

Environmental Performance of the Red Macroalgae, *Gracilaria* sp.: A Life Cycle Assessment (LCA) Approach

Razman Pahri Siti-Dina^{1*} and Adibi Md. Nor²

¹Centre for Research in Development, Social and Environment, Faculty of Social Sciences and Humanities, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia

²Institute for Advanced Studies, Universiti Malaya, 50603 Kuala Lumpur, Malaysia

ABSTRACT

The environmental sustainability of seaweed cultivation is gaining increased attention due to its potential to mitigate climate change, reduce eutrophication, and provide renewable biomass. This study assesses the environmental performance of the red seaweed *Gracilaria* sp. using a Life Cycle Assessment (LCA) approach. The analysis encompasses the full cultivation cycle, from seeding to storage, focussing on potential environmental impact categories such as global warming, acidification, eutrophication, ecotoxicity, human carcinogenic and human non-carcinogenic. The functional unit was 1 tonne of dry seaweed. Field data were collected from seaweed aquaculture farms, with a particular focuss on farming systems and environmental outputs, and were analysed using the ReCiPe 2016 v1.1 Midpoint (H) method in SimaPro version 9.3 with the Ecoinvent 3 database. The LCA results indicate the dominance of human carcinogenic impact with 152.98 kg 1,4-DCB, followed by freshwater ecotoxicity with 34.13 kg 1,4-DCB, marine ecotoxicity with 26.83 kg 1,4-DCB and freshwater eutrophication with 24.75 kg P eq. Packaging phase dominates most potential environmental impacts, followed by storage phase compared with other phases. Recommendations for reducing environmental impacts include reducing plastic-based materials, adopting renewable energy sources, integrating multi-trophic aquaculture systems, and conducting further research into nutrient management practices. This study has the potential to be the basis for improving environmental performance in the entire value chain of the seaweed industry towards supporting the implementation of the blue economy and green practices.

ARTICLE INFO

Article history:

Received: 14 December 2024

Accepted: 29 April 2025

Published: 06 February 2026

DOI: <https://doi.org/10.47836/pjst.34.1.11>

E-mail addresses:

sitidina@ukm.edu.my (Razman Pahri Siti-Dina)

adibi@um.edu.my (Adibi Md. Nor)

* Corresponding author

Keywords: Blue economy, environmental impact, *Gracilaria* sp., life cycle assessment

INTRODUCTION

Seaweed, or macroalgae, is a sustainable resource that is increasingly recognised and used with diverse applications in

various industries. Currently, seaweed is being utilised as nutraceuticals, cosmeceuticals, pharmaceuticals, biofuel, feed, food, and hydrocolloids downstream products that contribute to food security (Food and Agriculture Organisation of the United Nations, 2021; Food and Agriculture Organisation of the United Nations & World Health Organisation, 2022; Thierry & Albert, 2020). This commodity acts as food for humans and animals, and non-food applications, such as animal feed additives and fertiliser, generate socioeconomic benefits for many households, especially coastal communities. For other global communities, such as in Japan, consuming seaweed as a main food is associated with the belief that seaweed lowers the rate of cardiovascular disease (FAO, 2021). Seaweed can be sold in two forms, either dried or fresh, and at the downstream level, it is usually processed as carrageenan, agar, and alginate and exported to international markets. Seaweed cultivation has become one of the fastest-growing industries in the global aquaculture sector, with an annual growth rate of 7.3% and accounting for half of overall aquaculture production (FAO, 2022). In 2019, global seaweed trade was valued at USD 5.6 billion, indicating the contribution of this commodity to the global economy (FAO, 2021).

Seaweed is sourced from wild and cultivated areas (García-Poza et al., 2020). Wild production is still prevalent in most Asian countries, even though seaweed has begun to be cultivated (FAO, 2021; Hasselström & Thomas, 2022). According to the FAO (2021), global cultivated seaweed production increased from 4.2 million tonnes of wet weight in the 1990s to 34.7 million tonnes in 2019. This production controls 5.4% of world global production in 2019 (FAO, 2021). Five (5) seaweed species dominate cultivation production, namely *Laminaria / Saccharina* (35.4%), *Kappaphycus / Eucheuma* (33.5%), *Gracilaria* (10.5%), *Porphyra / Pyropia* (8.6%), and *Undaria* (7.4%). Southeast Asia dominates global seaweed production, especially *Kappaphycus / Eucheuma* spp (Kambey et al., 2021). This situation is also driven by the rapid development of the seaweed-based food industry in the Asian Region (Thierry & Albert, 2020).

Seaweed is an export commodity with high potential in Malaysia due to its various uses (Ministry of Agriculture and Food Industry, 2021). Seaweed farming is widely known to be dominated by the Sabah state as a valuable commodity that has brought a tremendous socioeconomic impact to the local community. Sabah is Malaysia's central seaweed-producing state, and this activity started as early as 1978 through various farming systems, such as longline and raft systems (Ahemad et al., 2006; Hanafi & Abdullah, 2017). Sabah's geographical condition facilitates cross-border seaweed production and trade (Asri et al., 2021). However, at that time, the low market value of seaweed became a repelling factor for local people's involvement in seaweed cultivation, and various other challenges were present (Ahemad et al., 2006). Migrants from the Philippines significantly contribute to seaweed cultivation despite security concerns (Asri et al., 2021). Seaweed production in Sabah increased after 1988, but there were fluctuations around 2014 (Hanafi & Abdullah,

2017). Nevertheless, encouragement given by the Government has prioritised promoting seaweed farming as a good source of income for local fishermen until now, reducing the poverty rate and benefiting the restoration of coral reef areas (Ahemad et al., 2006; Asri et al., 2021; Hanafi & Abdullah, 2017).

In 2023, Malaysia's seaweed system produced a substantial 225,077 tm of seaweed, primarily *Kappaphycus* and *Euचेuma* (Department of Fisheries Malaysia, 2023). Malaysia is home to 375 species of seaweed, many of which are underutilised, presenting a significant economic opportunity (Chin et al., 2023). The ideal conditions of Malaysian coastal waters, particularly in Sabah, make a perfect environment for seaweed farming (Hanafi & Abdullah, 2017). Recent studies have focussed on the nutritional value of seaweed to consumers, with brown seaweed being a good source of unsaturated fatty acids, calcium, and potassium, and red seaweed providing essential amino acids (Chin et al., 2023). Among the six Malaysian seaweeds studied, *Gracilaria changii* (*G. changii*), a red seaweed, exhibited the highest total dietary fibre (TDF) content, highlighting its economic potential. This high TDF content makes *G. changii* a valuable dietary fibre source, with potential applications in the food industry and as a nutritional supplement, thereby increasing its economic value and potential impact on the aquaculture industry (Chin et al., 2023).

Gracilaria sp., a red seaweed species abundant in Malaysian waters, including mangrove swamp forest areas, holds significant potential as a food source and a bioremediation agent in the aquaculture industry (Hasniyati et al., 2024; Phang et al. 2019). *Gracilaria* is used for agar production, while *Kappaphycus/Eucheuma* is for carrageenan, and both are consumed as food and have significant industry applications (FAO, 2021; Nor et al. 2020). *Gracilaria* cultivation provides nutritional value and plays a crucial role in reducing dissolved inorganic nitrogen and phosphorus, thereby enhancing water quality for fish health (Thierry et al., 2001).

However, seaweed farming faces a range of environmental challenges that can impact its sustainability. These include competition for coastal areas due to development and pollution (Cai et al., 2021). The growth and development of seaweed can also be affected by the increase in sea temperature due to the effects of climate change (Cai et al., 2021). This situation occurs because seaweed growth requires suitable light intensity, temperature, and nutrient availability; an increase in temperature can hinder photosynthesis and impact growth productivity (Alejandro et al., 2017). Other effects of climate change, such as natural disasters and extreme weather events, can also destroy seaweed farming areas, ultimately leading to socioeconomic losses (Cai et al., 2021). The cycle of natural factors in seaweed farming is two-way, where it can trigger other pollution chains, such as increasing the concentration of heavy metals in water bodies and microcystin outbreaks, which ultimately also impact the environment and human health (Cai et al., 2021). Other factors that can adversely impact seaweed farming are diseases, traditional farming systems, uncertain

market prices and damage to farming infrastructure due to natural disasters and others (Asri et al., 2021). Understanding and addressing these challenges is crucial for the sustainable development of the seaweed industry.

Malaysia's seaweed industry is growing from wild harvesting to aquaculture due to consumer demand (Amponsah et al., 2024). Nevertheless, the sustainability of the seaweed industry requires a comprehensive approach from the aspects of ecosystem conservation, genetics preservation, economic viability, technological development, and regulation (Asri et al., 2021; Fasahati et al., 2022). From the environmental management perspective, emerging issues such as deforestation, eutrophication, and ocean acidification are among the environmental impacts that threaten seaweed as a resource for food security and human health (Amponsah et al., 2024). Previous studies have also emphasised the importance of studying *Gracilaria* cultivation's environmental performance, hoping to demonstrate its viability as an environmentally friendly and sustainable industry.

Life cycle assessment (LCA) is one of the environmental tools that can measure environmental impact in the aquaculture sector. Other Asian countries such as Indonesia and Thailand have been exploring LCA as one of the best tools to identify the environmental impact associated with the specific farming system and develop a proper management plan to minimise the effect, including eco-labelling in promoting their safe seafood products (Mungkung et al., 2013).

