Volume 36 Number 1 2025

Journal of Energy in Southern Africa

# The feasibility of South African brown seaweed in biogas production and conversion to electricity

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***Abstract***

*South Africa is faced with persistent energy shortages and the need to develop sustainable, renewable resources. This research aimed to produce biomethane (biogas) via anaerobic digestion using a synthetic inoculum and the brown seaweed* Ecklonia maxima*. The biogas can be utilised in a simple combined heat and power process and converted to electricity and heat. Biogas production is estimated using the biomethane potential utilising the chemical composition of the seaweed. This is then compared to the actual biogas production from the anaerobic reaction of the seaweed and the inoculum at both mesophilic and thermophilic conditions. The research found that seaweed yielded 190.00 ml/g volatile solids (VS) of biogas after 28 days at a pH of 7.0 ±0.2 at mesophilic conditions, which is equivalent to 38% of the calculated biomethane potential of 499.64 ml/g VS.* Ecklonia maxima *can produce 255.18 kg biogas per ton of dry seaweed, with a possible associated 1417.71 kWh of electricity per ton of dry seaweed. Future work would investigate pre-treatment options for the seaweed to increase the biogas yield and increase the potential electricity output per ton of dry seaweed.*

***Keywords:*** *anaerobic digestion;* Ecklonia maxima*; load shedding; renewable energy*

***Highlights:***

- *The calculated biomethane potential of* Ecklonia maxima *is 499.64 ml/g VS.*
- Ecklonia maxima *produces 190.00 ml/g VS biogas at mesophilic conditions.*
- *The electricity potential of* Ecklonia maxima *is 1417.71 kWh/ton seaweed.*

Journal of Energy in Southern Africa 36(1),1–13

*DOI: https://dx.doi.org/10.17159/2413-3051/2025/v36i1a19096*

*Published by the University of Cape Town ISSN: 2413-3051 https://journals.assaf.org.za/jesa*



*Sponsored by the Department of Science and Innovation*

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## 1. Introduction

The South African economy is recovering from load-shedding, which sometimes lasts up to 12 hours per day (Mbomvu *et al.,* 2021). Load-shedding is the term given to the planned shutdown of specific sectors of the energy grid to prevent the entire grid from collapsing. The energy regulator in South Africa has approved load-shedding schedules up to stage 16, which means that up to 80% of the electricity grid could be switched off at any point. Load-shedding has been intermittent and been replaced by load-reduction in certain cities. Alternative energy solutions include diesel generators, solar energy panels with battery backup, and uninterruptable power supply units. Each of these has advantages and disadvantages, but all have cost implications for consumers, manufacturers, and households. Small and medium business enterprises (SMEs) are failing when alternative energy solutions are too costly for them to implement. The Small Enterprise Development Agency estimates that South Africa has a 75% failure rate of SMEs (JTB consulting, 30 Nov 2023). While the electricity problem South Africa is currently facing is not the overriding factor for businesses failing, it contributes significantly to small businesses' financial viability.

Rising coal and diesel prices have exacerbated a difficult situation, resulting in many municipalities actively considering alternative energy sources. Renewable energy sources are currently being investigated to mitigate the electricity problem. Since South Africa has good solar radiation, solar power is becoming a serious consideration. The initial costs and installation of solar panels have become significantly more affordable, with the capital expenditure for photovoltaic systems and the overall levelised cost of electricity declining substantially over the past decade (IRENA 2022). The Western Cape Government, for example, as part of its energy resilience programme, has a new energy generation program to enable the procurement, generation, and trading of low-carbon energy sources (Western Cape Energy Resilience Programme, 30 Nov 2023). The programme aims to reduce reliance in the province on the power utility Eskom, . The Western Cape government has set aside R1.1 billion over three years on projects to help alleviate the electricity shortage, starting in 2023. The City of Cape Town has set aside a further R3.9 billion.

There is a need for an alternative energy source, using an available resource that can easily be cultivated and collected and will not affect the country's food security. Macroalgae could be a consideration in producing biofuels. Over the last decade, some livestock farmers have invested in anaerobic digestion (AD) plants to produce biogas (biomethane), which is then converted to electricity using a combined heat and power (CHP) unit. Anaerobic digestion is the conversion of biomass to biogas in an anaerobic environment (one without oxygen) (Mata-Alvarez *et al.,* 2014). The AD process has four primary stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Hydrolysis is the process where proteins and fats are decomposed (Thompson *et al.,* 2019). It is widely seen as the rate-limiting step of the AD process. Acidogenesis occurs when the acidifying bacteria converts hydrolysis products to short-chain organic acids. Acetogenesis bacteria produce acetic acid, hydrogen and carbon dioxide from the fermentation products. The final step is methanogenesis, where methane is produced from acetic acid, hydrogen, and carbon dioxide (Milledge & Harvey, 2018). Methane production from AD is estimated to be 60% of the biogas produced, while the other 40% mainly consists of carbon dioxide and other trace gases. Table 1 gives an overview of selected biogas plants operating in South Africa (DFFE, 2021). Most of the biogas plants are situated in the Western Cape and Gauteng. Most of the plants operate based on waste feedstock, which is a by-product of the farming processes or feedstock collected on-site. Most of the feedstocks include manure, slaughterhouse waste and sewage waste.

