85% of the total. We simulated different scenarios by varying the main identified inputs of the system, which included plastic, fuel, and salt. Sustainability were evaluated using both biophysical and neoclassical economic approaches. The carrageenan market demonstrated low sustainability, with an Emergy Sustainability Index (ESI) of 0.22 and a Net Present Value (NPV) ranging from US$862,603 to US$929,899. The human consumption market also had a low sustainability level, with an ESI of 0.22. However, the NPV ranged from US$97,429,014 to US$97,496,310. In the LB scenario, the ESI ranged from 0.21 to 0.22, with NPVs ranging from US$98,782,897 to US$150,463,341. These results indicate the need to improve the farming system in order to increase the Emergy Sustainability Index beyond the tested scenarios. Overall, land-based systems showed a low level of sustainability from the perspective of Emergy Synthesis. However, their products may be more sustainable than similar alternatives, such as traditional fertilizers. The neoclassical approach indicates the system's economic sustainability. Seaweed land-based farming has the potential for further exploration but requires adjustments to enhance its sustainability.

Keywords: environmental accounting; bioeconomy; macroalgae; biorefinery

Formatted according to Ecological Indicators

1. Introduction

Seaweeds are one of the highest interest organisms to global aquaculture, contributing nearly 30 percent of the world aquaculture production in 2019 (FAO, 2021). Global algae production, mostly seaweeds, increased from 10.6 million tonnes in 2000 to 35.1 million in 2020 (FAO, 2022). Its values should rise to do the interest in seaweed uses and applications to the industry, their function in the IMTA systems, and the ecosystem services they can provide in a growing blue economy (FAO, 2022, 2018, 2013)

The red seaweed *Kappaphycus alvarezii* had the aquaculture originated in the Philippines and spread to other countries after research and carrageenan industry efforts (Bindu and Levine, 2011). This species represents ~5% of the world's aquaculture production algae species (FAO, 2022). The *K. alvarezii* major market is the hydrocolloid industry for carrageenan extraction (FAO, 2018, 2013). The *K. alverezzi*, also known as Elkhorn sea moss, presents different uses and applications in food, food processing, cosmetics, and other industrial usages (FAO, 2018; Pereira, 2016). Another attractive market for this seaweed is its use to produce biostimulants for the agroindustry (Ghosh et al., 2015). The *K. alvarezii* aquaculture is a success because of the competitive raw material with widespread applications, the availability of farm sites, and a suitable labor force to produce the material at a low cost (FAO, 2018).

The seaweed farming development comes together as a necessity of a sustainable blue economy. Only a few studies quantitatively evaluated seaweed farming sustainability (Collins et al., 2022; Hasselström et al., 2018; Pereira et al., 2021; Taelman et al., 2015). Besides that, only one evaluates sustainability considering all the dimensions: environmental, economic, and social. A set of diverse methods are available to evaluate sustainability in aquaculture systems, such as life cycle assessment, ecological footprint, indicators, and emergy synthesis (Valenti et al., 2018). Among these methodologies, the emergy synthesis is based on science to represent environmental, social, and economic values in the same measure to evaluate the total energy used directly and indirectly to generate a product (Odum, 1996). So, the emergy synthesis shows holistic sustainability insights with an ecosystemic perspective. The seaweed traditional farming in tropical areas is a low inputs and technology activity (Valderrama et al., 2015). However, different from seaweed sea-based farming, the seaweed land-based farming can require land occupation and other different inputs. Thus, the present study aims to

evaluate land-based *K. alvarezii* farming in different target markets through environmental accounting to identify the sustainable key factors and indicate improvements strategies.

2. Material and Methods

2.1. Study area and data collection

The Emergy Synthesis utilized data from a land-based seaweed farm operating in Piauí State, Northeastern Brazil. The farm employs a modular rafts system installed in a shrimp farm supply channel within an estuarine area, utilizing water with salinity ranging from 25 to 40. The estuarine water enters the seaweed farm and subsequently flows-out to another farm where marine shrimp are cultivated. The seaweed farm occupies a total area of 14.44 hectares, with 14.40 hectares designated as water area, 3.6 hectares filled with rafts, and 0.04 hectares used for buildings. There are a total of 128 rafts, with each raft serving as a module measuring 6 meters in width and equipped with 22 cables, each 25 meters in length (Figure 1A). Each 25-meter cable accommodates 160 seedlings. The seeds, obtained through vegetative propagation, enter the system weighing approximately 45 grams and are cultured for around 67 days, reaching an approximate weight of 1300 grams at the end of each cycle. The farm achieves a productivity rate of 3 kilograms per meter of rope per cycle, with approximately 5 cycles completed per year. Farming management involves manually brushing the seaweeds using a soft bristle brush to remove deposited particulate matter, as well as scraping the PVC tubes of the rafts to eliminate barnacles and other encrusting organisms.

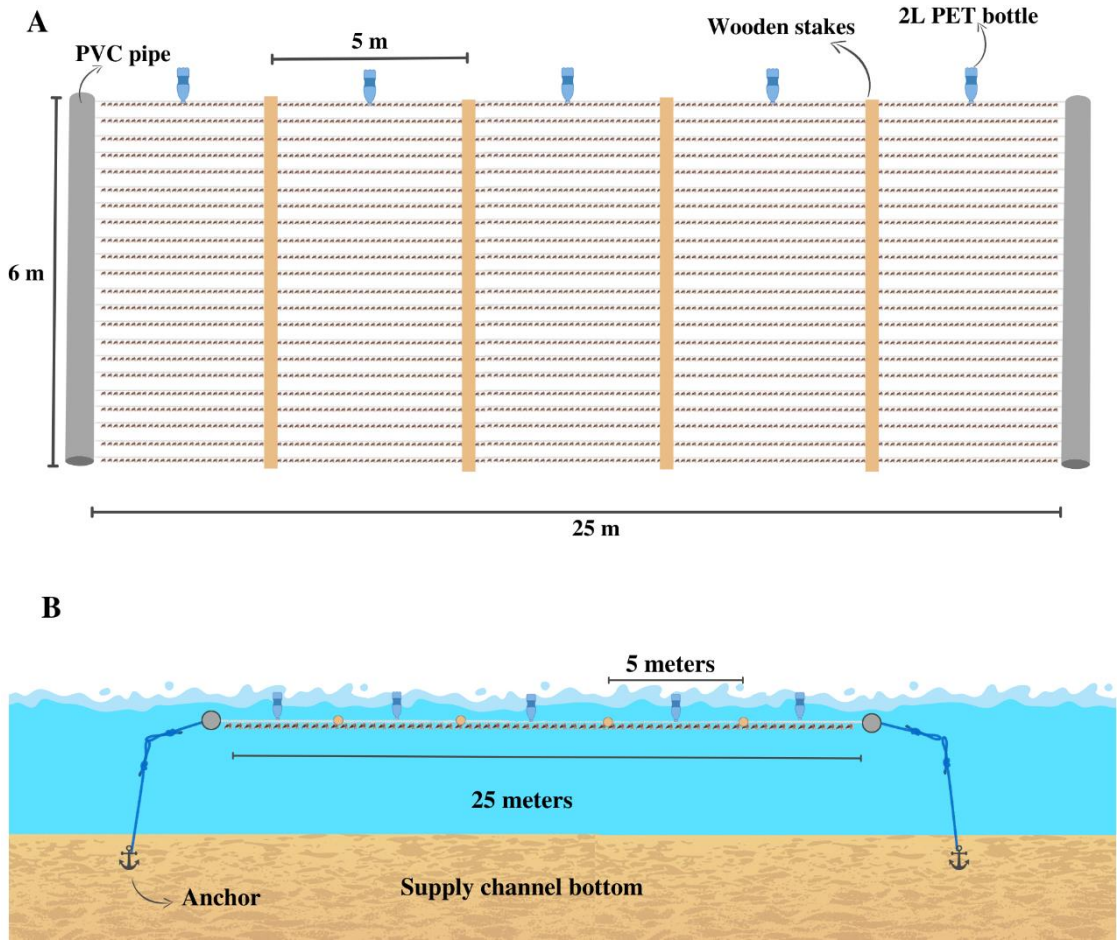

Figure 1. Land-based *Kappaphycus alvarezii* farming raft structure. A: top view of the farming structure. B: side view of the farming structure.

The installation of seaweed farming is in a pond used as a supply channel for a shrimp farm. The seaweed and shrimp farms are different enterprises. The estuarine water is pumped from the estuary to the supply channel and passes by seaweed farming before entering the shrimp ponds. The water discard occurs on the estuary after passing by shrimp farming. The land-based seaweed farming presents average water conditions of salinity 31 ± 8, pH 7.9 ± 0.3, total nitrogen 0.13 ± 0.13 mg/L, total phosphate 0.02 ± 0.02 mg/L, and 344 ± 302 mg/L of total suspended solids.

The obtaining of seaweed farming data on environmental and economic inputs were by a semi-structured form applied to the farmer. The questionnaire focused on accounting materials, types of equipment, purchased infrastructure, labor, taxes, and depreciation. All inputs were accounted for in units/hectare and corresponded to one year of the farm operation. Seaweed, seaweed biocompound and liquid biostimulant samples were collected by the

farmer and sent to the Laboratory of Sustainability in Aquaculture Research of the Center of Aquaculture of São Paulo State University for calorimetry analysis. Product samples were weighed on an analytical balance (Mettler Toledo AT21, precision 1 µg), oven dried at 95–100 ◦C, weighted again (AOAC, 1995, method 934.01), and combusted in an isoperibol calorimeter (IKA C2000 basic).

2.2. Market scenarios

We simulated three different market scenarios for land-based *K. alvarezii* farming. The first one is selling bleached and dry seaweed for the carrageenan industry (C), the second one is dehydrated seaweed for human consumption (HC), and the third one is non-industrial production of liquid biostimulant on-site for sale to the agroindustry (LB) (Figure 2). In this study, the system boundaries were considered as the seaweed farm limits, which includes the water surface occupied by rafts, and farm installations seaweed processing to products. The monetary values were acquired in the Brazilian market in the third quarter of 2022 and converted to US$ dollars (US$1.00 = R$5.38). All input values correspond to one year of farm operations on a one-hectare farm basis.

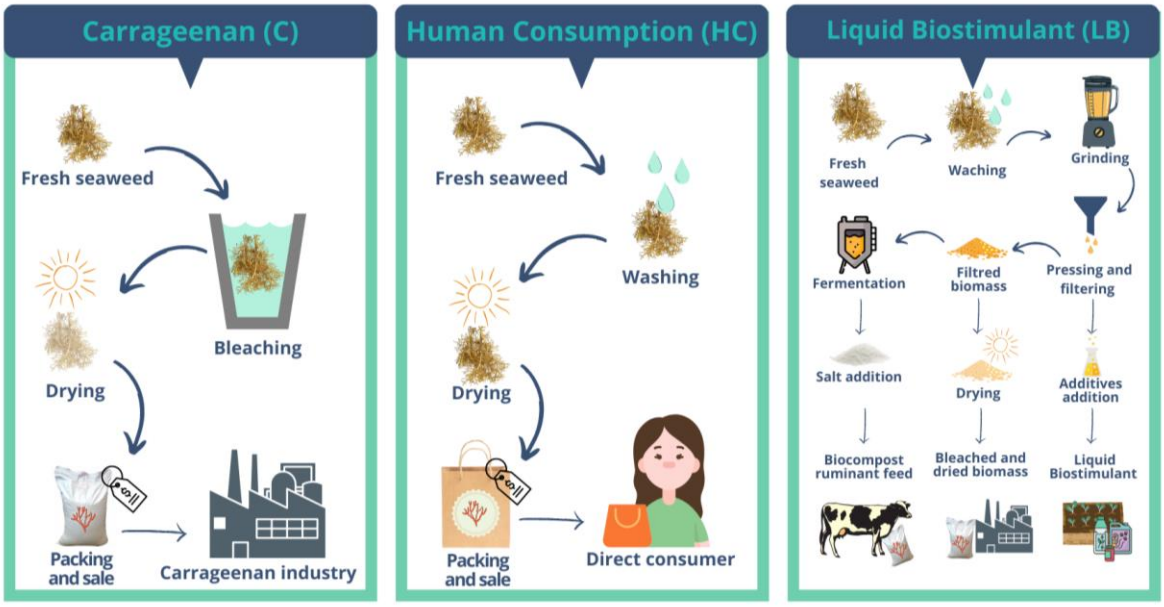

Figure 2. Seaweed processing for three different markets: carrageenan (C), human consumption (HC), and liquid biostimulant (LB).

2.2.1.Carrageenan industry (C)

The carrageenan industry scenario corresponds to the sale of bleached and dry seaweed biomass directly to the industry. The harvested seaweed is bleached by washing and soaking the biomass into freshwater to remove impurities and seaweed pigments. Afterwards, the biomass is sun dried until reaching 18% humidity. The commercialization occurs in raffia bags of 25 kg. The different strategy scenarios are described below:

2.2.1.1. Carrageenan industry using less and recycled plastic (C_{pr})

This scenario focuses on reducing the use of plastic materials to enhance Renewability. We have replaced the plastic ribbon, which was used to attach the seedlings to the longlines, with cotton yarn. Additionally, we have explored the possibility of using longline ropes made of 0 to 80% recycled material. However, it is important to note that this recycled material comes at a price that is 1.5 times higher than traditional plastic.

2.2.1.2. Carrageenan industry using biofuel (C_{fc})

In this scenario, there is a fuel change from gasoline to sugarcane alcohol. As a result of this change, the fuel consumption increases by 30%. Furthermore, the new input, sugarcane alcohol, has a Renewability rate of 31%.

2.2.1.3. Carrageenan industry using less and recycled plastic and biofuel (C_T)

This scenario combines all the previously tested scenarios to analyze whether the combinations of strategies can optimize and enhance sustainability. By merging the various strategies, the aim is to assess their collective impact on improving sustainability.

2.2.2. Human Consumption (HC)

The dehydrated seaweed biomass is sold directly to tourists, visitors, restaurants, and general final consumers. The harvested seaweed biomass is washed in freshwater to remove impurities. After this, the seaweed is sun dried until 18% humidity. The commercialization occurs in paper bags of 100 g or 1 kg. The different strategy scenarios are described below:

2.2.2.1. Human Consumption using less and recycled plastic (HC_{pr})

This scenario focuses on reducing the use of plastic materials to enhance Renewability. We have replaced the plastic ribbon, which was used to attach the seedlings to the longlines,

with cotton yarn. Additionally, we have explored the possibility of using longline ropes made of 0 to 80% recycled material. However, it is important to note that this recycled material comes at a price that is 1.5 times higher than traditional plastic.

2.2.2.2. Human Consumption using biofuel (HC_{fc})

In this scenario, there is a fuel change from gasoline to sugarcane alcohol. As a result of this change, the fuel consumption increases by 30%. Furthermore, the new input, sugarcane alcohol, has a Renewability rate of 31%.

2.2.2.3. Human Consumption using less and recycled plastic and biofuel (HC_T)

This scenario combines all the previously tested scenarios to analyze whether the combinations of strategies can optimize and enhance sustainability. By merging the various strategies, the aim is to assess their collective impact on improving sustainability.

2.2.3. Liquid biostimulant (LB)

The harvested seaweed biomass is washed with freshwater to eliminate other organisms and impurities. To produce the liquid biostimulant, the washed seaweed undergoes grinding, pressing, and filtering processes to separate the biomass from the liquid. The liquid biostimulant is then marketed for use in the fertilizer industry or directly by consumers as a ferlilizer complementation for crop cultivation. Following this process, there is a remaining 200g of seaweed by-product for every kilogram of ground seaweed. This co-product yields two additional products: a nutritional biocompound and biomass for carrageenan production.

The initial portion of the seaweed by-product undergoes a pre-drying process, during which fermentation releases the nutrients contained in the seaweed. Fermentation typically takes around 3 to 4 days. After this stage, the seaweed biocompound is combined with mineral salt, resulting a product with 65% moisture content. The enriched salt is sell as a biocompound for ruminant nutrition. The second portion of the seaweed by-product is washed and soaked in fresh water to remove pigments present in the seaweed. Subsequently, the biomass is dried in the sun until it reaches a humidity level of 18% for sale to the carrageenan industry. The different strategic scenarios are described below:

2.2.3.1. Liquid Biostimulant using less and recycled plastic (LB_{pr})

This scenario focuses on reducing the use of plastic materials to enhance Renewability. We have replaced the plastic ribbon, which was used to attach the seedlings to the longlines, with cotton yarn. Additionally, we have explored the possibility of using longline ropes made of 0 to 80% recycled material. However, it is important to note that this recycled material comes at a price that is 1.5 times higher than traditional plastic.

2.2.3.2. Liquid Biostimulant using biofuel (LB_{fc})

In this scenario, there is a fuel change from gasoline to sugarcane alcohol. As a result of this change, the fuel consumption increases by 30%. Furthermore, the new input, sugarcane alcohol, has a Renewability rate of 31%.

2.2.3.3. Liquid Biostimulant with no salt (LB_{sr})

In this scenario, the focus is on the removal of salt from the seaweeds biocompound. The resulting product is a fermented compound used in animal food supplementation. The productivity of this product is 6.5% compared to the biocompound derived from the liquid biostimulant base scenario. Additionally, the sale prices of this product are set at 72% of the original price.

2.2.3.4. Liquid Biostimulant using less and recycled plastic, biofuel, and no salt (LB_T)

This scenario combines all the previously tested scenarios to analyze whether the combinations of strategies can optimize and enhance sustainability. By merging the various strategies, the aim is to assess their collective impact on improving sustainability.

Table 2. Farming strategy scenarios description for the different markets: reducing and increasing plastic renewability (pr); fuel change (fc); salt removal (sr) and all scenarios combination (T). * The salt removal only applies to the liquid biostimulant market.

Scenario	Abbreviation	Description
Reducing and increasing plastic renewability	pr	Plastic ribbon replacement for cotton yarn and cables made from 80% renewable and recycled material.
Fuel change	fc	Consider sugarcane alcohol as fuel. It increases fuel consumption by 30% and is an item with 31% Rewability.
*Salt removal	sr	Consider not using mineral salt in the ruminant compound.
All scenarios combination	T	Combination of all strategic scenarios.

2.3. Emergy Synthesis

The Emergy Synthesis considered all the energy, directly and indirectly, used to generate a product or a service (Odum, 1996). Emergy Synthesis is a biophysical approach to establishing a value for natural resources that considers a holistic view, recognizing all nature efforts to make available a resource. The Emergy Synthesis procedure covers the following three main steps: (1) build an energy diagram to define the system boundaries and organize all inputs and outputs components and their relationships (Figure 3); (2) create the emergy tables with the quantitative flows and choose suitable Unit Emergy Values (UEVs); (3) calculate the emergy indicators.

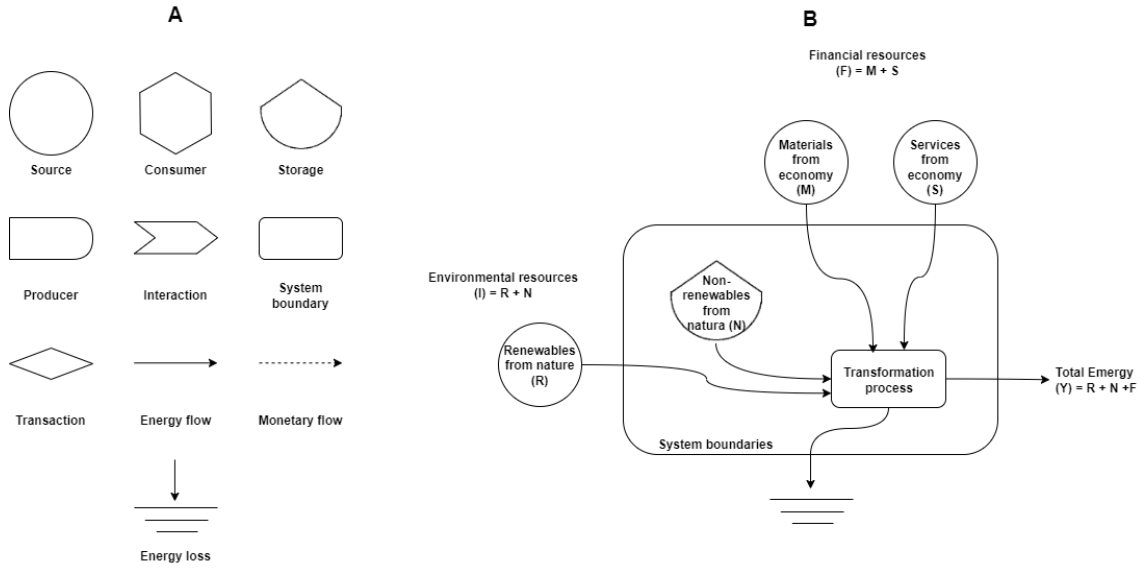

Figure 3. (A) Most commonly symbols used in energy systems diagrams (Odum, 1996). (B) Generic energy diagram with symbols and acronyms used in emergy synthesis to calculate the emergy indicators. R = renewable resources from nature; N = non-renewable resources from nature. Modified from Fonseca et al. (2022).