Previous studies for LCA in seaweed have addressed the environmental impacts of seaweed farming and its uses in biofuels, carbon sequestration, and nutrient management. Thomas et al. (2021) have conducted LCA for seaweed (kelp) cultivation using the longline method and complex processing systems and discovered that key impact hotspots include the physical cultivation infrastructure and high-energy preservation methods, such as freezing and air cabinet drying. Brockmann et al. (2015) focussed on onshore-grown green seaweed for bioethanol production and discussed the importance of co-product management in LCA models. This study discovered that ethanol production processes contribute an average of 26% to environmental impacts, notably affecting climate change and freshwater eutrophication.

Other global LCA studies for seaweed consists of cultivation and production of seaweed-based products such as biofuel, biorefinery, and feedstock, and vary by different species and region (Alvarado-Morales et al., 2013; Nillson et al., 2022; Seghetta et al., 2017; van Oirschot et al., 2017). Besides biofuels, seaweed has been used in carbon sequestration. Lian et al. (2023) evaluated the carbon sequestration of kelp (*Laminaria japonica*) throughout its life cycle and reported a carbon fixation of 97.73 g in Ailian Bay. This finding is in harmony with the argument made by Sander et al. (2023) that seaweed farming can help combat climate change by releasing carbon from the ocean. Moreover, seaweed farming is crucial in circular nutrient management as a biobased fertiliser. A study by Seghetta et al. (2016) indicated a net reduction in aquatic eutrophication levels of

32.29 kg N eq. per mg of seaweed. Nevertheless, despite all these studies, a recent study by Amponsah et al. (2024) has emphasised the limited LCA studies on global seaweed cultivation.

To our knowledge, seaweed-related LCA studies in Malaysia must also be improved. LCA studies in the aquaculture sector in Malaysia are currently focussed on shellfish, giant freshwater prawns, and tilapia commodities (Dullah et al., 2020; Haslawati et al., 2022; Pahri et al., 2016). This study aims to provide an understanding of the LCA approach in evaluating the environmental performance of the red algae, *Gracilaria* sp., in order to support the commercial growth effort of *Gracilaria* using the land-based method in Peninsular Malaysia. The study also aims to identify environmental hot spots that can improve this industry's sustainability in the future.

MATERIALS AND METHODS

This study follows the Life Cycle Assessment (LCA) approach, a systematic method to assess the environmental impact of a product or process from the extraction of raw materials to final disposal. LCA is one of the environmental tools that can measure potential environmental impact throughout the cycle life of a product or system, including raw material acquisition through production, use, end-of-life treatment, recycling, and final disposal (International Standards Organisation, 2006). LCA involves a compilation and evaluation of the inputs and outputs of product life cycles. This study involves four main phases in LCA: the goal and scope definition, inventory analysis, environmental impact analysis, and interpretation as shown in Figure 1.

Other methods for evaluating environmental impacts are carbon footprinting and environmental input-output analysis alongside LCA (Celekli & Zaric, 2023; Han et al., 2022; Rosales & Dhakal, 2024). LCA provides a comprehensive cradle-to-grave assessment, incorporating several environmental aspects not captured by other methods such as resource depletion, toxicity, and ecosystem damage (Finnveden et al., 2009; ISO, 2006; Petrova, 2023; Rosales & Dhakal, 2024). The use of LCA in aquaculture can help with decision-making by highlighting a system's hotspots. In this emphasising areas, environmental impacts can be minimised, and many options can be considered to determine which systems or processes have the lowest possible impact on the environment (Haslawati et al., 2022). LCA in aquaculture can be done at three different levels: micro-level, which concentrates on a single process, such as feed production; meso-level, which evaluates the entire aquaculture farm; and macro-level, which assesses aquaculture as an entire industry at the country level (Bohnes et al., 2018). This study applies LCA to ensure that all environmental burdens and benefits of the system are captured as entirely as possible, which is especially relevant for novel bioresources like red macroalgae, and allows a comparison of trade-offs between impact categories and more sound decision-making.

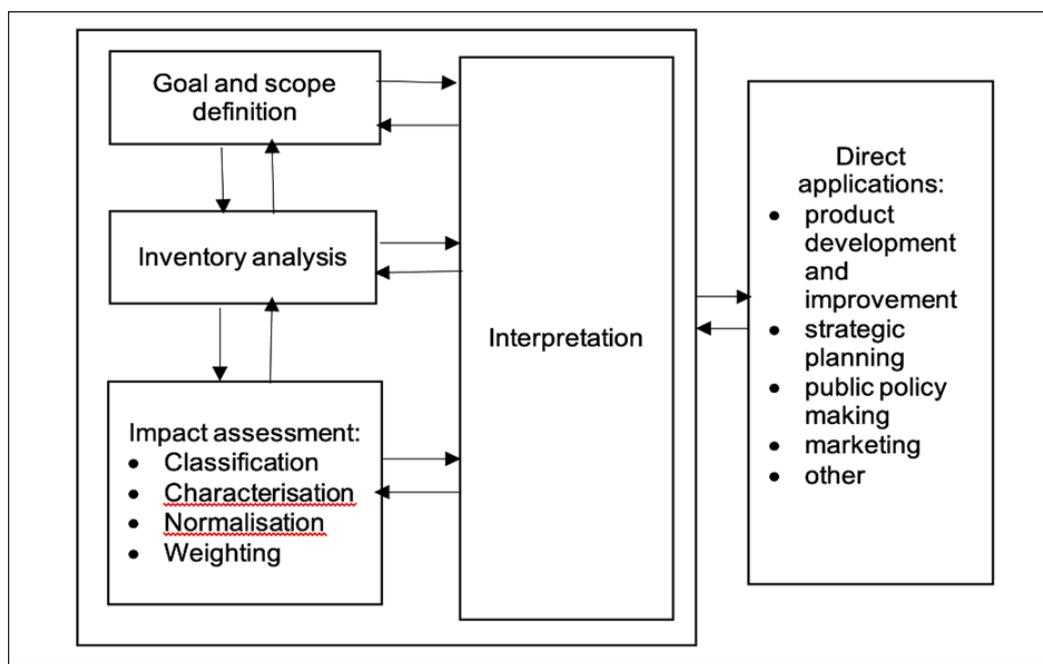


Figure 1. Life Cycle Assessment (LCA) procedure (International Standards Organisation, 2006)

***Gracilaria changii* (*G. changii*) Production System**

The cultivation of red macroalgae, *G. changii*, involves aquaculture ponds in the Muar area, Johor, Malaysia. The studied aquaculture farms have been operated since 2004, covering a few species of marine fishes, oysters, cockles, mussels, and seaweed (*G. changii*). They could be classified as Integrated Multi Trophic Aquaculture (IMTA). Nevertheless, after the global pandemic, COVID-19 struck the whole nation, the IMTA system could no longer be operated, and the farmers discovered the natural abundance of *G. changii* in the aquaculture ponds. *G. changii* seeds exist naturally in the site and entirely rely on natural food sources. Realising the high potential generated by this red macroalgae, the farmers transformed their fish farming area into an entire *G. changii* cultivation site. This seaweed cultivation area is among the pioneer seaweed farms in Peninsular Malaysia.

Figure 2 shows a schematic diagramme of the *G. changii* culture system in the study area. *G. changii* culture system entirely depends on seawater sources, comes in at high tide and is pumped into the aquaculture pond. The same drainage will again drain the seawater to the sea when the water recedes. Effluent from aquaculture sites is not treated, but water quality monitoring is carried out regularly. Consequently, the aquaculture site of *G. changii* discharges its effluent into the surrounding municipal water drainage system.

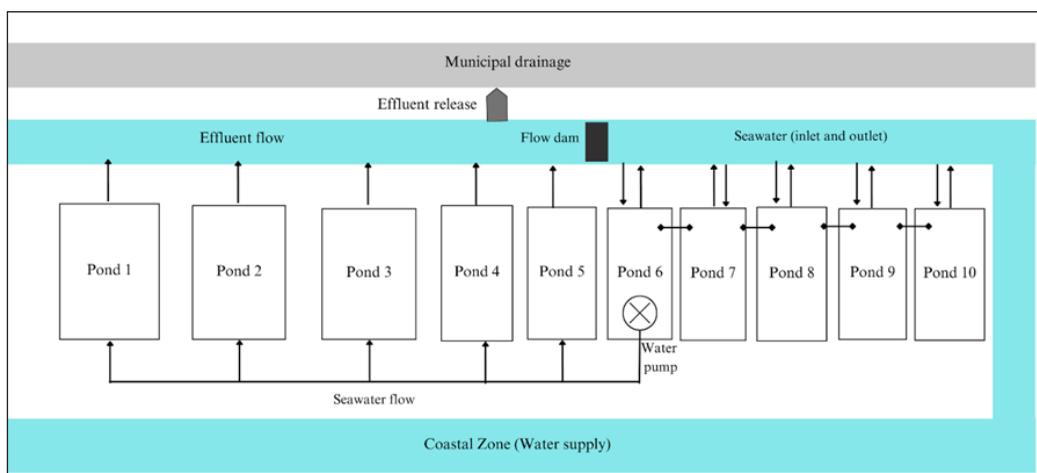


Figure 2. Schematic diagram showing the position of the land-based *G. changii* aquaculture ponds and the flow of seawater and effluent discharge

System Description

This study collected data from *G. changii* aquaculture ponds in the Muar area, Johor. This *G. changii* breeding area was selected based on the consistency of the average production produced, which is 100 kg wet weight (ww)/month, making the annual production 1200 kg ww/year. The studied farming area also produces tilapia fish as a by-product. Nevertheless, this study did not apply the allocation technique as the site evaluation discovered that tilapia breed naturally from the previous farming cycle and are not harvested for any income source or economic value.

