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Techno-economic feasibility study of *macroalgae* for anaerobic digestion

Roshni Paul[a], Lynsey Melville[b], Aminu Bature[c,*], Michael Sulu[d], Sri Suhartini[e]

[a] *S P Jain Global School of Management, Dubai Academic City, United Arab Emirates*
[b] *Birmingham City University, School of Engineering and the Built Environment, Birmingham, United Kingdom*
[c] *University of Reading, Henley Business School, Reading, United Kingdom.*
[d] *University College London, London, United Kingdom*
[e] *Universitas Brawijaya, Java, Indonesia*

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ABSTRACT

The techno-economic feasibility of brown macroalgae biomass species *Saccharina latissima* (*S. Latissima*) for anaerobic digestion (AD) in North West Europe was investigated in this research. The feasibility of the biomass as a single feedstock and for co-digestion was tested. In the techno economic analysis, AD of *S. Latissima* as a single digestion feedstock was found to be economically not viable due to the relatively high price of the macroalgae biomass. However, co-digestion with sugar beet — vegetable mix combined with a gate fee of 29 Euros per tonne was found to be economically viable with the macroalgae biomass priced at 50 Euros per tonne.

1. Introduction

Macroalgae (commonly known as seaweed) plays an important role within marine ecosystems. This globally cultivated macroalgae produce an estimated 23.8 million tonnes (Mt) (wet weight) biomass and 1.1 Mt are harvested from wild stocks from coastal regions. Compared to the global production figures, macroalgae production in Europe is negligible, at around 1 % (Camarena-Gómez et al., 2022). Norway and France are the main macroalgae producers in Europe (Camia et al., 2018) with a combined annual production of 181,565 t mostly harvested from wild stocks (Silva Marinho, 2016). Macroalgae have traditionally been harvested and processed as a food for both humans and animals and can be used as nutrient rich fertilisers for plants (Camarena-Gómez et al., 2022). It also contains compounds that can be processed into high value products such as *phycocolloids* (agars, alginates and *carrageenans*) (Häder, 2021), cosmetic ingredients, food supplements or as a high value gourmet food ingredient in the Western world (Milledge et al., 2014a, 2014b). Commenting on the three major imaginaries of bioenergy in the UK, Levidow and Papaioannou (2013) state that macroalgae biomass has the potential to meet the energy production goals and emissions targets of the country. Similar claims have also been made more recently. For example, in 2019 Jain et al. highlights that AD of macroalgae could potentially reduce global greenhouse gas emissions by up to 13 % (Jain et al., 2019). *Saccharina latissima*, is estimated to achieve greater gross energy yields from anaerobic digestion than those based on the current liquid biofuel systems such as ethanol from sugarcane and biodiesel from palm oil (Twigg et al., 2024). However, its feasibility for bio-energy production in full scale operation is still in limited (Kumar et al., 2021) by the need to develop tailored microbial communities, optimise the biomass production, and improve conversion rates through pre-treatments, co-digestion etc. (Twigg et al., 2024).

Macroalgae has been used to produce a variety of biofuels including biogas, bioethanol and pyrolysis oil etc. (Kumar et al., 2021; Wei et al., 2013). To date the majority of research has focused on anaerobic digestion as the preferred conversion route for macroalgae as it can directly utilise the wet biomass (Hughes et al., 2012; Allen et al., 2016). The high methane yields and conversion rates obtained from the different species of macroalgae biomass also contributes to this preference (Pardilhó et al., 2022). The feasibility of macroalgae cultivation and the utilisation of macroalgae biomass for bioenergy production is recognised in the literature, however fewer studies are available on the economic viability of the AD technology for biomass utilisation (Montingelli et al., 2016). Even though technical feasibility is important, economic assessments should also be conducted alongside it to determine the commercial viability of projects and illustrate how to harness the true potential of biomass. That is precisely where economic feasibility studies would allow the potential users to identify the bottlenecks associated with the systems and potentially reduce the costs and energy

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* Corresponding author.
E-mail addresses: Roshni.Paul@spjain.org (R. Paul), Lynsey.Melville@bcu.ac.uk (L. Melville), A.Bature@henley.ac.uk (A. Bature), M.sulu@ucl.ac.uk (M. Sulu), Ssuhartini@ub.ac.id (S. Suhartini).

