Life cycle assessment of bioenergy production from macroalgae: A review

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Abstract. The sustainability integration to achieve circular economy pressures the development of renewable raw material and bioenergy sources, including marine biomass such as macroalgae. The consideration of sustainable conversion technology for bioenergy from macroalgae is critically highlighted. Various studies have been emphasized that life cycle assessment (LCA) can be applied to assess the efficacy and environmental aspects of bioenergy production from cradle-to-grave. This systematic review attempts to critically evaluate the development of LCA studies on macroalgae valorisation for bioenergy. Several online databases (i.e., Science Direct, Wiley Online Library, Springer, DOAJ, and MDPI) were used to collect the relevant articles. Then, PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) method has been selected to screen the most recent research articles (from January 2011 to June 2021) published in peer-reviewed international journals. The studies presented the development, opportunities, challenges, and future research for the commercialization of macroalgae as a sustainable feedstock for bioenergy.

1. Introduction

The global energy demand continuously increases along with an increase in population density and economic growth. Large populations affect the energy demand for transportation, the industrial sector, and power generation [1]. The global population in 2019 was accounted for 7.7 billion people and is estimated to increase up to 9.7 billion in 2050 [2]. Meanwhile, according to the BP Statistical Review of World Energy [3], the world's total energy consumption in 2019 was 583.9 exajoules, of which 84% is derived from fossil fuels. An increase in energy demand may cause a depletion of petroleum-based energy resources; thus, exploring renewable energy sources is essential.

In recent years, bioenergy as one of the renewable energy sources has experienced an increase in the demand by three-fold since 2015. It is expected to contribute 17% of global energy by 2060 [4]. Biomass is the most available renewable energy source, accounting for more than 70% of global bioenergy production [5]. Furthermore, recent attention toward marine biomass has highlighted macroalgae (also known as seaweed) as one of the potential biomass of bioenergy production. Macroalgae contain high polysaccharides with few or no lignin [6]. In addition, macroalgae are abundantly available due to their high production yield, which is accounted at 2-20 times higher than the terrestrial biomass. It occurs as a result of photosynthetic efficiency, which positively affects the growth rate [7]. Macroalgae have a
higher growth rate efficiency of 6-8%, while terrestrial biomass is only 1.8-2.2% [8]. Furthermore, macroalgae can be cultivated in seawater, thus avoiding land competition and freshwater usage for agriculture and energy crops [9]. The utilization of macroalgae for bioenergy production can overcome the drawbacks of the first and second generations of biomass [10]. Valorisation of various species of macroalgae has been widely carried out for bioenergy production, include bioethanol [11], biogas [12], biohydrogen [13], bio-oil [14], and biobutanol [15].

Nowadays, sustainability pressures the development of bioenergy sources and conversion pathways to achieve a circular economy. However, the commercialization of bioenergy from macroalgae still faces many obstacles, such as environmental impacts, technical, economic, and social aspects [16]. Emphasizing sustainability concepts is important to produce green energy [17]. Consequently, many researchers attempted to analyse the environmental impact of bioenergy production by conducting a Life Cycle Assessment (LCA). LCA is an international standard framework to assess the environmental performance comprehensively over the entire product or process. The principles and steps are carried out according to ISO 14040:2006 [18]. Therefore, this review was conducted as a systematic review that compiled relevant articles and synthesized empirical evidence that meets predetermined criteria comprehensively and repeatedly to answer research questions [19]. This review aimed to evaluate the development of LCA studies on macroalgae valorisation for bioenergy from relevant research articles as well as to present the opportunities, challenges, and future research for the commercialization of macroalgae as a sustainable feedstock for bioenergy.

2. Methods
This article is a systematic review that adopts the PRISMA 2020 (Preferred Reporting Items for Systematic reviews and Meta-Analyses) method to collect and screen the relevant articles. The PRISMA 2020 is an evidence-based reporting tool for systematic reviews, and the PRISMA flow diagram showed the number of articles transparently during the selection process [20].