Goal and Scope Definition

The functional unit used in this study is the 1-tonne dry weight (dw), considering the final form of dry seaweed for the packaging process in the system boundary. Based on the information from farmers, 10 tonnes or 10,000 kg of ww production will produce 1-tonne dw. The annual production is 1200 kg or 1.2 tonnes ww/yr, equivalent to 0.12 tonnes dw/yr. Therefore, this study estimates the period taken to produce 1-tonne dw of *G. changii* is 8.3 years.

There are other biomass sources such as brown or green macroalgae, microalgae, terrestrial energy crops, and agricultural residues. Microalgae and terrestrial energy crops have their advantages and challenges. According to Chisti (2007), microalgae are also high in lipid yield and productivity, but their large-scale cultivation has been associated with high energy input, freshwater, and nutrient demand. Likewise, terrestrial crops are usually competitive with food production, for example, in the use of arable land and water and

therefore have a higher environmental impact. However, using red macroalgae such as *Gracilaria* sp. has several merits because of its fast growth, low nutrient, and freshwater demand, and capacity to grow in salt water (Holdt & Kraan, 2011). Such characteristics minimise the conflict with food crops and therefore the overall environmental effects which are important when evaluating sustainability (FAO, 2018; Holdt & Kraan, 2011). These environmentally friendly characteristics make *Gracilaria* sp. more sustainable from the life cycle assessment perspective.

The system boundary is cradle-to-gate and consists of eight main phases in *G. changii* production: seeding, cultivation, harvesting, washing and cleaning, drying, sorting and grading, packaging, and storage. The life cycle of *G. changii*, from seeding to harvestable produce, lasts approximately a month or 30 days. This site offers natural seaweed seeds and uses pumped seawater for irrigation. No water treatment is performed on incoming or outgoing water. Following harvesting, the wet seaweed is thoroughly washed and sun-dried for 3 to 4 days. Farm workers meticulously carry out the sorting and grading process to remove impurities, taking three days for each cycle of harvested seaweed. This cycle continues throughout the year through alternate production from seaweed ponds.

Figure 3 shows the entire life cycle of *G. changii* and the system boundary of the studied system, which only involves seeding to storage phases. The study did not include the delivery phase as the information on the site found no specific trends in transportation and traffic flow. Packaged seaweed products are sent to various suppliers using various types of transport based on current demand.

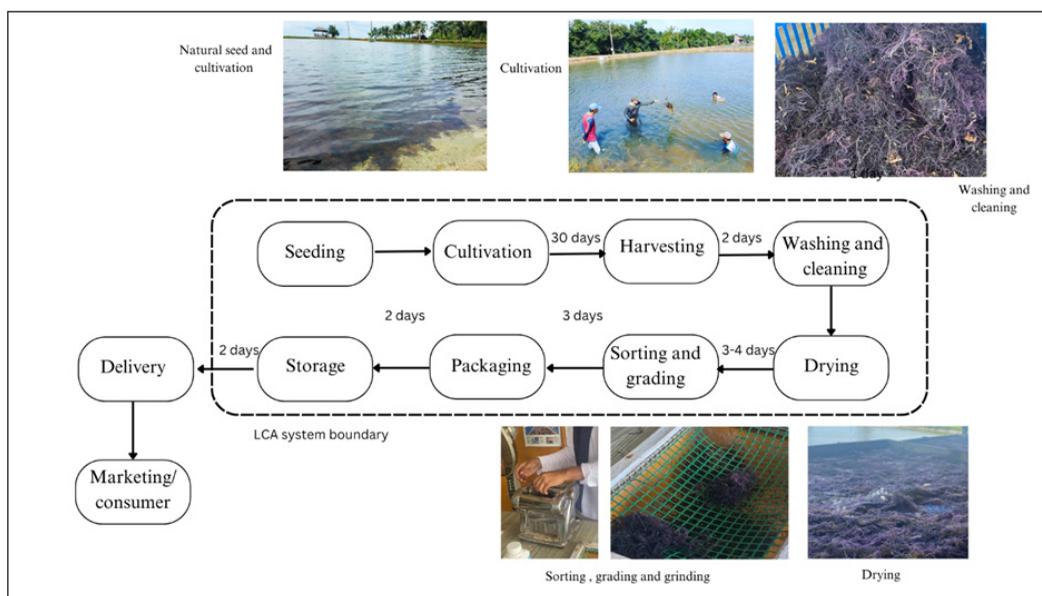


Figure 3. The complete life cycle of *G. changii*, from seeding to delivery for the market. The system boundary for the LCA study only consists of seeding until the storage phase

Data Collection and Inventory Analysis

The study involves collecting field data through survey forms and site observations. Secondary data were obtained through the literature references and water quality data from farmers. The cultivation process of *G. changii* was also cross-checked with the relevant experts in the field. Data collection aims to produce a comprehensive inventory to identify the flow of all inputs within the system boundary.

Table 1 shows the life cycle inventory analysis developed for this study. The natural inputs taken count natural seeds and seawater based on the pond capacity. Material inputs identified are activated carbon enzymes as seaweed treatment material and equipment usage for all phases in the studied system boundary, such as a rake, submersible pump, net, woven sacks, basket, and vacuum pack, for packaging. Material for each equipment was identified based on site observation, data searching via the internet and information from the farm workers. This is because material selection in infrastructure can significantly affect environmental emissions (Ampansoh *et al.*, 2024). Data for energy use was derived from farm electricity bills.

Table 1
Life cycle inventory analysis for the cradle-to-farm gate LCA study for G. changii production

Main inputs (materials, nature and processes) and output based on production phase	Units	Amount	Values (based on the production of 1-tonne dw of <i>G. changii</i>)
Seeding			
• Natural Seeds	NA	NA	NA
• Average pond capacity	m ³	72.6 x 10 ⁶	NA
Cultivation			
• Activated carbon enzyme	Litres	1 litre/3 months	33.2 litres
Harvesting			
• PVC heavy-duty rake	kg	5 units 5 kg/unit (life span: 8 years)	5 kg
Washing and Cleaning			
• Submersible pump 1 hp (cast iron)	Kg	1 unit 12 kg (life span: 8 years)	12 kg
Drying			
• Woods (drying racks)	m ³	200 kg (life span: 5 years)	0.332 m ³
• HDPE net	Kg	10 kg (life span: 3 years)	27.67 kg
Sorting and grading			
• Polypropylene woven sacks	Kg	1200 kg/yr (life span: 10 years)	996 kg

Table 1 (continued)

Main inputs (materials, nature and processes) and output based on production phase	Units	Amount	Values (based on the production of 1-tonne dw of <i>G. changii</i>)
Packaging			
• HDPE vacuum pack	g	1200kg/year (life span: 10 years)	27.5 x 10 ³ kg
Storage			
• Polypropylene (PPE) basket	Kg	30 units (life span: 10 years)	105 kg
Processes			
• Electricity (for all phases exclude seeding)	Kw		59 x 10 ³
Inputs from nature:			
• Water (from the ocean)	m ³		Estimated: 72.6 × 10 ⁶ m ³
Output to nature:			
• Untreated emissions to water	Nitrates	0-10mg/l	
	Phosphates	0.005-1 mg/l	
	pH	6.5-8.5	
	Temperature	28.32 °C	
	D.O	>4	

Impact Analysis

This study uses the ReCiPe 2016 v1.1 Midpoint (H) method in SimaPro software version 9.3 with the Ecoinvent 3 database due to its relevance on the global scale compared to other methods which focuss on the suitability for the European region. Other impact assessment tools include CML, TRACI, and Eco-indicator 99. The ReCiPe Midpoint (H) method was used because it offers a broad set of indicators that address many environmental effects e.g. human health, ecosystem quality, and resource depletion (Luu et al., 2024). The new version of ReCiPe includes global scale characterisation variables instead of the European ones only (Huijbregts et al., 2016). Nevertheless, some impact categories are compatible with country and continental size characterisation factors (Huijbregts et al., 2016). Current research can be found that has employed the ReCiPe Midpoint method for environmental impact assessment in different Asian regions proves its appropriateness for application in regions with specific ecological and socio-economic features (Adhikari & Prapasongsa, 2019). The ReCiPe Midpoint (H) method allows for a combined analysis of environmental effects across different impact categories. Although other methods may specialise on certain impacts, ReCiPe provides a holistic assessment of trade-offs throughout the product life cycle. This holistic evaluation is crucial for robust decision-making, regardless of whether the study is conducted on a global or regional, including Asian scale.

Ecoinvent 3 was selected because it is one of the most comprehensive, peer-reviewed, and transparent databases available. Other feasible alternatives are the GaBi database, the US Life Cycle Inventory (USLCI), and the European Life Cycle Database (ELCD). Its wide coverage of processes and geographical regions improves the credibility and comparability of the LCA results (Wernet et al., 2016). Applying the Ecoinvent database guarantees high data quality and reduces environmental inventory uncertainties. As for the accuracy of the results, they may differ slightly from the initial simulation when using a different database since the data can vary depending on the region and processes.

The SimaPro software has vast and easy-to-use databases, a flexible and understandable modelling framework, and is one of the most common tools used in both academic and commercial LCA studies (Speck et al., 2016). GaBi and OpenLCA are more examples of LCA software tools. Minor variations in output can occur because of different algorithms or data handling in various LCA software; however, using SimaPro ensures continuity with previous research and improves the replicability of the findings (Sečkář et al., 2024; Speck et al., 2016).