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input for their production and harvest, transportation, and develop overlap with the existing energy supply chains and conversion to fuels (Roesijadi et al., 2010). There are few techno-economic assessments performed on the AD of macroalgae biomass in the literature (Zamalloa et al., 2011; Konda et al., 2015; Dave et al., 2013; Llano et al., 2023).

Defra's ‘Anaerobic Digestion Shared Goals’ aspires a target of 1000 farm based AD plants in the UK by 2020. However, this target was not met by Defra and “the delays created a state of paralysis for LAs [local authorities], which, without clear timeframes and funding information, had been unable to work toward their legal targets proactively” (ADBA, 2023). Even though the number of farms have increased in the last few years, achieving the target still seems unlikely unless it is adopted at a small scale i.e. farm based AD plants. European AD knowledge especially the Danish and German case studies will be invaluable which has had solid governmental support for decades. However, the case is different in the UK owing to the difference in average type and size of farms, farming practices and environmental incentives. Therefore to achieve the targets and for sustainable energy generation through AD it is essential to highlight the benefits of AD to the farming community, where AD will have the greatest effect, reducing the environmental impact of farm pollution and also in a cost effective way for the farmer (Bywater, 2011). In this context, it is clear that there is a requirement for more analysis on the efficiency of the technical aspect of AD process hand in hand with the economic feasibility of the technology in a UK environment especially for a newer feedstock such as macroalgae biomass.

Therefore, in this study, we focused on two main questions:

- How does the cost of macroalgae biomass affect the biomass utilisation for AD?
- Will co-digestion make the bioenergy production from macroalgae biomass more sustainable?

Subsequently, the techno-economic analysis of AD of *S. Latissima* is performed to identify the effect of AD technology on the economics of the process – i.e. the benefits and challenges on the economics of the process utilising *S. Latissima* for anaerobic digestion.

2. Literature review

2.1. Potential biomethane yields of S. Latissima

Macroalgae species have been studied since the 1970s and have frequently been shown to be a suitable feedstock for anaerobic digestion (Borg et al., 2023; Murphy et al., 2015). There has been studies in the literature focusing on the factors influencing the biogas potential of macroalgae biomass. Factors such as the species and composition of the macroalgae that can impact the efficacy and efficiency of biogas production using AD have also being studied (Jung et al., 2013). Studies have also been performed to quantify the methane yields from different macroalgae species using theoretical and experimental methods. Theoretical methane yields from anaerobic digestion of macroalgae have been reported in the range of 0.14–0.40 m3/kg VS. However, the practical yields of the biogas from the macroalgae are experimentally found below their theoretical maximum (Milledge et al., 2014a, 2014b). Reported studies in the literature include green species like Ulva and brown species of *Laminaria digitata* and *Laminaria Hyperborea*. Methane yields of seaweed species have been found to strongly depend on the concentrations of storage carbohydrates and in the case of brown algae, among the storage sugars, laminarin and mannitol have been shown to have the highest biogas potential during digestion. Yet, alginic acid have a relatively lower methane yield. Moreover, it is reported that many microorganisms are not able to digest the biomass completely under strict anaerobic conditions. Microorganisms can hydrolyse laminarin easily and it can be easily degraded during anaerobic digestion. However alginates found in seaweed are reported to be more difficult to digest (Briand and Morand, 1997; Adams et al., 2011). For the species *S. Latissima*, studies are still evolving with testing for anaerobic digestion potential among other macroalgae species. The theoretical biochemical yield of *S. Latissima* has been reported to be 422 ml CH_4/g VS with a theoretical methane percentage of 50 % (Allen et al., 2015).

Even though brown algae biomass has been a focus for AD, most of the reported studies are observed to be feasibility studies trying to determine the effect of operational parameters on the digestion of the biomass. Therefore, it is important to review the literature on *S. Latissima* with reference to their location of collection, harvest seasons, and whether there is any difference in biomethane production between the wild and the cultivated biomass in anaerobic digestion.