Zandam Cheese farm, located 17 km outside of Durbanville in Cape Town, currently has an operating AD system using cow manure. The AD system was commissioned in 2016 at a capital cost of R9 200 000. The farm was designed to produce 75 kW of electricity, based on 6650 pigs providing approximately 22 tonnes of manure. The additional heat generated in the CHP was used on the farm for preheating processes. A power purchase agreement was signed between Zandam and Ibert for 15 years (South African-German Energy Program, 2017). Uilenkraal dairy farm showed a record-breaking 1 MWh electricity generation in 2015 (*Engineering News*, 15 August 2015). The AD process was commissioned in 2014 at a capital cost of R13 200 000. The electricity saving was estimated to provide payback within ten years (GreenCape, 2017). The AD processes at both farms currently supplement their operational electricity requirements. The biggest producer of biogas in the Western Cape was PetroSA, near George along the Garden Route. The biogas recovery AD plant was commissioned in October 2007 as part of a by-product system treating waste process water. The plant was developed by an offsite company that sells any electricity generated back to PetroSA. The project was funded by carbon credits, with a crediting period set to take place between 2006 and 2016 (United Nations Carbon Offset Platform, 30 June 2024). The plant was

**Table 1: Overview of selected biogas plants in South Africa (Department of Forestry, Fisheries and the Environment [DFFE], 2021)**

| *Establishment* | *Energy* | *Feedstock* |
|---|---|---|
| | *Western Cape* | |
| Zandam Cheese & Piggery | 75 kW | Pig manure |
| Elgin Fruit Juice | 500 kW | Fruit waste |
| Cape Town municipal sewage waste | Methane and carbon dioxide | Sewage |
| SAB Miller | | Industrial wastewater |
| Uilenkraal dairy farm | 600 kW | Cow manure |
| PetroSA – decommissioned in 2020 | 4.2 MW | Refinery waste |
| Hessequa Abattoir | 50 kW | Slaughterhouse waste |
| Distell | | Industrial wastewater |
| Green Create | 1.15 MW | Abattoir waste |
| | *Eastern Cape* | |
| Peninsula Piggery | 190 kW | Pig manure |
| | *Kwazulu Natal* | |
| Sucro Power | 16 kW | Napier grass |
| Bisasar Road landfill | 6 MW | Municipal sewage waste |
| Mariannhill landfill | 1.5 MW | Municipal sewage waste |
| | *Gauteng* | |
| Morgan Abattoir | 400 kW | Slaughterhouse waste |
| Cavalier Abattoir | 495 kW | Slaughterhouse waste |
| Bronkhorstspruit Biogas Plant | 4.6 MW | Manure |
| Northern Wastewater Treatment Works | 1.2 MW | Sewage sludge |
| Driefontein Wastewater Treatment Works | 750 kW | Wastewater |
| | *Northern Cape* | |
| Meat to Market | 135 kW | Slaughterhouse waste |

shut down in 2020 due to lack of feedstock. The Green Create facility in Worcester currently utilises abattoir waste to generate up to 1.55 MW of electricity and is currently (2025) the largest South African producer of biogas (Green Create 2025).

In Gauteng province, the biggest producer of biogas is the Bronkhorstspruit Biogas Plant. The plant was commissioned in 2015 (planning and construction started in 2012) and utilises waste biomass as a feedstock at a rate of 200–300 tons of waste per day. This has the added advantage of reducing the landfill waste in Gauteng. Once commissioned, it was capable of producing 4.6 MW of electricity. Between 25% and 30% of this electricity was sold to the BMW manufacturing plant next door (Energy and Environment Partnership/Southern and East Africa, 30 June 2024). The plant was expanded to 9.8 MW in 2023.

While the processes described above all contribute to the energy requirements of the establishments, it is a drop in the bucket of the energy requirements for the country. Anaerobic digestion is, however, an alternative for energy production for smaller, independent businesses. The feedstock for these farms is based on manure or waste products, which are available as part of the enterprise's operations. For enterprises where manure or waste products are not available, an alternate feedstock should be investigated, including macroalgae, marine microalgae and aquaculture waste. Seaweed, a brown macroalgae, was investigated as a possible feedstock for the AD process (Table 2).

The water mass of the oceans and seas covers 72% of the earth's surface. They can sequester up to 60 times more carbon dioxide than Earth's atmosphere (Sudhakar *et al.*, 2018). Based on the data, the

**Table 2: Overview of biomethane yield from brown seaweed**

| *Seaweed* | *Inoculum* | *Process conditions* | *Methane yield (ml/g VS)* | *Reference* |
|---|---|---|---|---|
| *Durvillea antarctica* | Cow manure | 37°C; 31 days | 179 | Vergara-Fernandez et al., 2008 |
| *Fucus serratus* | Bovine slurry | 35°C; 32 days | 60 | Venegas & Bartlett, 2013 |
| *Fucus serratus* | Digested sludge | 37°C; 50 days | 103 | Obata et al., 2020 |
| *Laminaria digitata* | Bovine slurry | 35°C; 32 days | 163 | Venegas & Bartlett, 2013 |
| *Laminaria digitata* | Digested sludge | 37°C; 50 days | 256 | Obata et al., 2020 |
| *Laminaria digitata* | Digested sludge | 35°C; 36 days | 240 | Migliore et al., 2012 |
| *Laminaria digitata* | Green peas | 37°C; 220 days | 500 | Akunna & Hierholtzer, 2016 |
| *Macrocystis pyrifera* | Cow manure | 37°C; 31 days | 181 | Vergara-Fernandez et al., 2008 |
| *Saccharina latissima* | Bovine slurry | 35°C; 32 days | 245 | Venegas & Bartlett, 2013 |
| *Saccharina latissima* | Bovine slurry | 35°C; 109 days | 565 | Venegas & Bartlett, 2013 |
| *Saccharina latissima* | Cattle manure sludge | 53°C; 34 days | 340 | Tabassum et al., 2018 |
| *Saccharina latissima* | Digested sludge | 37°C; 50 days | 229 | Obata et al., 2020 |