In the first step of the assessment, it is necessary to draw a diagram. The energy flow diagram uses a systemic perspective to identify all energy input sources of the system, the internal processes that occur, and all the systems outputs. This diagram allows a holistic view of the system and how it works (Odum, 1996). In the second step of the analysis, an energy inputs inventory is created with a table where the items are classified and organized as the source type as natural renewable resources (R), natural local non-renewable resources (N), or purchase resources from the economy (F). Input resources were accounted for in mass (g), energy (J), or money (US$) units. All resources need to be in the same unit to calculate the emergy synthesis, which is the solar emjoules (sej). So, we multiplied the quantified input resource flows by their respective UEVs. The UEVs were obtained in scientific literature and at the Emergy Evaluation Folios published by the Center of Environmental Policy from the University of Florida. The present work used the global baseline of 1.20E+25 sej/yr (Brown and Ulgiati, 2016). In this inventory table, the input quantity is multiplied by their respective UEVs, resulting in energy flows in solar emjoules (sej) and quantifying the system's outputs. All system outputs are considered as co-products, and are composed by all emergy demanded by the system for calculating their UEVs. The exception of this is seaweed seedlings, which accounted for only a proportion of inputs applied in seaweed farming, excluding the processing phase, as it enters in the system instead of being processed and sold. The third step consists of emergy indicator calculation and interpretation (Table 2).

Table 2. Emergy indicators used in the present study.

Indicators	Abbreviation	Formula	Description
Unit Emergy Value	UEV	UEV = Y/E	Ratio of the total emergy demanded by value UEV = Y / E the unity output. Example of units are sej/J, sej/kg and sej/$.
Renewability[a]	R%	m-R%=100 (R+Mr+Sr)/Y	Ratio of the nature and economy's renewable fraction by the total emergy demanded to produce dried seaweeds or seaweeds glycolic extract.
Environmental Loading Ratio [a]	ELR	m-ELR=(N+Mn+Sn)/(R+Mr+Sr)	Ratio of the total non-renewable loading ratio of resources by the total renewable resources.
Emergy Yield Ratio	EYR	EYR = Y/F	Ratio of the total emergy demanded to produce dried seaweeds or seaweeds glycolic extract by the resources from economy.
Emergy Investment Ratio	EIR	EIR = F/(R+N)	Ratio of the resources from economy by the nature renewable and non-renewable resources.
Emergy Exchange Ratio	EER	EER = Y/[($) x (sej/$)]	Ratio between the emergy contained in the product and the emergy contained in the money received by its sale. These indices express the exchange ratio of one or more exchange partnerships and is a measure of the relative advantage that is established between the exchange partners.
Emergy Sustainability Index	ESI	ESI = EYR/m-ELR	Ratio between the emergy yield ratio by the environmental loading ratio.

Indicators developed by Odum (1996); [a] Modified according to Agostinho et al. (2018). Y = total emergy; E = product/service total quantity; R = renewable from nature; N = non-renewable from nature; F = resources from economy; M = materials; S = services; r = renewable fraction; n = non-renewable fraction; m = modified considering partial renewability.

The Unit Emergy Value (UEV) measures the environmental cost of the product or service; it indicates the system efficiency when compared to others of the same hierarchical level. The Renewability (R%) indicates the renewability fraction of the total emergy demanded

delivering the product or service. This study considered the partial Renewability of each input for emergy indicator calculations according to Agostinho et al. (2008). The partial Renewability application is appropriate when the materials and services used are from the local economy. The resource's Renewability values were considered when available in the literature, as suggested by Agostinho et al. (2019). The Environmental Loading Ratio (ELR) indicates the pressure of a production system over the natural ecosystems. ELR values lower than 2 indicate low pressure, from 2 to 10 indicate moderate pressure, and higher than 10 indicate high pressure (Brown and Ulgiati, 2004). The Emergy Yield Ratio (EYR) indicates the system's net contribution to the economy beyond its operation. EYR values lower than 2 show a high dependence on purchased resources and a low contribution to the larger economy (Brown and Ulgiati, 2004). The Emergy Investment Ratio (EIR) evaluates the process efficiency in emergy invested use compared with alternatives. If the EIR is higher than other similar systems, it does not compete economically (Brown and Ulgiati, 2004). The Emergy Exchange Ratio (EER) indicates the relation between the product emergy and the money emergy by its sale. The EER equal to or lower than one shows a payment of the emergy spent on the offered product or service (Brown and Ulgiati, 2004). The Emergy Sustainability Index (ESI) indicates the system's contribution to the economy by the environmental pressure. The ESI values lower than 1 indicate non-sustainability, values ranging from 1 to 5 indicate short-term sustainability, and values higher than 5 indicate long-term sustainability (Brown and Ulgiati, 2004).

2.4. Bioeconomic analysis

All costs and prices were obtained in the Brazilian market in the fourth quarter of 2022 and converted to US$ dollars (US$1.00 = R$5.38). We used the sale prices published by Pereira et al. (2020) for carrageenan and direct human consumption updating the value according to inflation. The sale prices of liquid biostimulant and biocompound were given by farmer.

Fixed Costs (FC) included employee salaries, vehicle property tax, environmental taxes, licensing, maintenance of equipment and facilities, depreciation, and opportunity costs. The depreciation was calculated by the straight-line method (Engle, 2010). Opportunity costs were the interests of the fixed capital and remuneration of the entrepreneur. Variable Costs (VC) consisted of expenses with plastic raffia ribbon, cotton yarn, fuel, plastic raffia bag, manual

labor, and taxes. Cost and revenue data were used to determine Gross Revenue (GR), Net Revenue (NR), and Profit (P) as described below:

$$GR = Production\ x\ Selling\ price \quad (1)$$

$$NR = Gross\ revenue - Total\ costs \quad (2)$$

$$P = Net\ revenue - Opportunity\ costs \quad (3)$$

The cash flow analysis considered 20 years of operation. Year zero included the initial investments and working capital. Production was assumed to be 40 and 20% lower than the predicted values for the first and second years, respectively, to compensate for potential difficulties at the beginning of the venture such as technological adjustments, personnel training, and insertion of the product into markets.

Internal rate of return (IRR), net present value (NPV), benefit-cost ratio (BCR), and discounted payback period (DPP) were used to determine the financial feasibility. The four indicators were determined based on annual inputs and outputs according to calculations described in Engle (2010), Jolly and Clonts (1993) and Shang (1990):

$$\sum_{t=1}^{n} \frac{NCF_t}{(1+IRR)^t - NCF_n} = 0 \quad (4)$$

$$NPV = \sum_{t=1}^{n} \frac{NCF_t}{(1+i)^t - NCF_n} \quad (5)$$

$$BCR = \sum_{t=1}^{n} (NCF_t/(1+i)^t)/NCF_0 \quad (6)$$

DPP is the time t discounted at a given Minimum Attractive Rate of Return (MARR), where:

$$\sum_{t=0}^{n} NCF^{MARR} = 0 \quad (7)$$

NCF is the net cash flow; i is the discount rate; n is the number of years in operation (0, 1, 2, 3…n) and t is the year. The minimum attractive rate of return (MARR) and the discount rate were 13.75% per year, which was the interest on initial capital in Brazil in the first quarter of 2023.

Results

We show the systematic view of the Emergy Synthesis of *K.alvarezii* land-based farming commercialized for three distinct markets. All scenarios present the same energy diagram flow to the farm (Figure 4) with different energy diagram flows of processing the seaweed biomass to the final product (Figure 5).

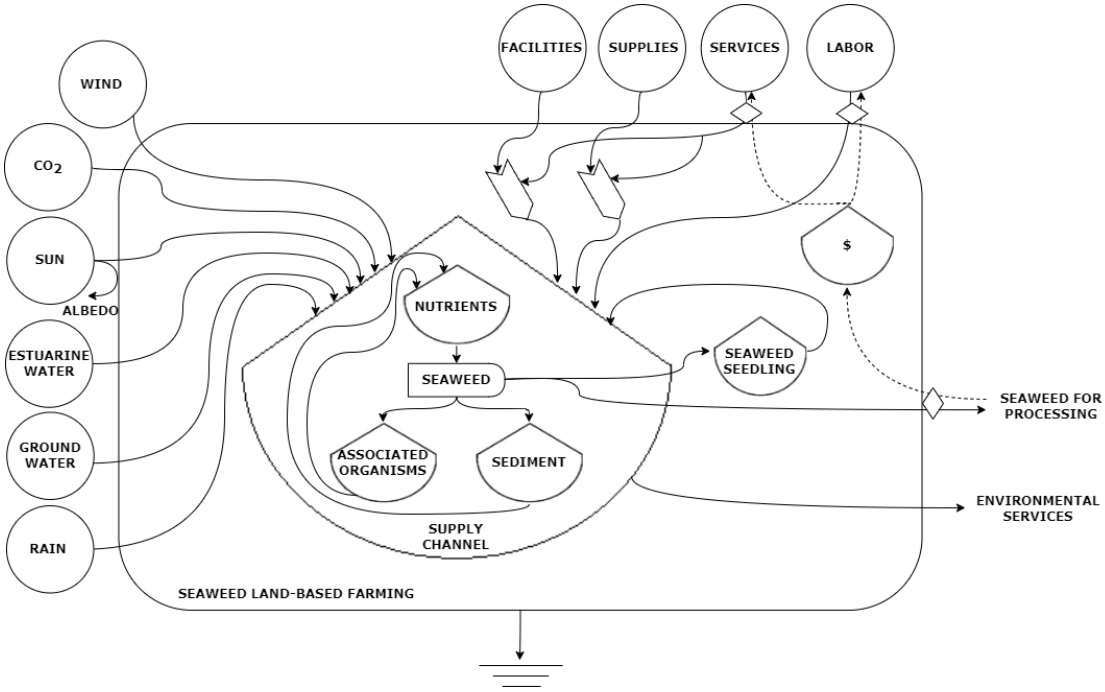

Figure 4. Energy diagram of the seaweed *K. alvarezii* land-based farming.

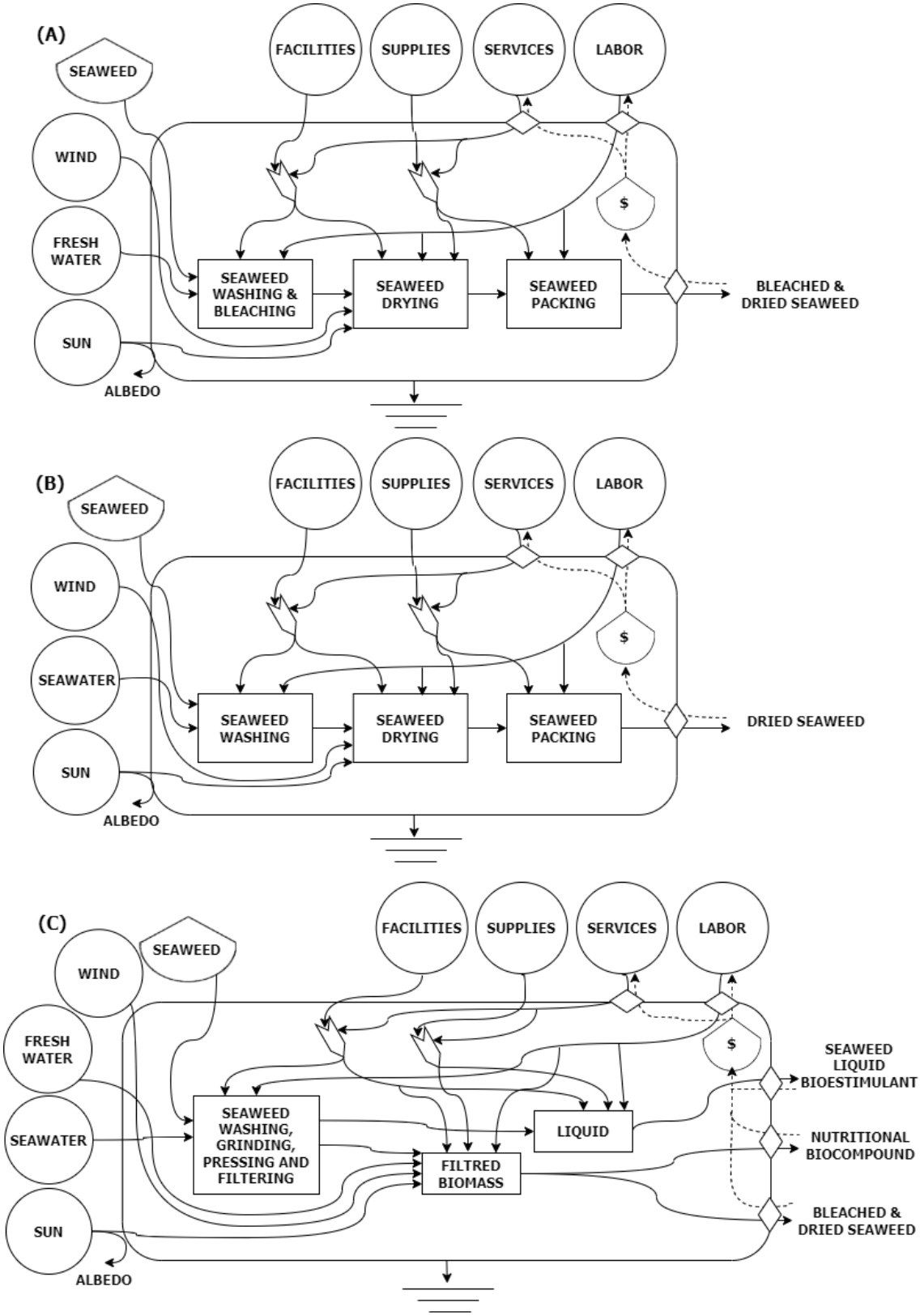

Figure 5. Seaweed biomass processing to the final product: A) carrageenan; B) human consumption; C) liquid biostimulant.

Table 2. Emergy table of sea-based *Kappaphycus alvarezii* farming for carrageenan market base scenario (C).

Note	Item	Unit	Amount (unit/ha/year)	UEV (sej/unit)	UEV Reference	Emergy E12 sej/ha/year	Emergy (%)
	Renewable nature resources (R)						
1	Sun	J	7.31E+13	1.00E+00	Odum (2000)	7.31E+01	0.01
2	Wind	J	4.56E+08	1.28E+03	Giannetti et al. (2019)	5.84E-01	0.00
3	Rain	J	6.50E+10	9.71E+03	Giannetti et al. (2019)	6.31E+02	0.04
4	Fresh water	J	2.75E+08	6.55E+04	Giannetti et al. (2019)	1.80E+01	0.00
5	Nitrogen	g	7.97E+05	1.14E+09	Odum andArding (1991)	9.11E+02	0.06
6	Phosphate	g	4.34E+04	1.03E+10	Odum and Arding (1991)	4.47E+02	0.03
	Non-renewable nature resources (N)						
7	Estuarine water	J	7.18E+09	4.05E+04	Giannetti et al. (2019)	2.91E+02	0.02
8	Ground water	J	4.02E+09	7.67E+04	Giannetti et al. (2019)	3.09E+02	0.02
9	Soil occupation	J	1.23E+03	9.38E+04	Odum (1996)	1.15E-04	0.00
	Resources from the larger economy (F)						
	Renewable materials (Mr)						
10	Electricity	J	4.04E+08	2.06E+05	Giannetti et al. (2019)	8.31E+01	0.01
11	Cotton	g	1.11E+04	1.45E+09	Blatt and Almeida (2017)	1.61E+01	0.00
	Non-renewable materials (Mn)						
12	Electricity	J	1.90E+08	2.06E+05	Giannetti et al. (2019)	3.91E+01	0.00
13	Plastic	J	7.00E+09	1.92E+05	Giannetti et al. (2019)	1.34E+03	0.10
14	Limestone	g	4.92E+08	1.23E+06	Odum et al., (2000)	6.04E+02	0.04
15	Gasoline	J	3.36E+10	4.16E+04	Giannetti et al. (2019)	1.40E+03	0.10
16	Rubber	g	6.59E+02	5.47E+09	Buranakan (1998)	3.60E+00	0.00
17	Cotton	g	2.19E+04	1.45E+09	Blatt and Almeida (2017)	3.17E+01	0.00
	Renewable infrastruture (Ifr)						
18	Steel	g	1.67E+02	2.29E+09	Brown and Bardi (2001)	3.82E-01	0.00
19	Cement	g	4.42E+03	2.52E+09	Buranakan (1998)	1.11E+01	0.00
	Non-renewable infrastruture (Ifn)						
20	Plastic	J	3.83E+09	1.92E+05	Giannetti et al. (2019)	7.36E+02	0.05
21	Iron	g	9.20E+04	4.15E+09	Oliveira et al. (2018)	3.82E+02	0.03
22	Steel	g	3.71E+03	2.29E+09	Brown and Bardi (2001)	8.48E+00	0.00

23	Wood	J	7.27E+08	2.85E+05	Buranakan (1998)	2.07E+02	0.01
24	Concret	g	1.02E+06	1.83E+09	Buranakan (1998)	1.87E+03	0.13
25	Cement	g	3.99E+04	2.52E+09	Buranakan (1998)	1.00E+02	0.01
26	Glass-fiber	g	4.93E+03	2.27E+09	Ulgiati and Brown (2002)	1.12E+01	0.00
27	Rubber	g	3.34E+03	5.47E+09	Buranakan (1998)	1.82E+01	0.00
28	Aluminum	g	4.28E+04	1.49E+10	Buranakan (1998)	6.37E+02	0.05
	Renewable services (Sr)						
29	Human labor	J	2.49E+09	8.72E+06	Bonilla et al. (2010)	2.17E+04	1.54
30	Services	$	3.48E+04	5.61E+12	Giannetti et al. (2018)	1.95E+05	13.84
	Non-renewable services (Sn)						
31	Human labor	J	8.84E+09	8.72E+06	Bonilla et al. (2010)	7.71E+04	5.46
32	Services	$	1.97E+05	5.61E+12	Giannetti et al. (2018)	1.11E+06	78.44
	Total Emergy					**1.41E+06**	**100.00**
	Total renewable resources from nature (R)					2.19E+05	15.54
	Total non-renewable resources from nature (N)					5.99E+02	0.04
	Total resources from large economy (F)					1.19E+06	84.42
	Outputs						
	Products						
33	Bleached and dry seaweed	g	1.45E+08	9.75E+09	present study		

Table 3. Emergy table of land-based *Kappaphycus alvarezii* farming for human consumption market base scenario.

Note	Item	Unit	Amount (unit/ha/year)	UEV (sej/unit)	UEV Reference	Emergy E12 sej/ha/year	Emergy (%)
	Renewable nature resources (R)						
1	Sun	J	7.31E+13	1.00E+00	Odum (2000)	7.31E+01	0.00
2	Wind	J	4.56E+08	1.28E+03	Giannetti et al. (2019)	5.84E-01	0.00
3	Rain	J	6.50E+10	9.71E+03	Giannetti et al. (2019)	6.31E+02	0.03
4	Nitrogen	g	7.97E+05	1.14E+09	Odum and Arding (1991)	9.11E+02	0.05
5	Phosphate	g	4.34E+04	1.03E+10	Odum and Arding (1991)	4.47E+02	0.02
	Non-renewable nature resources (N)						
6	Estuarine water	J	7.18E+09	4.05E+04	Giannetti et al. (2019)	2.91E+02	0.02
7	Ground water	J	4.02E+09	7.67E+04	Giannetti et al. (2019)	3.09E+02	0.02
8	Soil occupation	J	1.23E+03	9.38E+04	Odum (1996)	1.15E-04	0.00
	Resources from the larger economy (F)						
	Renewable materials (Mr)						
9	Electricity	J	2.06E+05	2.06E+05	Giannetti et al. (2019)	4.24E-02	0.00
10	Paper	g	7.35E+04	2.95E+09	Corcelli et al. (2018)	2.17E+02	0.01
11	Cotton	g	1.11E+04	1.45E+09	Blatt and Almeida (2017)	1.61E+01	0.00
	Non-renewable materials (Mn)					0.00E+00	
12	Electricity	J	1.90E+08	2.06E+05	Giannetti et al. (2019)	3.91E+01	0.00
13	Plastic	J	6.91E+09	1.92E+05	Giannetti et al. (2019)	1.33E+03	0.07
14	Limestone	g	4.92E+08	1.23E+06	Odum et al., (2000)	6.04E+02	0.03
15	Gasoline	J	3.36E+10	4.16E+04	Giannetti et al. (2019)	1.40E+03	0.08
16	Paper	g	1.37E+05	2.95E+09	Corcelli et al. (2018)	4.03E+02	0.02
17	Rubber	g	6.59E+02	5.47E+09	Buranakan (1998)	3.60E+00	0.00
18	Cotton	g	2.19E+04	1.45E+09	Blatt and Almeida (2017)	3.17E+01	0.00
	Renewable infrastruture (Ifr)					0.00E+00	
19	Steel	g	1.67E+02	2.29E+09	Brown and Bardi (2001)	3.82E-01	0.00
20	Cement	g	4.42E+03	2.52E+09	Buranakan (1998)	1.11E+01	0.00
	Non-renewable infrastruture (Ifn)						
21	Plastic	J	3.83E+09	1.92E+05	Giannetti et al. (2019)	7.36E+02	0.04
22	Iron	g	9.20E+04	4.15E+09	Oliveira et al. (2018)	3.82E+02	0.02

23	Steel	g	3.71E+03	2.29E+09	Brown and Bardi (2001)	8.48E+00	0.00
24	Wood	J	7.27E+08	2.85E+05	Buranakan (1998)	2.07E+02	0.01
25	Concret	g	1.02E+06	1.83E+09	Buranakan (1998)	1.87E+03	0.10
26	Cement	g	3.99E+04	2.52E+09	Buranakan (1998)	1.00E+02	0.01
27	Glass-fiber	g	4.93E+03	2.27E+09	Ulgiati and Brown (2002)	1.12E+01	0.00
28	Rubber	g	3.34E+03	5.47E+09	Buranakan (1998)	1.82E+01	0.00
29	Aluminum	g	4.28E+04	1.49E+10	Buranakan (1998)	6.37E+02	0.04
	Renewable services (Sr)						
30	Human labor	J	2.49E+09	8.72E+06	Bonilla et al. (2010)	2.17E+04	1.20
31	Services	$	4.56E+04	5.61E+12	Giannetti et al. (2018)	2.56E+05	14.09
	Non-renewable services (Sn)						
32	Human labor	J	8.84E+09	8.72E+06	Bonilla et al. (2010)	7.71E+04	4.25
33	Services	$	2.59E+05	5.61E+12	Giannetti et al. (2018)	1.45E+06	79.87
	Total Emergy					**1.82E+06**	**100.00**
	Total renewable resources from nature (R)					2.80E+05	15.42
	Total non-renewable resources from nature (N)					5.99E+02	0.03
	Total resources from large economy (F)					1.54E+06	84.54
	Outputs						
	Products						
34	Dehydrated seaweed	g	1.45E+08	1.25E+10	present study		

Table 5. Emergy table of land-based *Kappaphycus alvarezii* farming for liquid biostimulant market base scenario.