2.1. Data collection
An exploratory search was performed to collect and survey the most recent research articles (from January 2011 to June 2021) on LCA studies of macroalgae valorisation for bioenergy published in a peer-reviewed international journal. Several online databases (i.e., ScienceDirect, Wiley Online, Springer, DOAJ, and MDPI) were used to collect the relevant articles. Various keywords were combined in the search, for instance, “life cycle assessment,” “life cycle analysis,” followed by the word “production,” which presents the process or product of bioenergy, then “macroalgae,” or “seaweed.” Bioenergy products consist of biofuel and biopower, which include heat and electricity.

The PRISMA 2020 flow diagram to select relevant articles is shown in Figure 1. The search showed 1539 records which the title and abstract of the research articles indexed in all databases. Articles with the exact title, author, and publication year were removed to avoid articles duplication, thus counted as only 1 article. Then, the collected articles were screened on the title, abstract, and full text. The screening processes were based on the presence of LCA studies for macroalgae conversion to bioenergy and online full-text availability. Any articles that did not fit the criteria were excluded. Consequently, only 13 relevant articles were selected, which were published in several journals such as Journal of Cleaner Production (4 articles), Bioresource Technology (2 articles), and 1 article, respectively in Algal Research, Applied Energy, Biofuel, Bioproducts, and Biorefining, Energy, Energy Procedia, and Environmental Progress & Sustainable Energy.

2.2. Analysis
The analysis technique in this systematic review was carried out through data extraction and data synthesis of the selected articles, as shown in Figure 2.
2.2.1. Data extraction. Extracted data was obtained by grouping the important information on LCA. It generated a research results overview from the relevant articles such as macroalgae species, locations, types of bioenergy products, goal and scope of LCA study, system boundaries, functional units, the
2.2. Data synthesis. In this systematic review, the data were synthesized qualitatively, also known as a narrative review. According to Siddaway et al. [21], the narrative review became appropriate to synthesize quantitative studies with diverse methodologies without addressing the statistical significance of the findings. This aimed to develop or evaluate a theory that was carried out by reinterpretation of the linked studies on different methods. It can also be useful to provide a record of the development of research on a topic (although contributions to knowledge could be relatively minor). The narrative review was chosen in this study because it collected the environmental impact assessments results of LCA studies (quantitative) with different methods, scope, constructions, and units. It would reinterpret by comparing the important aspects of LCA, main findings, or the environmental impact of macroalgae utilization as raw material for bioenergy from all relevant articles. Therefore, an overview of the potential of macroalgae species and bioenergy production processes with lower environmental impact could be drawn.

3. Results and discussion

3.1. Current status of LCA studies on macroalgae conversion

The data extraction results are presented in Table 1. It can be seen that LCA is widely used to investigate, assess, and evaluate the environmental performance of the single bioenergy production or biorefinery concept of macroalgae valorisation. The LCA method was also used to compare the environmental impact of macroalgae and other biomass for bioenergy production. These LCA studies have assessed the conversion of macroalgae to produce biogas, bioethanol, biomethane, and bio-oil to provide heat and electricity or as a transportation fuel. Macroalgae contains high carbohydrates up to 50% [22], thus becoming the main attraction factor for bioenergy production. Despite high carbohydrates content, the compositions are also depended on the species, season, and harvest location. Additionally, macroalgae also have little or even no lignin; therefore, the conversion process does not require extreme pre-treatment, and it is suitable for the fermentation process or anaerobic digestion [23].

