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Determining The Seaweed Solid Waste-Based Ethanol Potential from Life Cycle Assessment (LCA) Perspective

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Abstract. The purpose of this study was to examine the environmental impact of ethanol production using solid waste as a raw material from the extraction of red seaweed. Sources of data used in this study derived from literature studies. The type of red seaweed studied was κ-carrageenan extracted from *Eucheuma cottoni*, *Eucheuma spinosum*, and *Gracilaria Manilaensis*. The system limitation in this study is gate-to-gate analysis, which includes processing raw materials to ethanol products using the relative mass and energy value method using a cut-off value of 5%. The value of CO_2 emissions from ethanol production using solid waste from *Eucheuma cottonii* is 2.97×10^{-14} kg CO_2eq/kg of ethanol. The production of ethanol using solid waste from *Eucheuma spinosum* and *Gracilaria manilaensis* resulted in CO_2 emissions of 5.72 and 2.87 kg CO_2 eq/kg of ethanol, respectively. Bioethanol from solid waste extracted from κ-carrageenan from *Eucheuma cottonii* becomes an environmentally friendly biofuel compared to bioethanol from sugarcane and sweet bagasse sorghum. The result of the main environmental impact study using the LCA method shows that the fermentation process, followed by the production of enzymes and electricity, is the main contributor to CO_2 emissions.

Keywords: Bioethanol; Life cycle assessment; Red seaweed; Solid waste

1. Introduction

Bioethanol and biogas are just a couple of examples of renewable energy sources that have been successfully developed from various types of seaweed (Jang *et al.*, 2012; Van Der Wal *et al.*, 2013). Because it contains a high concentration of carbs, seaweed can be fermented into ethanol. In addition to this, seaweed includes biological components, which, when broken down, can produce biogas as well as fertilizer.

Seaweed was categorized into 3 varieties, namely green seaweed (*Chlorophyceae*), brown seaweed (*Phaeophyceae)*, and red seaweed (*Rhodophyceae*) (Chen *et al.*, 2015). There are several species of red seaweed, the most common of which are *Kappaphycus alvarezii*, *Eucheuma Spinosum*, and *Gracilaria Manilaensis*. In the farming community, *Kap-*

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paphycus alvarezii is most commonly referred to as Eucheuma cottonii. *Eucheuma cottonii* and *Eucheuma spinosum* are the primary sources of κ-carrageenan, and so are used in over 88% of carrageenan production. Around 60% of global Kappaphycus production occurs in the BIMP-EAGA region, which includes Brunei, Indonesia, Malaysia, and the Philippines (Israel, Einav, and Seckbach, 2010). It was not surprising that Indonesia, along with Malaysia and the Philippines, is the largest carrageenan producer, which can produce around 120,000 dry tons per year (McHugh, 2003). For Gracilaria, according to FAO statistical data (FAO, 2020) annual the cultivation of Gracilaria has an increasing trend since 2014 and the production reached around 3.7 million tons.

κ-carrageenan extracted from red seaweed can be used in a variety of products, including food, health, and personal care (Kim *et al.*, 2013). Since κ-carrageenan content in seaweed was only 25-35% based on dry weight, the amount of solid waste left after the extraction process was quite large.

Seaweed solid waste comprises cellulose material with low lignin content, so it has the potency as a raw material for the production of third-generation bioethanol. The cellulose content in seaweed solid waste was about 99.8 ± 0.15-wt% dry basis (Tan and Lee, 2014, 2016). The saccharification process will convert cellulose into glucose and then ferment it to produce third-generation bioethanol. Thus, this is an opportunity to recycle solid waste from seaweed extraction into biofuels that have higher commercial value.

One innovative approach to reducing seaweed waste disposal and raising the value of seaweed waste biomass is the use of seaweed solid waste in bioethanol synthesis. Such production can also lead to the development of a seaweed-based biorefinery for the simultaneous production of carrageenan and bioethanol, which can increase the sustainability of the seaweed industry. Although many studies have been reported in the literature about the production of third-generation bioethanol, most of these studies have concentrated on raw seaweed as a feedstock. Since interest in using seaweed for bioethanol production was currently growing rapidly, the need for intensive research on the efficient utilization of solid waste from seaweed extraction has also received attention from researchers around the world.