Note	Item	Unit	Amount (unit/ha/year)	UEV (sej/unit)	UEV Reference	Emergy E12 sej/ha/year	Emergy (%)
	Renewable nature resources (R)						
1	Sun	J	7.31E+13	1.00E+00	Odum (2000)	7.31E+01	0.00
2	Wind	J	4.56E+08	1.28E+03	Giannetti et al. (2019)	5.84E-01	0.00
3	Rain	J	6.50E+10	9.71E+03	Giannetti et al. (2019)	6.31E+02	0.00
4	Fresh water	J	2.75E+08	6.55E+04	Giannetti et al. (2019)	1.80E+01	0.00
5	Nitrogen	g	7.97E+05	1.14E+09	Odum and Arding (1991)	9.11E+02	0.00
6	Phosphate	g	4.34E+04	1.03E+10	Odum and Arding (1991)	4.47E+02	0.00
	Non-renewable nature resources (N)						
7	Estuarine water	J	7.18E+09	4.05E+04	Giannetti et al. (2019)	2.91E+02	0.00
8	Ground water	J	4.02E+09	7.67E+04	Giannetti et al. (2019)	3.09E+02	0.00
9	Soil occupation	J	1.23E+03	9.38E+04	Odum (1996)	1.15E-04	0.00
	Resources from the larger economy (F)						
	Renewable materials (Mr)						
10	Electricity	J	4.04E+08	2.06E+05	Giannetti et al. (2019)	8.31E+01	0.00
11	Salt	g	5.09E+08	7.94E+08	Laganis and Debeljak (2006)	4.04E+05	0.75
12	Cotton	g	1.11E+04	1.45E+09	Blatt and Almeida (2017)	1.61E+01	0.00
	Non-renewable materials (Mn)						
13	Electricity	J	1.90E+08	2.06E+05	Giannetti et al. (2019)	3.91E+01	0.00
14	Plastic	J	9.56E+10	1.92E+05	Giannetti et al. (2019)	1.84E+04	0.03
15	Limestone	g	4.92E+08	1.23E+06	Odum et al., (2000)	6.04E+02	0.00
16	Fuel (gasoline)	J	3.36E+10	4.16E+04	Giannetti et al. (2019)	1.40E+03	0.00
17	Salt	g	7.29E+08	7.94E+08	Laganis and Debeljak (2006)	5.79E+05	1.07
18	Rubber	g	6.59E+02	5.47E+09	Buranakan (1998)	3.60E+00	0.00
19	Cotton	g	2.19E+04	1.45E+09	Blatt and Almeida (2017)	3.17E+01	0.00
	Renewable infrastruture (Ifr)						
20	Steel	g	2.33E+04	2.29E+09	Brown and Bardi (2001)	5.33E+01	0.00
21	Cement	g	4.42E+03	2.52E+09	Buranakan (1998)	1.11E+01	0.00
	Non-renewable infrastruture (Ifn)						

22	Plastic	J	2.07E+10	1.92E+05	Giannetti et al. (2019)	3.98E+03	0.01
23	Iron	g	9.20E+04	4.15E+09	Oliveira et al. (2018)	3.82E+02	0.00
24	Steel	g	5.17E+05	2.29E+09	Brown and Bardi (2001)	1.18E+03	0.00
25	Wood	J	7.27E+08	2.85E+05	Buranakan (1998)	2.07E+02	0.00
26	Concret	g	1.02E+06	1.83E+09	Buranakan (1998)	1.87E+03	0.00
27	Cement	g	3.99E+04	2.52E+09	Buranakan (1998)	1.00E+02	0.00
28	Glass-fiber	g	4.93E+03	2.27E+09	Ulgiati and Brown (2002)	1.12E+01	0.00
29	Rubber	g	3.34E+03	5.47E+09	Buranakan (1998)	1.82E+01	0.00
30	Aluminum	g	4.28E+04	1.49E+10	Buranakan (1998)	6.37E+02	0.00
	Renewable services (Sr)						
31	Human labor	J	2.60E+09	8.72E+06	Bonilla et al. (2010)	2.26E+04	0.04
32	Services	$	1.42E+06	5.61E+12	Giannetti et al. (2018)	7.94E+06	14.69
	Non-renewable services (Sn)						
33	Human labor	J	9.21E+09	8.72E+06	Bonilla et al. (2010)	8.03E+04	0.15
34	Services	$	8.02E+06	5.61E+12	Giannetti et al. (2018)	4.50E+07	83.24
	Total Emergy					**5.40E+07**	**100.00**
	Total renewable resources from nature (R)					8.37E+06	15.48
	Total non-renewable resources from nature (N)					5.99E+02	0.00
	Total resources from large economy (F)					4.57E+07	84.52
	Outputs						
	Products						
35	Liquid biostimulant	J	6.04E+12	8.94E+06	present study		
36	Biocompound	J	7.78E+14	6.94E+04	present study		
37	Bleached and dry seaweed	J	1.71E+11	3.15E+08	present study		

Renewable resources from nature (R) accounted for ~15% of all market strategies. Non-renewable resources from nature (N) were less than 0.04% for all three analyzed scenarios. Resources from economy (F) accounted for the highest participation of the inputs in energy flow to all market scenarios being ~85%. For all market scenarios, services were the highest emergy input representing more than 90% of resources used. For carrageenan, as the most representative inputs, we have in sequence: labor at 7%, plastic at 0.2%, concrete at 0.1%, and gasoline at 0.1%. For human direct consumption, as the most representative inputs, we have: labor at 5%, plastic at 0.1%, concrete at 0.1%, and gasoline at 0.1%. For the liquid biostimulant, the salt used to produce the secondary product for ruminants was the second most representative item with 2%.

The seaweed farming for the carrageenan industry has total emergy of 1.41E+18 sej/ha/year, in which 2.19E+17 sej/ha/year correspond to emergy of renewable from nature, 5.99E+14 sej/ha/year to non-renewable from nature, and 1.19E+18 sej/ha/year to economy resources. The Unit Emergy Value (UEV) ranged between 7.84 E+05 and 8.67E+05 sej/J for the bleached and dry seaweed (Table 6). Emergy indexes of seaweed farming to the carrageenan industry are present in Table 7. This scenario product displays a Renewability (R%) ranging from 15.5 to 15.6% and an Environmental Loading Ratio (ELR) ranging from 5.40 to 5.44. The Emergy Yield Ratio (EYR) ranges from 1.18 to 1.19, the Emergy Investment Ratio (EIR) from 5.39 to 5.42, an Emergy Exchange Ratio (EER) from 0.62 to 0.69, and an Emergy Sustainability Index (ESI) of 0.22.

Table 6. Unit Emergy Value (UEV) for the seaweed *Kappaphycus alvarezii* land-based farming for the carrageenan industry considering different strategies scenarios. Carrageenan base scenario (C); Carrageenan using less and recycled plastic (C_{pr}); Carrageenan using biofuel (C_{fc}); Carrageenan using less and recycled plastic and biofuel (C_T).

Products	**C**	**C_{pr}**	**C_{fc}**	**C_T**
Bleached and dry biomass (sej/J)	8.24E+05	8.67E+05	8.26E+05	7.84E+05
Bleached and dry biomass ws (sej/J)	5.94E+03	5.38E+03	6.45E+03	5.71E+03
Bleached and dry biomass (sej/g)	9.75E+09	1.03E+10	9.77E+09	9.28E+09
Bleached and dry biomass ws (sej/g)	7.03E+07	6.36E+07	7.63E+07	6.76E+07

Table 7. Emergy indicators for the seaweed *Kappaphycus alvarezii* land-based farming for the carrageenan industry considering different scenarios. Carrageenan base scenario (C); Carrageenan using less and recycled plastic (C_{pr}); Carrageenan using biofuel (C_{fc}); Carrageenan using less and recycled plastic and biofuel (C_T).

Indicator	Abbreviation	C	C_{pr}	C_{fc}	C_T
Renewability [a]	R%	15.54	15.54	15.55	15.61
Renewability [a] ws	R% ws	21.53	27.58	23.01	28.53
Environmental Loading Ratio [a]	ELR	5.44	5.43	5.43	5.40
Emergy Yield Ratio	EYR	1.18	1.18	1.18	1.19
Emergy Investment Ratio	EIR	5.42	5.42	5.41	5.39
Emergy exchange ratio	EER	0.65	0.69	0.66	0.62
Emergy Sustainability Index	ESI	0.22	0.22	0.22	0.22

[a] Indicators modified according to Agostinho et al. (2018).

The initial investment costs for land-based seaweed farming for the carrageenan market scenario ranged from US$1,804,118 to US$1,810,866 (Table 8), considering the land acquisition, which already had aquaculture ponds. The production costs ranged from US$653,143 to US$658,646. The annual profit was negative for all farm strategies. The Internal Rate of Return (IRR) ranged from 3.9 to 4.2%, and the Net Present Value (NPV) ranged from 862,603 to 929,899. The Benefit-Cost Ratio (BCR) was ~ 0.28 US$ per US$1 invested and ~16 years to recover invested capital. The plot of the relationship between ESI and NPV is in Figure 6.

Table 8. Cost-return analysis and indicators of the financial feasibility of seaweed land-based farming to carrageenan industry for different hypothetical farm strategies. Carrageenan base scenario (C); Carrageenan using less and recycled plastic (C_{pr}); Carrageenan using biofuel (C_{fc}); Carrageenan using less and recycled plastic and biofuel (C_T).

Item	C	C_{pr}	C_{fc}	C_T
Bleached and dried seaweed selling price (US$/kg)	0.60	0.60	0.60	0.60
Production yield (kg/year)	527,155	527,155	527,155	527,155
Production cost (US$/year)	658,632	658,559	653,143	658,646
Initial investment (US$/ha)	1,804,118	1,810,866	1,804,118	1,810,866
Gross revenue (US$)	316,489	316,489	316,489	316,489
Net revenue (US$)	97,645	94,486	97,603	94,443
Break-even price (US$/kg)	1.25	1.25	1.24	1.25
Profit (US$)	-342,143	-342,070	-336,654	-342,157
IRR (%/aa)	4.2	3.9	4.2	3.9
NPV (US$)	929,899	863,434	929,067	862,603
BCR (US$)	0.29	0.28	0.29	0.28
DPP (years)	15.63	16.03	15.64	16.04

IRR: Internal Rate of Return; NPV: Net Present Value; BCR: Benefit-Cost Ratio; PP: Discounted Pay-Back Period

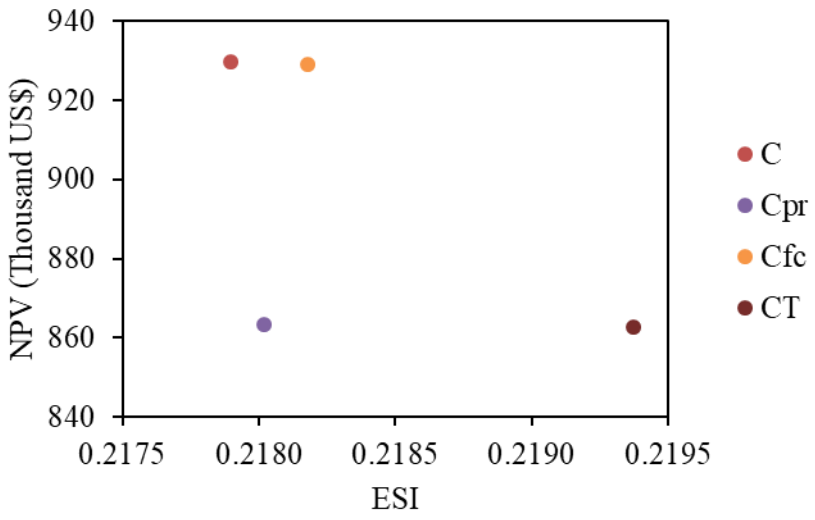

Figure 6. Emergy Sustainability Index (ESI) and Net Present Value (NPV) of seaweed land-based farming for the carrageenan market. Comparison of the base scenario and different management strategies. Carrageenan base scenario (C); Carrageenan using less and recycled plastic (C_{pr}); Carrageenan using biofuel (C_{fc}); Carrageenan using less and recycled plastic and biofuel (C_T).

The seaweed farming for direct human consumption has total emergy of 1.82E+18 sej/ha/year, in which 2.80E+17 sej/ha/year corresponds to emergy of renewable from nature, 5.99E+14 sej/ha/year to non-renewable from nature, and 1.54E+18 sej/ha/year to economy resources. The Unit Emergy Value (UEV) ranged between 1.06E+06 and 1.10E+06 sej/J for the dehydrated seaweed (Table 9). Emergy indicators of Renewability (R%) range from 26 to 85%, and Environmental Loading Ratio (ELR) ranges from 0.18 to 3.19. The Emergy Yield Ratio (EYR) ranges from 1.31 to 6.87, the Emergy Investment Ratio (EIR) from 0.17 to 3.19, an Emergy Exchange Ratio (EER) from 0.00 to 0.08, and an Emergy Sustainability Index (ESI) from 0.41 to 38.61.

Table 9. Unit Emergy Value (UEV) for the seaweed *Kappaphycus alvarezii* land-based farming for the human consumption industry considering different scenarios. Human consumption base scenario (HC); Human consumption using less and recycled plastic (HC_{pr}); Human consumption using biofuel (HC_{fc}); Human consumption using less and recycled plastic and biofuel (HC_T).

Products	**HC**	**HC_{pr}**	**HC_{fc}**	**HC_T**
Dehydrated seaweed (sej/J)	1.06E+06	1.10E+06	1.06E+06	1.10E+06
Dehydrated seaweed ws (sej/J)	6.28E+03	5.72E+03	6.16E+03	5.59E+03
Dehydrated seaweed (sej/g)	1.25E+10	1.30E+10	1.26E+10	1.31E+10
Dehydrated seaweed ws (sej/g)	7.43E+07	6.77E+07	7.29E+07	6.62E+07

Table 10. Emergy indicators for the seaweed *Kappahycus alvarezii* land-based farming for the human consumption industry considering different scenarios. Human consumption base scenario (HC); Human consumption using less and recycled plastic (HC_{pr}); Human consumption using biofuel (HC_{fc}); Human consumption using less and recycled plastic and biofuel (HC_T).

Indicator	Abbreviation	HC	HC_{pr}	HC_{fc}	HC_T
Renewability [a]	R%	15.42	15.43	15.45	15.45
Renewability [a] $_{ws}$	R% $_{ws}$	22.21	27.96	26.13	32.40
Environmental Loading Ratio [a]	ELR	5.48	5.48	5.47	5.47
Emergy Yield Ratio	EYR	1.18	1.18	1.18	1.18
Emergy Investment Ratio	EIR	5.47	5.47	5.46	5.46
Emergy exchange ratio	EER	0.05	0.05	0.05	0.05
Emergy Sustainability Index	ESI	0.22	0.22	0.22	0.22

[a] Indicators modified according to Agostinho et al. (2018).

Initial investment costs for seaweed farming for direct human consumption market scenario ranged from US$1,804,118 to US$1,810,866 (Table 8). The production costs ranged from US$2,785,474 to US$2,791,065. The annual profit ranged from US$3,640,621 to US$3,646,211, and the cash flow analysis showed liquidity over the project lifetime with a discounted payback time of ~1.4 years. The Internal Rate of Return (IRR) ranged from 161.5% to 162.1%, and the Net Present Value (NPV) was between 97,429,014 and 97,496,310. The Benefit-cost Ratio (BCR) was between US$10.21 and US$10.26 per dollar invested. The plot of the relationship between ESI and NPV is in Figure 7.

Table 11. Cost-return analysis and indicators of the financial feasibility of seaweed land-based farming to human consumption for different hypothetical farm strategies. Human consumption base scenario (HC); Human consumption using less and recycled plastic (HC_{pr}); Human consumption using biofuel (HC_{fc}); Human consumption using less and recycled plastic and biofuel (HC_T).

Item	HC	HC_{pr}	HC_{fc}	HC_T
Dehydrated seaweed selling price (US$/kg)	12.20	12.20	12.20	12.20
Production yield (kg/year)	527,155	527,155	527,155	527,155
Production cost (US$/year)	2,785,474	2,790,978	2,785,562	2,791,065
Initial investment (US$/ha)	1,804,118	1,810,866	1,804,118	1,810,866
Gross revenue (US$)	6,431,685	6,431,685	6,431,685	6,431,685
Net Revenue (US$)	5,182,065	5,178,905	5,182,023	5,178,863
Break-even price (US$/kg)	5.28	5.29	5.28	5.29
Profit (US$)	3,646,211	3,640,708	3,646,124	3,640,621
IRR (%/aa)	162.1	161.5	162.1	161.5
NPV (US$)	97,496,310	97,429,845	97,495,478	97,429,014
BCR (US$)	10.26	10.21	10.26	10.21
DPP (years)	1.44	1.44	1.44	1.44

IRR: Internal Rate of Return; NPV: Net Present Value; BCR: Benefit-Cost Ratio; PP: Discounted Pay-Back Period

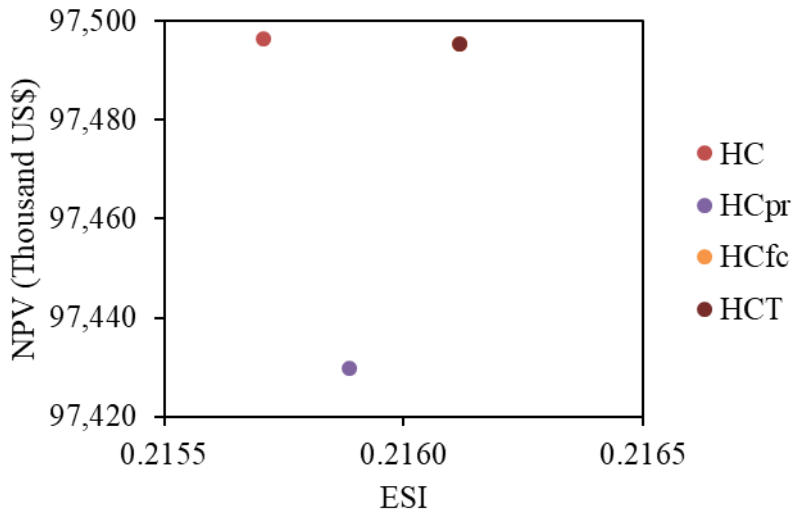

Figure 7. Emergy Sustainability Index (ESI) and Net Present Value (NPV) of seaweed land-based farming for the human consumption market. Comparison of the base scenario and different management strategies. Human consumption base scenario (HC); Human consumption using less and recycled plastic (HC_{pr}); Human consumption using biofuel (HC_{fc}); Human consumption using less and recycled plastic and biofuel (HC_T).

The seaweed farming for the liquid biostimulant has total emergy of 5.40E+19 sej/ha/year, in which 8.37E+18 sej/ha/year correspond to emergy of renewable from nature, 5.99E+14 sej/ha/year to non-renewable from nature, and 4.57E+19 sej/ha/year to economy resources. The liquid biostimulant Unit Emergy Value (UEV) ranged between 1.36E+06 and 8.96E+06 sej/J, the biocompound from 1.06E+04 to 6.95E+04 sej/J, the bleached and dry seaweed from 4.81E+07 to 3.15E+08 sej/J (Table 12). Emergy indexes of seaweed farming to the liquid biostimulant are present in Table 13. This scenario product displays a Renewability (R%) ranging from 15.0 to 15.5% and an Environmental Loading Ratio (ELR) ranging from 5.46 to 5.66. The Emergy Yield Ratio (EYR) of 1.18, the Emergy Investment Ratio (EIR) from 5.64 to 5.66, an Emergy Exchange Ratio (EER) from 0.80 to 5.15, and an Emergy Sustainability Index (ESI) from 0.21 to 0.22.

Table 12. Unit Emergy Value (UEV) for the seaweed *Kappaphycus* alvarezii land-based farming for the liquid biostimulant considering different strategies scenarios. Liquid biostimulant base scenario (LB); Liquid biostimulant using less and recycled plastic (LB_{pr}); Liquid biostimulant using biofuel (LB_{fc}); Liquid biostimulant with no salt (LB_{sr}); Liquid biostimulant using less and recycled plastic, biofuel, and no salt (LB_T).