There were 10 of the 13 articles that were attracted to utilize brown macroalgae (i.e., *Laminaria digitata, Saccharina japonica, Saccharina latissima, Macrocystis pyrifera*, and *Nereocystis luetkeana*). Eight articles used brown macroalgae as a single feedstock, and two articles were co-substrated with other species. Green macroalgae assessed for bioenergy production were *Ulva lactuca* and *Ulva prolifera*, while red macroalgae was *Glacilaria chilensis*. Brown macroalgae have a very complex chemical composition that is dominated by 60% carbohydrates, including alginate, laminarin, mannitol, and fucoidan [24]. Brown macroalgae have more attraction than red or green macroalgae to generate biogas, biomethane, or bioethanol. This is because red or green macroalgae are more commonly used for food and hydrocolloid production compared to bioenergy.
| Species | Location | Product | Goal and Scope | Functional unit (FU) | System boundary | Impact indicators | CC or GWP result | Main findings | Refs. |
|---------|----------|---------|----------------|----------------------|-----------------|------------------|-----------------|--------------|------|
| *G. chilensis* | Chile | Bioethanol, Electricity from Biogas | To determine the most sustainable scenario of cultivation and bioenergy production | 1 MJ of energy | Cradle-to-Gate | ACP, EP, GWP, HTP ODP, POFP | **−0.28 kg CO₂̅-eq** | The most sustainable scenario was obtained from bottom cultivation then produced for bioethanol and electricity from biogas | [25] |
| *M. pyrifera* | | | | | | | **−0.04 kg CO₂̅-eq** | | | |
| *L. digitata* | Denmark | Bioethanol, Biogas | To assess and compare the environmental impacts of two scenarios (i.e. biogas and sequent biotechanol+biogas production) | 1 ton of dried seaweed | Cradle-to-Gate | ACP, EP, GWP | **−446 kg CO₂̅-eq** | Biogas production scenario showed better environmental performance than bioethanol+biogas production for all impact indicators | [26] |
| *L. digitata* | Denmark | Bioethanol | To assess and evaluate the environmental performance of base case biotechanol production and six alternative scenarios | 1 ha of the sea under cultivation | Cradle-to-Grave | CC, CED-T, CED-F, HTP-C, HTP-NC, MEU, MEU-Phosphorus-limited | **−0.1×10⁸ Kg CO₂̅-eq** | High productivity scenario potentially reduced the impacts of CC, ME, MEU-Phlin, CED-T, and CED-F from the base case due to the increase of biorefinery products | [27] |
| *L. digitata* | Denmark | Heat and Electricity from Biogas | To assess the environmental performance of biogas production to provide decision support for future industrial-scale | 1 ha of cultivation area | Cradle-to-Gate | CC, CED-T, CED-F, HTP-C, HTP-NC, MEU, MEU-Phosphorus-limited | **−18.7×10⁸ Kg CO₂̅-eq** | Biogas production from dried *Laminaria digitata* had the most favorable environmental performance | [28] |
| Species       | Location   | Product   | Goal and scope                                                                 |
|--------------|------------|-----------|--------------------------------------------------------------------------------|
| *L. digitata*| Ireland    | Biomethane| To assess the environmental impacts of integrated seaweed and salmon farming for biomethane production in a country with a temperate oceanic climate |
|              |            |           | Functional unit (FU): 1 MJ of biomethane                                        |
|              |            |           | System boundary: Cradle-to-Gate                                                 |
|              |            |           | Impact indicators: ACP, CC, FEU, MEU, TEU                                       |
|              |            |           | CC or GWP result: 49.26 g CO$_2$-eq.                                           |
|              |            |           | Main findings: The base case of integrated seaweed and salmon farming system showed high emissions in all impact categories, however by replaced 70% mineral fertilizer with digestate could achieve a minimum GHG savings |
|              |            |           | Refs.: [29]                                                                    |
| *S. japonica*| South Korea| Bioethanol| To compare the environmental performance between seaweed and terrestrial biomass-based bioethanol production |
|              |            |           | Functional unit (FU): 1 kL of bioethanol                                         |
|              |            |           | System boundary: Cradle-to-Gate                                                  |
|              |            |           | Impact indicators: GWP                                                           |
|              |            |           | CC or GWP result: 1202 kg CO$_2$-eq/year                                        |
|              |            |           | Main findings: Seaweed-based bioethanol has a lower GWP than terrestrial biomass in the long term (200 years) due to its cultivation does not incur N$_2$O emission and carbon debt as well as no need for fertilizers |
|              |            |           | Refs.: [30]                                                                    |
| *S. japonica*| South Korea| Bioethanol| To determine the optimal design of bioethanol production by using superstructure optimization to minimize CO$_2$ emissions and freshwater consumption |
|              |            |           | Functional unit (FU): 1 kg bioethanol                                             |
|              |            |           | System boundary: Gate-to-Gate                                                    |
|              |            |           | Impact indicators: GWP                                                           |
|              |            |           | CC or GWP result: 3.67 kg/FU                                                     |
|              |            |           | Main findings: The optimal design of superstructure results was obtained of 90% reduction in CO$_2$ emissions and 38.6% reduction in freshwater consumption |
|              |            |           | Refs.: [31]                                                                    |
| *S. latissima*| France     | Biomethane| To evaluate the environmental impacts of methane production from macroalgae and alginate extraction residues |
|              |            |           | Functional unit (FU): 1 km trip with a gas-powered car                          |
|              |            |           | System boundary: Cradle-to-Grave                                                 |
|              |            |           | Impact indicators: ALO, CC, FD, FECO, FEU, HTP, IR, MD, MECO, WD, MEU, NLT, ODP, PMF, POFP, TAC, TECO, ULO |
|              |            |           | CC or GWP result: ~40%                                                          |
|              |            |           | Main findings: Both substrates decreased GHG emissions and fossil depletion in comparison with natural gas. Macroalgae also improved the marine eutrophication index and decreased ozone depletion |
|              |            |           | Refs.: [32]                                                                    |
### Table 1. Data extraction of LCA study on macroalgae conversion for bioenergy (Continue).