The impacts analysed are global warming (kg CO₂ equivalent), terrestrial acidification (kg SO₂ equivalent to water), freshwater eutrophication (kg P equivalent), terrestrial ecotoxicity, freshwater ecotoxicity (kg 1,4-DCB-equivalent to freshwater), human carcinogenic activity (kg 1,4-DCB-equivalent to urban water), and human non-carcinogenic activity (kg 1,4-DCB-equivalent to urban water). Environmental impact analysis involves assessment based on the inputs and outputs from the established inventory. The impact analysis seeks to identify the environmental hotspots, which impacts, and in what phases require attention and improvement. These environmental hotspots could exist either in material use or current farming practices. Identification of environmental hotspots and the associated environmental impacts is important in establishing sustainable aquaculture farming practices.

RESULTS AND DISCUSSION

Environmental Impact of *G. changii* Production

Environmental performance for *G. changii* production has been measured and presented in two aspects: (i) the most dominant environmental impact and (ii) the *G. changii* production phase that contains a high potential for environmental impact. Figure 4 shows the potential environmental impacts for 1-tonne dw of *G. changii* production consisting of eight (8) main phases in the production of *G. changii*, which are seeding, cultivation, harvesting, washing and cleaning, drying, sorting and grading, packaging, and storage. Human carcinogenic toxicity has the most dominant potential impact, followed by freshwater ecotoxicity, freshwater eutrophication, and marine ecotoxicity. This outcome was foreseen, given the primary use of plastic-based materials as packaging materials, potentially contributing to a significant environmental impact.

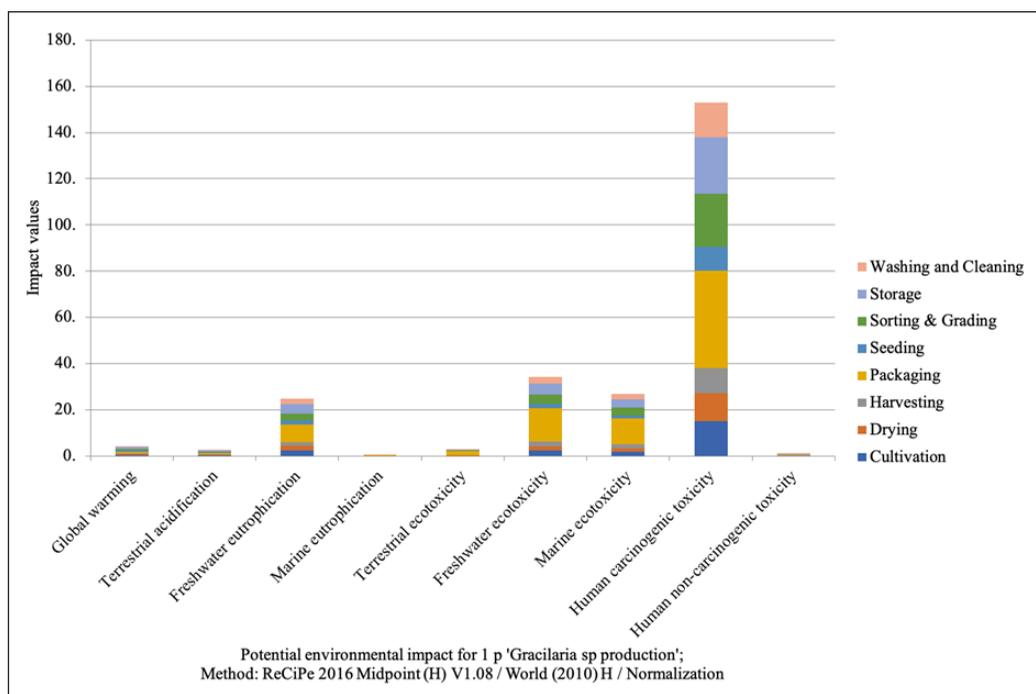


Figure 4. Environmental impact analysis for the eight main phases of the 1-tonne dry-weight *G. changii* production chain

Table 2 shows the details of the environmental impact analysis for each *G. changii* production phase. This impact analysis was conducted for normalisation values based on the ReCiPe 2016 method. Although normalisation is an optional step in LCA, it is frequently used as it assists in comprehending LCA results and provides information on the magnitude of impact, which may assist communication to stakeholders when making decisions (De Laurentiis et al., 2023). It was found that the packaging phase dominated all environmental impacts, namely global warming (20.17%), terrestrial acidification (19.27%), freshwater eutrophication (30.26%), marine eutrophication (49.50%), terrestrial ecotoxicity (54.32%), freshwater ecotoxicity (42.75%), marine ecotoxicity (42.34%), human carcinogenic activity (27.62%), and human non-carcinogenic activity (33.77%). This high impact is mainly due to the energy-intensive production and processing of packaging materials and challenges related to their disposal or recycling.

The storage phase is the second major contributor to all impacts, except for marine eutrophication and terrestrial ecotoxicity, in which the cultivation, sorting, and grading phases contributed more to these two impacts. Storage phase contributes to global warming (17.71%), terrestrial acidification (17.99%), freshwater eutrophication (15.97%), freshwater ecotoxicity (13.82%), marine ecotoxicity (13.77%), human carcinogenic activity (16.05%),

Table 2
Environmental impact for *G. changii* production with functional unit 1-tonne dry weight

Impact category (method: ReCiPe 2016/ Midpoint (H) V1.08)	Significant phases in <i>G. changii</i> production							
	Seeding	Cultivation	Harvesting	Washing and Cleaning	Drying	Sorting and Grading	Packaging	Storage
Global warming (kg CO ₂ eq)	0.31 (7.37%)	0.45 (10.75%)	0.32 (7.56%)	0.45 (10.68%)	0.34 (8.51%)	0.73 (17.61%)	0.84 (20.17%)	0.74 (17.71%)
Terrestrial acidification (kg SO ₂ eq)	0.20 (7.587)	0.29 (11.02%)	0.20 (7.79%)	0.29 (10.97%)	0.23 (8.66%)	0.43 (16.71%)	0.50 (19.27%)	0.47 (17.99%)
Freshwater eutrophication (kg P eq)	1.69 (6.84%)	2.47 (9.96%)	1.72 (6.95%)	2.45 (9.89%)	1.87 (7.56%)	3.11 (12.57%)	7.49 (30.26%)	3.95 (15.97%)
Marine eutrophication (kg N eq)	0.02 (4.47%)	0.04 (10.91%)	0.02 (4.52%)	0.02 (6.44%)	0.02 (5.28%)	0.03 (8.43%)	0.18 (49.50%)	0.04 (10.44%)
Terrestrial ecotoxicity (kg 1,4-DCB)	0.08 (2.87%)	0.14 (4.72%)	0.12 (4.13%)	0.17 (5.85%)	0.16 (5.56%)	0.36 (12.43%)	1.60 (54.32%)	0.30 (10.11%)
Freshwater ecotoxicity (kg 1,4-DCB)	1.53 (4.48%)	2.29 (6.71%)	2.00 (5.875)	2.83 (8.30%)	1.90 (5.57%)	4.27 (12.50%)	14.59 (42.75%)	4.72 (13.82%)
Marine ecotoxicity (kg 1,4-DCB)	1.24 (4.61%)	1.85 (6.89%)	1.57 (5.86%)	2.22 (8.29%)	1.53 (5.71%)	3.36 (12.53%)	11.36 (42.34%)	3.70 (13.77%)
Human carcinogenic toxicity (kg 1,4-DCB)	10.30 (6.73%)	15.02 (9.82%)	10.87 (7.11%)	14.96 (9.78%)	12.16 (7.95%)	22.88 (14.96%)	42.24 (27.62%)	24.55 (16.05%)
Human non-carcinogenic toxicity (kg 1,4-DCB)	0.05 (6.11%)	0.08 (8.93%)	0.06 (6.52%)	0.08 (9.25%)	0.06 (7.22%)	0.11 (13.08%)	0.29 (33.77%)	0.13 (15.11%)

and human non-carcinogenic activity (15.11%). These findings are consistent with prior LCA studies on similar agricultural and marine products, where packaging, storage, and transport frequently account for the largest share of environmental impacts (e.g., Brockmann et al., 2015; Pessarrodona et al., 2022).

In contrast, earlier phases, such as seeding, cultivation, harvesting, washing, and cleaning, exhibit lower impacts due to their reliance on less intensive inputs. The relatively lower environmental impact from phases such as seeding, cultivation, harvesting, washing, and cleaning reflects the limited input of harmful resources and energy during these stages, suggesting that farming is less resource-intensive and has a minor environmental impact.

In this study, raw material allocation was not conducted due to the focus on the primary product (seaweed) and the negligible contribution of co-products to the overall environmental impact. Seaweed production systems are inherently multifunctional, providing additional environmental benefits such as nutrient bioremediation and carbon capture. In the case of seaweed, the allocation methods used can significantly affect the assessment outcomes, particularly when considering the multifunctional nature of seaweed production, which often yields multiple products and services (Thomas et al. 2020; Thomas et al. 2021). Future research could explore allocation methods to provide a more comprehensive understanding of seaweed production systems.

Table 3 shows a more comparison of major environmental impacts with the related previous studies. This comparison is conducted to provide more insight into the environmental impact of seaweed production based on the set boundary system and also the research dimensions.