Products	**LB**	**LB_{pr}**	**LB_{fc}**	**LB_{sr}**	**LB_T**
Liquid Biostimulant (sej/J)	8.94E+06	8.96E+06	8.94E+06	1.36E+06	8.78E+06
Liquid Biostimulant $_{ws}$(sej/J)	1.68E+05	1.68E+05	1.68E+05	5.24E+03	4.80E+03
Liquid Biostimulant (sej/L)	8.40E+13	8.41E+13	8.40E+13	1.28E+13	8.24E+13
Liquid Biostimulant $_{ws}$(sej/L)	1.58E+12	1.57E+12	1.57E+12	4.92E+10	4.50E+10
Biocompound (sej/J)	6.94E+04	6.95E+04	6.94E+04	1.06E+04	6.81E+04
Biocompound $_{ws}$ (sej/J)	1.30E+03	1.30E+03	1.30E+03	4.07E+01	3.72E+01
Biocompound (sej/g)	4.37E+10	4.37E+10	4.37E+10	1.02E+11	6.60E+11
Biocompound $_{ws}$ (sej/g)	8.20E+08	8.19E+08	8.19E+08	3.93E+08	3.60E+08
Bleached and dry biomass (sej/J)	3.15E+08	3.16E+08	3.15E+08	4.81E+07	3.10E+08
Bleached and dry biomass $_{ws}$ (sej/J)	5.92E+06	5.92E+06	5.92E+06	1.85E+05	1.69E+05
Bleached and dry biomass (sej/g)	3.73E+12	3.74E+12	3.73E+12	5.69E+11	3.66E+12
Bleached and dry biomass $_{ws}$ (sej/g)	7.01E+10	7.00E+10	7.00E+10	2.19E+09	2.00E+09

Table 13. Emergy indicators for the seaweed *Kappaphycus alvarezii* land-based farming for the liquid biostimulant industry considering different *scenarios.* Liquid biostimulant base scenario (LB); Liquid biostimulant using less and recycled plastic (LB_{pr}); Liquid biostimulant using biofuel (LB_{fc}); Liquid biostimulant with no salt (LB_{sr}); Liquid biostimulant using less and recycled plastic, biofuel, and no salt (LB_T).

Indicator	**Abbreviation**	**LB**	**LB_{pr}**	**LB_{fc}**	**LB_{sr}**	**LB_T**
Renewability [a]	R%	15.48	15.48	15.48	15.06	15.01
Renewability [a] ws	R% ws	40.03	40.10	40.08	7.04	8.54
Environmental Loading Ratio [a]	ELR	5.46	5.46	5.46	5.64	5.66
Emergy Yield Ratio	EYR	1.18	1.18	1.18	1.18	1.18
Emergy Investment Ratio	EIR	5.46	5.46	5.46	5.64	5.66
Emergy exchange ratio	EER	3.44	3.45	3.44	0.80	5.15
Emergy Sustainability Index	ESI	0.22	0.22	0.22	0.21	0.21

[a] Indicators modified according to Agostinho et al. (2018).

Initial investment costs for seaweed farming for the liquid biostimulant market scenario ranged from US$1,901,980 to US$1,908,729 (Table 14). The production costs ranged from US$292,864,00 to US$ 4,500,277. The annual profit ranged from US$ 3,634,295 to US$ 5,576,068. The cash flow analysis showed liquidity over the project lifetime with a discounted payback time of ~1.4 years. The IRR ranged from 156.1 to 209.3%, and the NPV was between US$ 98,782,897 and US$ 150,563,341. The Benefit-Cost Ratio was between US$52.90 and US$80.39 per dollar invested. The plot of the relationship between ESI and NPV is in Figure 10.

Table 14. Cost-return analysis and indicators of the financial feasibility of seaweed land-based farming for the liquid biostimulant industry considering different scenarios. Liquid biostimulant base scenario (LB); Liquid biostimulant using less and recycled plastic (LB_{pr}); Liquid biostimulant using biofuel (LB_{fc}); Liquid biostimulant with no salt (LB_{sr}); Liquid biostimulant using less and recycled plastic, biofuel, and no salt (LB_T).

Item	LB;	LB_{pr}	LB_{fc}	LB_{sr}	LB_T
Biostimulant selling price (US$/L)	2.73	2.73	2.73	2.73	2.73
Biostimulant production yield (L/year)	2,342,912	2,342,912	2,342,912	2,342,912	2,342,912
Biocompound selling price (US$/kg)	0.81	0.81	0.81	0.59	0.59
Biocompound production yield (kg/year)	4,504,248.32	4,504,248.32	4,504,248.32	292,864.00	292,864.00
Bleached and dry seaweed selling price (US$/kg)	0.60	0.60	0.60	0.60	0.60
Bleached and dry seaweed production yield (kg/year)	52,715.52	52,715.52	52,715.52	52,715.52	52,715.52
Production cost (US$/year)	4,494,774	4,500,277	4,494,861	2,960,518	2,966,108
Initial investment (US$/ha)	1,901,980	1,908,729	1,901,980	1,901,980	1,908,729
Gross revenue (US$)	10,070,842	10,070,842	10,070,842	6,600,403	6,600,403
Net revenue (US$)	7,987,759	7,984,599	7,987,717	5,258,955	5,255,753
Break-even price (US$/kg)	1.92	1.92	1.92	1.26	1.27
Profit (US$)	5,576,068	5,570,565	5,575,981	3,639,885	3,634,295
IRR (%/aa)	209.3	208.6	209.2	156.6	156.1
NPV (US$)	150,563,341	150,496,876	150,562,510	98,850,193	98,782,897
BCR (US$)	80.39	80.08	80.39	53.12	52.90
DPP (years)	1.32	1.32	1.32	1.45	1.46

IRR: Internal Rate of Return; NPV: Net Present Value; BCR: Benefit-Cost Ratio; PP: Discounted Pay-Back Period

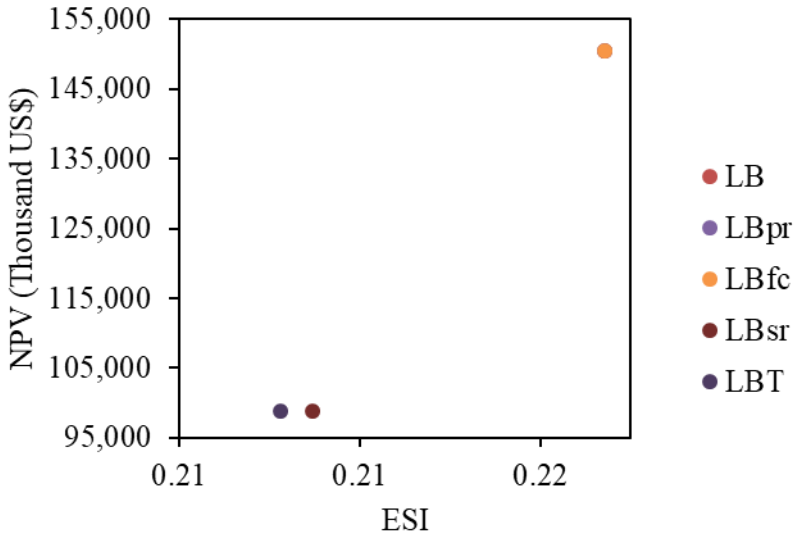

Figure 10. Emergy Sustainability Index (ESI) and net present value (NPV) of land-based farming for the liquid biostimulant industry considering different scenarios. Liquid biostimulant base scenario (LB); Liquid biostimulant using less and recycled plastic (LB_{pr}); Liquid biostimulant using biofuel (LB_{fc}); Liquid biostimulant with no salt (LB_{sr}); Liquid biostimulant using less and recycled plastic, biofuel, and no salt (LB_T).

4. Discussion

The present study provides comprehensive information on tropical seaweed land-based farming for different market strategies and its impact on system sustainability. The total emergy demand for land-based seaweed farming ranged from 1.41E+18 to 5.40E+19 sej/ha/year. Land-based farming requires a larger land area and higher economic resources when compared with sea-based farming. It is considered a low-technology system compared to other marine land-based production systems and necessitates more land infrastructure when compared to sea-based seaweed farming (see Chapter 1).

The transformities of seaweed products, ranging from 1.06E+04 to 3.16E+08 sej/J, may be lower than other land-based marine products such as mullet with 1.89E+06 sej/J (Li et al., 2011), salmon with 5.8E+06 sej/J (Wilfart et al., 2013), and shrimps with 18.9E+06 sej/J (Odum, 2000). Despite seaweed's low caloric value, it is a highly nutritious feed and a raw material rich in substances of significant industrial interest (FAO, 2018). The present study demonstrates lower emergy indicators for land-based seaweed farming compared to sea-based farming (see Chapter 1). However, it exhibits feasible economic indicators for all the different markets.

The critical analysis of Emergy Synthesis and neoclassical approaches facilitates decision-making and helps formulate more sustainable farming strategies. From an Emergy Synthesis perspective, there are no significant differences in the emergy indicators across different market scenarios. On the other hand, the neoclassical economic analysis reveals that the biostimulant market is more economically attractive, followed by direct human consumption. These economic differences are associated with the value aggregation of the product in each market niche. The value of seaweed products tends to increase inversely with market volume (Brasil and Garcia, 2016). The carrageenan market, being a high-volume scenario but with a low-value product compared to food and fertilizers, exhibits liquidity over time but a lower Internal Rate of Return (IRR) than the Minimum Acceptable Rate of Return (MARR), making it an unattractive investment.

The seaweed biomass processing to the carrageenan and direct human consumption markets are very similar in terms of emergy inputs. The difference between these scenarios is the water source used for the seaweed washing process, packaging, and prices of sale. Freshwater is used for seaweed bleaching in the carrageenan obtaining process instead of filtered seawater for seaweeds destined for human consumption. Another difference is the

plastic raffia bags packaging for carrageenan sales and paper bags for human consumption seaweed. The biomass processing for seaweeds in the liquid biostimulant market also involves the use of freshwater. All market scenarios have the addition of lime to water used in the seaweed washing, because of the organic materials and small animals accumulation in seaweed. Emergy demand was similar for all the market scenarios analyzed, with renewable resources from nature of ~15%, non-renewable from nature less than 0.04%, and resources from the economy ~85%.The most representative items for carrageenan and human consumption were services that comprehended the economic value expended in manufacturing products from the economy, followed by labor, plastic, concrete from the anchors, and fuel. From all these inputs, services and labor are the only inputs that are partially renewable. The services comprise the monetary value paid for the economic resources, services provided to the producer, and wages. Labor is the direct energy input expended by workers to perform work in seaweed cultivation. Part of these resource inputs is from the local economy, for example, the labor source. Therefore, we can presume that the enterprise high services and labor costs can generate regional social and economic development, providing income and employment for the community. The other items in the seaweed farming process exhibit low or no Renewability but can be replaced with more renewable resources, with the exception of the anchor's concrete. However, further studies and tests can be conducted to explore alternative materials for anchors. In the case of the liquid biostimulant scenario, services were the most significant input, followed by salt used in biocompound manufacturing. These inputs have a partial Renewability. In an effort to improve the emergy indicators, we attempted to replace the low-renewable items to observe the effect and analyzed the neoclassical economy.

The hydrocolloid industry is the priority market for *K. alvarezii* nowadays (FAO, 2018). The bleached and dry seaweed transformity was 9.75E+09 sej/g, and the system Renewability was 15.5%. This Renewability is low compared with the seaweed for the carrageenan industry produced by a sea-based seaweed farming system of 83.4% (see Chapter 1). The Environmental Loading Ratio of 5.44 displays moderate pressures on ecosystems, and the Emergy Yield Ratio of 1.18 shows a high dependency on purchased resources with low contribution to the larger economy. The Emergy Investment Ratio of 5.42 showed less competition power, compared with 0.20 EIR of the bleached and dried seaweed for the carrageenan industry from *Hypnea pseudomusciformis* sea-based farming (see Chapter 1). However, the Emergy Exchange Ratio of 0.65 indicates that the value paid by the market

recompenses the emergy value spent to produce the final bleached and dry seaweed. So, according to the biophysical economy of Emergy Synthesis, the value paid by the traditional neoclassic economy should be ~2.10U$S/kg of bleached and dried seaweed. However, there is instability in the carrageenan market once its sales prices vary according to the international market, causing a fluctuation in the product value in the market and also influencing EER value over time. Despite the neoclassic economy analyzes displaying feasibility for *K. alvarezii* land-based farming, it is not an attractive investment with a low IRR of 4.18%/a.a. The Environmental Sustainability Index of 0.22 suggests land-based seaweed systems are not environmentally feasible to produce bleached and dried seaweed to carrageenan industry. The bleached and dried seaweed *H. pseudomusciformis* farm in a sea-based system for the carrageenan industry shows an ESI of 30.36. These land-based emergy indicators low performance compared to sea-based may be due to the land-based system higher input of purchased materials. Land-based farming uses ~85% of its resources from the economy, while the sea-based uses ~15% only (see Chapter 1).

The emergy indicators slightly increased systems sustainability with fuel change and with the combination of using less and recycled plastic and biofuel. The combination of plastic reduction and biofuel was the best scenario to increase emergy indicators to carrageenan market. However, even with this increase, the Emergy Sustainability Index of 0.22 for the bleached and dried seaweed from the land-based system are lower than 30.36 for seaweed from the sea-based system. The neoclassic economic analysis showed feasibility but it is not attractive, with a low IRR and a DPP of more than 15.6 years. Despite not being attractive, the neoclassic economic indicator results of land-based farming are better than sea-based farming, which showed no economic feasibility (see Chapter 1). It may be due to the higher productivity per meter of rafts systems compared with the long-line technique used in the sea-based study case (Chapter 1). The analysis of ESI versus NPV indicates that the combination using less and recycled plastic and biofuel strategies is better for the land-based farmer to make the enterprise profitable and the seaweed product sustainable.

The human consumption market shows a dehydrated seaweed transformity of 1.25E+10 sej/g, which is higher than for seaweed *H. pseudomusciformis* produced in a sea-based system with a transformity of 4.57E+09 sej/g (see chapter 1). One explanation is the *K. alvarezii* land-based system higher emergy demand of 1.41E+18 sej/ha/year compared with the *H. pseudomusciformis* sea-based farming of 5.50E+16 sej/ha/year. The *K. alvarezii* land-based culture for the human market presents Renewability low to moderate of 15.4% which is lower

compared sea-based farmed seaweed of 83% (see chapter 1), and with the aquaponic vegetables of 33 to 38% (David et al., 2022). Regardless of seaweed and aquaculture vegetables, *K. alvarezii* can be more renewable than traditional vegetables. Albino and Callado (2012) showed Renewability values of 12 and 13% for leaf and mixed vegetables, respectively. The Environmental Loading Ratio of 5.48 displays moderate pressures on ecosystems, and the Emergy Yield Ratio of 1.18 shows a high dependency on resources from economy. The Emergy Investment Ratio of 5.47 showed less competition power compared to the seaweed *H. pseudomusciformis* for human consumption of 0.20 (see chapter 1) andleaf and mixed vegetables, which shows an EIR ranging from 4.68 to 5.26 (Albino and Callado, 2012). Futhermore, Emergy Exchange Ratio of 0.05 indicates that the value paid by the market recompenses the emergy value spent to produce the final products. The Emergy Sustainability Index of 0.22 suggests systems low sustainability. The ESI of *K. alvarezii* for human consumption was lower than for *H. pseudomusciformis* for the same market, which was 29.17 (see chapter 1).

The direct human consumption emergy indicators improves using less and recycled plastic and biofuel strategies The combined strategies scenario displays the higher emergy indindicators to dehydrated seaweeds compared with the other strategies alone. However, even with this increase, the Emergy Sustainability Index of 0.22 was lower than sea-based system of 29.17. The neoclassic economic analysis showed feasibility and attractivity with a high IRR of 162.1%/a.a. and a DPP lower than two years. Recent studies suggest that the direct consumption market is the most interesting niche for seaweed farming (FAO 2021; Pereira et al. 2020). The neoclassical economy analysis showed that *K. alvarezii* land-based farming is more attractive than *H. pseudomusciformis* sea-based farming which presented a IRR of 112.4%/a.a. It is explained by the higher *Kappaphycus* productivity. The analysis of ESI versus NPV indicates that the combination of using less and recycled plastic and biofuel is the better strategy for improve land-based farming sustainability to direct human consumption market.

A set of studies shows the interest in using seaweed substances in agriculture to improve the plants health, resistance, and productivity (Mukherjee and Patel, 2020; Raghunandan et al., 2019; Zafar et al., 2022). The seaweed liquid biostimulant production enables a biorefinery system, which generates three different products: liquid biostimulant, biocompound, and bleached dried biomass. The liquid biostimulant transformity was 8.40E+13 sej/L, the bio compound 4.37E+10 sej/g, and the bleached and dried biomass was

3.73E+12 sej/g. The liquid biostimulant UEV of 8.40E+13 sej/L was higher than traditional chemical sulfur-based fertilizers utilized in China, which are ~6.46E+09sej/kg (Chen et al., 2020). The present study system renewability is low to moderate, nearly 16% which is higher than traditional fertilizers systems production of ~2% (Chen et al., 2020). The Environmental Loading Ratio of 5.46 displays moderate pressures on ecosystems, and the Emergy Yield Ratio of 1.18 shows a high dependency on resources from the economy. The Emergy Investment Ratio of 5.46 showed less competition power with similar systems or products. The Emergy Exchange Ratio of 3.44 indicates that the value paid did not recompenses the emergy value spentd to produce the final products, and the market value should be 3 times the actual price. However, the neoclassic economy analysis displayed feasibility with a return of US$ 80.39 per dollar invested. However, the liquid biostimulant produced by land-based seaweed farming is more sustainable than traditional fertilizers, which can present an ESI of 0.02 (Chen et al., 2020). From the Emergy Synthesis perspective, the bleached and dried seaweed produced in the market scenario exclusively for the carrageenan industry (C) is slightly more sustainable than in the biorefinery of liquid biostimulant production scenario, where the bleached and dried seaweed is a liquid biostimulant by-product. However, for the neoclassic economy perspective, it is more attractive obtain the bleached dried biomass as a by-product of liquid biofertilizer. It is probably because of the biorefinery strategy of the liquid biostimulant biorefinery scenario, which can increase the inputs use efficiency to produce more than one product.

Seaweed land-based farming generally presented low emergy sustainability indicators. One explanation is the high number of purchased inputs that are not renewable materials. However, compared with other similar products, such as the case of direct human consumption and liquid biofertilizer, seaweed land-based products may be a more sustainable choice. From the economic approach, *K. alvarezii* land-based farming was more attractive than *H. pseudomusciformis* sea-based farming for all market scenarios. It is because of the different productivity of the farmed species and systems. Variations in productivity will directly affect the results. The rafts systems enable an increase in the line numbers per square meter. Also, the system evaluated in the present study presents a high yield with a seedling harvest of ~1.3kg and a productivity of 8.32kg/m or 30.51kg/m. It is higher than other *K. alvarezii* productivity obtained in the Brazilian Southeastern, which was 4.55 kg/m, using tubular nets (Nogueira and Henriques, 2020) and 7.0 to 13.2 kg/m², using rafts (Hayashi et al., 2011). A study of *Kappaphycus* sea-based farming with longlines and off-bottom systems in

the Philippines also showed productivity ranging from less than 1kg/m/yr to 16 kg/m/yr (Hurtado et al., 2001). High seedlings' final weight may cause biomass losses, as reported by Hayashi et al. (2011). Also, *Kappaphycus* farming is subject to disease appearance, such as "ice-ice" and "whitening of branch tips", which may result in productivity decline (Trono and Valdestamon, 1994). These productivity fluctuations may represent a risk for Kappaphycus sea-based farming. A decline of 30% in productivity turns the system unfeasible in all scenarios.

The liquid biostimulant emergy indicators did not improve with the strategies of using less and recycled plastic and biofuel. The emergy indicators reduce with the salt removal from the biocompound and the combination of using less and recycled plastic, biofuel and no salt. Despite salt being an economic resource in high demand, it presents a high Renewability of 41%. So salt removal reduces the proportion of renewable fractions in the system. The neoclassic economic analysis showed feasibility and attractivity with a high IRR of 209.3%/a.a., and a DPP lower than two years. The neoclassic economy analysis showed that *K. alvarezii* land-based farming with biorefinery to produce liquid biostimulants and by-products is very attractive. Analyzing the relationship between ESI and NPV did not enable the identification of a farming strategy that could improve the sustainability of land-based farming for this market scenario.

The land-based farming also provides ecosystem services. In the present study, we could identify services, such as eutrophication regulation by nitrogen and phosphate absorption. These environmental ecosystem services are not valued once they are intrinsic to the systems process in the Emergy Synthesis approach. We could also identify another possible ecosystem service, the presence of seahorses that utilizes the seaweeds as habitat. We could not measure the seahorses presence in farming. A specific study is necessary to analyze and value this seaweed habitat provision service and other possible ecosystem services provided by seaweeds. Furthermore, it is interesting to see seaweed land-based farming emergy indicators performance in an integrated system. Once the integrated system can display a high efficiency in resource use (Chopin et al., 2012), it may improve seaweed land-based system Emergy Synthesis sustainability. Search for strategies like IMTA to increase seaweed land-based sustainability is important once seaweed land-based farming demands more emergy than sea-based farming. Also, seaweed land-based occupies an estuary and mangrove areas, the same as shrimp farming. Despite the not arable characteristic of these lands and a low rate of soil

erosion, estuarine areas represent a high-importance environment for the ocean, a breeding region for different marine species, and with high vulnerability.

5. Conclusion

In general, *K. alvarezii* land-based farming presents a low sustainability indicators performance compared with seaweed sea-based farming from the perspective of the Emergy Synthesis approach due to the high demand for purchased materials, mainly services. However, the study suggests that seaweed land-based farming products may be more sustainable than similar products in the market, such as the liquid biostimulant compared with traditional fertilizers. The neoclassicapproach indicates that the system is sustainable from the economic view but needs attention to the crop risks of reducing systems productivity. Seaweed land-based farming is a potential system to explore, but it still needs adjustments to improve sustainability. IMTA systems may be a key to improving the systems efficiency and resilience, but it is still a developing technology for seaweed farming. The present study information may serve decision-makers, public policymakers, farmers, researchers, and consumers for more sustainable strategies, better sector development, and knowledge.