starter microbial population plays a significant role in methane formation using brown seaweed. Extended hydraulic retention time in anaerobic digestion enhances methane yield because the algal polysaccharides require prolonged time to degrade. It is widely accepted that the hydrolysis of polysaccharides is the rate-limiting step in the anaerobic digestion process (Milledge & Harvey 2018). Moreover, operating at thermophilic temperatures (typically 50–60°C) increases the hydrolysis rate, increasing methane production from certain seaweed feedstocks. It is important to note that biomethane production is possible using brown sea-weeds and an inoculum, whether organic or synthetic. Therefore, investigations utilising a locally based brown seaweed for biogas production seemed feasible.

*Ecklonia maxima* is a benthic brown seaweed of the order *Laminariales.* It grows up to 10 m long and is found along the southern coast of the Western Cape of South Africa, from Cape Columbine for approximately 1600 km (Rothman *et al.,* 2017). The seaweed is fast-growing and can yield crops up to eight times annually (Dave *et al.*, 2013) if cultivated and harvested correctly. The seaweed grows in salt water and does not compete with land-based crops (Ghadiryanfar *et al.*, 2016). *Ecklonia maxima* has a higher growth rate than most terrestrial plants, making the macroalgae a suitable, available resource for biofuel production with minimal environmental impact (Ross *et al.*, 2008). The current research uses untreated South African seaweed and synthetic inoculum to produce biomethane using an anaerobic digestion process. *Ecklonia maxima,* though widely available, is underutilised as an abalone feedstock. Coastal communities that regularly collect and dispose of beach-cast seaweeds could valorise this underutilised biomass as a co-digestion feedstock. This can be particularly effective when combined with other locally available organic wastes for biogas production. Integrating beach-cast seaweed into anaerobic digestion strategies presents a novel, circular approach to coastal waste management while also enhancing the generation of renewable energy. Using a synthetic inoculum would ensure a consistent composition of the inoculum, which would introduce the biological culture required for the degradation of the seaweed. The critical considerations included (i) the biogas yield, (ii) the conversion of biomethane to electricity, and (iii) the actual costs of producing biogas from seaweed feedstock. This paper aims to explore these considerations and determine if seaweed could be a feasible feedstock for the AD process to produce electricity using a CHP process.

## 2. Materials and methods

### *2.1 Feedstock preparation*

The seaweed was bought dry and bagged in 25 kg from a Somerset West company. There are more cost-effective ways of obtaining seaweed, like using beach-cast seaweed, but to obtain sufficient seaweed with a similar composition, it was decided to purchase it. The dried seaweed was ground and sieved to particles approximately 2 mm in diameter, then soaked in distilled water for 24 hours until saturated. A 400 ml 20% (w/w) solution of seaweed was prepared. A further 400 ml of inoculum was prepared based on a 1:1 volatile solid ratio with the seaweed. The mixtures were homogenised at a temperature of within 0.2°C of 37°C for 24 hours.

### *2.2 Inoculum preparation*

The synthetic inoculum is a blended, organic, all-purpose fertiliser that was available as a pelletised solid and ground to a powder. The VS was determined in the same way as for the seaweed. The inoculum was mixed with water to make up a 20% (w/w) solution and stored in an airtight container for later use. No adjustment to the pH was made at this point.

### *2.3 Experimental setup*

The setup is shown in Figure 1. Experiments were run over 28 days in a batch configuration, with daily mixing for 30 seconds. Experiments were duplicated at 37°C (±0.5°C) and 52°C (± 0.5°C). The loading ratio of seaweed to inoculum was 1:1 based on the VS content of the *Ecklonia maxima* and the inoculum.

The working volume of each reactor was 800 ml, which consisted of 400 ml of a 20% (w/w) seaweed solution and 400 ml of a 20% (w/w) inoculum slurry. The initial pH for all experiments was 7.0 ± 0.2. The pH was adjusted in each reactor to 7.0 ± 0.2 periodically over the 28 days.

### *2.4 Biomethane potential of the feedstock*

Biomethane potential (BMP) was determined based on the modified Buswell equation, in Equation 1 (Achinas & Euverink 2016).

$$TBMP = \frac{22.4x\left(\frac{a}{2}+\frac{b}{8}-\frac{c}{4}-\frac{3d}{8}-\frac{e}{4}\right)}{12.017a + 1.0079b + 15.999c + 14.0067d + 32.065e} \qquad (1)$$

The coefficients a, b, c, d, and e are the ultimate analysis of the seaweed's carbon, hydrogen, oxygen, nitrogen, and sulphur. This analysis was determined by an outside laboratory. These coefficients were utilised in Equation 2 to determine the stoichiometric equation of the seaweed.

$$C_aH_bO_cN_dS_e + \left(a-\frac{b}{4}-\frac{c}{2}+\frac{3d}{4}+\frac{e}{2}\right)H_2O \rightarrow \left(\frac{a}{2}+\frac{b}{8}-\frac{c}{4}-\frac{3d}{8}-\frac{e}{4}\right)CH_4 + \left(\frac{a}{2}-\frac{b}{8}+\frac{c}{4}+\frac{3d}{8}+\frac{e}{2}\right)CO_2 + dNH_3 + eH_2S \qquad (2)$$

The proximate analysis was provided by the supplier of the seaweed. The volatile solids were determined using a standard loss on ignition (LOI) method.