The most appropriate method for identifying the ecological effects of seaweed biofuel production is the Life Cycle Assessment (LCA) method (Bradley, Maga, and Antón, 2015; Chiaramonti *et al.*, 2015). To the best of the author's knowledge, there are no papers focused on LCA studies to assess the conversion of seaweed solid waste into biofuels. Parsons *et al.* (2019) used LCA to calculate the potency of environmental effects associated with the production of single-cell oils (SCO) using Saccharina lattisima as feedstock. Besides replacing existing terrestrial oils, SCO can be used for food, biochemicals, and biodiesel. Czyrnek-Delêtre (2017) calculated the environmental impact of integrated seaweed and salmon farming on biomethane production in Ireland. Brockmann (2015) examined the effects of the ecosystem of producing bioethanol from cultivated seaweed in France using the LCA method. Not to mention, Aitken (2014) calculated the environmental impact of the production of biogas, bioethanol, and bioethanol + biogas from red seaweed and brown seaweed cultivated offshore in Chile using the LCA method (Aitken *et al.*, 2014). The potential of seaweed biomass as a biofuel source was investigated by Aresta (2005), who also developed software for estimating net consumption using the LCA method (Aresta, Dibenedetto, and Barberio, 2005). Langlois (2012) conducted the environmental effects of biogas production on brown grass cultivated offshore (Langlois *et al.*, 2012). Moreover, an LCA study on biofuels from brown seaweed grown offshore was conducted by Alvaredo-Morales and discovered biogas production and biogas + bioethanol from these seaweeds (Alvarado-Morales *et al.*, 2013).

Additionally, Pilicka (2011) used a cradle-to-grave boundary system in an LCA research to evaluate the ecological effects of green seaweed biogas production (Pilicka, Blumberg, and Romagnoli, 2011). Based on that explanation, we see previous biofuel studies there used seaweed as raw materials, either in the form of cultivated seaweed, or integrated seaweed with others, for producing biofuel. Previous research has primarily focused on using red and brown seaweed as a raw material for biofuel. No paper discusses at discusses LCA studies for the production of ethanol derived from solid waste produced from the κ-carrageenan extraction of seaweed.

It is necessary to carry out a life-cycle assessment (LCA) to determine the effect that the production of ethanol from the solid waste of seaweed would have on the surrounding environment. This research assesses a variety of environmental concerns, one of which is the possibility of CO_2 gas emissions being produced during the production of ethanol. In addition, other environmental effects were calculated, namely abiotic and ozone layer depletion, ecotoxicity to humans, freshwater, and seawater, as well as photochemical oxidation, acidification, and eutrophication. The value of CO_2 emissions resulting from the production of ethanol using solid waste from seaweed as raw material is extremely important because seaweed has different characteristics from other lignocellulosic raw materials. The dissolved CO_2 in seawater can be absorbed by seaweed, which then converts it into O_2. Because of the emissions of CO_2 gas that are released into the environment, seaweed has the potential to lessen the effects of global warming. However, because the creation of ethanol results in the release of CO_2 emissions into the environment, the use of seaweed as a raw material for the production of ethanol is in direct contradiction to the characteristics that seaweed possesses. Because of this, a study was carried out to determine the effect that the production of ethanol utilizing the solid waste of red seaweed had on the environment, particularly in terms of the CO2 emissions that were caused by the process. If the CO_2 emissions generated from the production of ethanol from solid waste of seaweed are not as large as the CO_2 emissions produced when using seaweed as raw material, then the results of this study can be a consideration for industry and researchers to use solid waste, which is usually used as feed for animal, instead of using seaweed as raw material for biofuel. Therefore, this research has focused on the study of the environmental effects of bioethanol from solid waste produced from κ-carrageenan extraction of red seaweed, i.e. *Kappaphycus alvarezii*, *Euchema spinosum*, as well as solid waste from agar extraction of *Gracilaria manilaensis*. Because of its abundance in Indonesian waters, particularly in the eastern regions, red seaweed was chosen as the study's subject. Data from the existing literature on the manufacture of ethanol from red seaweed solid waste was utilized during the course of this research.

The results of the LCA analysis show the value of emissions produced or discharged into the environment by the product or system and this information is needed by the researchers, practitioners, and the seaweed industry in deciding the utilization of seaweed. Gate-to-gate analysis was used as the boundary system in the LCA calculation and carried out by considering the life cycle starting from raw materials (seaweed solid waste) to processing into a product (ethanol).