2.2. Impact of location of collection on the biochemical methane yields of S. Latissima

The studies in the literature reporting the use of *S. Latissima* indicate their reference of collection from a particular location. These are not studies intended to study any impact of location on the biomethane potential of the species rather these are mainly feasibility studies to select the best feasible species from a number of locally available species where the study has been carried out. Nielsen and Heiske (2011) compared four macroalgae species harvested in Denmark for the suitability for anaerobic digestion and the study included *S. Latissima.* The study showed that *S. Latissima* was highly suitable for anaerobic digestion with a methane yield of 340 ml CH_4/g VS during thermophilic batch tests (Nielsen and Heiske, 2011). However, as *Ulva lactuca* had a higher potential for cultivation under Nordic conditions, Ulva was selected for further studies by the authors (Nielsen et al., 2011). In another study where *S. Latissima* was collected from Norway, a biogas production of 223 CH_4/gVS was observed (Vivekanand et al., 2012). Some 117 ml CH_4/g VS less than Nielsen and Heiske (2011) batch tests mentioned above. Study, by Jard et al. (2012) compared anaerobic digestion potential of *Palmaria palmata* and *S. Latissima* collected in Brittany, France. Contrary to the previous study, it was observed that *P. palmata* offered better methane production both in batch (500 ml) and semi continuous digestion tests (3 *l*) due to its high volatile solids content and low cations content (Jard et al., 2012). Both the tests were carried out at mesophilic temperatures (35 °C). *Palmaria palmata* showed a methane production of 257 ml CH_4/g VS and *S. Latissima* showed a methane production of 209 *ml* CH_4*/g VS* (Jard et al., 2012). In Ireland, Vanegas and Bartlett (2013) compared the biogas potential of five Irish species and based on the results, *S. Latissima* and *S. polyschides* offered the highest biogas production at mesophilic temperatures with 335 *ml* CH_4*/g VS* and 255 *ml* CH_4*/g VS* respectively in batch assays (120 and 1000 ml) (Vanegas and Bartlett, 2013). In another study conducted in Ireland, Allen et al. (2015) collected ten varieties of seaweed species in Cork, Ireland and tested for their biomethane potential which included *S. Latissima*. The BMP of the species showed a methane production of 341 *ml* CH_4*/g VS* (Allen et al., 2015).

From briefly reviewing these studies, it can be seen that the species *S. Latissima* has demonstrated different methane potentials. This could be due to the fact that they were collected from different locations. The species has shown a BMP ranging from 209 to 341 *ml* CH_4*/g VS*. T. The biomass utilised by Vivekanand et al. was grown for one season in Trondheim, Norway (63°N, 10°E) by Seaweed Energy solution and was collected in August 2010. As for the biomass utilised by Jard et al. (2012) they were collected from Lézardrieux (Côtes d'Armor, Brittany, France) by Aleor seaweed farms. The biomass used in the Irish study by Vanegas and Bartlett was collected from a wild rocky outcrop of Streedagh beach, County Sligo, Ireland during low tide in September 2011. The biomass utilised by Allen et al. (2015) however was collected from collected from beaches in Cork, South of Ireland (51°N, −9°E). The seaweeds were beach cast and harvested from their wild natural environment. The environmental conditions where this biomass were grown is different as it ranges from Norwegian Sea (Seaweed energy farm), Western part of Atlantic Ocean (Brittany), to Northern part of Atlantic

Ocean (Sligo) and Celtic Sea (Cork). No information as to the environmental conditions where they were grown is provided by the studies. Therefore, there is a need to ascertain whether location is a significant factor and which environmental factors are critical for increasing methane production utilising macroalgae biomass.