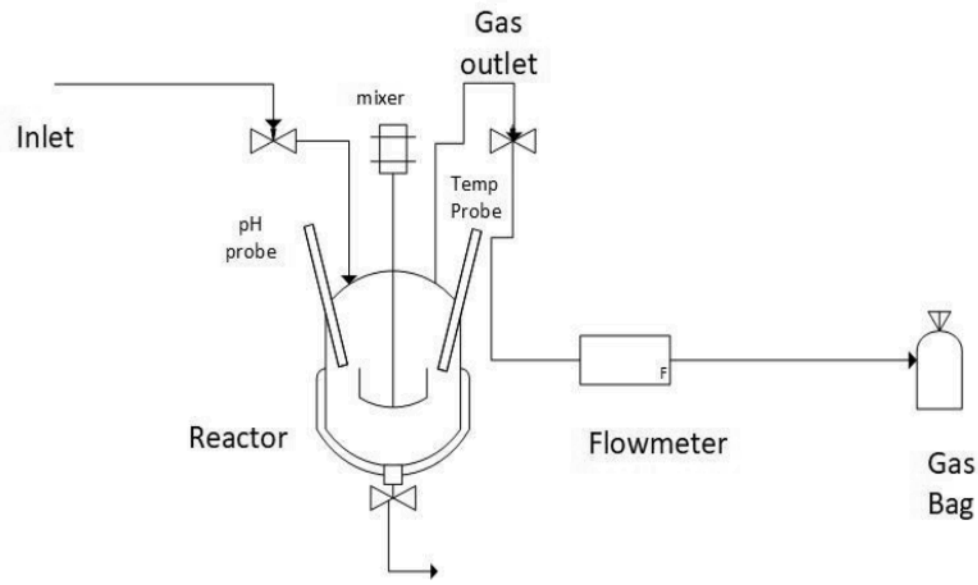


**Figure 1: Experimental setup**

### 2.5 Actual biomethane yield

The biomethane yield of the AD process was determined based on experimentation performed over 42 days at mesophilic conditions. The previously prepared seaweed substrate and inoculum solutions were mixed in a reactor. The pH was adjusted to 7 (± 0.2). The reactor was flushed with nitrogen until the dissolved oxygen reading was less than 1. The reactor was sealed and connected to a gas bag to collect the gas yield. Feeding of the reactor took place twice a week, with 240 ml of the substrate being removed and replaced with 240 ml of a 20% (w/w) solution of seaweed. The substrate removed was analysed for volatile solids to complete a material balance of the process. Biogas production was measured at each feeding, and the biogas composition was determined using a biogas analyser. The pH was adjusted to 7 (±0.2) at each feeding.

### 2.6 Electricity potential of *Ecklonia maxima*

Biomethane yield is based on the carbon conversion to methane, as in Equation 3.

$$Carbon\ conversion\ to\ methane = \frac{fraction\ of\ methane\ formed}{methane\ fraction + carbon\ dioxide\ fraction} \quad (3)$$

The assumption is that the seaweed's carbon balance is converted to carbon dioxide (Garcia). The methane yield per kilogram of seaweed is determined by Equation 4:

$$Methane\ Yield = Fraction\ of\ Carbon\ in\ Seaweed\ x\ Carbon\ conversion\ to\ Methane \quad (4)$$

The maximum possible electricity is based on the methane yield, as per Equation 5:

$$E\left(\frac{kWh}{annum}\right) = m_{biogas} \times Energy\ content_{biogas} \times Efficiency_{CHP} \quad (5)$$

The CHP unit's efficiency is usually 35% for electricity conversion. The calorific value of biomethane is between 20 and 26 MJ/m$^3$, and the density of biomethane is 0.657 kg/m$^3$.

### 2.7 Data analysis

The gas samples analysed using the portable gas analyser were standardised for volume at standard temperature and pressure. All methane calculations performed were based on the VS amounts in the reactor during the gas formation period. Volatile solids were determined for the substrate at the end of the 28 days HRT. The total daily volatile solids were averaged over the time frame based on the reactor's initial and final VS values.

### 2.8 Statistical analysis

Experimental data was statistically analysed using a paired sample t-test to compare the effect of temperature on methane production. The test was performed for a 95% confidence interval. The null hypothesis was that digestion temperature does not affect biogas production. If the calculated P-value for the t-test was less than 0.05, the null hypothesis would be rejected, and it would be concluded that the temperature affects biogas production. If the p-value is more than 0.05, the null hypothesis would be valid, and it would be concluded that the digestion temperature does not affect the biogas production.

## 3. Results and discussion

### 3.1 Biomethane potential of the feedstock

The biomethane potential of the feedstock is based on the chemical composition of the seaweed. Table 3 gives an overview of the biomass composition of the dry seaweed obtained from the supplier and the energy dispersive X-ray spectroscopy (EDS) and carbon-hydrogen-nitrogen-sulphur (CHNS) analysis completed independently for dry seaweed.