The environmental effects of seaweed farming systems differ from one study to another due to factors such as the species used, the system boundaries, the functional units, and the life cycle impact assessment (LCIA) methods. This study on cultivation of *G. changii* using a cradle-to-gate system and ReCiPe 2016 v1.1 Midpoint (H) methodology revealed that the most significant environmental impacts are human carcinogenic toxicity (152.98 kg 1,4-DCB), freshwater ecotoxicity (34.13 kg 1,4-DCB), freshwater eutrophication (24.75 kg P eq) and marine ecotoxicity (26.83 kg 1,4-DCB). These results show possible toxicity-related challenges associated with the cultivation of *G. changii*, especially in aquatic environments. For instance, Nillson et al. (2022) focussed on cultivating *S. latissima* for biorefinery production and used EF 3.0 (adapted) and a functional unit of 1000 kg dry weight. Their findings indicated that the post-harvest drying phase contributed to the climate impact with 6.12 kg CO₂ eq per kg dry seaweed). This comparison suggested that the cultivation of *S. latissima* has a lower toxicity burden than *G. changii* but has a higher carbon footprint.

Similarly, Thomas et al. (2020) assessed *S. latissima* cultivation using the CML baseline 2000 (v2.05) and reported cumulative energy demand (4.33E+03) and ozone layer depletion (1.18E-04) as key impacts, primarily driven by the energy-intensive freezing process.

Table 3

Comparisons of environmental impact for seaweed cultivation in previous studies

Authors	Species and Boundary System	Functional Unit	Life Cycle Impact Analysis Method	Major Environmental Impacts	Main Contributor (Production Phase)
This study	<i>G. changii</i> cultivation / Cradle-to-gate	1 tonne dry weight	ReCiPe 2016 v1.1 Midpoint (H)	Human carcinogenic toxicity (152.98 kg 1,4-DCB) Freshwater ecotoxicity (34.13 kg 1,4-DCB) Freshwater eutrophication (24.75 kg P eq) Marine ecotoxicity (26.83 kg 1,4-DCB)	Packaging phase
Nillson et al. (2022)	<i>S. latissima</i> cultivation to biorefinery production	1000 kg dry weight	EF 3.0 (adapted)	For cultivation phase: Climate impact (6.12 kg CO ₂ eq per kg dry seaweed)	Post harvest drying phase
Thomas et al. (2020)	<i>S. latissima</i> cultivation Cradle-to-gate	1 tonne of fresh kelp, cultivated <i>S. latissima</i>	The CML baseline 2000 (v2.05)	Cumulative energy demand (4.33E+03) Ozone layer depletion Categories (1.18E-04)	Energy-intensive freezing process

This indicates that energy consumption and associated emissions are critical factors in *S. latissima* production, particularly during post-harvest processing. The dissimilarities in the environmental effects between these two studies may be ascribed to the following factors.

First, the species type has played a privileged role since *G. changii* and *S. latissima* has different growing conditions and production technologies, which lead to variations in resource use and emissions. Second, the system boundaries and the functional units are different: some studies analyse the cultivation phase (cradle-to-gate), while others include biorefinery production or post-harvest processing. Third, the LCIA methods used in this analysis include ReCiPe 2016, EF 3.0 and CML baseline 2000, which have different characterisation factors and impact categories due to which the results and their interpretation differ. For instance, ReCiPe 2016 is concerned with the toxicity impacts, while EF 3.0 and CML baseline 2000 are concerned with climate change and energy-related impacts, respectively. This shows that, for the two species, it is vital to select cultivation

technologies that are specific to the species and processing methods that have minimal effects on the environment.

This study also determined that the packaging process produced the highest global warming impact, 0.84 kg CO₂ eq for producing 1-tonne dw of *G. changii*. Nevertheless, this value is in the low range compared to previous LCA studies for seaweed. Thomas et al. (2021) found the production of 55.2 kg CO₂ eq for a 1-tonne ww of seaweed in the seeding phase. Seaweed in the biorefinery industry has contributed 5187.6 kg CO₂ eq /tonne dw as carbon emissions (Zhang et al., 2021). In an LCA study for seaweed as bioplastic, Ayala et al. (2023) discovered carbon emissions of 0.082 kg CO₂ eq for 1 kg ww of seaweed.

In the case of *G. changii*, it may be worth paying attention to reducing toxicity-related effects by improving the management of nutrients and wastes. In the case of *S. latissima*, decreasing energy consumption during the processing phase and using renewable energy sources would greatly improve the carbon footprint and the ozone depletion potential. This comparison shows a need to develop standard approaches and system scopes for LCA of seaweed cultivation systems to facilitate more accurate and comparable analyses.

Sensitivity Analysis

A sensitivity study was conducted by reducing the input of HDPE materials in the packaging phase by 50%. This comparison will provide insights into the influence of the usage of plastic materials, which provides a considerable difference in the environmental impact study for *G. changii*. As a result, Figure 5 illustrates the reduction range for all environmental impacts, which is 20% to 44%.

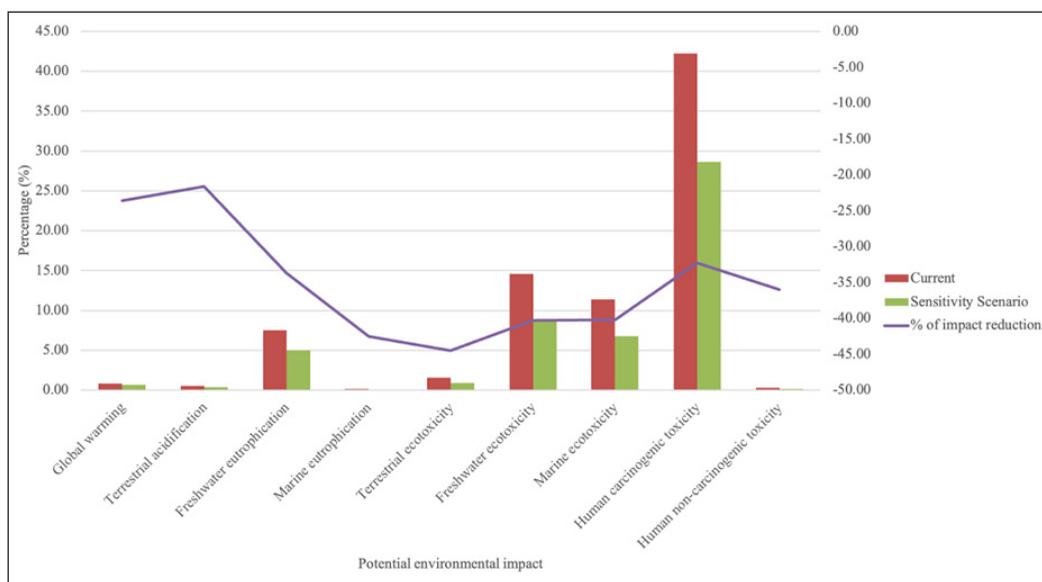


Figure 5. Summary of 50% percentage reduction of HDPE material in the packaging phase

It is worth mentioning that using plastic materials during packaging stages may pose risks related to potential human health issues such as carcinogenic toxicity and eutrophication concerns. This situation highlights the importance of the entire aquaculture industry, not only seaweed commodity, in addressing waste and minimising the use of biodegradable plastics in its production processes. The extensive use of non-biodegradable plastic material in the aquaculture production chain pose a concern that extends to various downstream seafood products and their packaging methods. Plastics are primarily derived from non-renewable resources, raising sustainability concerns, and their poor degradability contributes to significant environmental pollution (Kanagesan et al., 2022). Ayala et al. (2023), who utilised LCA as a tool to evaluate environmental impact and carbon uptake in the production of seaweed as bioplastic film, reported that the specific film fabrication phase was the primary hotspot due to the use of glycerol in this process. In comparison, the study of life cycle carbon assessment for seaweed by Lian et al. (2023) found that using polyethylene rope in farming has implications for carbon emissions. Nevertheless, on the opposite view, seaweed can be seen as having great potential to reduce the use of nonbiodegradable plastic. Seaweed contains hydrocolloids, high molecular weight polysaccharides that are valuable for bioplastics as a sustainable alternative due to their biodegradability (Kanagesan et al., 2022).

Implementing solutions such as process optimisation and transition to renewable energy sources can decrease both human carcinogenic and broader environmental impacts of *Gracilaria changii*'s life cycle. For example, replacing energy inputs from fossil fuels with cleaner energy sources cuts down on greenhouse gas emissions and the release of harmful chemicals that are carcinogenic to humans. Furthermore, improved extraction methods and greener chemical alternatives can reduce toxic substances, occupational exposure and environmental pollution. Enhanced waste management and the recycling of process by-products also help prevent the formation of harmful pollutants, reducing the overall environmental impact of the product life cycle.

The Sustainability of Seaweed Industry using LCA Approach

Currently, global LCA studies for seaweed consist of the cultivation and production of seaweed-based products such as biofuel, biorefinery, and feedstock, and vary by different species and region. Past LCA studies have explored seaweed harvesting methods, including various mechanical and manual methods (Amponsah et al., 2024). Advanced technologies are being developed to reduce labour intensity in harvesting, so this potential increases the impact of energy usage and optimisation measures (Amponsah et al., 2024). LCA studies may benefit the seaweed industry's environmental performance, making it the first option for consumers as a healthy, easily accessible, and inexpensive food source. *G. changii* stands out for its high dietary fibre content compared to local vegetables, which is between

53.96 to 76.97 g/100 g dry weight, compared to other local vegetables ranges from 0.5 to 1.6 g/100 g fresh weight (Chin et al., 2023).