2.3. Impact of harvest seasons on the biochemical methane yields of S. Latissima

There are few studies in the literature which have evaluated the impact of seasonal variation in the biochemical methane potential of *S. Latissima*. Adams et al. (2011) explored the AD potential of *Laminaria digitata* harvested from three beaches - Barnacarry beach, Argyll and Bute, in the UK during the period from December 2007 till October 2008 for their anaerobic digestion potential. Methane production was observed for batch assays of 36 days. All samples followed a similar trend where there was a linear production of methane until the first five days of digestion and after which the methane production decreases. Samples from the summer months produced a higher cumulative methane with harvest from July producing the highest amount of methane. This was attributed to the high laminarin and mannitol concentrations. The samples from the first 5 months of the year had lower concentrations of these carbohydrates and therefore lower methane yields. In addition, these samples also had higher alginic acids concentrations which could also have decreased the rate of hydrolysation in the biomass resulting in lower methane yields (Adams et al., 2011). There are few studies in the literature that investigated the effect of seasonal variation on the biochemical methane potential of *S. Latissima*. However, a study by Marinho et al. (2016) focussed on the seasonal variation of *S. Latissima* grown in Danish waters for its bioremediation, and biorefining potential with succinic acid production with integrated multitrophic aquaculture. The study noted that November was the preferable harvest time for the species, due to high protein content. November harvest would increase the nutritional value of the seaweed to be used as a protein ingredient for fish feed. However the focus was fermentation based succinic acid production and not anaerobic digestion of the biomass (Marinho et al., 2016). From the above discussion it becomes clearer that, there is a gap in the literature to assess biomass harvested at different times of the year for their biochemical methane production characteristics owing to their varying biochemical composition at the time of their harvest. However, the generic rule that can be noted from the review is that if biomass is intended for AD, high carbohydrate content in the biomass should be targeted hence summer to early autumn could be the best times of harvest for *S. Latissima*.

2.4. Impact of wild and/or cultivated biomass on the biochemical methane yields of S. Latissima

In the literature, where studies have been performed on *S. Latissima*, there is a limitation to compare the results as the studies have utilised either wild sourced biomass, or long line cultivated biomass or simply beach cast biomass. However, at the time of this study no research was found to have compared the variation in the methane production of any species obtained from the wild sources and cultivated sources from the same location. This could be because as wild and cultivated biomass is genetically identical, their biomethane potential are also considered to be identical. Allen et al. (2015) and Vanegas and Bartlett (2013) utilised wild biomass. In contrast, Jard et al. (2012), and Vivekanand et al. (2012) sourced their biomass from cultivated long lines. These research studies did not emphasise on the growth conditions and their impact on the methane potential of the biomass rather they were more focused on testing the overall feasibility of the species for anaerobic digestion. However, they can be used as indicators of methane production from cultivated or wild biomass from that location. More importantly, as wild sources are unsustainable, these studies can inform cultivation practices to cultivate biomass with specific characteristics intended for anaerobic digestion.

An initial review of the literature has highlighted the inherent variability of macroalgae biomass and the potential impact of location and environmental conditions on the biomass growth and characteristics. However, there remains little information on the species *S. Latissima* which will be the focus of this study. While there is some limited data in the literature on the utilisation of *S. Latissima* for AD there is very little relating this to biomass cultivation conditions. This gap in the knowledge needs to be explored in order to effectively manage the use of this biomass. The species will be studied to explore the extent to which environmental conditions at a given location growth cycle and consequently harvest time and growth type (wild or cultivated) impacts on biomass characteristics and methane potential. Batch studies have their limitations, and are generally used as an indicator of suitability of a biomass for AD. Continuous studies performed in literature would show the advantages and challenges of utilising the biomass in detail with a large array of AD parameters observed as part of such studies.

2.5. Techno economic studies of S. Latissima

Techno-economic (TE) analysis of the overall AD process has been reported in the literature. Zamalloa et al. (2011) analysed the techno-economic potential of AD and stressed on the importance of governmental support mechanisms such as feed-in-tariffs as it is shown as the major determinant of the net present value providing almost 96 % of the revenues. The other factors found important for a techno-economic view point were productivities of the biomass, loading rate, number of operational days of the digester and associated operational costs (Zamalloa et al., 2011). Techno economic viability of the macroalgae cultivation systems are reported from a number studies which indicate that optimisation is still required for the long line cultivation techniques utilised in European countries (Roesijadi et al., 2008, 2010; Kraan, 2013).