2. Methods

2.1. *Life cycle assessment (LCA)*

The Life cycle assessment (LCA) method has been widely used to evaluate the potential environmental impact of a product or process. For a life cycle assessment (LCA), the resources used and carbon dioxide (CO_2) emissions produced by a system are measured and quantified within the limits of the system boundary (SNI ISO 14040:2016;

SNI ISO 14044:2017). The procedures in LCA are described in the International ISO 14040 and ISO 14044 standards. The procedures are followings: (1) defining the objectives and scope; (2) inventory analysis; (3) impact analysis or measurement, (4) interpretation (SNI ISO 14040:2016). There are four options for determining the used system based on the ISO 14044 standard in the LCA study: (1) *Cradle-to-grave*: includes materials and production chain all processes from raw material extraction through production, transportation, and use stages to the final product in the life cycle, (2) *Cradle-to-gate*: includes all processes of extracting raw materials through the production stage (a process within the factory), used to determine the environmental impact of a product's production, (3) *Gate-to-grave*: includes the process from post-production use to the end of the phase of life cycle life, used to determine the environmental impact of the product after leaving the factory, (4) *Gate-to-gate*: consists of the process from the production stage only, used to determine the environmental impact of the production step or process.

In this study, the LCA method was also applied to determine the environmental impact, especially the Global Warming Potential (GWP), which was produced from the production of bioethanol using solid waste as raw material from seaweed extraction. Some literature was used as a data source on the basis of calculating LCA because there was no laboratory analysis data related to this topic in Indonesia. The reference sources used in this paper include bioethanol production using solid waste from *Eucheuma cottonii* (Tan and Lee, 2016), ethanol production derived from solid waste extracted from *Eucheuma Spinosum* (Alfonsín, Maceiras, and Gutiérrez, 2019), and ethanol production derived from solid waste extracted from *Gracilaria Manilaensis* (Hessami, Salleh, and Phang, 2020). Energy consumption during the production process was also included in the scope of this analysis. In general, the LCA method consisted of, (1) a Definition of The Objectives and Scope, (2) a Life Cycle Inventory (LCI), and (3) a Life Cycle Impact Assessment (LCIA), along with the assumptions and limitations of the study (Putri, Waluyo, and Setiawan, 2018).

2.1.1. Goal and scope definition

The purpose of this study, as mentioned in the first section (introduction), was to evaluate the environmental impact of bioethanol production from seaweed solid waste obtained after extraction. The raw material used in this study was red seaweed, including *Kappaphycus alvarezii* (*Eucheuma cottonii*, *Eucheuma spinosum*, and *Gracilaria manilaensis*, using the LCA methodology approach. Using the mass and energy value method and a cutoff value of 5%, the system limitations for analysis were determined. The scope includes the entire ethanol production process, from raw materials to final products. During the production process from the raw material into the ethanol product, the total mass and energy values of each input were calculated using the LCA method approach. Because the value of this functional unit (FU) is closely related to the modeling of the production system that is being studied, determining the definition of the functional unit (FU) is an extremely crucial step in the LCA method.

The functional unit is described as the function of a product which will be the basic reference for all impact assessment calculations. The determination of FU in the LCA study is affected by the sector or type of product that is the object of the study. For food-based products, the FU standard used in the LCA calculation is usually based on mass. In the energy sector, the unit that is frequently used to define a functional unit is energy and is followed by mass, for example, the mass of a particular fuel. In general, the most widely used quantity is mass, followed by energy, volume, and area. This research was related to the energy sector, namely biofuels, and the functional unit commonly used in this sector is mass, therefore the functional unit that defined in this paper was 1 kg of ethanol product.

The results of the LCA analysis conducted for this study will present information regarding the environmental emissions caused by the production of 1 kilogram of ethanol.

Energy evaluation adopted the same FU used for LCA (1 kg of ethanol) and was carried out for each specific step and the entire process. The following energy indicators were calculated: the net energy value (NEV, e.g. the difference between total energy output and input) and the net energy ratio (NER, e.g. the ratio between net energy output/input). Process simulation techniques were integrated into LCA and energy evaluation to reduce bias parameters in processing data collection.