| Species                        | Location                          | Product                      | Goal and scope                                                                 | Functional unit (FU and thermal) | System boundary | Impact indicators                                                                 | CC or GWP result         | Main findings                                                                                                                                                                                                 | Refs. |
|--------------------------------|-----------------------------------|------------------------------|--------------------------------------------------------------------------------|---------------------------------|-----------------|-----------------------------------------------------------------------------------|--------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------|
| U. lactuca                      | Italy                             | Biogas                       | To compare and evaluate the environmental performances of macroalgae, mix agricultural feedstock, and natural gas in the biogas pilot plant | 1.02 kWh of electricity, 10.92 MJ of thermal                                  | Cradle-to-Grave    | ACP/EP, CC, Ecotoxicity, LTP, MID, Respiratory inorganics                          | ~(-0.13) mPt             | Macroalgae-based biogas was favourable to replace land-based feedstock. Macroalgae showed better environmental performance of 10% than agricultural feedstock and 38 times to natural gas                            | [33]  |
| U. prolifera                    | United Arab Emirates (UAE)        | Biogas                       | To compare the environmental impact between macroalgae and cattle manure for biogas production | 1 GJ of energy                  | Cradle-to-Grave    | ACP/EP, CC, FD, LTP, MID, ODP, Carcinogen, Ecotoxicity, Respiratory organics, and inorganics, Radiation | 75.38 mPt                | The macroalgae showed better environmental performance than cattle manure in recovered biogas to the biorefinery system. However, macroalgae slightly worse in utilization biogas for grid electricity and transportation fuel | [34]  |
| Ulva sp.                        | France                            | Bioethanol                    | To evaluate the environmental performance of lab-scale bioethanol production from onshore-cultivated macroalgae | 1 MJ of bioethanol combustion   | Cradle-to-Grave    | ACP, CC, FD, FECO, FEU, HTP-C, LTP, MD, MEU, ODP, PMF, POC, TEU, WD              | ~0.08 kg CO₂-eq.         | ACP, IR, FD, FEU, HTP-C, and MD indicators gave the largest environmental burdens due to electricity consumption and nutrients needed in the cultivation                                                          | [35]  |
| A mixture of brown and red algae with chicken manure | Northeast Germany from Biogas | Heat and Electricity from Biogas | To assess the environmental impact of macroalgae to substitute energy crops in a biogas plant | 1 MJ of biogas                 | Cradle-to-Gate    | ACP, EP, GWP, LTP                                                               | 13.9 kg CO₂-eq.          | Macroalgae-based biogas showed a lower of 52% GWP, 83% ACP, 41% EP, and 8% LTP from the current feedstock                                                                 | [36]  |
Table 1. Data extraction of LCA study on macroalgae conversion for bioenergy (Continue).