Techno-economic assessment particularly focuses on improving the overall feasibility of the process utilising the biomass. An extensive TE analysis evaluating performance of the brown species *Laminaria digitata* in European market was conducted by Dave et al. (2013). The study performed the analysis on the ECLIPSE model assuming 8.64 t dry biomass per day (feed rate) for a community based (AD capacity of 1.6 MW) CHP production unit. The findings of the study stressed that even though the current market is economically favourable for extracted high value compounds from the macroalgae biomass in Europe, a community-based CHP plant could be a favourable option in utilising green energy from the brown algae biomass. The study considered the annual variations of the biomass, with the line breeding near shore cultivation systems for utilising 8 t of biomass per day (dry basis) for a moderately sized AD plant assuming an algal conversion rate of 64 % within 15 days. The total macroalgae cost was assumed to be 50 euros/t. The plant generated 237 kWE (net) electricity and 367 kW heat. No government incentives were considered for this study, however the study recommended that support systems such as Feed in tariffs and Renewable Obligation Certificates could significantly improve the project viability. The economic viability of the plant was measured in terms of internal rate of return in connection with the different feedstock prices, total annual power generation and the capex expenditure. The study found that the major cost factors were associated with the feedstock cost, maintenance and operating costs, any additional treatment facilities cost for biomass utilisation (drying, pre-treatment etc.). Moreover, the study also stressed on the reliability of continuous supply of feedstock, hence suggesting co-digestion with other biomass and wastes such as sewage sludge, food waste etc. as a potential solution (Dave et al., 2013).

In 2015, Konda et al. performed a techno-economic assessment on *S. Latissima* to understand the cost drivers and identify the economic potential of the biomass at industrial scale. Despite the advantages over other biomass feedstock for reduced water usage, pollution control, etc., the actual success of the macroalgae based biorefinery was reliant on the economic performances of the processes which were converting the biomass into fuels or products. The study focused on ethanol production from macroalgae biomass with an industrial scale facility of 2000 Mt/day dry biomass processing capacity. The preliminary results showed that the maximum allowable price for the seaweed was 28$/Mt (approx. €25.36/Mt) (dry) in order to produce ethanol at 2.2$/gal (approx. €1.99/gal) or less with a production cost ranging between 21 and 112 $/Mt (approx. €19.02 – €101.46/Mt) (depending on the species and the cultivation method employed). The same study found that *S. Latissima* to sugars platform is economically viable, easily scalable, and efficient, however downstream technologies i.e. purification and effective product recovery systems are still required to make the chemicals from the biomass cost competitive to the petroleum derived products. The other main critical factor identified through the study was the reduction in the macroalgae feedstock price and the need for the development of supply chain and logistics for the utilisation of such biomass (Konda et al., 2015). Therefore, there is definitely a need for more studies to evaluate the technoeconomic feasibility of species *S. Latissima* for its utilisation for AD.

From this review it also becomes clear that a biorefinery based approach is essential for an economically viable, scaled up system for biogas production from macroalgae biomass. Regardless of economic impacts, from a sustainability point of view it is important to consider metrics such as carbon, nutrient, and water balances, recycle opportunities and delivery sources, which are all location specific. For a commercial level realisation and economic viability of microalgae biomass utilisation, the use of spent biomass beyond biogas generation is recommended alongside creating high value by-products with market sustainability of such co-products (Davis et al., 2003). For macroalgae biomass, the system should have a balance of high value products, and bioenergy from co-digestion with other available waste resources alongside production of biogas and digestate for the use as fertiliser (Ramirez, 2017). Bio-methane from macroalgae is definitely shown to be one of the promising systems for bioenergy production for future. Research suggests that this can be achieved by integrating the seaweed cultivation similar to IMTA techniques, using innovative designs for cultivation systems, ensuring optimal species and composition, reusing digestate and utilising renewable electricity to power the plant operations (Czyrnek-Delêtre, 2017). From the discussion it is also clear that techno-economic studies for macroalgae biomass is a developing field where most of the studies have focused on the feasibility of the species in terms of cultivation, and producing high value compounds or its suitability for a particular energy derivation path way. Therefore, from an AD perspective, efforts should be focused on decreasing the feedstock cost, increasing the methane yield of the biomass and identifying low cost effective pre-treatment facilities and suitable co-digestion strategies for macroalgae utilisation for AD. Hence, in this study, techno-economics analysis is chosen as an approach to identify the effect of AD technology on the overall economics of the process – i.e. the benefits and adverse effects of AD, mono-digestion and co-digestion on economics utilising *S. Latissima*.