*Ecklonia maxima*, in this study, contains 51.15% carbon and 3.78% oxygen. Darko *et al.* (2021) reported a carbon content for *Ecklonia maxima* of 43.4% and an oxygen content of 37.06%. While the carbon contents are both high for the two batches of *Ecklonia maxima*, the oxygen content from the previous study is almost ten times that of the batch of seaweed in this research. The *Ecklonia maxima* in this study has a higher nitrogen content of nearly

**Table 3: *Ecklonia maxima* characterisation**

| *Elemental analysis (w/w %)* | | | | |
|---|---|---|---|---|
| %C | %H | %N | %O | %S |
| 51.15 | 4.72 | 19.99 | 3.78 | 11.51 |
| *Organic composition (w/w %)* | | | | |
| Protein | | Carbohydrates | Ash | Lignin |
| 7.80 | | 43.10 | 24.30 | 29 |

20% compared to the 7.68% reported by Darko *et al.* (2021). The varying compositions of the *Ecklonia maxima* could be attributed to the differences in composition across the plant (frond, stripe and holdfast) due to varying growth conditions and seasonal changes. Depending on which part of the plant was used during the experimentation, there could be distinct differences in composition – the frond and the holdfast, for instance, sequester nutrients differently. The time of year the seaweed is harvested also plays a role in the overall composition of the seaweed (Kamal *et al.* 2023; Lafeuille *et al.* 2023; Hrstich-Manning & Aguirre 2024). The ash content of *Ecklonia maxima* is high at 24.3%. According to Tabassum *et al.* (2017), the ash-to-volatile solids ratio is critical to seaweed digestion. The ratio of ash to VS is 0.3356 or 33.56%. A pre-treatment step could be considered to reduce the amount of ash in the seaweed before digestion (Montingelli *et al.* 2016). Macroalgae are reported to have low levels of lignin (Dave *et al.* 2013; Obata *et al.* 2020; Ra *et al.* 2016; Pfromm *et al.* 2011; Yanagisawa *et al.* 2013; Ghadiryanfar *et al.* 2016). Rabemanolontsoa and Saka (2013) reported the lignin content of the brown seaweed *Sargassaceae* as between 6% and 12.9% of the dry weight of the seaweed. The calculation was completed using a modified version of the Klason method, where the hydrolysis stage was accelerated through two hours of heating at 47°C to solubilise the carbohydrate. The assumption in this study was that whatever substance did not ash at the elevated temperature after hydrolysis was, in fact, lignin. The higher-than-expected value of 29% in this study could result from not all the carbohydrates being soluble after the first hydrolysis stage. The seaweed might require an extended period for the first hydrolysis process or a secondary hydrolysis process to solubilise residual carbohydrates further.

The BMP calculation yielded the stoichiometric Equation 6.

$$C_{0.0426}H_{0.0472}O_{0.0024}N_{0.0143}S_{0.0036} + 0.0422H_2O \rightarrow 0.0204CH_4 + 0.0223CO_2 + 0.0143NH_3 + 0.0036H_2S \quad (6)$$

The BMP was calculated to be 499.64 ml/g VS using Equation 1. The corresponding expected carbon conversion to methane based on the coefficients of carbon dioxide and methane in the stoichiometric equation is 47.78%. Therefore, these calculations do not consider the hydrolysis stage and are a higher estimate than the actual yield. A modified version of the Buswell equation was used, which also considers the formation of hydrogen sulphide. Based on the calculated BMP, 95 ml/g VS and 405 ml/g VS yield is expected.

### *3.2 Actual biomethane yield*

After 28 days, a cumulative methane yield of 190 ml/g VS for mesophilic temperature and 158.8 ml/g VS for thermophilic temperature was recorded (Figure 2). The horizontal line just below the 500 ml/g VS yield indicates the calculated biomethane potential of the seaweed.