| Species          | Location | Product | Goal and scope                                                                 | Functional unit (FU) | System boundary | Impact indicators | CC or GWP result | Main findings                                                                                     | Refs. |
|------------------|----------|---------|---------------------------------------------------------------------------------|----------------------|-----------------|-------------------|------------------|-----------------------------------------------------------------------------------------------|-------|
| N. luetkeana and S. latissima | USA      | Upgraded Biocrude to renewable diesel, naphtha, butanol | To investigate the GHG emissions of macroalgae for biofuel production concept through Hydrothermal Liquefaction (HTL) technology | 1 MJ of fuel produced | Well-to-Wheel | GWP               | 19 g CO₂-eq. | HTL contributed the highest GHG emissions due to the requirement of large amounts of electricity, natural gas, and catalysts | [37]  |

**Abbreviation:** ACP: Acidification, ALO: Agricultural land occupation, CC: Climate Change, CED-F: Cumulative Energy Demand Fossil, CED-T: Cumulative Energy Demand Total, EP: Eutrophication, FD: Fossil depletion, FECO: Freshwater Aqua Ecotoxicity, FEU: Freshwater Eutrophication, GWP: Global Warming Potential, HTP: Human Toxicity, -C: Cancer, -NC: Non-Cancer, IR: Ionizing radiation, LTP: Land Transformation, MEU: Marine Eutrophication, MECO: Marine Aquatic Eco-toxicity, MD: Metal depletion, MID: Mineral depletion, NLT: Natural land transformation, ODP: Ozone Depletion, PMF: Particulate matter formation, POCP: Photochemical Ozone Creation Potential, POFP: Photochemical Oxidants Formation, TAC: Terrestrial acidification, TEU: Terrestrial Eutrophication, TECO: Terrestrial Eco-toxicity, ULO: Urban land occupation, WD: Water depletion potential
Based on its definition, LCA studies can also be described as a cradle-to-grave assessment, indicating that the studies covered the cultivation process to the bioenergy use stage and the end-of-life phase. Five articles have emphasized the cradle-to-grave system boundary. These articles assessed the environmental impacts from the cultivation stage, the production process for bioethanol or biomethane to the utilization stage either as fuel or electricity. For example, Seghetta et al. [27] studied the LCA, which covered the cultivation to utilization stage of bioethanol combustion for car fuel. Meanwhile, Langlois et al. [32] evaluated the environmental impact from offshore cultivation stage to the combustion of biomethane in engines as car fuel. Furthermore, two remaining cradle-to-grave articles covered the use stage of biogas for heat and electricity. These articles were also compared green macroalgae utilization to generate biogas for energy suppliers of existing conventional plants. For instance, Cappelli et al. [33] compared macroalgae with agricultural mix feedstock in Italy and Giwa [34] compared the cattle manure in the UAE by encompassed cradle-to-grave approach. However, several articles only covered cradle-to-gate, which means that the environmental impact assessment was starting from the macroalgae cultivation process to the bioenergy production stage, without further calculating the impact of the utilization phase. Moreover, there was also 1 article that encompassed just the usage stage called well-to-wheel. This means that the system boundary only covered the stages when the product was readily used as vehicle fuel, without assessing the environmental impact of the cultivation and production processes. This was aimed to estimate GHG emissions from microalgae-based biofuels utilization. In conducting LCA, system boundary was varied depending on the goal and concept of the research. If the scope of the assessed system is wider, the life cycle inventory (LCI) analysis is becoming more considerable and complex. Yet, the results of the LCA assessment can provide more detailed information on which process gives the highest environmental impact. Thus, it can be evaluated for improvement, concept development, or policy-making in order to achieve sustainable goals.