2.1.2. Life cycle inventory

As outlined in Section 2.1, the data for ethanol production from red seaweed solid waste was obtained from a variety of publications. Researchers utilized the LCA modeling software SimaPro 8.2.0.0 to perform the LCA modeling. As it is known that SimaPro 8.2.0.0 was LCA modeling software. Inventory data for the ethanol production process based on seaweed solid waste, such as chemicals used, ethanol yield, by-products, energy use, and emissions, were collected from various sources, including published literature and databases (i.e. EcoInvent v3.0). When the data of the process were not available, the assumptions were established, process engineering calculations were conducted, and data were analyzed.

2.1.3. Life Cycle Impact Assessment (LCIA)

Based on the inputs and outputs of the system determined in the Life Cycle Inventory calculation, the potency of environmental impacts was measured in the Life Cycle Impact Assessment (LCIA) phase. The following are some categories of the impact that were measured in the research: Global Warming Potential (GWP) (kg CO_2--eq), abiotic depletion (kg Sb--eq), abiotic depletion (fossil fuels) (MJ), ozone layer depletion (kg CFC-11--eq), human toxicity (kg 1,4-DB--eq), freshwater ecotoxicity (kg 1,4-DB--eq), seawater ecotoxicity (kg 1,4-DB--eq), terrestrial ecotoxicity (kg 1,4-DB--eq), eq), photochemical oxidation (kg C_2H_4--eq), acidification (kg SO_2--eq), and eutrophication (kg PO_4--eq).

2.2. Ethanol production from solid waste derived after extraction from red seaweed

2.2.1. Solid waste of *Eucheuma cottonii*

The composition of solid waste-carrageenan from *Eucheuma cottonii* consisted of 99.8 wt% cellulose, 0.03 wt% protein, 0.14 wt% ash, and 0.03 wt% lipid (Tan and Lee, 2016). Based on the research of Tan *et al.* (2016) there was 15833.3 kg/hour of solid waste and 69262.85 kg/hour of water to produce 7626 kg/hour of anhydrous bioethanol and 3372 kg/hour of liquid organic fertilizer (Tan and Lee, 2016). This literature describes the SSF process, in which the enzymes Saccharomyces cerevisiae (1316.2 kg/hour) and cellulase (316.19 kg/hour) are utilized to produce bioethanol (Tan and Lee, 2016). As for the production of cellulase, other nutrients such as glucose, ammonia, and sulfur dioxide were needed for the growth of *Trichoderma reesei* (Humbird *et al.*, 2011). In this study, Tan *et al.* used glucose at 1327 kg/hour, sulfur dioxide at 9,545 kg/hour sulfur dioxide, and ammonia at 63.15 kg/hour (Tan amd Lee, 2016). To dehydrate the resulting bioethanol, 62.07 kg/hour of ethylene glycol was used as a solvent during extractive distillation. From the dehydration process, 59 kg/hour of ethylene glycol waste was produced (Tan and Lee, 2016). The recovered ethanol was delivered to a pre-concentration distillation column for further purification.

In terms of energy consumption, cooling water contributed to 39.71 GJ/h in the distillation column. Refrigerated water contributed to 36.69 GJ/h for the fermentation process. For the heating process, low-pressure steam contributed 23.77 GJ/h of heating duty, and medium-pressure steam contributed 43.16 GJ/h for the designed plant (Tan and

Lee, 2016). Based on the literature the CO_2 emissions value resulting from the ethanol production process was around 9182.47 kg/h (Tan and Lee, 2016).

2.2.2. Solid waste of *Eucheuma Spinosum*

This research is based on previous work by Alfonsín (2019) who found that the cellulose content of the solid waste produced during the seaweed extraction process was approximately 37% and that the waste itself contained a considerable amount of water (roughly 35%) (Alfonsín, Maceiras, and Gutiérrez, 2019). An embodied carbon coefficient for main and supplement materials was taken into account in processing the solid waste into ethanol. The total organic carbon contained in seaweed solid waste was 2.89% (Alfonsín, Maceiras, and Gutiérrez, 2019). The residue of acid hydrolysis was characterized by elemental and immediate analysis. According to elemental analysis, the embodied carbon in hydrolysis residue was 0.43%, whereas the fixed carbon was 3.77%.