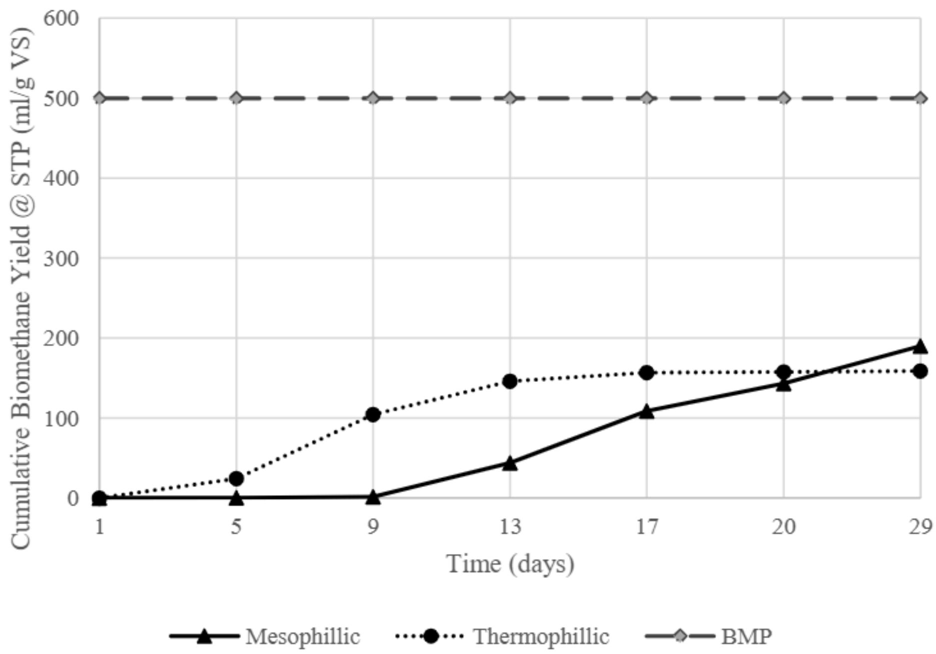


**Figure 2: Cumulative methane yield**

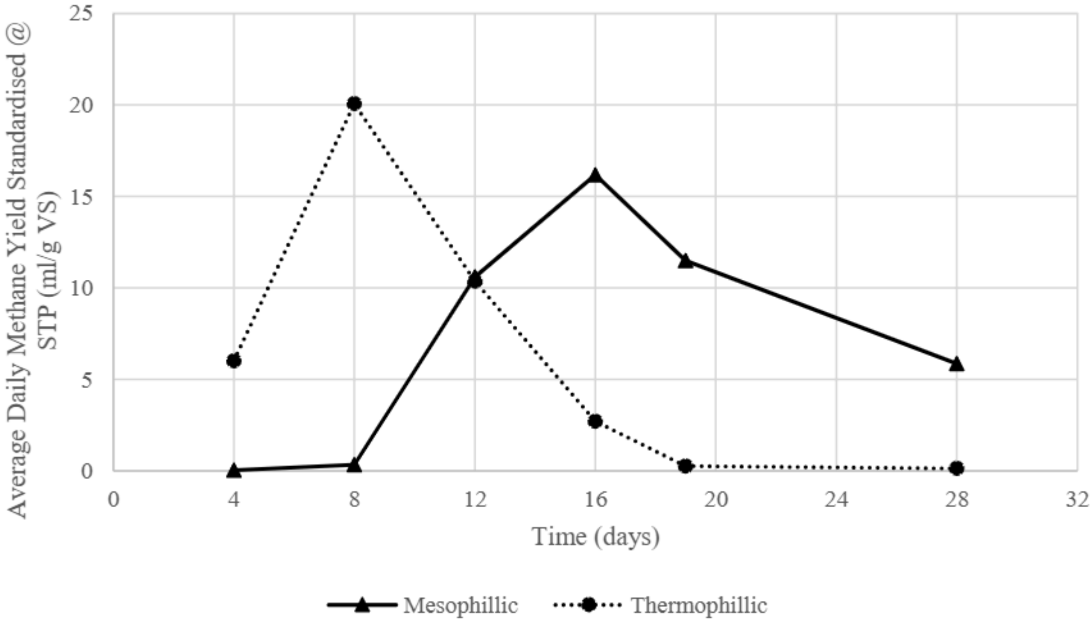


**Figure 3: Average daily methane yield**

The thermophilic methane yield was initially very fast compared to the mesophilic methane yield, as the elevated temperature initially caused faster hydrolysis of the seaweed. The lower temperature shows a lag phase of almost nine days due to the first feeding of the system only taking place on day eight. Both the temperature profiles show a steep increase, indicating an exponential or growth phase in the AD bacteria. After approximately 17 days, the exponential phase starts levelling into a stationary phase for the thermophilic profile. This means the experimentation can be stopped as very little biomethane would be produced past this stage. The hydraulic retention time could be set to 17 days for the thermophilic region, at which point additional inoculum should be introduced.

The mesophilic profile continues to show an upward trend, indicating that after 28 days the microbial population is still active and biomethane is still being produced. This implies the mesophilic biomethane yield could be much higher than the 190 ml/g VS indicated previously. For mesophilic conditions, the yield is 38.03% of the calculated BMP amount of 499.64 ml/g VS. The yield for thermophilic conditions is 31.78% of the calculated BMP. This is within the range of 19% to 81%, as Tabassum *et al.* (2018) recommended.

Biomethane yield for *Laminaria Digitata* was recorded at 163 ml/g VS (Venegas & Bartlett 2013) with a HRT of 32 days and 256 ml/g VS (Obata *et al.*, 2020) with a HRT of 50 days. The mesophilic yield of 190 ml/g VS aligns well with the recorded value at 32 days. However, biomethane yields for *Laminaria Hyperborea* reported a higher yield of 280–430 ml/g VS for the mesophilic temperature profile (Montingelli et al. 2016). The thermophilic yield of 159 ml/g VS is lower than expected. The expectation was that hydrolysis rate would increase, and therefore the biomethane yield would increase. The decrease could result from the rapid breakdown of the substrate, leading to the formation of free ammonia, which in large doses could be toxic to the methanogens. Other brown seaweeds reported methane yields in the 110–565 ml/g VS range.

To improve the yield for the *Ecklonia maxima*, it is recommended that pre-treatment processes be investigated to optimise the hydrolysis process, which is seen as the rate-limiting step in the anaerobic digestion process. The significant ranges in yields could be due to the varying seaweed compositions, as discussed previously, as well as different experimental process conditions and inoculum used. An optimal experimental process is required to properly compare the same batch of seaweed and the same inoculum.

Daily methane formation (Figure 3) shows a steady increase in methane, followed by a decline due to the system not being fed fresh organic matter. The mesophilic conditions yielded a slightly lower daily rate initially when compared to the thermophilic conditions. This was expected, as the elevated temperature would lead to the more rapid breakdown of organic material, making the hydrolysis phase easier (Samson & Leduy, 1982). The thermophilic methane formation starts to decline after day 12 and is close to zero at day 18. The mesophilic methane formation starts to decline after 16 days, but the decline is not as pronounced as the thermophilic decline. The mesophilic yield is consistent with a higher overall cumulative biomethane yield.

The maximum daily methane yield of approximately 20 ml/g VS was recorded at thermophilic temperatures, slightly higher than the BMP of 17.84 ml/g VS averaged out over 28 days. While the BMP is not a true reflection of the actual expected daily BMP, it does indicate the expected performance of the seaweed for methane production.

### *3.3 Statistical analysis of methane yield*

Statistical analysis using a paired, two-sample t-test showed a p-value of 0.023, less than 0.05, as shown in Table 4. Therefore, the hypothesis indicated in the statistical analysis that temperature does not affect the biomethane formation is rejected.