3. Material and methods

3.1. Feedstock and Inoculum

The feedstock utilised for this research study involved macroalgae and organic feedstock supplied by local partners including agricultural crop waste residues, pig manure and brewery spent grain. The macroalgae species was evaluated for its anaerobic digestion potential as a single and co-digestion feedstock with the traditional organic AD feedstock mentioned above. The macroalgae species used in this study is *S. Latissima* (*S. Latissima* and was, obtained from Northern Ireland (Belfast)), Southern Ireland (Ventry Harbour) and Scotland. The samples were harvested from the long lines, and transported immediately in sealed containers. On arrival at the Birmingham City University (BCU) campus they were removed from the packaging, labelled and stored in the freezer at −20 °C in zip lock bags for long term storage and for regular use for experiments. The storage method was followed as described in (Schiener, 2014) and (Silva Marinho, 2016). The pre-treatment of the received seaweed prior to the experiments and storage are detailed under the Section 3.1.3 below.

3.1.1. Organic feedstock

The organic feedstock that were used in the experiments included agricultural waste residues, pig manure and brewery spent grain. The agriculture crop waste feedstock and brewery spent gain was collected, separately stored in individually sealed and labelled zip lock bags and kept in a freezer (−20 °C) for storage until the experiments. The agricultural crop waste residues included corn silage, wheat residues, grass silage, and sugar beet-vegetable mix (SBV mix). This feedstock was collected from Vale Green Energy plant in Worcestershire, UK. The samples were collected from the storage area in the energy plant. The cemented shelters which served as storage area had large piles of crop residues and vegetables mix. These were stocked on the outside to allow daily feeding into the on-farm digesters. The crop residue samples were collected from the storage area and vegetable mix collected from the pile of daily feed for the digesters. These wastes were from the farm's latest harvest having stored there for a few days. All of the samples were collected, separated, prepared and stored on the same day. Brewery Spent Grain (BSG) samples were collected from a local brewery (Froth Blowers Brewing Company, Erdington in Birmingham, UK). The samples were received after the initial extraction operations in the brewery and separated from the wort liquid. The pig manure obtained was in dry, pelletised form. It was packed in an air tight container and stored until used for experiments. Pig manure was received from European Bioenergy Research Institute, (EBRI), at Aston University, Birmingham, UK. The pig manure pellets were ground to fine powder and not soaked prior to the BMP tests for this study.

3.1.2. Inoculum

The inoculum used for biochemical methane potential (BMP) tests and the semi continuous digestion experiments was collected from Severn Trent Waste Water Treatment Plant, (STWWTP), in Minworth, Sutton Coldfield, West Midlands, UK. The inoculum was collected from an active digester operating at 37 °C. The inoculum was maintained at (37 °C) in a temperature-controlled water bath until the start of experiments. The inoculum was tested for the pH, total and volatile solids content in triplicate on the same day of collection prior to further experiments. The processing and storage of inoculum for biochemical methane potential tests and semi-continuous tests are detailed separately in subsequent sections below. For BMP testing, the collected inoculum was sieved using a stainless steel sieve (size 5 mm) to separate any bulk impurities like glass or stones. The sieved inoculum was then degassed for two days in a temperature controlled water bath at 37 °C (Suhartini, 2014). While, for semi continuous trial, the freshly collected inoculum was directly filled into all reactor at volume of 2 L. The variability observed for the methane potential of the inoculum collected at various intervals will be discussed in the results section.