Climate change is an emerging global issue and many current LCA studies for seaweed production chain have been carried out, emphasising carbon emission or carbon sequestration and its importance against climate change (Fasahati et al., 2022; Lian et al., 2023). CO₂ production from fossil fuel combustion during seaweed transport, such as wet trucks and dry trucks, as well as the use of diesel during the farming process, also becomes among the possible environmental hotspots that contribute to the impact of climate change (Fasahati et al., 2022; Lian et al., 2023). On the other perspectives, seaweed cultivation is also acknowledged as an emerging Blue Carbon option, acting as a large-scale carbon sink, and it offers a promising means of addressing several sustainable development goals, most notably climate action (Duarte et al., 2022; Lian et al., 2023; Lovelock & Duarte, 2019). Growing seaweed does not rely on freshwater sources or agricultural land, nor does it require a lot of inputs like chemicals or feed that may put pressure on the impact of climate change.

Brockmann et al. (2015) and Thomas et al. (2020) highlight that energy-intensive processes like nutrient inputs, preservation methods (e.g., freezing and drying), and component extraction significantly drive indirect emissions. While direct emissions from fertilisers and cultivation inputs remain relevant, Pessarrodona et al. (2022) underscores the need to prioritise energy-related emissions in life cycle assessments (LCA) and integrate seaweed cultivation into broader carbon flux analyses to understand its environmental footprint better. Therefore, future research for seaweed in Malaysia with intensive farming systems should continue refining LCA methodologies to capture these dynamics better and explore strategies for reducing direct and indirect emissions in seaweed cultivation.

Integrated Multi-Trophic Aquaculture (IMTA) can mitigate the environmental impacts of fish farming and promote sustainable farming practices (Alejandro et al., 2017; Amponsah, et al., 2024). IMTA systems, which incorporate the farming cycle of multiple aquaculture species, such as the combination of marine fishes, seaweed and mollusc, can enhance nutrient management and economic diversification (Thierry & Albert, 2020). In comparison to monoculture systems, seaweed contributes to pollutant absorption and improved water quality in IMTA (Hasniyati et al., 2024). Lian et al. (2023) discover that integrated multi-nutrient seaweed farming mitigates environmental issues from shrimp farming. This situation is because IMTA systems utilise waste outputs from one species as inputs for another, and seaweed can assimilate nutrients and pollutants, aiding in eutrophication reduction (Amponsah et al., 2024). Nevertheless, IMTA faces technical and operational challenges as farmers may need more expertise in effectively cultivating multiple species (Cai et al., 2021). Therefore, more LCA studies should be conducted to assist farmers in determining the most successful farming species for IMTA system.

Blue economy is an inclusive global concept for the utilisation of marine sources based on sustainability principles, namely social inclusion, environmental sustainability and innovation in the marine sector (Choudary et al., 2021; Hossain et al., 2021; Islam et al., 2024; Smith-Godfrey, 2016). LCA studies throughout the seaweed production chain and seaweed based products can contribute to the empowerment of blue economy. Seaweed potentially contributed towards blue economic growth, by providing positive economic impact, enhancing food security, environmental advantages, biotechnology uses in various industries, supporting social values and promoting sustainable farming practices, which potentially increase the value of marine resources as shown in Figure 6.

Seaweed cultivation has the potential to minimise land use pressures and diversify coastal economic resources. Seaweed requires no arable land or freshwater (Fasahati et al., 2022). Its cultivation relies on natural conditions, and intensive cultivation may need active intervention as its growth factor relies on environmental factors such as light, temperature, salinity and nutrient availability (Amponsah et al., 2024). Cultivating seaweed pushes the need for a clean water body that is clear from pollution.

Regarding food security, seaweed is high in vitamins, minerals, and proteins and can be promoted as a future food for consumers. Aside from that, seaweed has a huge potential in downstream industries such as bioplastics, biofuels, pharmaceuticals, cosmetics, and

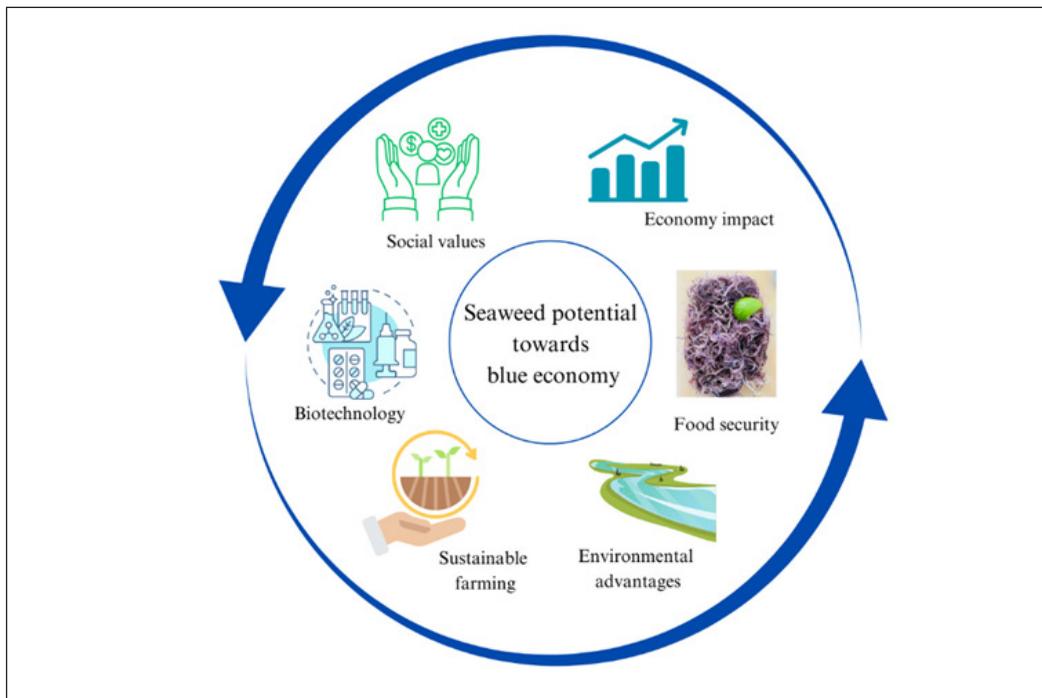


Figure 6. Seaweed potential towards blue economy growth

others (Ayala et al., 2023; Phang, 2010). Cooperation between seaweed farmers and large corporations could boost a larger-scale seaweed industry and increase seaweed production simultaneously, as well as increase socioeconomics via the enlargement of agriculture, tourism, and manufacturing processes by this promising industry (Ahemad et al., 2006).

Seaweed cultivation supports the blue-green bioeconomy and enhances ecosystem services (Hasselström & Thomas, 2022). From an environmental point of view, seaweed serves as a habitat and breeding ground for marine species, contributing significantly to the abundance of marine biodiversity. Seaweed farming can prevent eutrophication by absorbing excess nutrients from fish farms, and also capture carbon through photosynthesis where possible, reducing the impact of climate change and having a low carbon footprint (Cai et al., 2021; FAO, 2021; Koesling et al., 2021). This multifunctional commodity has demonstrated its capability in mitigating the consequences of ocean acidification and climate change (Duarte et al., 2017; Sultana et al. 2023).

Farmed seaweed is a sustainable protein source for aquaculture and seaweed commodity may be considered an underutilised resource for food, feed, energy, and fertiliser (Hasselström & Thomas, 2022; Koesling et al., 2021). To truly understand the seaweed industry, it's essential to consider not just environmental factors but also economic and social aspects, which help improve community resilience and promote social equity. Expanding the seaweed industry needs to involve the importance of social dimensions such as workforce issues, women's involvement in downstream activities, community well-being and socioeconomic implications such as job creation and local economic development (FAO, 2013; Rimmer et al., 2021; Sultana et al., 2023; Valderrama, 2012). Thus, advocating for a stronger legal framework is vital to ensure the socio-economic benefits of *G. changii* cultivation are fully realised and fairly distributed. This supports the conclusions of Penadés-Plà et al. (2020), who stress the importance of integrating economic and social factors into environmental assessments to support sustainable development. Through a social LCA-based study, stakeholders can assess the social sustainability of seaweed cultivation projects, identify social hotspots and improve the standard of living of local communities. A holistic approach that includes these elements will make policies for *G. changii* farming more effective and legitimate.

CONCLUSION

LCA studies are vital for seaweed cultivation and should be expanded to include additional data, considering allocation when farming with other species of substantial economic importance, such as tilapia, sea bass, or molluscs. An understanding of resource use efficiency throughout the seaweed production process can be obtained through LCA. Environmental impact can be reduced by using appropriate material inputs throughout the seaweed production cycle. Key environmental impacts need to be identified to suggest

ways to lessen their effects, which may involve switching to renewable energy sources or integrating them into IMTA, along with further research on nutrient management methods. More research can be conducted to promote LCA as an environmental tool for aquaculture in achieving blue economy goals.

ACKNOWLEDGEMENT

This research was funded by the Geran Galakan Penyelidik Muda (GGPM-2022-048) of Universiti Kebangsaan Malaysia.