The alternative hypothesis is accepted, and it is clear that temperature does affect the biomethane yield. This is corroborated by the varying biomethane yields obtained at mesophilic and thermophilic ranges after 28 days of experimentation.

### *3.4 Electricity potential of Ecklonia maxima*

The actual biogas produced per mass unit of dry seaweed is calculated using Equation 4. To use this equation, the actual conversion of available carbon to methane needs to be determined using Equation 3. Since a carbon conversion to methane corresponds to a BMP of 499.64 ml/g VS, and the actual methane formation is only 190.07 ml/g VS for mesophilic conditions and 158.83 ml/g VS for thermophilic conditions, an equivalent percentage for the actual carbon-to-methane conversion can be determined. For mesophilic conditions, only 18.98% of the available carbon is converted to biomethane, and 15.86% of the available carbon is converted to methane for the thermophilic temperature range. The methane yield per ton of seaweed is 147.76 $m^3$/ton for mesophilic conditions and 123.47 $m^3$/ton for thermophilic conditions, based on Equation 4. Results are shown in Table 5.

**Table 4: T-test: Paired two sample for means**

| | *Meso* | | *Thermo* |
|---|---|---|---|
| Mean | 54.351 | | 96.254 |
| Variance | 5470.641 | | 4764.666 |
| Observations | 9 | | 9 |
| Pearson correlation | | 0.721 | |
| Hypothesised mean difference | | 0 | |
| df | | 8 | |
| t Stat | | -2.346 | |
| P(T<=t) one-tail | | 0.023 | |
| t Critical one-tail | | 1.859 | |
| P(T<=t) two-tail | | 0.047 | |
| t Critical two-tail | | 2.306 | |

**Table 5: Annual biogas determination**

| | *Theoretical* | *Actual mesophilic* | *Actual thermophilic* |
|---|---|---|---|
| Total carbon (% ) (w/w) | 51.15 | 51.15 | 51.15 |
| Carbon conversion to methane (%) $= \frac{Fraction\ of\ methane}{Methane\ fraction + Carbon\ dioxide\ \ fraction}$ | 49.89 | 18.98 | 15.86 |
| Carbon conversion to carbon dioxide (%) $= 100 - carbon\ conversion\ to\ methane$ | 50.11 | 81.02 | 84.14 |
| Methane yield per ton (kg/ton) $= 1000 * total\ Carbon\ \% * carbon\ conversion\ to\ methane$ | 255.19 | 97.08 | 81.12 |
| Density of methane (kg/$m^3$) | 0.657 | 0.657 | 0.657 |
| Methane yield ($m^3$/ton seaweed) $= \frac{Methane\ yield\ per\ tonne}{Density}$ | 388.41 | 147.76 | 123.47 |

**Table 6: Potential electricity generated from methane biogas**

| *Electricity potential based on 20 MJ/m³* | | | |
|---|---|---|---|
| *Calculations per ton of seaweed* | *Theoretical* | *Actual mesophilic* | *Actual thermophilic* |
| Biomethane mass (kg) | 255.19 | 97.08 | 81.12 |
| LCV of biomethane (MJ/kg) | 50 | 50 | 50 |
| LCV of biomethane (kJ/kg) | 50 000 | 50 000 | 50 000 |
| Efficiency CHP (%) | 40 | 40 | 40 |
| E (kWh/ton) | 1417.71 | 539.31 | 450.67 |
| E (KWh/kg) | 1.47 | 0.54 | 0.45 |

The actual conversion to methane for both the mesophilic and thermophilic runs are much lower than the expected conversion. It is often the case that the actual carbon conversion to methane is lower than the theoretical conversion. This could be due to the presence of inhibitors to methanogenesis or the incomplete degradation of the biomass. Lignin is highly resistant to microbial degradation. The carbon present in the lignin therefore remains unconverted, which reduces the overall methane yield (Meegoda et al. 2018) The seaweed contains a relatively high percentage of 29%, which negatively affects the methane yield. A pre-treatment step could be implemented to help break down the lignin prior to the AD process. Methanogenesis is very sensitive to pH, with the optimal operating pH for anaerobic digestion being between 6.5–8. Deviations outside this pH range inhibits the activity of the methanogen's, therefore reducing the expected methane yield. pH adjustments were made during the sampling process when the pH fell below this range, indicating that the system had periodically fallen into an acetogenesis state.

Based on the biogas production, the potential of the seaweed to produce electricity using a CHP unit is determined using Equation 5. CHP units' operational efficiencies are usually 40–85%. The results shown in Table 6 are obtained using the lower estimate for the biomethane calorific value of 50 MJ/kg.

The maximum theoretical electricity generated is 1417.71 kWh per ton of dry seaweed. Since the biogas produced was only a fraction of the total possible, the possible electricity generation is also less than the maximum possible as indicated in Table 6. Figure 4 gives an overview of the electricity generation potential of the seaweed at the biomethane yield.

The conversion of biogas to electricity is based on the total amount of biogas produced. As the biogas produced is 31.8 and 38.3 for thermophilic and mesophilic temperatures respectively, it is expected that a similar conversion will be seen for the electricity conversion when compared to the theoretical value. Figure 5 gives an overview of the biogas yield vs the electricity potential at the CHP efficiency of 40%.