3.2. Environmental impact assessment

The main objective of LCA is to assess the environmental impact resulting from all resources as inputs in the system and all products, co-products to waste, and emissions released into the environment. All of these aspects are identified then quantified and evaluated for their environmental performance at the life cycle impact assessment (LCIA) stage by considering various impact indicators. The selection of impact indicators is influenced by an LCIA method. It can choose a middle-point or end-point approach. According to Li et al. [38], the mid-point is oriented towards environmental problems early in the cause-effect chain, while the end-point focuses on the damage at the end of the cause-effect chain, or it is called the actual damage. The end-point is just classified into three aspects: damage to human health, ecosystems, and natural resource availability.

Various mid- or end-point impact indicators are used in LCA studies of macroalgae conversion for bioenergy, such as acidification, climate change, eutrophication, eco-toxicity, human toxicity, global warming potential, land-use change, fossil fuel, minerals, and freshwater depletion, etc. Based on the data extraction (Table 1), the most widely used in all research is Climate Change (CC) or Global Warming Potential (GWP). Climate change is determined by GWP over a time horizon of 20, 100, or 500 years, but GWP100 is being the most common. These showed the changing of global temperature by greenhouse gases such as CO$_2$, CH$_4$, and N$_2$O (including indirect or direct emissions of NH$_3$ and NO) [29]. These indicators are widely used because the assessment related to bioenergy production (i.e. liquid or gaseous biofuel, heat and electricity). The production process until the utilization phase releases greenhouse gases. Additionally, CC or GWP allows evaluation from a global perspective, crossing regional and national borders [18]. These indicators are also needed for a comparison with fossil fuels in order to find out better environmental performance. Therefore, CC or GWP becomes a critical environmental impact indicator in LCA studies of macroalgae conversion for bioenergy.

The environment impact results of CC and GWP from the relevant articles also showed in Table 1. All of the articles calculated the impact of climate change or global warming potential, however, in diverse units such as kg CO$_2$-eq., mPt, etc. The impact indicators CC and GWP are normally presented
in units of kg CO$_2$ equivalent, but in the LCA study, there is also a common unit like 1 point (1 Pt). This is the average environmental impact score per capita in Europe yearly and is usually represented in mPt, which means one-thousandth of the yearly environmental impact of an average European inhabitant [34]. CC and GWP are selected to achieve CO$_2$ neutral or negative [28]. Based on Table 1, there are 6 articles achieved net negative in CC and GWP, but 7 articles obtained net positive. Net positive score indicates increased environmental impact [36], whereas net negative score means the system avoids impact or to be more environment-friendly [27]. Brown macroalgae _Laminaria digitata_ for biogas production showed the lowest GWP score [26], while _Saccharina japonica_ for bioethanol obtained the highest score [30]. However, the CC or GWP scores cannot be compared directly because of the unit difference and also depending on functional unit which affects result interpretation.

Based on Table 1, the impact indicators of acidification (ACP) and eutrophication (EP) are commonly used in various studies. These mid-point indicators are commonly chosen because the high nutrient content of feedstock and digestate can increase these impacts into ecosystem or natural environment [18, 39]. ACP is acidity condition of water and soil systems by increasing the hydrogen ion (H$^+$) concentration. This condition is caused by the atmospheric deposition of acidifying substances, such as nitrogen oxides (NO$_x$), sulphur dioxide (SO$_2$) (from fossil fuels combustion) and ammonia (NH$_3$) (contributes during nitrification) [29, 36]. Similarly, EP potential evaluates the impact of excessive amounts of nitrogen (N) and phosphorus (P) in marine, freshwater and terrestrial ecosystems. Terrestrial eutrophication occurred due to the deposition of airborne emissions of N-compounds and is expressed in moles of N-eq. Freshwater and marine eutrophication are caused by water-borne emissions. The limiting nutrient for eutrophication in freshwater ecosystems is phosphorus thus expressed in kg P-eq. Meanwhile, nitrogen is the limiting nutrient for eutrophication in marine ecosystems and is expressed in kg N-eq [29]. In addition, impact indicators that are affecting human health were also assessed as known as human toxicity potential (HTP). HTP is the chemicals toxic effect on the human body, divided into several mid-point indicators such as carcinogenic, non-carcinogenic, ozone layer depletion, photochemical oxidation, radiation, and respiratory organic or inorganics [39]. HTP is also commonly selected in order to underpin the need for upcycling technologies as a risk management tool to avoid externalities in a circular economy [28]. Further, impact indicators related to the availability of natural resources were also chosen in the relevant articles such as minerals, fossil, and renewable depletion, as well as land transformation.