REFERENCES

- Adhikari, B., & Prapasongsa, T. (2019). Environmental sustainability of food consumption in Asia. *Sustainability*, *11*(20), 5749. <https://doi.org/10.3390/su11205749>
- Ahemad, S., Ismail, A., & Mohammad, R. M. A. (2006). The seaweed industry in Sabah, East Malaysia. *Journal of Southeast Asian Studies*, *11*, 2006.
- Alvarado-Morales, M., Boldrin, A., Karakashev, D. B., Holdt, S. L., Angelidaki, I., & Astrup, T. (2013). Life cycle assessment of biofuel production from brown seaweed in Nordic conditions. *Bioresource Technology*, *129*, 92-99. <https://doi.org/10.1016/j.biortech.2012.11.029>
- Alejandro, H. B., Carolina, C., Javier, I., Amir, N., Álvaro, I., María, C. H.-G., Sandra, V. P., Juan, L. G.-P., Alexander, G., Niva, T.-S., & Alan, T. C. (2017). Seaweed production: Overview of the global state of exploitation, farming, and emerging research activity. *European Journal of Phycology*, *52*(4), 391-406. <https://doi.org/10.1080/09670262.2017.1365175>
- Amponsah, L., Chuck, C., & Parsons, S. (2024). Life cycle assessment of seaweed cultivation and harvesting in Europe and the United States. *Sustainability Science and Technology*, *1*, 012001. <https://doi.org/10.1088/2977-3504/ad6ce0>
- Asri, A., Verginie, L. M., Valéria, M., Phaik, E. L., Adibi, M. N., Hanafi, H., & Louise, S. (2021). The role of migrants in the Malaysian seaweed value-chain. *Marine Policy*, *134*, 104812.
- Ayala, M., Thomsen, M., & Pizzol, M. (2023). Life cycle assessment of pilot scale production of seaweed-based bioplastic. *Algal Research*, *71*, 103036. <https://doi.org/10.1016/j.algal.2023.103036>
- Bohnes, F. A., Hauschild, M. Z., Schlundt, J., & Laurent, A. (2018). Life cycle assessments of aquaculture systems: A critical review of reported findings with recommendations for policy and system development. *Reviews in Aquaculture*, *11*, 1061-1079.
- Brockmann, D., Pradinaud, C., Champenois, J., Benoît, M., & Hélias, A. (2015). Environmental assessment of bioethanol from onshore grown green seaweed. *Biofuels, Bioproducts and Biorefining*, *9*(6), 696-708. <https://doi.org/10.1002/bbb.1577>
- Cai, J., Lovatelli, A., Aguilar-Manjarrez, J., Cornish, L., Dabbadie, L., Desrochers, A., Diffey, S., Garrido Gamarro, E., Geehan, J., Hurtado, A., Lucente, D., Mair, G., Miao, W., Potin, P., Przybyla, C., Reantaso, M., Roubach, R., Tauati, M., & Yuan, X. (2021). *Seaweeds and microalgae: An overview for unlocking*

- their potential in global aquaculture development*. FAO Fisheries and Aquaculture Circular No. 1229. FAO. <https://doi.org/10.4060/cb5670en>
- Chin, Y. Y., Chang, K. A., Ng, W. M., Eng, Z. P., & Chew, L. Y. (2023). A comparative evaluation of nutritional composition and antioxidant properties. *Food Chemistry Advances*, 3, 100426. <https://doi.org/10.1016/j.focha.2023.100426>
- Chisti, Y. (2007). Biodiesel from microalgae. *Biotechnology Advances*, 25(3), 294-306. <https://doi.org/10.1016/j.biotechadv.2007.02.001>
- Choudhary, P., Subhash, G. V., Khade, M., Savant, S., Musale, A., Raja Krishna Kumar, G. R. K., Chelliah, M. S., & Dasgupta, S. (2021). Empowering blue economy: From underrated ecosystem to sustainable industry. *Journal of Environmental Management*, 291, 112697. <https://doi.org/10.1016/j.jenvman.2021.112697>
- De Laurentiis, V., Amadei, A., Sanyé-Mengual, E., & Sala, S. (2023). Exploring alternative normalisation approaches for life cycle assessment. *International Journal of Life Cycle Assessment*, 28(10), 1382-1399. <https://doi.org/10.1007/s11367-023-02188-4>
- Department of Fisheries Malaysia. (2023). *Annual fisheries statistics 2023*. <https://www.dof.gov.my/sumber/perangkaan-perikanan-i/>
- Duarte, C. M., Bruhn, A., & Krause-Jensen, D. (2022). A seaweed aquaculture imperative to meet global sustainability targets. *Nature Sustainability*, 5(3), 185-193. <https://doi.org/10.1038/s41893-021-00773-9>
- Duarte, C. M., Wu, J., Xiao, X., Bruhn, A., & Krause-Jensen, D. (2017). Can seaweed farming play a role in climate change mitigation and adaptation? *Frontiers in Marine Science*, 4, Article 100. <https://doi.org/10.3389/fmars.2017.00100>
- Dullah, H., Malek, M. A., & Hanafiah, M. M. (2020). Life cycle assessment of Nile tilapia (*Oreochromis niloticus*) farming in Kenyir Lake, Terengganu. *Sustainability*, 12(6), 2268. <https://doi.org/10.3390/su12062268>
- Fasahati, P., Dickson, R., Saffron, C. M., Woo, H. C., & Liu, J. J. (2022). Seaweeds as a sustainable source of bioenergy: Techno-economic and life cycle analyses of its biochemical conversion pathways. *Renewable and Sustainable Energy Reviews*, 157, 112011. <https://doi.org/10.1016/j.rser.2021.112011>
- Finnveden, G., Hauschild, M. Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D. W., Suh, S., & Swarr, T. (2009). Recent developments in life cycle assessment. *Journal of Environmental Management*, 91(1), 1-21. <https://doi.org/10.1016/j.jenvman.2009.06.018>
- Food and Agriculture Organisation of the United Nations. (2021). *Global seaweeds and microalgae production, 1950-2019*. FAO. <https://www.fao.org/fishery/en/publications/280709>
- Food and Agriculture Organisation of the United Nations. (2022). *The state of world fisheries and aquaculture 2022: Towards blue transformation*. FAO. <https://doi.org/10.4060/cc0461en>
- Food and Agriculture Organisation of the United Nations & World Health Organisation. (2022). *Report of the expert meeting on food safety for seaweed: Current status and future perspectives*. FAO. <https://doi.org/10.4060/cc0846en>
- García-Poza, S., Leandro, A., Cotas, C., Cotas, J., Marques, J. C., Pereira, L., & Gonçalves, A. M. M. (2020). The evolution road of seaweed aquaculture: Cultivation technologies and the industry 4.0. *International Journal of Environmental Research and Public Health*, 17(18), 6528. <https://doi.org/10.3390/ijerph17186528>

- Han, J., Tan, Z., Chen, M., Zhao, L., Yang, L., & Chen, S. (2022). Carbon footprint research based on input-output model: A global scientometric visualization analysis. *International Journal of Environmental Research and Public Health*, *19*(18), 11343. <https://doi.org/10.3390/ijerph191811343>
- Hanafi, H., & Abdullah, K. (2017). Seaweed cultivation and coastal communities in Malaysia: An overview. *Asian Fisheries Science*, *30*, 87-100. <https://doi.org/10.33997/j.afs.2017.30.2.003>
- Haslawati, B., Saadiah, I., Siti-Dina, R. P., Othman, M., & Latif, M. T. (2022). Environmental assessment of giant freshwater prawn farming through life cycle assessment. *Sustainability*, *14*(22), 14776. <https://doi.org/10.3390/su142214776>
- Hasniyati, M., Zazali, A., Adibi, M. N., & Norhidayah, M. T. (2024). Co-cultured red hybrid tilapia and *Gracilaria changii*: Effects on water quality, growth performance and algal density. *Phycologia*, *63*(3), 303-311. <https://doi.org/10.1080/00318884.2024.2336876>
- Hasselström, L., & Thomas, J-B. E. (2022). A critical review of the life cycle climate impact in seaweed value chains to support carbon accounting and blue carbon financing. *Cleaner Environmental Systems*, *6*(2022) 100093. <https://doi.org/10.1016/j.cesys.2022.100093>
- Holdt, S. L., & Kraan, S. (2011). Bioactive compounds in seaweed: Functional food applications and legislation. *Journal of Applied Phycology*, *23*, 543-597. <https://doi.org/10.1007/s10811-010-9632-5>
- Hossain, M. S., Sharifuzzaman, S. M., Nobil, M. N., Chowdhury, M. S. N., Sarker, S., Alamgir, M., Uddin, S. A., Chowdhury, S. R., Rahman, M. M., Rahman, M. S., Sobhan, F., & Chowdhury, S. (2021). Seaweed farming for sustainable development goals and blue economy in Bangladesh. *Marine Policy*, *128*, 104469. <https://doi.org/10.1016/j.marpol.2021.104469>
- Huijbregts, M. A. J., Steinmann, Z. J. N., Elshout, P. M. F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., & van Zelm, R. (2017). ReCiPe2016: A harmonised life cycle impact assessment method at midpoint and endpoint level. *The International Journal of Life Cycle Assessment*, *22*, 138-147. <https://doi.org/10.1007/s11367-016-1246-y>
- Islam, M. R., Akter, T., Hossain, A., Tora, A. T., Mely, S. S., Hossain, M. A., & Haque, M. M. (2024). Contribution and prospect of marine fisheries in the economy of Bangladesh and sustainable blue economy challenges: A review. *Marine Science and Technology Bulletin*, *13*(1), 41-55. <https://doi.org/10.33714/masteb.1337034>
- International Organisation for Standardization. (2006). *ISO 14040: Environmental management—Life cycle assessment—Principles and framework*. ISO. <https://www.iso.org/standard/37456.html>
- Kanagesan, K., Abdulla, R., Derman, E., Sabullah, M. K., Govindan, N., & Gansau, J. A. (2022). A sustainable approach to green algal bioplastics production from brown seaweeds of Sabah, Malaysia. *Journal of King Saud University - Science*, *34*, 102268. <https://doi.org/10.1016/j.jksus.2022.102268>
- Kambey, C. S. B., Iona, C., Elizabeth, J. C.-C., Adibi, R. M. N., Azhar, K., Ahemad, S., & Phaik-Eem, L. (2021). Evaluating biosecurity policy implementation in the seaweed aquaculture industry of Malaysia using the quantitative knowledge, attitude, and practices (KAP) survey technique. *Marine Policy*, *134*, 104800. <https://doi.org/10.1016/j.marpol.2021.104800>
- Koesling, M., Kvasdheim, N. P., Halfdanarson, J., Emblemsvåg, J., & Rebour, C. (2021). Environmental impacts of protein production from farmed seaweed: Comparison of possible scenarios in Norway. *Journal of Cleaner Production*, *307*, 127301. <https://doi.org/10.1016/j.jclepro.2021.127301>