6. References

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Supplementary Materials

Article: The sustainability of the seaweed *Kappaphycus alvarezii* farming at shrimp farm Chanel for different markets in Brazil: An emergy and neoclassic approach

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Table 1. List of Units Emergy Values (UEVs) actualized to the baseline 1.20E+25 sej/year according to Brown and Ulgiati (2016).

	Itens	Unit	Reference UEV (sej/unit)	UEV updated (sej/unit)	Reference Baseline (sej/yr)	Reference UEV
1	Sun	J	1.00E+00	1.00E+00		Odum (2000)
2	Wind	J	1.28E+03	1.28E+03	1.20E+25	Giannetti et al. (2019)
3	Rain chemical energy	J	9.71E+03	9.71E+03	1.20E+25	Giannetti et al. (2019)
4	Fresh water	J	6.55E+04	6.55E+04	1.20E+25	Giannetti et al. (2019)
5	Dissolved Nitrogen	g	9.00E+08	1.14E+09	9.44E+24	Odum and Arding (1991)
6	Dissolved Phosphate	g	8.10E+09	1.03E+10	9.44E+24	Odum and Arding (1991)
7	Estuarine Water	J	4.05E+04	4.05E+04	1.20E+25	Giannetti et al. (2019)
8	Ground water	J	7.67E+04	7.67E+04	1.20E+25	Giannetti et al. (2019)
9	Organic soil	J	7.38E+04	9.38E+04	9.44E+24	Odum (1996)
10	Electricity	J	2.06E+05	2.06E+05	1.20E+25	Giannetti et al. (2019)
11	Plastic	J	1.92E+05	1.92E+05	1.20E+25	Giannetti et al. (2019)
12	Limestone	J	1.62E+06	1.23E+06	1.58E+25	Odum et al., (2000)
13	Gasoline	J	4.16E+04	4.16E+04	1.20E+25	Giannetti et al. (2019)
14	Etanol	J	4.87E+04	3.69E+04	1.58E+25	Pereira and Ortega (2010)
15	Rubber	g	4.30E+09	5.47E+09	9.44E+24	Buranakan (1998)
16	Cotton	g	1.45E+09	1.45E+09	1.20E+25	Blatt and Almeida (2017)
17	Paper	g	2.95E+09	2.95E+09	1.20E+25	Corcelli et al. (2018)
18	Salt	g	1.05E+09	7.94E+08	1.58E+25	Laganis and Debeljak (2006)
19	Human Labor	J	1.15E+07	8.72E+06	1.58E+25	Bonilla et al. (2010)
20	Monetary (EmDollar Brazil)	$	5.61E+12	5.61E+12	1.20E+25	Giannetti et al. (2018)
21	Iron	g	4.15E+09	4.15E+09	1.20E+25	Oliveira et al. (2018)
22	Steel	g	1.80E+09	2.29E+09	9.44E+24	Brown and Bardi (2001)
23	Wood	J	2.24E+05	2.85E+05	9.44E+24	Buranakan (1998)
24	Concrete	g	1.44E+09	1.83E+09	9.44E+24	Buranakan (1998)
25	Cement	g	1.98E+09	2.52E+09	9.44E+24	Buranakan (1998)
26	Glass fiber	g	3.00E+09	2.27E+09	1.58E+25	Ulgiati and Brown (2002)
27	Aluminum ingot	g	1.17E+10	1.49E+10	9.44E+24	Buranakan (1998)

Table 2. Calculations for the seaweed land-based farming for carrageenan industry.

Note	Item	Value	Unit	Reference
	Inputs			
1	**Sun**			
	Insolation	8.96E+13	J/ha/year	EMBRAPA (2004)
	Solar transmittance coefficient	81.60	%	Sangpradit (2014)
	Annual flow	7.31E+13	J/ha/year	
	UEV	1.00E+00	sej/J	By definition
	Emergy	7.31E+13	sej/ha/year	
	Sun = (8.96E+13 J/ha/year)(0.8 absorbed)*(1.00E+00) = 7.31E+13 sej/ha/year*			
2	**Wind**			
	Density of air	1.20E+00	kg/m³	
	Wind velocity	2.83E+00	m/s	INMET (2022)
	Time	3.15E+07	s	
	Drying area	5.65E+01	m²	
	Annual flow	4.56E+08	J/ha/year	
	UEV	1.28E+03	sej/J	Giannetti et al. (2019)
	Emergy	5.84E+11	sej/ha/year	
	Wind = ((((0.5)(1.20)*(5.65E+01)*(2.83^3))/1000*24 hours)*(3.60E+06 J/kWh)*(5days)*(5 cycles))/(3.64 productive area)*(1.28E+03)=5.84E+11 sej/ha/year*			
3	**Rain**			
	Annual average rainfall	1.30E+03	mm/ano	EMBRAPA (2004)
	Annual average rainfall	1.30E+04	m³/ha/ano	
	Water density	1.00E+03	kg/m³	
	Water energy	5.00E+03	J/kg	Gibbs energy
	Annual flow	6.50E+10	J/ha/year	
	UEV	9.71E+03	sej/J	Giannetti et al. (2019)
	Emergy	6.31E+14	sej/ha/year	
	*Rain = (1.30E+04)*1.00E+03*5.00E+03 = 6.31E+14 sej/ha/year*			
4	**Fresh water**			
	Quantity	5.49E+01	m³/ha/ano	
	Water density	1.00E+03	kg/m³	
	Water energy	5.00E+03	J/kg	Gibbs energy
	Annual flow	2.75E+08	J/ha/ano	
	UEV	6.55E+04	sej/J	Giannetti et al. (2019)
	Emergy	1.80E+13	sej/ha/year	
	*Fresh water = 5.49E+01*1.00E+03*5.00E+03*6.55E+04 = 1.80E+13 sej/ha/year*			
5	**Nitrogen**			
	Nutrient concentration	5.50E+00	g/kg	
	Seaweed annual dried biomass	1.45E+05	kg/ha/year	
	Annual flow	7.97E+05	g/ha/year	
	UEV	1.14E+09	sej/g	Odum and Arding (1991)
	Emergy	9.11E+14	sej/g/year	
	*Nitrogen = 5.50E+00*1.45E+05*1.14E+09 = 9.11E+14 sej/ha/year*			

6	**Phosphate**			
	Nutrient concentration	3.00E-01	g/kg	
	Seaweed annual dried biomass	1.45E+05	kg/ha/year	
	Annual flow	4.34E+04	g/ha/year	
	UEV	1.03E+10	sej/g	Odum and Arding (1991)
	Emergy	4.47E+14	sej/g/year	
	*Phosphate = 3.00E-01*1.45E+05*1.03E+10 = 4.47E+14 sej/ha/year*			
7	**Estuarine water**			
	Seaweed water biomass	2.40E+06	kg/ano	
	Water density	1.00E+03	kg/m³	
	Seaweed biomass water	2.39E+03	m³/ha/ano	
	Transformation	3.00E+06	J/m³	Odum andArding (1991)
	Annual flow	7.18E+09	J/ha/year	
	UEV	4.05E+04	sej/J	Giannetti et al. (2019)
	Emergy	2.91E+14	sej/ha/year	
	*Estuarine water = ((2.40E+06/1.00E+03)/(3.64 productive area)) * 4.05E+04 = 2.91E+14 sej/ha/year*			
8	**Ground water**			
	Quantity	8.05E+02	m³/ha/ano	
	Water density	1.00E+03	kg/m³	
	Water energy	5.00E+03	J/kg	
	Annual flow	4.02E+09	J/ha/ano	
	UEV	7.67E+04	sej/J	Giannetti et al. (2019)
	Emergy	3.09E+14	sej/ha/year	
	*Ground water = (8.05E+02*1.00E+03*5.00E+03)*7.67E+04 = 3.09E+14 sej/ha/year*			
9	**Soil occupation**			
	Soil erosion rate	1.00E-04	g/m²/ano	Labrière et al. (2015)
	Percentage of organic soil	1.49	%	Jimenez et al. (2021)
	Organic soil energy	5.40E+00	kcal/g	Brandt-Williams (2002)
	Top soil liquid loss	3.64	g/ano	
	Transformation	4.19E+03	kcal/J	
	Annual flow	1.23E+03	J/ha/year	
	UEV	9.38E+04	sej/J	Odum (1996)
	Emergy	1.15E+08	sej/ha/year	
	*Soil occupation = (((3.64 productive area) * 100000) * 1.00E-04) * (0.0149) * 5.40E+00 * 4.19E+03 * 9.38E+04) = 1.15E+08sej/ha/year*			
10	**Electricity**			
	Quantity	2.16E+09	J	
	Renewable fraction	68	%	Giannetti et al. (2015)
	Annual flow	4.04E+08	J/ha/year	
	UEV	2.06E+05	sej/J	Giannetti et al. (2019)
	Emergy	8.31E+13	sej/ha/year	
	*Electricity = (2.16E+09/(3.64 productive area)) * 0.68 * 2.06E+05 = 8.31E+13 sej/ha/year*			
11	**Cotton**			
	Quantity	1.20E+05	g	
	Renewable fraction	33.69	%	Blatt and Almeida (2017)
	Annual flow	1.11E+04	g/ha/year	
	UEV	1.45E+09	sej/g	Blatt and Almeida (2017)
	Emergy	1.61E+13	sej/ha/year	
	*Cotton = (1.20E+05/(3.64 productive area)) * 0.34 * 1.45E+09 = 1.61E+13 sej/ha/year*			

12	**Electricity**			
	Quantity	2.16E+09	J	
	Non-renewable fraction	32	%	Giannetti et al. (2015)
	Annual flow	1.90E+08	J/ha/year	
	UEV	2.06E+05	sej/J	Giannetti et al. (2019)
	Emergy	3.91E+13	sej/ha/year	
	*Electricity = (2.16E+09/(3.64 productive area)) * 0.32 * 2.06E+05 = 3.91E+13 sej/ha/year*			
13	**Plastic (Materials)**			
	Quantity	2.55E+10	J	
	Annual flow	7.00E+09	J/ha/year	
	UEV	1.92E+05	sej/J	Giannetti et al. (2019)
	Emergy	1.34E+15	sej/ha/year	
	*Plastic (Materials) = (2.55E+10/(3.64 productive area))*1.92E+05 = 3.39E+14 sej/ha/year*			
14	**Limestone**			
	Quantity	2.93E+06	g	
	Conversion to joules	6.11E+02	J/g	
	Annual flow	4.92E+08	J/ha/ano	
	UEV	1.23E+06	sej/J	Odum et al., (2000)
	Emergy	6.04E+14	sej/ha/year	
	*Limestone = (2.93E+06 * 6.11E+02/(3.64 productive area)) * 1.23E+06 = 6.04E+14 sej/ha/year*			
15	**Gasoline**			
	Quantity	1.22E+11	J	
	Annual flow	3.36E+10	J/ha/year	
	UEV	4.16E+04	sej/J	Giannetti et al. (2019)
	Emergy	1.40E+15	sej/ha/year	
	*Gasoline = (1.22E+11/(3.64 productive area))*4.16E+04 = 1.40E+15 sej/ha/year*			
16	**Rubber (Materials)**			
	Quantity	2.40E+03	g	
	Annual flow	6.59E+02	g/ha/year	
	UEV	5.47E+09	sej/g	Buranakan (1998)
	Emergy	3.60E+12	sej/ha/year	
	*Rubber = (2.40E+03/(3.64 productive area))*5.47E+09 = 3.60E+12 sej/ha/year*			
17	**Cotton**			
	Quantity	1.20E+05	g	
	Non-renewable fraction	66.31	%	Blatt and Almeida (2017)
	Annual flow	2.19E+04	g/ha/year	
	UEV	1.45E+09	sej/g	Blatt and Almeida (2017)
	Emergy	3.17E+13	sej/ha/year	
	*Cotton = (1.20E+05/(3.64 productive area)) * 0.66 * 1.45E+09 = 3.17E+13 sej/ha/year*			
18	**Steel**			
	Quantity	1.41E+05	g	
	Lifetime	10	years	
	Renewable fraction	4.31	%	Pan et al. (2016)
	Annual flow	1.67E+02	g	
	UEV	2.29E+09	sej/g	Brown and Bardi (2001)
	Emergy	3.82E+11	sej/ha/year	
	*Steel = ((1.41E+05/(3.64 productive area))/10)*0.04*2.29E+09 = 3.82E+11 sej/ha/year*			
19	**Cement**			
	Quantity	1.61E+06	g	
	Lifetime	10	years	

	Renewable fraction	9.96	%	Asgharipour et al. (2020)
	Annual flow	4.42E+03	g/ha/year	
	UEV	2.52E+09	sej/g	Buranakan (1998)
	Emergy	1.11E+13	sej/ha/year	

*Cement = ((1.61E+06/(3.64 productive area))/10)*0.10*2.52E+09 = 1.11E+13 sej/ha/year*

20	**Plastic (Equipments and Infrastructure)**			
	Quantity	6.98E+10	J	
	Lifetime	5	years	
	Annual flow	3.83E+09	J/ha/ano	
	UEV	1.92E+05	sej/J	Giannetti et al. (2019)
	Emergy	7.36E+14	sej/ha/year	

*Plastic = ((6.98E+10/(3.64 productive area))/5)*1.92E+05 = 7.36E+14 sej/ha/year*

21	**Iron**			
	Quantity	1.67E+06	g	
	Lifetime	5	years	
	Annual flow	9.20E+04	g/ha/ano	
	UEV	4.15E+09	sej/g	Oliveira et al. (2018)
	Emergy	3.82E+14	sej/ha/year	

*Iron = ((1.67E+06/(3.64 productive area))/5)*4.15E+09 = 3.82E+14 sej/ha/year*

22	**Steel**			
	Quantity	1.41E+05	g	
	Lifetime	10	years	
	Non-renewable fraction	95.69	%	Pan et al. (2016)
	Annual flow	3.71E+03	g/ha/ano	
	UEV	2.29E+09	sej/g	Brown and Bardi (2001)
	Emergy	8.48E+12	sej/ha/year	

*Steel = ((1.41E+05/(3.64 productive area))/10)*0.96*2.29E+09 = 8.48E+12 sej/ha/year*

23	**Wood**			
	Quantity	2.64E+10	J	
	Lifetime	10	years	
	Annual flow	7.27E+08	J/ha/ano	
	UEV	2.85E+05	sej/J	Buranakan (1998)
	Emergy	2.07E+14	sej/ha/year	

*Wood = ((2.64E+10/(3.64 productive area))/10)*2.85E+05 = 2.07E+14 sej/ha/year*

24	**Concrete**			
	Quantity	3.72E+07	g	
	Lifetime	10	years	
	Annual flow	1.02E+06	g/ha/ano	
	UEV	1.83E+09	sej/g	Buranakan (1998)
	Emergy	1.87E+15	sej/ha/year	

*Concrete = ((3.72E+07/(3.64 productive area))/10)*1.83E+09 = 1.87E+15 sej/ha/year*

25	**Cement**			
	Quantity	1.61E+06	g	
	Lifetime	10	years	
	Non-renewable fraction	90.04	%	Asgharipour et al. (2020)
	Annual flow	3.99E+04	g/ha/year	
	UEV	2.52E+09	sej/g	Buranakan (1998)
	Emergy	1.00E+14	sej/ha/year	

*Cement = ((1.61E+06/(3.64 productive area))/10)*0.90*2.52E+09 = 1.00E+14 sej/ha/year*

26	**Glass fiber**			

	Quantity	1.79E+05	g	
	Lifetime	10	years	
	Annual flow	4.93E+03	g/ha/year	
	UEV	2.27E+09	sej/g	Ulgiati and Brown (2002)
	Emergy	1.12E+13	sej/ha/year	

*Glass fiber = ((1.79E+05/(3.64 productive area))/10)*2.27E+09 = 1.12E+13 sej/ha/year*

27	**Rubber (Equipments and Infrastructure)**			
	Quantity	6.08E+04	g	
	Depreciation	5	years	
	Annual flow	3.34E+03	g/ha/year	
	UEV	5.47E+09	sej/g	Buranakan (1998)
	Emergy	1.82E+13	sej/ha/year	

*Rubber = ((6.08E+04/(3.64 productive area))/5)*5.47E+09 = 1.82E+13 sej/ha/year*

28	**Aluminum ingot**			
	Quantity	1.56E+06	g	
	Lifetime	10	years	
	Annual flow	4.28E+04	g/ha/year	
	UEV	1.49E+10	sej/g	Buranakan (1998)
	Emergy	6.37E+14	sej/ha/year	

*Aluminum ingot = ((1.56E+06/(3.64 productive area))/10)*1.49E+10 = 6.37E+14 sej/ha/year*

29	**Human labor**			
	Man-works fixed	19	persons	
	Man-works temporary	2	persons	
	Calories	2.92E+02	kcal/hour	
	Work-hour	8	hours/day	
	Days of fixed labor	220	days/person/year	
	Days of temporary labor	25	days/person/year	
	Annual work	9.86E+06	kcal/year	
	Conversion to J	4.18E+03	J/kcal	
	Renewable fraction	22.00	%	Agostinho et al. (2019)
	Annual flow	2.49E+09	J/ha/year	
	UEV	8.72E+06	sej/J	Bonilla et al. (2010)
	Emergy	2.17E+16	sej/ha/year	

*Human labor = (((19 * 220)+(2 * 25)) * 2.92E+02 * 8 * 4.18E+03* / (3.64 productive area))) * 0.22 * 8.72E+06 = 2.17E+16 sej/ha/year*

30	**Services**			
	Quantity	8.46E+05	$	
	Renewable fraction	15.00	%	Giannetti et al. (2018)
	Annual flow	3.48E+04	$/ha/year	
	UEV	5.61E+12	sej/$	Giannetti et al. (2018)
	Emergy	1.95E+17	sej/ha/year	

*Services = (8.46E+05 / (3.64 productive area))*0.15*5.61E+12 = 1.95E+17 sej/ha/year*

31	**Human labor**			
	Man-works fixed	19	persons	
	Man-works temporary	2	persons	
	Calories	292	kcal/hour	
	Work-hour	8	hours/day	
	Days of fixed labor	220	days/person/year	
	Days of temporary labor	25	days/person/year	
	Annual work	9.86E+06	kcal/year	

	Conversion to J	4.18E+03	J/kcal	
	Non-renewable fraction	78.00	%	Agostinho et al. (2019)
	Annual flow	8.84E+09	J/ha/year	
	UEV	8.72E+06	sej/J	Bonilla et al. (2010)
	Emergy	7.71E+16	sej/ha/year	

*Human labor = (((19 * 220)+(2 * 25)) * 2.92E+02 * 8 * 4.18E+03* / (3.64 productive area))) * 0.78 * 8.72E+06 = 7.71E+16 sej/ha/year*

32	**Services**			
	Quantity	7.52E+05	$	
	Renewable fraction	85.00	%	Giannetti et al. (2018)
	Annual flow	1.97E+05	$/ha/year	
	UEV	5.61E+12	sej/$	Giannetti et al. (2018)
	Emergy	1.11E+18	sej/ha/year	

*Services = (7.52E+05 / (3.64 productive area))*0.85*5.61E+12 = 1.11E+18 sej/ha/year*

	Outputs			
33	**Bleached and dry seaweed**			
	Harvest biomass	5.27E+08	g/year	
	Annual flow	1.45E+08	g/ha/year	
	Self-consumption	0.00	%	
	UEV	9.75E+09	sej/g	Present study
	Emergy	1.41E+18	sej/ha/year	

*Bleached and dry seaweed = (5.27E+08 / (3.64 productive area))*9.75E+09 = 1.41E+18 sej/ha/year*

Table 3. The initial investments cost for the seaweed land-based farming for the carrageenan market. Comparison of the base scenario and different management strategies. Carrageenan base scenario (C); Carrageenan using less and recycled plastic (C_{pr}); Carrageenan with biofuel (C_{fc}); Carrageenan using less and recycled plastic and biobuel (C_T).

Items	C		C_{pr}; C_{fc}; C_T	
	US$	%	US$	%
100 mm PVC pipes *	3,814	0.21	3,814	0.21
4mm braided polypropylene rope*	12,732	0.71	19,099	1.05
Wooden stakes*	428	0.02	428	0.02
PET bottle*	251	0.01	251	0.01
Concrete anchor**	1,152	0.06	1,152	0.06
Marine plywood**	149	0.01	149	0.01
Wooden rafter**	59	0.00	59	0.00
5/16 Iron rod**	8	0.00	8	0.00
3hp pressure washer**	558	0.03	558	0.03
200kg capacity scale**	186	0.01	186	0.01
75hp water pump**	3,625	0.20	3,625	0.20
50 hp centrifugal pump**	14,870	0.82	14,870	0.82
Notebook **	1,301	0.07	1,301	0.07
Inkjet printer**	93	0.01	93	0.01
Multiparameter probe**	617	0.03	617	0.03
2000L fiber tank**	520	0.03	520	0.03
Plastic platform**	11	0.00	11	0.00
Brass shelf**	7	0.00	7	0.00
Lawn mower**	167	0.01	167	0.01
Drill**	65	0.00	65	0.00
Knife**	33	0.00	33	0.00
Wooden shelf**	37	0.00	37	0.00
3/4 plastic hose*	37	0.00	37	0.00
Diving kit*	1,175	0.07	1,175	0.06
Circular saw**	167	0.01	167	0.01
Extension cables**	669	0.04	669	0.04
Life jacket**	297	0.02	297	0.02
Pickup truck**	18,703	1.04	18,703	1.03
Office and warehouse**	10,443	0.58	10,443	0.58
Shed**	12,040	0.67	12,040	0.66
Concrete tanks **	3,470	0.19	3,470	0.19
Land***	1,614,312	89.48	1,614,312	89.15
Project cost	102,120	5.66	102,502	5.66
Total	**1,804,118**	**100.00**	**1,810,866**	**100.00**
Total (R$/ha)	**496,018**		**497,874**	

* Useful life estimated at 5 years; ** Useful life estimated at 10 years; *** Useful life estimated at 10 years

Table 4. Annual costs (US$) and the percentage (%) of operating costs for sale to seaweed land-based farming for the carrageenan market. Comparison of the base scenario and different management strategies. Carrageenan base scenario (C); Carrageenan using less and recycled plastic (C_{pr}); Carrageenan with biofuel (C_{fc}); Carrageenan using less and recycled plastic and biofuel (C_T).