The production of ethanol was started through the pretreatment of solid waste extracted from seaweed, which was then followed by acid hydrolysis. Then, yeast (Saccharomyces cerevisiae) was used to ferment the reduced sugar to obtain bioethanol. Finally, the bioethanol was separated by distillation and characterized. With a sulfuric acid concentration of 9 wt% and an acid/dry seaweed ratio of 7, the highest bioethanol yield was 11.6 g EtOH/g of seaweed (Alfonsín, Maceiras, and Gutiérrez, 2019). Seaweed solid waste can produce about 0.1 g bioethanol/g waste and 0.12 g bioethanol/g reducing sugar with an ethanol concentration of 36.6 g/L using acid hydrolysis and yeast fermentation. Ethanol conversion efficiency was approximately 75% theoretical (Alfonsín, Maceiras, and Gutiérrez, 2019).

This research examines an alternate LCA analysis by Aitken *et al.* (2014), which was based on data from an experimental study (Luo *et al.*, 2010), and used data tested for fermentation and distillation processes. Table 1 illustrates the inputs per MJ of bioethanol. The energy consumption values were multiplied by the lower heating value of the bioethanol produced.

Table 1 Alternative inputs for fermentation/distillation of microalgae per MJ of bioethanol

Process	Energy consumption (MJ/MJ_{ETOH})
Fermentation	0.056
Vapour compression steam stripping (Heat)	0.161
Molecular sieve (Heat)	0.056
Vapour compression steam stripping (Electricity)	0.051
Vapour compression distillation (Electricity)	0.067

2.2.3. Solid waste of *Gracilaria Manilaensis*

Hessami Salleh, and Phang (2020) conducted a study regarding ethanol production using seaweed solid waste derived from *Gracilaria Manilaensis* (Hessami Salleh, and Phang, 2020). In the literature, 13.81±0.54 g of solid waste was used as raw material obtained from 100 g of dry matter *Gracilaria Manilaensis*. The hydrolysis enzyme used 7 g of solid waste, which had an ash-free dry weight content of 6.90±0.73. The highest hydrolysis yield was achieved in a 10:1 liquid: solid waste ratio, where 85.12% of the solid waste was converted to glucose. The remaining hydrolyzate was fermented into ethanol using *Saccharomyces cerevisiae*. The concentration of bioethanol produced was 51.10±1.21 g/L, which was achieved after 36 hours of incubation (Hessami Salleh, and Phang, 2020).

This study modeled the processing of solid waste into ethanol using LCA studies, namely the fermentation or distillation of ethanol. The model relied on Ecoinvent data for fermentation or distillation because no research has been undertaken on the energy consumption associated with converting Gracilaria Manilasis solid waste to ethanol (Aitken *et al.*, 2014). The cumulative energy demand and impacts were calculated using data from the Ecoinvent v3.0 database for electricity, heat, and material consumption required to produce 85.12% ethanol from solid waste.

3. Results and Discussion

3.1. *Environmental emissions*

Figure 1 shows an analysis of the contribution to the production of 1 kg of bioethanol from red seaweed solid waste. The value of the Global Warming Potential (GWP) of the functional mass unit ethanol production (1 kg of ethanol) is presented in Figure 1. GWP values can be generated not only from the production of utilities such as heat and electricity but also by the utilization of chemicals. This study revealed that among the three types of red seaweed analyzed, the GWP value produced from bioethanol production using solid waste from Eucheuma cottonii was the lowest, at around 2.97E-14 kg CO_2--eq. While the GWP produced from bioethanol production uses solid waste from two other red seaweed variants, each of which is around 5.72 kg CO_2--eq/kg ethanol and 2.87 kg CO_2--eq/kg ethanol for *Eucheuma spinosum* and *Gracilaria Manilaensis*, respectively. This difference may be because of the different assumptions used during the ethanol production process, which results in higher ethanol yields, as in the case of the process energy is used in each of these different raw materials. The number of CO_2 released during ethanol fermentation is taken into account. The simultaneous saccharification and fermentation reaction produced 75% of the CO_2 emissions, 20% by the production of enzymes, and the remaining by the consumption of electricity.

Figure 2 compares the production of 1 kg of ethanol from sugarcane and sweet bagasse sorghum with the production of 1 kg of ethanol from solid waste resulting from the extraction of red seaweed to classify the environmental impact of the former. Sugarcane is the biomass with the lowest average GWP for the first generation of ethanol. The average GWP for the second generation is lower than the first generation. Bioethanol from sweet bagasse sorghum is the most eco-friendly bioethanol in the ecoinvent database. Nonetheless, the bioethanol produced from Eucheuma cottonii seaweed solid waste in this study is the most eco-friendly option, even when compared to the bioethanol produced from sweet bagasse sorghum.