LCA study reported by Langlois et al. [32], showed that biomethane as a car fuel was favourable to the environment because it reduced GHG emissions, ozone, and fossil depletion if compared to natural gas. Cappelli et al. [33] also revealed that macroalgae as feedstock for biogas production were also more environmentally beneficial to replace land-based feedstock. They claimed that using macroalgae showed better environmental performance by 10% compared to that of the agricultural feedstock, with biogas production of 38-times higher than natural gas. Then, Ertem et al. [36] also stated that using macroalgae-based biogas to supply 500 kWh plants could reduce impact indicators on GWP, acidification, eutrophication, and land transformation in comparison with the current biogas feedstock (i.e., maize, grass, rye, and chicken manure). In addition, Jung et al. [30] also obtained an assessment on macroalgae bioethanol which has a lower GWP impact than that of the terrestrial in the long term. Due to macroalgae cultivation does not incur N$_2$O emissions, carbon debt, and no need for fertilizers, making the scenario of macroalgae-based bioethanol as sustainable option.

Despite its sustainability assessment, the conversion of macroalgae into bioenergy has environmental burdens, as reported in several studies. Brockmann et al. [35] revealed that out of 16 environmental impact indicators, bioethanol production using onshore-cultivated green macroalgae generate a lower performance in 6 indicators (i.e. human toxicity- cancer effect, ionizing radiation HH, ionizing radiation E (interim), acidification, freshwater eutrophication, and mineral, fossil & renewable resource depletion), compared to that of the sugarcane-based bioethanol and petrol. It was possibly due to the high electricity consumption and nutrients needed during the cultivation. In addition, Greene et al. [37] also carried out the LCA assessment to investigate the greenhouse gas emissions from the production of bio-oil upgraded to renewable diesel, naphtha, butanol through the hydrothermal liquefaction (HTL)
process. The results showed that the production process using HTL contributes the highest GHG emissions, possibly due to a large demand of electricity, natural gas, and catalysts needed during the process.

4. Conclusion and future direction

LCA has been widely used to evaluate the environmental impact of macroalgae conversion into bioenergy. The findings confirmed that macroalgae are favourable and sustainable as feedstock for bioenergy production because of their high environmental efficiency. Moreover, the results also revealed that macroalgae are potential to replace the biogas feedstock in the existing plants. Unfortunately, several studies have also revealed that the bioenergy from macroalgae was not superior to that of the first-generation biomass. Therefore, it is necessary to identify problems and weaknesses as well as to examine alternative biorefinery scenarios as a solution to improve the environmental performance. With LCA study, the hotspot process which contributes a high environment impact can be obtained. Such information is critical to develop or improve the sustainable macroalgae valorisation scenario.

In addition, the development of macroalgae utilization for bioenergy should be explored continuously with consideration upon macroalgae’s type (e.g. red or green macroalgae), conversion technology, and variations in biorefinery scenario, as well as its sustainability assessment. Sustainability cannot be achieved only from an environmental aspect, but also need to involve economic and social aspects. Hence, the life cycle sustainability assessment which consists of LCA, Life Cycle Cost (LCC) and Life Cycle Social Assessment (LCSA) is needed to be done in the macroalgae valorisation for bioenergy in future researches. In addition, techno-economic analysis is also essential to assess the technical and economic aspects for commercialization of bioenergy from macroalgae.

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