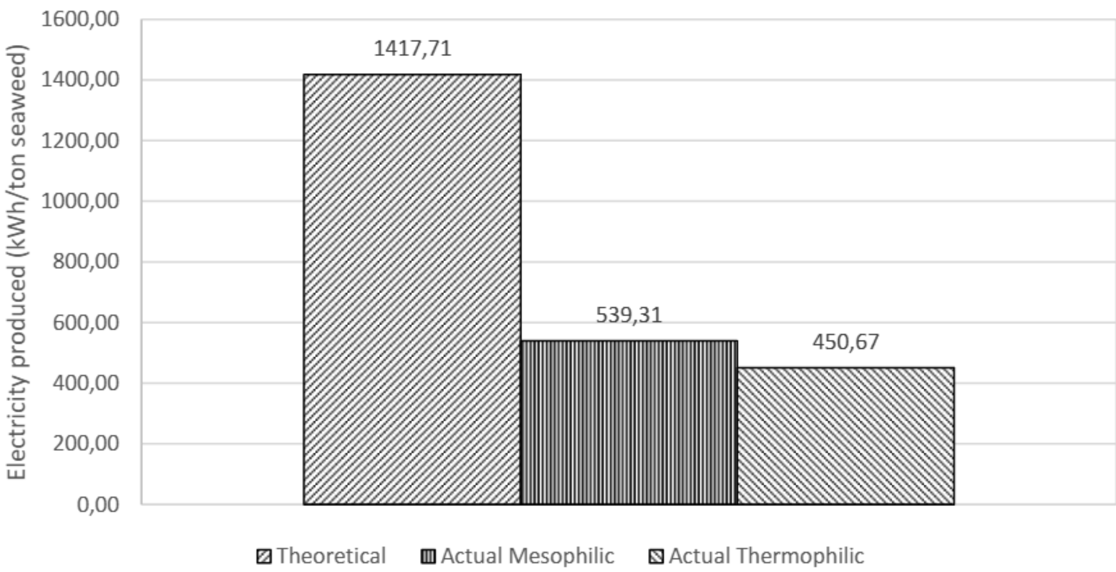


**Figure 4: Potential electricity generation of biomethane**

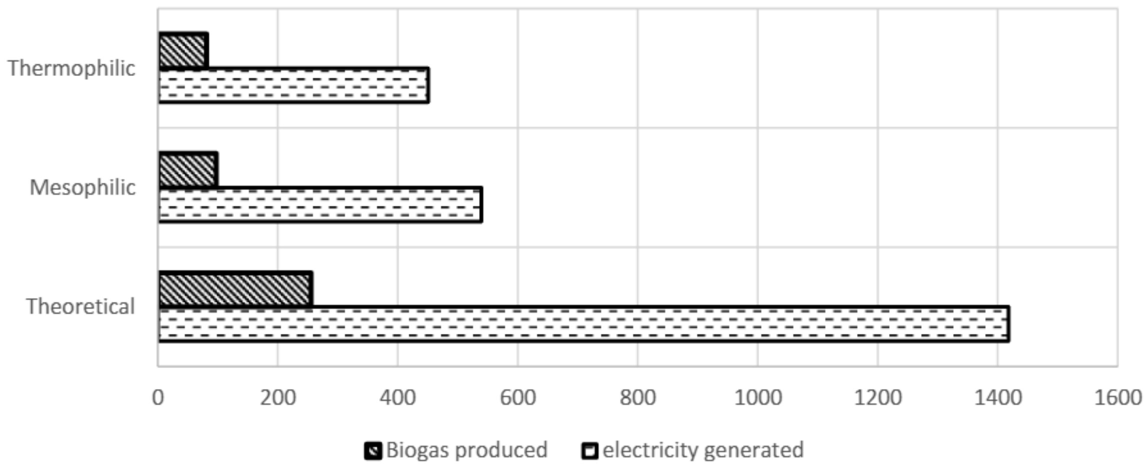


**Figure 5: Biogas yield vs electricity potential**

Since the electricity generated is a direct function of the amount of biogas produced, increasing the conversion of available carbon to biomethane is a priority.

## 4. Conclusion

The stoichiometric biomethane potential of the *Ecklonia maxima* is 499.64 ml/g VS based on the modified Buswell equation. The experimental cumulative methane yield is 38% of this amount for mesophilic conditions and 31.79% for thermophilic conditions. The cumulative yield is 190 ml $CH_4$/g VS at mesophilic conditions and 159 ml $CH_4$/g VS at thermophilic conditions. The null hypothesis is rejected based on the statistical analysis. Temperature does have an impact on the biomethane yield. It is recommended that the anaerobic digestion process be fed sooner for the mesophilic range to reduce the lag phase and increase the biogas yield.

To maintain bioreactor stability, it is recommended that the reactor is operated at mesophilic rather than thermophilic temperatures. A pre-treatment step of the seaweed is recommended to improve the hydrolysis stage of the anaerobic digestion process to overcome the high ash content of the seaweed.

The maximum theoretical carbon conversion to methane is 49.89%. The actual carbon conversion to methane ranged between 15.86% and 18.98% – the methane yield per ton of dry seaweed ranges between 81.12 kg and 97.08 kg. Using a CHP unit, seaweed can produce between 450.67 kWh and 539.31 kWh of electricity per ton of dry seaweed, at a 40% efficiency of the CHP unit.

## 5. Scope for future investigation

Pre-treatment processes, including mechanical, thermal and chemical, should be applied to the seaweed to optimise biomethane production. The aim is to have the highest possible conversion of carbon to methane to increase the electricity potential of the seaweed. This study did not consider the other products from the CHP unit. Subsequent investigations should consider using the heat generated from the CHP unit and the usage of the by-products of the AD process.


## Acknowledgements

This work was supported by the National Research Fund [grant number TTK190408428082]. Thanks are due to Rawkelp for the donation of the seaweed.


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