- Lian, Y., Wang, R., Zheng, J., Chen, W. X., Chang, L., Li, C., & Yim, S. C. (2023). Carbon sequestration assessment and analysis in the whole life cycle of seaweed. *Environmental Research Letters*, *18*, 074013. <https://doi.org/10.1088/1748-9326/acdae9>
- Lovelock, C. E., & Duarte, C. M. (2019). Dimensions of blue carbon and emerging perspectives. *Biology Letters*, *15*(3), 20180781. <https://doi.org/10.1098/rsbl.2018.0781>
- Luu, L. Q., Cellura, M., Longo, S., & Guarino, F. (2024). A comparison of the life-cycle impacts of the concentrating solar power with the product environmental footprint and ReCiPe methods. *Energies*, *17*(17), 4461. <https://doi.org/10.3390/en17174461>
- Ministry of Agriculture and Food Industry. (2021). *Action plan national agrofood policy 2021-2030 (NAP 2.0): Agrofood modernization—Safeguarding the future of national food security*. Ministry of Agriculture and Agrofood Industries, Malaysia. <https://www.kpkm.gov.my/en/agro-food-policy/national-agrofood-policy>
- Mungkung, R., Aubin, J., Prihadi, T. H., Slembrouck, J., van der Werf, H. M. G., & Legendre, M. (2013). Life cycle assessment for environmentally sustainable aquaculture management: A case study of combined aquaculture systems for carp and tilapia. *Journal of Cleaner Production*, *57*, 249-256. <https://doi.org/10.1016/j.jclepro.2013.05.029>
- Nor, A. M., Gray, T. S., Caldwell, G. S., & Stead, S. M. (2020). A value chain analysis of Malaysia's seaweed industry. *Journal of Applied Phycology*, *32*, 2161-2171. <https://doi.org/10.1007/s10811-019-02004-3>
- Nilsson, A. E., Bergman, K., Gomez Barrio, L. P., Cabral, E. M., & Tiwari, B. K. (2022). Life cycle assessment of a seaweed-based biorefinery concept. *Algal Research*, *65*, 102725. <https://doi.org/10.1016/j.algal.2022.102725>
- Pahri, S. D. R., Mohamed, A. F., & Samat, A. (2016). Life cycle assessment of cockles (*Anadara granosa*) farming: A case study in Malaysia. *EnvironmentAsia*, *9*(2), 80-90. <https://doi.org/10.14456/ea.2016.11>
- Penadés-Plà, V., Martínez-Muñoz, D., García-Segura, T., Navarro, I., & Yepes, V. (2020). Environmental and social impact assessment of optimised post-tensioned concrete road bridges. *Sustainability*, *12*(10), 4265. <https://doi.org/10.3390/su12104265>
- Pessarrodona, A., Howard, J., Pidgeon, E., Wernberg, T., & Filbee-Dexter, K. (2024). Carbon removal and climate change mitigation by seaweed farming: A state of knowledge review. *Science of the Total Environment*, *918*, 170525. <https://doi.org/10.1016/j.scitotenv.2024.170525>
- Petrova, V. (2023). Assessment of the ecological footprint of industrial processes: An integrated approach to life cycle analysis. *The Eurasia Proceedings of Science, Technology, Engineering and Mathematics*, *26*, 67-74. <https://doi.org/10.55549/epstem.1409314>
- Phang, S. M. (2010). Potential products from tropical algae and seaweeds. *Malaysian Journal of Science*, *29*(2), 160-166. <https://doi.org/10.22452/mjs.vol29no2.7>
- Phang, S. M., Yeong, H. Y., & Lim, P. E. (2019). The seaweed resources of Malaysia. *Botanica Marina*, *62*(3), 265-273. <https://doi.org/10.1515/bot-2018-0067>
- Raja, K., Kadirvel, V., & Subramaniyan, T. (2022). Seaweeds as an aquatic plant-based protein for sustainable nutrition: A review. *Future Foods*, *5*, 100142. <https://doi.org/10.1016/j.fufo.2022.100142>

- Rimmer, M. A., Larson, S., Lapong, I., Purnomo, A. H., Pong-Masak, P. R., Swanepoel, L., & Paul, N. A. (2021). Seaweed aquaculture in Indonesia contributes to social and economic wellbeing. *Sustainability*, *13*(19), 10946. <https://doi.org/10.3390/su131910946>
- Rosales, M. V., & Dhakal, S. (2024). *A comparative analysis of carbon accounting methodologies and tools*. In *Proceedings of the 2024 International Conference on Sustainable Energy: Energy Transition and Net-Zero Climate Future (ICUE)* (pp. 1-7). Pattaya City, Thailand. <https://doi.org/10.1109/ICUE63019.2024.10795543>
- Sečkář, M., Schwarz, M., Pochyba, A., & Polgár, A. (2024). A comparative analysis of the environmental impacts of wood-aluminum window production in two life cycle assessment software. *Sustainability*, *16*(21), 9581. <https://doi.org/10.3390/su16219581>
- Seghetta, M., Romeo, D., D'Este, M., Alvarado-Morales, M., Angelidaki, I., Bastianoni, S., & Thomsen, M. (2017). Seaweed as innovative feedstock for energy and feed. *Journal of Cleaner Production*, *150*, 1-15. <https://doi.org/10.1016/j.jclepro.2017.02.022>
- Seghetta, M., Tørring, D., Bruhn, A., & Thomsen, M. (2016). Bioextraction potential of seaweed in Denmark. *Science of the Total Environment*, *563-564*, 513-529. <https://doi.org/10.1016/j.scitotenv.2016.04.010>
- Smith-Godfrey, S. (2016). Defining the blue economy. *Maritime Affairs*, *12*, 58-64. <https://doi.org/10.1080/09733159.2016.1175131>
- Speck, R., Selke, S., Auras, R., & Fitzsimmons, J. (2016). Life cycle assessment software: Selection can impact results. *Journal of Industrial Ecology*, *20*(1), 18-28. <https://doi.org/10.1111/jiec.12245>
- Sultana, F., Wahab, M. A., Nahiduzzaman, M., Mohiuddin, M., Iqbal, M. Z., Shakil, A., Mamun, A. Al., Khan, M. S. R., Wong, L. L., & Asaduzzaman, M. (2023). Seaweed farming for food and nutritional security, climate change mitigation and adaptation, and women empowerment: A review. *Aquaculture and Fisheries*, *8*(5), 463-480. <https://doi.org/10.1016/j.aaf.2022.09.001>
- Thierry, C., Alejandro, H. B., Christina, H., Max, T., Nils, K., Amir, N., George, P. K., José, A. Z.-G., Charles, Y., & Christopher, N. (2001). Integrating seaweeds into marine aquaculture systems: A key toward sustainability. *Journal of Phycology*, *37*, 975-986. <https://doi.org/10.1046/j.1529-8817.2001.01137.x>
- Thierry, C., & Albert, G. J. T. (2020). Importance of seaweeds and extractive species in global aquaculture production. *Reviews in Fisheries Science & Aquaculture*, *29*(2), 139-148. <https://doi.org/10.1080/23308249.2020.1810626>
- Thomas, J. B. E., Sodr e Ribeiro, M., Potting, J., Cervin, G., Nylund, G. M., Olsson, J., Albers, E., Undeland, I., Pavia, H., & Gr ndahl, F. (2021). A comparative environmental life cycle assessment of hatchery, cultivation, and preservation of the kelp *Saccharina latissima*. *ICES Journal of Marine Science*, *78*(1), 451-467. <https://doi.org/10.1093/icesjms/fsaa112>
- Valderrama, D. (2012). Social and economic dimensions of seaweed farming: A global review. *Proceedings of the Sixteenth Biennial Conference of the International Institute of Fisheries Economics and Trade*. <https://api.semanticscholar.org/CorpusID:92986279>
- van Oirschot, R., Thomas, J. B. E., Gr ndahl, F., Fortuin, K. P. J., Brandenburg, W., & Potting, J. (2017). Explorative environmental life cycle assessment for system design of seaweed cultivation and drying. *Algal Research*, *27*, 43-54. <https://doi.org/10.1016/j.algal.2017.07.025>

- Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2016). The ecoinvent database version 3 (EC3): Overview and methodology. *The International Journal of Life Cycle Assessment*, 21(3), 420-428. <https://doi.org/10.1007/s11367-016-1087-8>
- Zhang, X., Border, A., Goosen, N., & Thomsen, M. (2021). Environmental life cycle assessment of cascade valorisation strategies of South African macroalga *Ecklonia maxima* using green extraction technologies. *Algal Research*, 58, 102348. <https://doi.org/10.1016/j.algal.2021.102348>