Itens description	Unit	Price/Unit	C			Cpr			Cfc			CT		
		(US$)	Quantity	Total Cost	%	Quantity	Total Cost	%	Quantity	Total Cost	%	Quantity	Total Cost	%
Variable cost				**78,230**	**46.3**		**79,989**	**46.9**		**78,272**			**80,031**	
Electricity	kWh	2.95	600	1,768	1.0	600	1,768	1.0	600	1,768	1.0	600	1,768	1.0
Gasoline	L	1.19	4,000	4,773	2.8	4,000	4,773	2.8	-	-	-	-	-	-
Ethanol	L	0.93	-	-	-	-	-	-	5,200	4,813	2.8	5,200	4,813	2.8
50 kg raffia bags	unit	0.28	10,543	2,940	1.7	10,543	2,940	1.7	10,543	2,940	1.7	10,543	2,940	1.7
Lime	kg	0.16	3,060	483	0.3	3,060	483	0.3	3,060	483	0.3	3,060	483	0.3
Sunscreen	kg	18.59	12	223	0.1	12	223	0.1	12	223	0.1	12	223	0.1
PPE hat	unit	2.60	40	104	0.1	40	104	0.1	40	104	0.1	40	104	0.1
Plastic ribbon	kg	3.72	751	2,792	1.7	-	-	-	751	2,792	1.7	-	-	-
Cotton yarn	kg	5.95	-	-	-	751	4,467	2.6	-	-	-	751	4,467	2.6
PPE dive boots	unit	9.29	80	743	0.4	80	743	0.4	80	743	0.4	80	743	0.4
PPE pants	unit	7.43	120	892	0.5	120	892	0.5	120	892	0.5	120	892	0.5
PPE T-shirts	unit	5.58	120	669	0.4	120	669	0.4	120	669	0.4	120	669	0.4
PPE sunglasses	unit	1.49	80	119	0.1	80	119	0.1	80	119	0.1	80	119	0.1
Eventual labor	daily	13.94	50	697	0.4	50	697	0.4	50	697	0.4	50	697	0.4
Rural Social Security Special Contribution[a]				12,091	7.2	0	12,091	7.1	0	12,091	7.2	0	12,091	7.1
Tax on the sale of the product[b]				46,209	27.4	0	46,209	27.1	0	46,209	27.3	0	46,209	27.1
General costs[c]				3,725	2.2	0	3,809	2.2	0	3,727	2.2	0	3,811	2.2
Fixed cost				**602,959**	**53.7**		**601,127**	**53.1**		**597,428**	**53.7**		**601,172**	**53.7**
Vehicle property tax[d]				390	0.2		390	0.2		390	0.2		390	0.2
Rural Land Tax (ITR)				406	0.2		406	0.2		406	0.2		406	0.2
Environmental tax Ibama/CONAMA				1,012	0.6		1,012	0.6		1,012	0.6		1,012	0.6

Occupancy Tax (SPU)				1,561	0.9	1,561	0.9	1,561	0.9	1,561	0.9
Field operator	annual wage	51,853.72	16	51,854	30.7	51,854	30.4	51,854	30.7	51,854	30.7
Foreman	annual wage	8,650.56	2	8,651	5.1	8,651	5.1	8,651	5.1	8,651	5.1
Production manager	annual wage	7,703.35	1	7,703	4.6	7,703	4.5	7,703	4.6	7,703	4.6
Pro labore	annual wage	14,498.14	1	14,498	8.6	14,498	8.5	14,498	8.6	14,498	8.6
Licensing				4,647	2.8	4,647	2.7	4,647	2.7	4,647	2.7
Maintenance [e]				34,040		34,167		34,040		34,167	
Annual depreciation				26,755		28,029		26,755		28,029	
Interest on working capital [f]				11,615		11,736		11,618		11,739	
Remuneration on fixed capital [g]				124,033		124,497		124,033		124,497	
Remunerations of the entrepreneur				40,892		40,892		40,892		40,892	
Remuneration on land				105,948		100,372		100,372		100,372	
Total Production Cost (TPC)				**602,959**		**601,127**		**597,428**		**601,172**	

[a] 3.14% of gross revenue; [b] 12% of gross revenue; [c] 5% of variable cost; [d] 4% of vehicle value; [e] 2% of investments; [f] 13.75% a.a. on haf of the effective operational cost; [g] 13.75% on haf fixed investments

Table 5. Calculations for the seaweed land-based farming for direct human consumption.

Note	Item	Value	Unit	Reference
	Inputs			
1	**Sun**			
	Insolation	8.96E+13	J/ha/year	Embrapa (2004)
	Solar transmittance coefficient	8.16E+01	%	Sangpradit (2014)
	Annual flow	7.31E+13	J/ha/year	
	UEV	1.00E+00	sej/J	By definition
	Emergy	7.31E+13	sej/ha/year	
	Sun = (8.96E+13 J/ha/year)(0.8 absorbed)*(1.00E+00) = 7.31E+13 sej/ha/year*			
2	**Wind**			
	Density of air	1.20E+00	kg/m³	
	Wind velocity	2.83E+00	m/s	INMET (2022)
	Time	3.15E+07	s	
	Drying area	5.65E+01	m²	
	Annual flow	4.56E+08	J/ha/year	
	UEV	1.28E+03	sej/J	Giannetti et al. (2019)
	Emergy	5.84E+11	sej/ha/year	
	Wind = ((((0.5)(1.20E+00)*(5.65E+01)*(2.83^3))/1000*24 hours)*(3.60E+06 J/kWh)*(5days)*(5 cycles))/(3.64 productive area)*(1.28E+03) = 5.84E+11 sej/ha/year*			
3	**Rain**			
	Annual average rainfall	1.30E+03	mm/ano	EMBRAPA (2004)
	Annual average rainfall	1.30E+04	m³/ha/ano	
	Water density	1.00E+03	kg/m³	
	Water energy	5.00E+03	J/kg	Gibbs energy
	Annual flow	6.50E+10	J/ha/year	
	UEV	9.71E+03	sej/J	Giannetti et al. (2019)
	Emergy	6.31E+14	sej/ha/year	
	*Rain = (1.30E+04)*1.00E+03*5.00E+03 = 6.31E+14 sej/ha/year*			
4	**Nitrogen**			
	Nutrient concentration	5.50E+00	g/kg	
	Seaweed annual dried biomass	1.45E+05	kg/ha/year	
	Annual flow	7.97E+05	g/ha/year	
	UEV	1.14E+09	sej/g	Odum and Arding (1991)
	Emergy	9.11E+14	sej/g/year	
	*Nitrogen = 5.50E+00*1.45E+05*1.14E+09 = 9.11E+14 sej/ha/year*			
5	**Phosphate**			
	Nutrient concentration	3.00E-01	g/kg	
	Seaweed annual dried biomass	1.45E+05	kg/ha/year	
	Annual flow	4.34E+04	g/ha/year	
	UEV	1.03E+10	sej/g	Odum and Arding (1991)
	Emergy	4.47E+14	sej/g/year	
	*Phosphate = 3.00E-01*1.45E+05*1.03E+10 = 4.47E+14 sej/ha/year*			
6	**Estuarine water**			
	Seaweed water biomass	2.40E+06	kg/ano	
	Water density	1.00E+03	kg/m³	
	Seaweed biomass water	2.39E+03	m³/ha/ano	
	Transformation	3.00E+06	J/m³	Odum andArding (1991)
	Annual flow	7.18E+09	J/ha/year	

	UEV	4.05E+04	sej/J	Giannetti et al. (2019)
	Emergy	2.91E+14	sej/ha/year	

*Estuarine water = ((2.40E+06/1.00E+03)/(3.64 productive area)) * 4.05E+04 = 2.91E+14 sej/ha/year*

7	**Ground water**			
	Quantity	8.05E+02	m³/ha/ano	
	Water density	1.00E+03	kg/m³	
	Water energy	5.00E+03	J/kg	
	Annual flow	4.02E+09	J/ha/ano	
	UEV	7.67E+04	sej/J	Giannetti et al. (2019)
	Emergy	3.09E+14	sej/ha/year	

*Ground water = (8.05E+02*1.00E+03*5.00E+03)*7.67E+04 = 3.09E+14 sej/ha/year*

8	**Soil occupation**			
	Soil erosion rate	1.00E-04	g/m²/ano	Labrière et al. (2015)
	Percentage of organic soil	1.49	%	Jimenez et al. (2021)
	Organic soil energy	5.40E+00	kcal/g	Brandt-Williams (2002)
	Top soil liquid loss	3.64E+00	g/ano	
	Transformation	4.19E+03	kcal/J	
	Annual flow	1.23E+03	J/ha/year	
	UEV	9.38E+04	sej/J	Odum (1996)
	Emergy	1.15E+08	sej/ha/year	

*Soil occupation = (((3.64 productive area) * 100000) * 1.00E-04) * (0.0149) * 5.40E+00 * 4.19E+03 * 9.38E+04) = 1.15E+08 sej/ha/year*

9	**Electricity**			
	Quantity	2.16E+09	J	
	Renewable fraction	68	%	Giannetti et al. (2015)
	Annual flow	4.04E+08	J/ha/year	
	UEV	2.06E+05	sej/J	Giannetti et al. (2019)
	Emergy	8.31E+13	sej/ha/year	

*Electricity = (2.16E+09/(3.64 productive area)) * 0.68 * 2.06E+05 = 8.31E+13 sej/ha/year*

10	**Paper**			
	Quantity	7.65E+05	g	
	Renewable fraction	34.95	%	Corcelli et al. (2018)
	Annual flow	7.35E+04	g/ha/year	
	UEV	2.95E+09	sej/g	Corcelli et al. (2018)
	Emergy	2.17E+14	sej/ha/year	

*Paper = (7.65E+05/(3.64productive area)) * 0.35 * 2.95E+09 = 2.17E+14 sej/ha/year*

11	**Cotton**			
	Quantity	1.20E+05	g	
	Renewable fraction	33.69	%	Blatt and Almeida (2017)
	Annual flow	1.11E+04	g/ha/year	
	UEV	1.45E+09	sej/g	Blatt and Almeida (2017)
	Emergy	1.61E+13	sej/ha/year	

*Electricity = (1.20E+05/(14.44 productive area)) * 0.34 * 1.45E+09 = 4.06E+12 sej/ha/year*

12	**Electricity**			
	Quantity	2.16E+09	J	
	Non-renewable fraction	32	%	Giannetti et al. (2015)
	Annual flow	1.90E+08	J/ha/year	
	UEV	2.06E+05	sej/J	Giannetti et al. (2019)
	Emergy	3.91E+13	sej/ha/year	

*Electricity = (2.16E+09/(3.64 productive area)) * 0.32 * 2.06E+05 = 3.91E+13 sej/ha/year*

13	**Plastic (Materials)**			
	Quantity	2.51E+10	J	
	Annual flow	6.91E+09	J/ha/year	
	UEV	1.92E+05	sej/J	Giannetti et al. (2019)
	Emergy	1.33E+15	sej/ha/year	

*Plastic (Materials) = (2.51E+10/(3.64 productive area))*1.92E+05 = 1.33E+15 sej/ha/year*

14	**Limestone**			
	Quantity	2.93E+06	g	
	Conversion to joules	6.11E+02	J/g	
	Annual flow	4.92E+08	J/ha/ano	
	UEV	1.23E+06	sej/J	Odum et al., (2000)
	Emergy	6.04E+14	sej/ha/year	

*Limestone = (2.93E+06*6.11E+02/(3.64 productive area))*1.23E+06 = 6.04E+14 sej/ha/year*

15	**Gasoline**			
	Quantity	1.22E+11	J	
	Annual flow	3.36E+10	J/ha/year	
	UEV	4.16E+04	sej/J	Giannetti et al. (2019)
	Emergy	1.40E+15	sej/ha/year	

*Gasoline = (1.22E+11/(3.64 productive area))*4.16E+04 = 1.40E+15 sej/ha/year*

16	**Paper**			
	Quantity	7.65E+05	g	
	Renewable fraction	65.05	%	Corcelli et al. (2018)
	Annual flow	1.37E+05	g/ha/year	
	UEV	2.95E+09	sej/g	Corcelli et al. (2018)
	Emergy	4.03E+14	sej/ha/year	

*Paper = (7.65E+05/(3.64 productive area)) * 0.65 * 2.95E+09 = 4.03E+14 sej/ha/year*

17	**Rubber (Materials)**			
	Quantity	2.40E+03	g	
	Annual flow	6.59E+02	g/ha/year	
	UEV	5.47E+09	sej/g	Buranakan (1998)
	Emergy	3.60E+12	sej/ha/year	

*Rubber = (2.40E+03/(7.51productive area))*5.47E+09 = 9.09E+11 sej/ha/year*

18	**Cotton**			
	Quantity	1.20E+05	g	
	Non-renewable fraction	66.31	%	Blatt and Almeida (2017)
	Annual flow	2.19E+04	g/ha/year	
	UEV	1.45E+09	sej/g	Blatt and Almeida (2017)
	Emergy	3.17E+13	sej/ha/year	

*Cotton = (1.20E+05/(3.64 productive area)) * 0.66 * 1.45E+09 = 3.17E+13 sej/ha/year*

19	**Steel**			
	Quantity	1.41E+05	g	
	Lifetime	10	years	
	Renewable fraction	4.31	%	Pan et al. (2016)
	Annual flow	1.67E+02	g	
	UEV	2.29E+09	sej/g	Brown and Bardi (2001)
	Emergy	3.82E+11	sej/ha/year	

*Steel = ((1.41E+05/(3.64 productive area))/10)*0.04*2.29E+09 = 3.82E+11 sej/ha/year*

20	**Cement**			
	Quantity	1.61E+06	g	

	Lifetime	10	years	
	Renewable fraction	9.96	%	Asgharipour et al. (2020)
	Annual flow	4.42E+03	g/ha/year	
	UEV	2.52E+09	sej/g	Buranakan (1998)
	Emergy	1.11E+13	sej/ha/year	

*Cement = ((1.61E+06/(3.64 productive area))/10)*0.10*2.52E+09 = 1.11E+13 sej/ha/year*

21	**Plastic (Equipments and Infrastructure)**			
	Quantity	6.98E+10	J	
	Lifetime	5	years	
	Annual flow	3.83E+09	J/ha/ano	
	UEV	1.92E+05	sej/J	Giannetti et al. (2019)
	Emergy	7.36E+14	sej/ha/year	

*Plastic = ((6.98E+10/(3.64 productive area))/5)*1.92E+05 = 7.36E+14 sej/ha/year*

22	**Iron**			
	Quantity	1.67E+06	g	
	Lifetime	5	years	
	Annual flow	9.20E+04	g/ha/ano	
	UEV	4.15E+09	sej/g	Oliveira et al. (2018)
	Emergy	3.82E+14	sej/ha/year	

*Iron = ((1.67E+06/(3.64 productive area))/5)*4.15E+09 = 3.82E+14 sej/ha/year*

23	**Steel**			
	Quantity	1.41E+05	g	
	Lifetime	10	years	
	Non-renewable fraction	95.69	%	Pan et al. (2016)
	Annual flow	3.71E+03	g/ha/ano	
	UEV	2.29E+09	sej/g	Brown and Bardi (2001)
	Emergy	8.48E+12	sej/ha/year	

*Steel = ((1.41E+05/(3.64 productive area))/10)*0.96*2.29E+09 = 8.48E+12 sej/ha/year*

24	**Wood**			
	Quantity	2.64E+10	J	
	Lifetime	10.00	years	
	Annual flow	7.27E+08	J/ha/ano	
	UEV	2.85E+05	sej/J	Buranakan (1998)
	Emergy	2.07E+14	sej/ha/year	

*Wood = ((2.64E+10/(3.64 productive area))/10)*2.85E+05 = 2.07E+14 sej/ha/year*

25	**Concrete**			
	Quantity	3.72E+07	g	
	Lifetime	10	years	
	Annual flow	1.02E+06	g/ha/ano	
	UEV	1.83E+09	sej/g	Buranakan (1998)
	Emergy	1.87E+15	sej/ha/year	

*Concrete = ((3.72E+07/(3.64 productive area))/10)*1.83E+09 = 1.87E+15 sej/ha/year*

26	**Cement**			
	Quantity	1.61E+06	g	
	Lifetime	10	years	
	Non-renewable fraction	90.04	%	Asgharipour et al. (2020)
	Annual flow	3.99E+04	g/ha/year	
	UEV	2.52E+09	sej/g	Buranakan (1998)
	Emergy	1.00E+14	sej/ha/year	

*Cement = ((1.61E+06/(3.64 productive area))/10)*0.90*2.52E+09 = 1.00E+14 sej/ha/year*

27	**Glass fiber**			
	Quantity	1.79E+05	g	
	Lifetime	10	years	
	Annual flow	4.93E+03	g/ha/year	
	UEV	2.27E+09	sej/g	Ulgiati and Brown (2002)
	Emergy	1.12E+13	sej/ha/year	

*Glass fiber = ((1.79E+05/(3.64 productive area))/10)*2.27E+09 = 1.12E+13 sej/ha/year*

28	**Rubber (Equipments and Infrastructure)**			
	Quantity	6.08E+04	g	
	Depreciation	5	years	
	Annual flow	3.34E+03	g/ha/year	
	UEV	5.47E+09	sej/g	Buranakan (1998)
	Emergy	1.82E+13	sej/ha/year	

*Rubber = ((6.08E+04/(3.64 productive area))/5)*5.47E+09 = 4.60E+12 sej/ha/year*

29	**Aluminum ingot**			
	Quantity	1.56E+06	g	
	Lifetime	10	years	
	Annual flow	4.28E+04	g/ha/year	
	UEV	1.49E+10	sej/g	Buranakan (1998)
	Emergy	6.37E+14	sej/ha/year	

*Aluminum ingot = ((1.56E+06/(3.64 productive area))/10)*1.49E+10 = 6.37E+14 sej/ha/year*

30	**Human labor**			
	Man-works fixed	19	persons	
	Man-works temporary	2	persons	
	Calories	2.92E+02	kcal/hour	
	Work-hour	8	hours/day	
	Days of fixed labor	220	days/person/year	
	Days of temporary labor	25	days/person/year	
	Annual work	9.86E+06	kcal/year	
	Conversion to J	4.18E+03	J/kcal	
	Renewable fraction	22.00	%	Agostinho et al. (2019)
	Annual flow	2.49E+09	J/ha/year	
	UEV	8.72E+06	sej/J	Bonilla et al. (2010)
	Emergy	2.17E+16	sej/ha/year	

*Human labor = (((19 * 220)+(2 * 25)) * 2.92E+02 * 8 * 4.18E+03* / (3.64 productive area))) * 0.22* 8.72E+06 = 2.17E+16 sej/ha/year*

31	**Services**			
	Quantity	1.11E+06	$	
	Renewable fraction	15.00	%	Giannetti et al. (2018)
	Annual flow	4.56E+04	$/ha/year	
	UEV	5.61E+12	sej/$	Giannetti et al. (2018)
	Emergy	2.56E+17	sej/ha/year	

*Services = (1.11E+06/(3.64 productive area))*0.15*5.61E+12 = 2.56E+17 sej/ha/year*

32	**Human labor**			
	Man-works fixed	19	persons	
	Man-works temporary	2	persons	
	Calories	292	kcal/hour	
	Work-hour	8	hours/day	
	Days of fixed labor	220	days/person/year	
	Days of temporary labor	25	days/person/year	

	Annual work	9.86E+06	kcal/year	
	Conversion to J	4.18E+03	J/kcal	
	Non-renewable fraction	78.00	%	Agostinho et al. (2019)
	Annual flow	8.84E+09	J/ha/year	
	UEV	8.72E+06	sej/J	Bonilla et al. (2010)
	Emergy	7.71E+16	sej/ha/year	

*Human labor = (((19 * 220)+(2 * 25)) * 2.92E+02 * 8 * 4.18E+03* / (3.64 productive area))) * 0.78 * 8.72E+06 = 7.71E+16 sej/ha/year*

33	**Services**			
	Quantity	1.11E+06	$	
	Renewable fraction	85.00	%	Giannetti et al. (2018)
	Annual flow	2.59E+05	$/ha/year	
	UEV	5.61E+12	sej/$	Giannetti et al. (2018)
	Emergy	1.45E+18	sej/ha/year	

*Services = (1.11E+06/(3.64 productive area))*0.85*5.61E+12 = 1.45E+18 sej/ha/year*

	Outputs			
34	**Dehydrated seaweed**			
	Harvest biomass	5.27E+08	g/year	
	Annual flow	1.45E+08	g/ha/year	
	Self-consumption	0.00	%	
	UEV	1.25E+10	sej/g	Present study
	Emergy	1.82E+18	sej/ha/year	

*Dehydrated seaweed= (5.27E+08 / (3.64productive area))*1.25E+10 = 1.82E+18 sej/ha/year*

Table 6. The initial investments cost to the seaweed land-based farming for the human consumption market. Comparison of the base scenario and different management strategies. Human consumption base scenario (HC); Human consumption using less and recycled plastic (HC_{pr}); Human consumption with biofuel (HC_{fc}); Human consumption using less and recycled plastic and biofuel (HC_T).