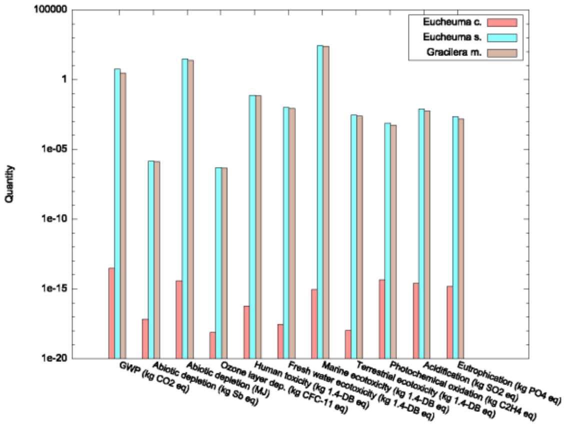

Figure 1 Contribution analysis for production of 1 kg ethanol from solid waste of extraction from red seaweed

Figure 2 shows that in almost all impact categories, except for GWP, bioethanol from solid waste *Eucheuma cottonii* has a lower environmental impact than bioethanol from sugarcane and sweet bagasse sorghum, and it has environmental competitiveness. For GWP produced from bioethanol-derived solid waste *Eucheuma cottonii* has a higher value than bioethanol from sweet sorghum and sugarcane, researchers hypothesized that the main contributor to the GWP value is coming from the fermentation process, then followed by enzyme production.

Table 3 displays the results of a more in-depth assessment of the environmental impact of producing 1 kg of ethanol from solid waste produced from red seaweed extraction. This assessment focused on the use of heat and electricity, as well as nutrients and chemicals. Table 3 depicts the several impact categories that were significantly affected by the production of enzymes, while a relatively small number of areas were significantly affected by the use of heat and electricity to produce ethanol. The magnitude of the impact of enzyme production on climate change is the result of the energy-intensive process of enzyme production. Further improvement of the bioethanol environmental performance of *Eucheuma cottonii* can be obtained with a more refined and detailed enzyme inventory in the ecoinvent v3.0 database, as it will reduce uncertainty in the impact assessment results associated with enzyme production.

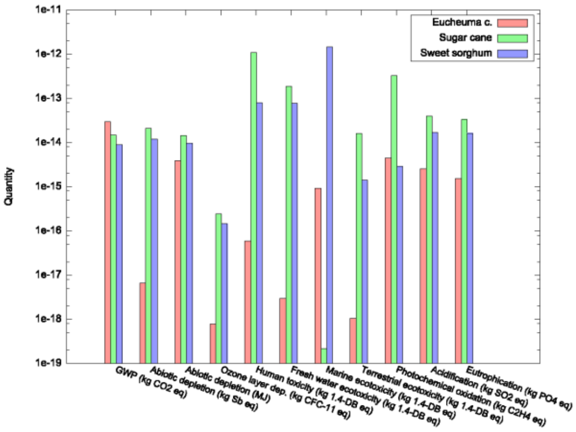

Figure 2 Comparison of the production of 1 kg of ethanol from solid waste of *Eucheuma cottonii*, ethanol from sugarcane, and sweet sorghum

There are enormous variations in energy use and emission data for cellulase enzyme production based on the diversity of enzymes and production techniques implemented (Spatari, Bagley, and MacLean, 2010). The range for possible enzyme emission was 1000-10,000 g CO_2--eq./kg depending on the technology used (MacLean and Spatari, 2009). Emissions from enzyme production were higher for this study due to the assumption of relatively low enzyme activity (45-50 FPU g^{-1}), which resulted in a higher amount of enzyme used. It has been discovered that various literature studies use enzymes in various ways because researchers assume varied enzyme activities in different production processes.

The magnitude of the influence of electricity consumption on GWP derived from electricity data in the ecoinvent v3.0 database. The authors used the assumption of "Mixed grid electricity, AC, mixed consumption, to consumers, 230V CH S" in the ecoinvent v3.0 database as the basis for LCA modeling. The data represents the average electricity supply specific to the user's country or region, including own consumption, along with net losses, and imports from neighboring countries. The official statistics for the reference year are used to determine the composition of the national energy grid utilized for electricity production as well as data on efficiency, net loss, and consumption. Most of the literature uses a breakdown value power generation model, which incorporates the added emissions calculated for emissions that do not exceed organics or heavy metals. For this research, electricity demand inventory data is mostly based on primary industry data and partly on secondary literature data.