Items	HC		HC_{pr}; HC_{fc}; HC_T	
	US$	%	US$	%
100 mm PVC pipes *	3,814	0.21	3,814	0.21
4mm braided polypropylene rope*	12,732	0.71	19,099	1.05
Wooden stakes*	428	0.02	428	0.02
PET bottle*	251	0.01	251	0.01
Concrete anchor**	1,152	0.06	1,152	0.06
Marine plywood**	149	0.01	149	0.01
Wooden rafter**	59	0.00	59	0.00
5/16 Iron rod**	8	0.00	8	0.00
3hp pressure washer**	558	0.03	558	0.03
200kg capacity scale**	186	0.01	186	0.01
75 hp water pump**	3,625	0.20	3,625	0.20
50 hp centrifugal pump**	14,870	0.82	14,870	0.82
Notebook **	1,301	0.07	1,301	0.07
Inkjet printer**	93	0.01	93	0.01
Multiparameter probe**	617	0.03	617	0.03
2000L fiber tank**	520	0.03	520	0.03
Plastic platform**	11	0.00	11	0.00
Brass shelf**	7	0.00	7	0.00
Lawn mower**	167	0.01	167	0.01
Drill**	65	0.00	65	0.00
Knife**	33	0.00	33	0.00
Wooden shelf**	37	0.00	37	0.00
3/4 plastic hose*	37	0.00	37	0.00
Diving kit*	1,175	0.07	1,175	0.06
Circular saw**	167	0.01	167	0.01
Extension cables**	669	0.04	669	0.04
Life jacket**	297	0.02	297	0.02
Pickup truck**	18,703	1.04	18,703	1.03
Office and warehouse**	10,443	0.58	10,443	0.58
Shed**	12,040	0.67	12,040	0.66
Concrete tanks **	3,470	0.19	3,470	0.19
Land***	1,614,312	89.48	1,614,312	89.15
Project cost	102,120	5.66	102,502	5.66
Total	**1,804,118**	**100.00**	**1,810,866**	**100.00**
Total (R$/ha)	**496,018**		**497,874**	

* Useful life estimated at 5 years; ** Useful life estimated at 10 years; *** Useful life estimated at 10 years

Table 7. Annual costs (US$) and the percentage (%) of operating costs for sale to seaweed land-based farming for the human consumption market. Comparison of the base scenario and different management strategies. Human consumption base scenario (HC); Human consumption using less and recycled plastic (HC_{pr}); Human consumption with biofuel (HC_{fc}); Human consumption using less and recycled plastic and biofuel (HC_T).

Itens description	**Unit**	**Price/Unit**	**HC**			**HC_{pr}**			**HC_{fc}**			**HC_T**		
		(US$)	**Quantity**	**Total Cost**	**%**	**Quantity**	**Total Cost**	**%**	**Quantity**	**Total Cost**	**%**	**Quantity**	**Total Cost**	**%**
Variable cost				**1,098,102**	**92.4**		**1,099,861**	**92.4**		**1,098,145**	**92.4**		**1,099,903**	**92.4**
Electricity	kWh	2.95	600	1,768	0.1	600	1,768	0.1	600	1,768	0.1	600	1,768	0.1
Gasoline	L	1.19	4,000	4,773	0.4	4,000	4,773	0.4	-	-	-	-	-	-
Ethanol	L	0.93	-	-	-	-	-	-	5,200	4,813	0.4	5,200	4,813	0.4
50 kg raffia bags	unit	0.01	5,271,552	58,791	4.9	5,271,552	58,791	4.9	5,271,552	58,791	4.9	5,271,552	58,791	4.9
Lime	kg	0.16	3,060	483	0.0	3,060	483	0.0	3,060	483	0.0	3,060	483	0.0
Sunscreen	kg	18.59	12	223	0.0	12	223	0.0	12	223	0.0	12	223	0.0
PPE hat	unit	2.60	40	104	0.0	40	104	0.0	40	104	0.0	40	104	0.0
Plastic ribbon	kg	3.72	751	2,792	0.2	-	-	-	751	2,792	0.2	-	-	-
Cotton yarn	kg	5.95	-	-	-	751	4,467	0.4	-	-	-	751	4,467	0.4
PPE dive boots	unit	9.29	80	743	0.1	80	743	0.1	80	743	0.1	80	743	0.1
PPE pants	unit	7.43	120	892	0.1	120	892	0.1	120	892	0.1	120	892	0.1
PPE T-shirts	unit	5.58	120	669	0.1	120	669	0.1	120	669	0.1	120	669	0.1
PPE sunglasses	unit	1.49	80	119	0.0	80	119	0.0	80	119	0.0	80	119	0.0
Eventual labor	daily	13.94	50	697	0.1	50	697	0.1	50	697	0.1	50	697	0.1
Rural Social Security Special Contribution[a]				201,955	17.0	0	201,955	17.0	0	201,955	17.0	0	201,955	17.0
Tax on the sale of the product[b]				771,802	64.9	0	771,802	64.8	0	771,802	64.9	0	771,802	64.8
General costs[c]				52,291	4.4	0	52,374	4.4	0	52,293	4.4	0	52,376	4.4
Fixed cost				**90,723**	**7.6**		**90,723**	**7.6**		**90,723**	**7.6**		**90,723**	**7.6**
Vehicle property tax[d]				390	0.0		390	0.0		390	0.0		390	0.0
Rural Land Tax (ITR)				406	0.0		406	0.0		406	0.0		406	0.0
Environmental tax Ibama/CONAMA				1,012	0.1		1,012	0.1		1,012	0.1		1,012	0.1

Occupancy Tax (SPU)				1,561	0.1	1,561	0.1	1,561	0.1	1,561	0.1
Field operator	annual wage	3,240.86	16	51,854	4.4	51,854	4.4	51,854	4.4	51,854	4.4
Foreman	annual wage	4,325.28	2	8,651	0.7	8,651	0.7	8,651	0.7	8,651	0.7
Production manager	annual wage	7,703.35	1	7,703	0.6	7,703	0.6	7,703	0.6	7,703	0.6
Pro labore	annual wage	14,498.14	1	14,498	1.2	14,498	1.2	14,498	1.2	14,498	1.2
Licensing				4,647	0.4	4,647	0.4	4,647	0.4	4,647	0.4
Maintenance [e]				34,040		34,167		34,040		34,167	
Annual depreciation				26,755		28,029		26,755		28,029	
Interest on working capital [f]				81,732		81,853		81,735		81,856	
Remuneration on fixed capital [g]				124,033		124,497		124,033		124,497	
Remunerations of the entrepreneur				40,892		40,892		40,892		40,892	
Remuneration on land				100,372		100,372		100,372		100,372	
Total Production Cost (TPC)				**2,785,474**		**2,790,978**		**2,785,562**		**2,791,065**	

[a] 3.14% of gross revenue; [b] 12% of gross revenue; [c] 5% of variable cost; [d] 4% of vehicle value; [e] 2% of investments; [f] 13.75% a.a. on haf of the effective operational cost; [g] 13.75% on haf fixed investments

Table 8. Calculations for the seaweed land-based farming for liquid biostimulant industry.

Note	Item	Value	Unit	Reference
	Inputs			
1	**Sun**			
	Insolation	8.96E+13	J/ha/year	EMBRAPA (2004)
	Solar transmittance coefficient	81.6	%	Sangpradit (2014)
	Annual flow	7.31E+13	J/ha/year	
	UEV	1.00E+00	sej/J	By definition
	Emergy	7.31E+13	sej/ha/year	
	Sun = (8.96E+13 J/ha/year)(0.8 absorbed)*(1.00E+00) = 7.31E+13 sej/ha/year*			
2	**Wind**			
	Density of air	1.20E+00	kg/m³	
	Wind velocity	2.83E+00	m/s	INMET (2022)
	Time	3.15E+07	s	
	Drying area	5.65E+01	m²	
	Annual flow	4.56E+08	J/ha/year	
	UEV	1.28E+03	sej/J	Giannetti et al. (2019)
	Emergy	5.84E+11	sej/ha/year	
	Wind = ((((0.5)(1.20)*(5.65E+01)*(2.83^3))/1000*24 hours)*(3.60E+06 J/kWh)*(5days)*(5 cycles))/(3.64 productive area)*(1.28E+03) = 5.84E+11 sej/ha/year*			
3	**Rain**			
	Annual average rainfall	1.30E+03	mm/ano	EMBRAPA (2004)
	Annual average rainfall	1.30E+04	m³/ha/ano	
	Water density	1.00E+03	kg/m³	
	Water energy	5.00E+03	J/kg	Gibbs energy
	Annual flow	6.50E+10	J/ha/year	
	UEV	9.71E+03	sej/J	Giannetti et al. (2019)
	Emergy	6.31E+14	sej/ha/year	
	*Rain = (1.30E+04)*1.00E+03*5.00E+03 = 6.31E+14 sej/ha/year*			
4	**Fresh water**			
	Quantity	5.49E+01	m³/ha/ano	
	Water density	1.00E+03	kg/m³	
	Water energy	5.00E+03	J/kg	Gibbs energy
	Annual flow	2.75E+08	J/ha/ano	
	UEV	6.55E+04	sej/J	Giannetti et al. (2019)
	Emergy	1.80E+13	sej/ha/year	
	*Fresh water = 5.49E+01*1.00E+03*5.00E+03*6.55E+04 = 1.80E+13 sej/ha/year*			
5	**Nitrogen**			
	Nutrient concentration	5.50E+00	g/kg	
	Seaweed annual dried biomass	1.45E+05	kg/ha/year	
	Annual flow	7.97E+05	g/ha/year	
	UEV	1.14E+09	sej/g	Odum and Arding (1991)
	Emergy	9.11E+14	sej/g/year	
	*Nitrogen = 5.50E+00*3.65E+04*1.14E+09 = 9.11E+14 sej/ha/year*			
6	**Phosphate**			
	Nutrient concentration	3.00E-01	g/kg	
	Seaweed annual dried biomass	1.45E+05	kg/ha/year	
	Annual flow	4.34E+04	g/ha/year	
	UEV	1.03E+10	sej/g	Odum and Arding (1991)

	Emergy	4.47E+14	sej/g/year	

*Phosphate = 3.00E-01*3.65E+04*1.03E+10 = 4.47E+14 sej/ha/year*

7	**Estuarine water**			
	Seaweed water biomass	2.40E+06	kg/ano	
	Water density	1.00E+03	kg/m³	
	Seaweed biomass water	2.39E+03	m³/ha/ano	
	Transformation	3.00E+06	J/m³	Odum andArding (1991)
	Annual flow	7.18E+09	J/ha/year	
	UEV	4.05E+04	sej/J	Giannetti et al. (2019)
	Emergy	2.91E+14	sej/ha/year	

*Estuarine water = ((2.40E+06/1.00E+03)/(3.64 productive area)) * 4.05E+04 = 2.91E+14 sej/ha/year*

8	**Ground water**			
	Quantity	8.05E+02	m³/ha/ano	
	Water density	1.00E+03	kg/m³	
	Water energy	5.00E+03	J/kg	
	Annual flow	4.02E+09	J/ha/ano	
	UEV	7.67E+04	sej/J	Giannetti et al. (2019)
	Emergy	3.09E+14	sej/ha/year	

*Ground water = (8.05E+02*1.00E+03*5.00E+03)*7.67E+04 = 3.09E+14 sej/ha/year*

9	**Soil occupation**			
	Soil erosion rate	1.00E-04	g/m²/ano	Labrière et al. (2015)
	Percentage of organic soil	1.49	%	Jimenez et al. (2021)
	Organic soil energy	5.40E+00	kcal/g	Brandt-Williams (2002)
	Top soil liquid loss	3.64E+00	g/ano	
	Transformation	4.19E+03	kcal/J	
	Annual flow	1.23E+03	J/ha/year	
	UEV	9.38E+04	sej/J	Odum (1996)
	Emergy	1.15E+08	sej/ha/year	

*Soil occupation = (((3.64 productive area) * 100000) * 1.00E-04) * (0.0149) * 5.40E+00 * 4.19E+03 * 9.38E+04) = 1.15E+08 sej/ha/year*

10	**Electricity**			
	Quantity	2.16E+09	J	
	Renewable fraction	68	%	Giannetti et al. (2015)
	Annual flow	4.04E+08	J/ha/year	
	UEV	2.06E+05	sej/J	Giannetti et al. (2019)
	Emergy	8.31E+13	sej/ha/year	

*Electricity = (2.16E+09/(3.64 productive area)) * 0.68 * 2.06E+05 = 8.31E+13 sej/ha/year*

11	**Salt**			
	Quantity	4.51E+09	g	
	Renewable fraction	41.09	%	Laganis and Debeljak (2006)
	Annual flow	5.09E+08	g/ha/year	
	UEV	7.94E+08	sej/g	Laganis and Debeljak (2006)
	Emergy	4.04E+17	sej/ha/year	

*Salt = (4.51E+09/(3.64 productive area)) * 0.41 * 7.94E+08 = 4.04E+17 sej/ha/year*

12	**Cotton**			
	Quantity	1.20E+05	g	
	Renewable fraction	33.69	%	Blatt and Almeida (2017)
	Annual flow	1.11E+04	g/ha/year	

	UEV	1.45E+09	sej/g	Blatt and Almeida (2017)
	Emergy	1.61E+13	sej/ha/year	

*Cotton = (1.20E+05/(3.64 productive area)) * 0.34 * 1.45E+09 = 1.61E+13 sej/ha/year*

13	**Electricity**			
	Quantity	2.16E+09	J	
	Non-renewable fraction	32	%	Giannetti et al. (2015)
	Annual flow	1.90E+08	J/ha/year	
	UEV	2.06E+05	sej/J	Giannetti et al. (2019)
	Emergy	3.91E+13	sej/ha/year	

*Electricity = (2.16E+09/(3.64 productive area)) * 0.32 * 2.06E+05 = 3.91E+13 sej/ha/year*

14	**Plastic (Materials)**			
	Quantity	3.48E+11	J	
	Annual flow	9.56E+10	J/ha/year	
	UEV	1.92E+05	sej/J	Giannetti et al. (2019)
	Emergy	1.84E+16	sej/ha/year	

*Plastic (Materials) = (3.48E+11/(3.64 productive area))*1.92E+05 = 1.84E+16 sej/ha/year*

15	**Limestone**			
	Quantity	2.93E+06	g	
	Conversion to joules	6.11E+02	J/g	
	Annual flow	4.92E+08	J/ha/ano	
	UEV	1.23E+06	sej/J	Odum et al., (2000)
	Emergy	6.04E+14	sej/ha/year	

*Limestone = (2.93E+06*6.11E+02/(3.64 productive area))*1.23E+06 = 6.04E+14 sej/ha/year*

16	**Gasoline**			
	Quantity	1.22E+11	J	
	Annual flow	3.36E+10	J/ha/year	
	UEV	4.16E+04	sej/J	Giannetti et al. (2019)
	Emergy	1.40E+15	sej/ha/year	

*Gasoline = (1.22E+11/(3.64 productive area))*4.16E+04 = 1.40E+15 sej/ha/year*

17	**Salt**			
	Quantity	4.51E+09	g	
	Renewable fraction	58.91	%	Laganis and Debeljak (2006)
	Annual flow	7.29E+08	g/ha/year	
	UEV	7.94E+08	sej/g	Laganis and Debeljak (2006)
	Emergy	5.79E+17	sej/ha/year	

*Salt = (4.51E+09/(3.64 productive area)) * 0.59 * 7.94E+08 = 5.79E+17 sej/ha/year*

18	**Rubber (Materials)**			
	Quantity	2.40E+03	g	
	Annual flow	6.59E+02	g/ha/year	
	UEV	7.94E+08	sej/g	Laganis and Debeljak (2006)
	Emergy	5.24E+11	sej/ha/year	

*Rubber = (2.40E+03/(3.64 productive area))*5.47E+09 = 5.24E+11 sej/ha/year*

19	**Cotton**			
	Quantity	1.20E+05	g	
	Non-renewable fraction	66.31	%	Blatt and Almeida (2017)
	Annual flow	2.19E+04	g/ha/year	
	UEV	1.45E+09	sej/g	Blatt and Almeida (2017)

	Emergy	3.17E+13	sej/ha/year	
	*Cotton = (1.20E+05/(3.64 productive area)) * 0.66 * 1.45E+09 = 7.99E+12 sej/ha/year*			
20	**Steel**			
	Quantity	1.97E+07	g	
	Lifetime	10	years	
	Renewable fraction	4.31	%	Pan et al. (2016)
	Annual flow	2.33E+04	g	
	UEV	2.29E+09	sej/g	Brown and Bardi (2001)
	Emergy	5.33E+13	sej/ha/year	
	*Steel = ((1.97E+07/(3.64 productive area))/10)*0.04*2.29E+09 = 5.33E+13 sej/ha/year*			
21	**Cement**			
	Quantity	1.61E+06	g	
	Lifetime	10	years	
	Renewable fraction	9.96	%	Asgharipour et al. (2020)
	Annual flow	4.42E+03	g/ha/year	
	UEV	2.52E+09	sej/g	Buranakan (1998)
	Emergy	1.11E+13	sej/ha/year	
	*Cement = ((1.61E+06/(3.64 productive area))/10)*0.10*2.52E+09 = 1.11E+13 sej/ha/year*			
22	**Plastic (Equipments and Infrastructure)**			
	Quantity	3.77E+11	J	
	Lifetime	5	years	
	Annual flow	2.07E+10	J/ha/ano	
	UEV	1.92E+05	sej/J	Giannetti et al. (2019)
	Emergy	3.98E+15	sej/ha/year	
	*Plastic = ((3.77E+11/(3.64 productive area))/5)*1.92E+05 = 3.98E+15 sej/ha/year*			
23	**Iron**			
	Quantity	1.67E+06	g	
	Lifetime	5	years	
	Annual flow	9.20E+04	g/ha/ano	
	UEV	4.15E+09	sej/g	Oliveira et al. (2018)
	Emergy	3.82E+14	sej/ha/year	
	*Iron = ((1.67E+06/(3.64 productive area))/5)*4.15E+09 = 3.82E+14 sej/ha/year*			
24	**Steel**			
	Quantity	1.97E+07	g	
	Lifetime	10	years	
	Non-renewable fraction	95.69	%	Pan et al. (2016)
	Annual flow	5.17E+05	g/ha/ano	
	UEV	2.29E+09	sej/g	Brown and Bardi (2001)
	Emergy	1.18E+15	sej/ha/year	
	*Steel = ((1.97E+07/(3.64 productive area))/10)*0.96*2.29E+09 = 1.18E+15 sej/ha/year*			
25	**Wood**			
	Quantity	2.64E+10	J	
	Lifetime	10	years	
	Annual flow	7.27E+08	J/ha/ano	
	UEV	2.85E+05	sej/J	Buranakan (1998)
	Emergy	2.07E+14	sej/ha/year	
	*Wood = ((2.64E+10/(3.64 productive area))/10)*2.85E+05 = 2.07E+14 sej/ha/year*			
26	**Concrete**			
	Quantity	3.72E+07	g	
	Lifetime	10	years	

	Annual flow	1.02E+06	g/ha/ano	
	UEV	1.83E+09	sej/g	Buranakan (1998)
	Emergy	1.87E+15	sej/ha/year	

*Concrete = ((3.72E+07/(3.64 productive area))/10)*1.83E+09 = 1.87E+15 sej/ha/year*

27	**Cement**			
	Quantity	1.61E+06	g	
	Lifetime	10	years	
	Non-renewable fraction	90.04	%	Asgharipour et al. (2020)
	Annual flow	3.99E+04	g/ha/year	
	UEV	2.52E+09	sej/g	Buranakan (1998)
	Emergy	1.00E+14	sej/ha/year	

*Cement = ((1.61E+06/(3.64 productive area))/10)*0.90*2.52E+09 = 1.00E+14 sej/ha/year*

28	**Glass fiber**			
	Quantity	1.79E+05	g	
	Lifetime	10	years	
	Annual flow	4.93E+03	g/ha/year	
	UEV	2.27E+09	sej/g	Ulgiati and Brown (2002)
	Emergy	1.12E+13	sej/ha/year	

*Glass fiber = ((1.79E+05/(3.64 productive area))/10)*2.27E+09 = 1.12E+13 sej/ha/year*

29	**Rubber (Equipments and Infrastructure)**			
	Quantity	6.08E+04	g	
	Depreciation	5	years	
	Annual flow	3.34E+03	g/ha/year	
	UEV	5.47E+09	sej/g	Buranakan (1998)
	Emergy	1.82E+13	sej/ha/year	

*Rubber = ((6.08E+04/(3.64 productive area))/5)*5.47E+09 = 1.82E+13 sej/ha/year*

30	**Aluminum ingot**			
	Quantity	1.56E+06	g	
	Lifetime	10	years	
	Annual flow	4.28E+04	g/ha/year	
	UEV	1.49E+10	sej/g	Buranakan (1998)
	Emergy	6.37E+14	sej/ha/year	

*Aluminum ingot = ((1.56E+06/(3.64 productive area))/10)*1.49E+10 = 6.37E+14 sej/ha/year*

31	**Human labor**			
	Man-works fixed	19	persons	
	Man-works temporary	9	persons	
	Calories	2.92E+02	kcal/hour	
	Work-hour	8	hours/day	
	Days of fixed labor	220	days/person/year	
	Days of temporary labor	25	days/person/year	
	Annual work	1.03E+07	kcal/year	
	Conversion to J	4.18E+03	J/kcal	
	Renewable fraction	22.00	%	Agostinho et al. (2019)
	Annual flow	2.60E+09	J/ha/year	
	UEV	8.72E+06	sej/J	Bonilla et al. (2010)
	Emergy	2.26E+16	sej/ha/year	