Because the data on electricity generated from Indonesia is not available in the ecoinvent v3.0 database, the authors used the data on electricity generated from China instead of Europe. Geographically, both China and Indonesia are located on the continent of Asia. According to the Keyhole Markup Language (KML), Indonesia and China are the countries having no overlapping market regions for electricity (Treyer and Bauer, 2013). All of the adopted technology power plant in Indonesia is mostly from China, namely 3019 MW of subcritical power plant (Tritto, 2021). It is due to the inflexibility of technology in Indonesia, as remote areas may have a limited grid capacity, which may only support subcritical power plants.

Table 3 Contributions to the environmental impact of producing 1 kg ethanol from solid waste of red seaweed

	E. Cottonii				*E. Spinosum*				*G. Manilaensis*			
	Heat	Electricity	Enzymes	Consumables	Heat	Electricity	Enzymes	Consumables	Heat	Electricity	Enzymes	Consumables
Global warming potential	0.2172	0.0889	8.35	0.0554	37.1	0.624	13.2	0.779	64.21	1.99	15.4	18.40
Abiotic depletion	9.34	26.8	0	69.9	79.9	20	0	0.118	73.8	19.7	0	6.460
Abiotic depletion (fossil fuel)	7.3659	0.367	87.2	12.46	11	10	9.64	0.308	20.5	14.2	10.4	54.80
Ozone layer depletion	1.41	72.1	0	6.29	90	9.7	0	0.018	74.8	21.5	0	3.67
Human toxicity	7.39	13	45.4	27.61	62.9	36.3	0.667	0.131	45	18.9	0.281	35.8
Freshwater aquatic ecotoxicity	7.82	41.53	0	50.65	71.5	28.4	0	0.074	54.1	28.8	0	17.1
Marine aquatic ecotoxicity	5.57	74	0	20.43	83.1	16.8	0	0.065	46.7	37.8	0	15.5
Terrestrial ecotoxicity	3.64	64.5	0	31.76	12.67	87	0	0.025	52.9	89.4	0	10.6
Photochemical oxidation	0.0936	0	41	0.629	16.8	18.1	64.9	0.220	18	13.8	38.7	29.50
Acidification	0.25	0.368	76	1.239	36.4	16.5	44.3	2.819	33.15	8.45	22.8	35.60
Eutrophica-tion	0.101	0	94.9	0.303	17.82	0.18	78.7	3.288	22.72	0.28	65.9	11.11

From the perspective of global impact, the authors discovered that among the three species of red seaweed, *Eucheuma cottonii* had the lowest negative effects on the environment for the CO_2 emissions generated by the use of heat, electricity, enzyme production, and consumables. Solid waste from the extraction of *Eucheuma cottonii* into biofuel will produce low environmental emissions. Therefore, this assessment result contributes to the environmental aspects of utilizing seaweed solid waste and assists the government to determine policies for the use of renewable energy using biomass as raw materials to obtain environmentally friendly energy products with relatively low environmental emission impact values (Minakov, Lobanov, and Dyatlov, 2020; Sheth and Sarkar, 2019; Shafie, Othman, and Hami, 2018).

4. Conclusions

An environmental impact analysis of bioethanol production using solid waste obtained from red seaweed extraction as raw materials was conducted using the Life Cycle Assessment (LCA) methodology. In conducting this research, researchers used some literature data on the production of ethanol from red seaweed solid waste. The result of the assessment showed that bioethanol from the solid waste of *Eucheuma cottonii* was more environmentally friendly than two other red seaweed species, namely *Eucheuma Spinosum* and *Gracilaria Manilaensis*. However, when compared to the first and second generations of bioethanol, the production of bioethanol from *Eucheuma cottonii* solid waste was the most environmentally friendly. It can be concluded that solid waste from red seaweed may produce the most ecologically friendly bioenergy fuel. There was 75% of the CO_2 emission produced from the simultaneous saccharification and fermentation reaction, followed by 20% produced the enzyme production, and the remaining from electricity consumption. The environmental impact of enzyme production and electricity may result from inventory data of these in the EcoInvent 3.0 database. To reduce the uncertainty that comes with enzyme production and how it affects results, it is important to find more detailed and refined enzymes.

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