*Human labor = (((19 * 220)+(9 * 25)) * 2.92E+02 * 8 * 4.18E+03* / (3.64 productive area))) * 0.22* 8.72E+06 = 2.26E+16 sej/ha/year*

32	**Services**			
	Quantity	3.43E+07	$	

	Renewable fraction	15.00	%	Giannetti et al. (2018)
	Annual flow	1.42E+06	$/ha/year	
	UEV	5.61E+12	sej/$	Giannetti et al. (2018)
	Emergy	7.94E+18	sej/ha/year	

*Services = (3.43E+07/(3.64 productive area))*0.15*5.61E+12 = 7.94E+18 sej/ha/year*

33	**Human labor**			
	Man-works fixed	19	persons	
	Man-works temporary	9	persons	
	Calories	292	kcal/hour	
	Work-hour	8	hours/day	
	Days of fixed labor	220	days/person/year	
	Days of temporary labor	25	days/person/year	
	Annual work	10272460	kcal/year	
	Conversion to J	4184	J/kcal	
	Non-renewable fraction	78.00	%	Agostinho et al. (2019)
	Annual flow	9.21E+09	J/ha/year	
	UEV	8.72E+06	sej/J	Bonilla et al. (2010)
	Emergy	8.03E+16	sej/ha/year	

*Human labor = (((19 * 220)+(9 * 25)) * 2.92E+02 * 8 * 4.18E+03* / (3.64 productive area))) * 0.78 * 8.72E+06 = 8.03E+16 sej/ha/year*

34	**Services**			
	Quantity	3.43E+07	$	
	Non-renewable fraction	85.00	%	Giannetti et al. (2018)
	Annual flow	8.02E+06	$/ha/year	
	UEV	5.61E+12	sej/$	Giannetti et al. (2018)
	Emergy	4.50E+19	sej/ha/year	

*Services = (3.43E+07/(3.64 productive area))*0.85*5.61E+12 = 4.50E+19 sej/ha/year*

	Outputs			
35	**Liquid biostimulant**			
	Produced volume	2.34E+06	L/year	
	Annual flow	6.44E+05	L/ha/year	
	Self-consumption	0	%	
	UEV	8.40E+13	sej/L	Present study
	Emergy	5.40E+19	sej/ha/year	

*Liquid biostimulant = (2.34E+06 / (3.64 productive area))*8.40E+13 = 5.40E+19 sej/ha/year*

36	**Biocompound**			
	Biocompound biomass	4.50E+06	g/ha/year	
	Annual flow	1.24E+06	g/ha/year	
	Self-consumption	0	%	
	UEV	4.37E+10	sej/g	Present study
	Emergy	5.40E+16	sej/ha/year	

*Biocompound = (4.50E+06 / (3.64 productive area))*4.37E+10 = 5.40E+16 sej/ha/year*

37	**Dried and bleached seaweed**			
	Harvest biomass	1.45E+07	g/year	
	Annual flow	1.18E+04	g/ha/year	
	Self-consumption	0	%	
	UEV	3.73E+12	sej/g	Present study
	Emergy	4.42E+16	sej/ha/year	

*Dried and bleached seaweed = (3.65E+06 / (3.64 productivityarea))*3.73E+12 = 4.42E+16 sej/ha/year*

Table 9. The initial investments cost to the seaweed land-based farming for the liquid biostimulant industry considering different scenarios. Liquid biostimulant base scenario (LB); Liquid biostimulant with less and recycled plastic (LB_{pr}); Liquid biostimulant with biofuel (LB_{fc}); Liquid biostimulant with no salt (LB_{sr}); Liquid biostimulant with less and recycled plastic and less and recycled plastic, biofuel and no salt (LB_T).

Items	LB		$LB_{pr};LB_{fc};LB_{sr};LB_T$	
	R$	%	R$	%
100 mm PVC pipes *	3,814	0.20	3,814	0.20
4mm braided polypropylene rope*	12,732	0.67	19,099	1.00
Wooden stakes*	428	0.02	428	0.02
PET bottle*	251	0.01	251	0.01
Concrete anchor**	1,152	0.06	1,152	0.06
Marine plywood**	149	0.01	149	0.01
Wooden rafter**	59	0.00	59	0.00
5/16 Iron rod**	8	0.00	8	0.00
3hp pressure washer**	558	0.03	558	0.03
200kg capacity scale**	186	0.01	186	0.01
75 hp water pump**	3,625	0.19	3,625	0.19
50 hp centrifugal pump**	14,870	0.78	14,870	0.78
Notebook **	1,301	0.07	1,301	0.07
Inkjet printer**	93	0.00	93	0.00
Multiparameter probe**	617	0.03	617	0.03
2000L fiber tank**	520	0.03	520	0.03
Plastic platform**	11	0.00	11	0.00
Brass shelf**	7	0.00	7	0.00
Lawn mower**	167	0.01	167	0.01
Drill**	65	0.00	65	0.00
Knife**	33	0.00	33	0.00
Wooden shelf**	37	0.00	37	0.00
3/4 plastic hose*	37	0.00	37	0.00
Diving kit*	1,175	0.06	1,175	0.06
Circular saw**	167	0.01	167	0.01
Extension cables**	669	0.04	669	0.04
Life jacket**	297	0.02	297	0.02
Pickup truck**	18,703	0.98	18,703	0.98
½ hp industrial blender 25L **	2,602	0.14	2,602	0.14
2hp hydraulic press**	502	0.03	502	0.03
1000L IBC container**	89,219	4.69	89,219	4.67
Office and warehouse**	10,443	0.55	10,443	0.55
Shed**	12,040	0.63	12,040	0.63
Concrete tanks **	3,470	0.18	3,470	0.18
Land***	1,614,312	84.88	1,614,312	84.58
Project cost	107,659	5.66	108,041	5.66
Total	**1,901,980**	**100.00**	**1,908,729**	**100.00**
Total (R$/ha)	**522,924**		**524,780**	

* Useful life estimated at 5 years; ** Useful life estimated at 10 years; *** Useful life estimated at 10 years

Table 10. Annual costs (US$) and the percentage (%) of operating costs for sale to seaweed land-based farming for the liquid biostimulant industry considering different scenarios. Liquid biostimulant base scenario (LB); Liquid biostimulant with less and recycled plastic (LB_{pr}); Liquid biostimulant with biofuel (LB_{fc}); Liquid biostimulant with no salt (LB_{sr}); Liquid biostimulant with less and recycled plastic and less and recycled plastic, biofuel and no salt (LB_T).

Itens description	**Unit**	**Price/Unit**	**LB**			**LBpr**			**LBfc**			**LBsr**			**LBT**		
		US$	**Quantity**	**Total Cost**	**%**	**Quantity**	**Total Cost**	**%**	**Quantity**	**Total Cost**	**%**	**Quantity**	**Total Cost**	**%**	**Quantity**	**Total Cost**	**%**
Variable cost				**1,866,082**	**93.2**		1,867,841	**93.2**		1,866,124	**93.2**		1,133,621	**89.2**		1,126,249	**89.2**
Electricity	kWh	2.95	600	1,768	0.1	600	1,768	0.1	600	1,768	0.1	600	1,768	0.1	600	1,768	0.1
Gasoline	L	1.19	4,000	4,773	0.2	4,000	4,773	0.2	-	-	-	4,000	4,773	0.4	-	-	-
Ethanol	L	0.93	-	-	-	-	-	-	5,200	4,813	0.2	-	-	-	5,200	4,813	0.4
50 kg raffia bags	unit	0.28	1,054	294	0.0	1,054	294	0.0	1,054	294	0.0	1,054	294	0.0	1,054	294	0.0
Lime	kg	0.16	3,060	483	0.0	3,060	483	0.0	3,060	483	0.0	3,060	483	0.0	3,060	483	0.0
Sunscreen	kg	18.59	12	223	0.0	12	223	0.0	12	223	0.0	12	223	0.0	12	223	0.0
PPE hat	unit	2.60	40	104	0.0	40	104	0.0	40	104	0.0	40	104	0.0	40	104	0.0
Plastic ribbon	kg	3.72	751	2,792	0.1	-	-	-	751	2,792	0.1	751	2,792	0.2	-	-	-
Cotton yarn	kg	5.95	-	-	-	751	4,467	0.2	-	-	-	-	-	-	751	4,467	0.4
PPE dive boots	unit	9.29	80	743	0.0	80	743	0.0	80	743	0.0	80	743	0.1	80	743	0.1
PPE pants	unit	7.43	120	892	0.0	120	892	0.0	120	892	0.0	120	892	0.1	120	892	0.1
PPE T-shirts	unit	5.58	120	669	0.0	120	669	0.0	120	669	0.0	120	669	0.1	120	669	0.1
PPE sunglasses	unit	1.49	80	119	0.0	80	119	0.0	80	119	0.0	80	119	0.0	80	119	0.0
Salt	Salt	0.22	811,008	180,894	9.0	811,008	180,894	9.0	811,008	180,894	9.0	-	-	-	-	-	-
20L plastic gallon	unit	9.29	2,636	24,496	1.2	2,636	24,496	1.2	2,636	24,496	1.2	2,636	24,496	1.9	2,636	24,496	1.9
Sodium benzoate	kg	11.15	203	29,395	1.5	203	29,395	1.5	203	29,395	1.5	203	29,395	2.3	203	29,395	2.3
Pure d'limonene	kg	18.59	36	678	0.0	36	678	0.0	36	678	0.0	36	678	0.1	36	678	0.1
Eventual labor			225	3,137	0.2	225	3,137	0.2	225	3,137	0.2	225	3,137	0.2	225	3,137	0.2
Rural Social Security Special Contribution[a]				316,439	15.8		316,439	15.8		316,439	15.8		209,279	16.5		207,467	16.4
Tax on the sale of the product[b]				1,209,321	60.4		1,209,321	60.3		1,209,321	60.4		799,793	62.9		792,868	62.8
General costs[c]				88,861	4.4		88,945	4.4		88,863	4.4		53,982	4.2		53,631	4.2

Fixed cost				**2,003,113**	**6.8**	**2,004,872**	**6.8**	**2,003,155**	**6.8**	**1,270,652**	**10.8**	**1,263,280**	**10.8**
Vehicle property tax[d]				390	0.0	390	0.0	390	0.0	390	0.0	390	0.0
Rural Land Tax (ITR)				406	0.0	406	0.0	406	0.0	406	0.0	406	0.0
Environmental tax Ibama/CONAMA				1,012	0.1	1,012	0.1	1,012	0.1	1,012	0.1	1,012	0.1
Occupancy Tax (SPU)				1,561	0.1	1,561	0.1	1,561	0.1	1,561	0.1	1,561	0.1
Field operator	annual wage	5,776.93	16	92,431	4.6	92,431	4.6	92,431	4.6	92,431	7.3	92,431	7.3
Foreman	annual wage	6,519.09	2	13,038	0.7	13,038	0.7	13,038	0.7	13,038	1.0	13,038	1.0
Production manager	annual wage	9,046.84	1	9,047	0.5	9,047	0.5	9,047	0.5	9,047	0.7	9,047	0.7
Pro labore	annual wage	14,498.14	1	14,498	0.7	14,498	0.7	14,498	0.7	14,498	1.1	14,498	1.1
Licensing				4,647	0.2	4,647	0.2	4,647	0.2	4,647	0.4	4,647	0.4
Maintenance [e]				35,886		36,014		35,886		35,886		36,014	
Annual depreciation				45,170		46,443		45,170		45,170		46,443	
Interest on working capital [f]				137,714		137,835		137,717		87,357		86,850	
Remuneration on fixed capital [g]				130,761		131,225		130,761		130,761		131,225	
Remunerations of the entrepreneur				40,892		40,892		40,892		40,892		40,892	
Remuneration on land				100,372		100,372		100,372		100,372		100,372	
Total Production Cost (TPC)				**4,497,021**		**4,502,524**		**4,497,108**		**2,981,743**		**2,968,356**	

[a] 3.14% of gross revenue; [b] 12% of gross revenue; [c] 5% of variable cost; [d] 4% of vehicle value; [e] 2% of investments; [f] 13.75% a.a. on haf of the effective operational cost; [g] 13.75% on haf fixed investments

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DISCUSSÃO GERAL

A Síntese Emergética é uma ferramenta eficiente para avaliar a sustentabilidade dos sistemas de produção aquícola considerando seus aspectos ecossistêmicos. Essa ferramenta possibilitou uma visão holística do sistema de cultivo e a identificação dos principais itens que afetam a sustentabilidade. A Síntese Emergética tem a perspectiva biofísica, baseada no valor ecossistêmico dos recursos da natureza e da economia (Odum 1996). Essa perspectiva é diferente da economia atual vigente, a qual se baseia no sistema capitalista pós Segunda Guerra (OECD, 1999). Esse aspecto faz com que a Síntese Emergética sozinha não seja a ferramenta mais adequada para mensurar os sistemas produtivos hoje, visto que a viabilidade econômica, um importante aspecto da sustentabilidade, precisa ser medida conforme a economia vigente, que é a neoclássica. Por isso, é importante realizar uma análise exploratória da sustentabilidade usando mais de uma ferramenta, para reduzir as limitações que possam ser apresentadas. Na literatura, foram encontrados trabalhos que mediram a sustentabilidade de sistemas de produção de macroalgas por meio do conjunto de indicadores (Pereira et al., 2021) e Análise do Ciclo de Vida (ACV) combinada com análise econômica (Collins et al., 2022). Pereira et al., 2021 aborda de maneira completa a sustentabilidade do cultivo de macroalgas em seus diferentes aspectos ambientais, econômicos e sociais. De modo geral, o conjunto de indicadores proposto por Valenti et al. (2018) atendem bem a sustentabilidade com uma abordagem merística, dividindo os sistemas nas três dimensões e uma medida individualizada dos elementos que compõem cada dimensão. Além disso, a dimensão econômica considera a contribuição da natureza para o sistemas de produção por meio do conceito de externalidades (Pigou, 2005). A ACV é um método padronizado que aborda da perspectiva mais ambiental a sustentabilidade dos sistemas (Ciambrone,1997). A combinação da ACV com a análise econômica trouxe informações interessantes sobre as emissões de CO_2 do cultivo de algas e contribuições econômicas do cultivo (Collins at al., 2022), porém não trouxe uma abordagem completa, pensando na dimensão social da sustentabilidade. A atual economia baseada no capitalismo gerou uma crise ecossistêmica e econômica para o mundo, sentida principalmente pelos países de “terceiro mundo” com a industrialização descontrolada gerando uma crise ecológica de escassez,

distribuição e abundância (OECD, 1999). Assim, a associação da Síntese Emergética (perspectiva biofísica) com a análise econômica (neoclássica – capitalista) foi capaz de nos proporcionar uma visão conciliada entre os diferentes sistemas. O presente estudo indica que a metodologia da Síntese Emergética é complementada com a análise econômica neoclássica, garantindo informações consistentes para uma melhor tomada de decisão quanto à sustentabilidade da atividade.

A Síntese Emergética é uma ferramenta que é cada vez mais utilizada para avaliar a sustentabilidade de diferentes sistemas aquícolas (David et al. 2021; Morales et al. 2022). Apesar de servir para comparar produtos e sistemas, observamos uma dificuldade na comparação dos sistemas aquícolas. Isso se deve aos diferentes itens que são contabilizados no momento do inventário nos diferentes trabalhos publicados. A flexibilidade da ferramenta e a priorização dos inputs essenciais para serem contabilizados pelo pesquisador, em cada tipo de sistema, abre possibilidade para pesquisadores não contabilizarem itens que são indispensáveis para os sistemas aquícolas de um modo geral. Um exemplo é a água, a qual não é considerada como input em alguns trabalhos que avaliam a síntese emergética (Morales et al., 2022). Desse modo, é necessário fazer uma análise crítica dos estudos antes de utilizá-los como comparativos. No entanto, a perspectiva é que os grupos que aplicam a síntese emergética na aquicultura se formem e consigam se organizar melhor quanto a trabalhos futuros (Morales et al., 2022). No geral, observamos como os principais recursos da natureza a serem considerados no sistema de cultivo de macroalgas: circulação oceânica, vento, água absorvida pela biomassa colhida, sol, CO_2 atmosférico, e nutrientes absorvidos pela biomassa. Já os principais itens da economia são: mão de obra, o material das estruturas de cultivo, infraestrutura geral, combustível (quando aplicável), mudas (quando houver propagação sexuada em laboratório), e ocupação de solo (quando o cultivo for em terra).

A Síntese Emergética mostrou que o cultivo de macroalgas no mar pode apresentar elevada sustentabilidade com o Índice de Sustentabilidade Emergética (ESI) de 30,36 para o mercado da carragena e de 29,17 para o consumo humano. No entanto a sustentabilidade é mais reduzida para a fabricação do extrato glicólico, com o .ESI de 0,31. Mudanças estratégicas como redução do uso do

plástico e do tempo de cultivo combinadas podem aumentar a sustentabilidade do sistema. A análise econômica do cultivo no mar mostrou que o mercado de carragena não é economicamente viável, diferentemente dos mercados de consumo humano e extrato glicólico apresentam viabilidade econômica.

O cultivo de macroalgas em terra apresentou baixo sustentabilidade com o Índice de Sustentabilidade Emergética de 0,22 de para os mercados de carragena, consumo humano e bioestimulantes. O cenário dos bioestimulantes não melhorou os índices de sustentabilidade, mesmo produzindo três produtos diferentes. Mudanças como redução do uso do plástico, combustível mais renovável não surtiram efeito sobre os índices de sustentabilidade. Foi observada uma elevada dependência do item da economia “serviços”, o que sugere a contribuição do empreendimento com a geração de trabalho e renda para a comunidade local. A análise econômica mostrou viabilidade financeira para todos os mercados analisados. No entanto, ressaltamos que a produtividade considerada para a espécie foi maior do que a literatura, havendo riscos econômicos para o produtor em caso de perda igual ou superior a 30%.

Os cultivos de macroalgas não apresentam grandes volumes de inputs da econômia comparado com outros sistemas aquícolas e agrícolas, como por exemploração e fertilizantes (Pereira et al., 2021). Desse modo, se evidenciam outros inputs como mão de obra e materiais plásticos utilizados no cultivo. Existe uma similaridade entre os sistemas de cultivo de macroalgas no mar e na terra que é a demanda de materiais plásticos nas estruturas de cultivo. O plástico já foi apontado como um item crítico em estudo prévio da sustentabilidade do cultivo de macroalgas no mar (Collins et al. 2022). Uma solução proposta é a troca das cordas e cabos tradicionais por feitos de material de 80% de material reciclado. No entanto, fontes de plastico alternativos como bioplático e reciclados ainda são pouco utilizados na aquicultura devido a disponibilidade no mercado e ao valor mais elevado (Arantzamendi et al., 2023). O cultivo no mar tem menor impacto dos itens de serviços como infraestrutura e materiais de consumo quando comparado com o cultivo em terra. De modo geral, os produtos a base de algas foram alternativas mais sustentáveis a produtos similares nos diferentes mercados analisados Duarte et al. (2022) apontam que produtos à base de macroalgas podem apresentar menor pegada de carbono e contribuir para a

redução das emissões de carbono e colaborar com os ODSs da ONU. Na presente tese, podemos comprovar que as algas como vegetais são alternativas sustentáveis em relação à produção de vegetais folhosos terrestres, e o bioestimulante de algas pode ser um complemento importante e com Índice de Sustentabilidade Emergética de 0,22, mais elevado que os fertilizantes agrícolas convencionais de 0,02, o que pode representar um uso complementar dos dois tipos de produtos. No entanto, como apontado por Collins et al. (2022) que estudou a ACV do cultivo de macroalgas, as mudanças de espécies, localização do cultivo e uso de insumos podem impossibilitar a comparação de sistemas ou produtos similares. Assim, é recomendável uma análise crítica dos resultados no momento da comparação com demais trabalhos encontrados na literatura. Outra comparação que não é possível realizar é o risco do uso de espécies exóticas, o que não é avaliado na síntese emergética, mas sim na análise do conjunto de indicadores.

Os resultados apresentados demonstraram altos indicadores emergéticos para sustentabilidade do sistema de cultivo de macroalgas no mar com o ESI entre 0,31 e 30,36, e baixa sustentabilidade do cultivo em terra com ESI de 0,22. Sob a perspectiva econômica clássica, ambos sistemas de cultivo podem ser sustentáveis, dependendo do mercado alvo. A baixa performance dos índices emergéticos pode estar relacionada com fatores chave que geram um grande *input* emergético ou baixa produtividade (Fonseca et al., 2022). O sistema de cultivo de macroalgas é muito simples comparado com outros sistemas de produção, e não apresenta um alto rendimento de biomassa seca, que é como normalmente a macroalga é comercializada ou processada. Além disso, as macroalgas apresentam baixo valor calórico, aumentando assim a transformidade dos produtos. Porém, apesar desses aspectos, é possível observar o potencial de sustentabilidade da atividade. Além disso, as macroalgas são um produto de elevado valor nutritivo e funcional (FAO, 2018). Mais estudos para reduzir os itens críticos do sistema de produção, aumentar a produtividade e gerar tecnologias que viabilizem a integração a outros sistemas aquícolas podem ser itens fundamentais para garantir a sustentabilidade da atividade em terra. Além disso, também são necessários estudos que avaliem a capacidade de suporte das áreas marinhas para o cultivo das macroalgas, uma vez observado o crescente

interesse em se cultivar esses organismos. Os resultados obtidos complementam informações da literatura e trazem uma análise da sustentabilidade dos sistemas que englobam a economia biofísica e neoclássica. Assim, as informações aqui presentes podem auxiliar no desenvolvimento estratégias de manejo, formulações de políticas públicas, desenvolvimento sustentável da algicultura e suporte para mais estudos na área.

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