3.1.3. Pre-treatment of feedstock – macroalgae biomass

Following collection of seaweed, a number of steps were undertaken to produce a homogenised product suitable for long term storage. The collected seaweed (as sent) was visually inspected on arrival for cleaning and removing holdfasts and foreign materials such as stones, shells, other seaweeds and invertebrates. The fronds of the wild samples of seaweed, when sparsely or irregularly covered with epiphytes, were retained as this is considered to be an unavoidable and natural occurrence on wild harvests (Forbord et al., 2012). The second stage of sample preparation for samples was maceration. A household food blender (Bosch MCM 41, UK) was used to macerate the seaweed into smaller particles. The particle size of the shredded seaweed was approximately 1 cm. The macerated seaweed was then mixed in a larger container to ensure a homogenous and representative sample could be taken. Samples were then divided into 0.5 to 1Kg portions for storage. Each portion of the macerated seaweed was sealed in a plastic bag, labelled and stored in the freezer at −20 °*C. prior* to the analyses and experiments, the samples used for this study were taken from their storage and allowed to defrost to reach room temperature in the respective storage containers. Freezing the samples was not observed affecting the biodegradation of the biomass. The sample preparation steps were adopted from previous studies on *S. Latissima* published by (Schiener, 2014) and (Vivekanand et al., 2012).

3.2. Feedstock characteristics

The characteristics of *S. Latissima* used for semi continuous digestion sourced from Dingle Bay seaweed Ltd. is given in Table 1. The biomass had total solids content of 15 (%WW) and an ash content of 4 (%WW). The elemental composition analysis highlighted that the sample was comprised 29 % carbon, 1.7 % nitrogen and 0.4 % sulphur (as a %TS). The C/N ratio of the biomass was found to be 17.1. The BMP of the biomass was found to be 0.391 $L\ CH_4\ kg/$VS added.

3.2.1. Inoculum characteristics

The inoculum was sourced from Severn Trent Wastewater sewage treatment. This inoculum was used for both mesophilic and thermophilic experiments. No buffers were added to the inoculum to maintain the pH. The inoculum characteristics and the standard deviations are given in Table 2. The experiments were performed in duplicates for the semi-continuous digestion run.

3.3. Macroalgae species and organic feedstock

The techno-economic assessment is based on the species *S. Latissima*. In northwest Europe the species is cultivated in long lines with a yield of approximately 10 kg/m long line with a growing period of 20 weeks at sea. The species (*S. Latissima*) used in this study was harvested during the summer at Ventry Harbour, Ireland. The organic feedstock used in this study included agricultural waste residues, pig manure and brewery spent grain. The agricultural crop waste residues included corn silage, wheat residues, grass silage, and sugar beet-vegetable mix (SBV mix). This feedstock was collected from Vale Green Energy plant in Worcestershire, United Kingdom. Pig manure was received from European Bioenergy Research Institute, (EBRI), at Aston University, Birmingham, UK. Brewery Spent Grain (BSG) samples were collected from a local brewery (Froth Blowers Brewing Company, Erdington in Birmingham, UK).

3.4. Biochemical methane potential and semi-continuous digestion of S. Latissima

Biochemical methane potential tests and continuous digestion of *S. Latissima* was performed as a part of this study. The economic analyses were part of the research study where the macroalgae was first analysed for its characteristics and methane potential. All materials were processed and characterised at Birmingham city university including the standard methane potential tests. The digester parameters and the BMP values for the model were obtained from these experimental results. See Dr. Paul (2018), for the protocol used for the BMP tests. The inoculum used for biochemical methane potential (BMP) tests and the semi-continuous digestion experiments was collected from Severn Trent Waste Water Treatment Plant, (STWWTP), in Minworth, Sutton Coldfield, West Midlands, UK. The inoculum was collected from an active digester operating at 37 °C. Anaerobic batch tests were conducted using Automated Methane Potential Test System (APMTS II, Bio Process Control, Sweden) (Bioprocess Control, 2017) while laboratory scale semi continuous anaerobic digestion experiments were carried out in a continuously stirred tank reactor (CSTR).

Table 2
Characteristics of inoculum used for semi continuous digestion.

Inoculum source	Severn trent wastewater treatment plant
Inoculum source temperature	Mesophilic (37 °C)
Total Solids, TS (% WW)	3.10 ± 0.01
Volatile Solids, VS (%WW)	2.01 ± 0.01
Ash (%WW)	1.07 ± 0.01
Moisture (%WW)	96.94 ± 0.24
VS (%TS)	64.84
pH	7.4 ± 0.04
BMP (L CH_4/kg VS added)	0.056

The specific methane production (SMP) of various organic feedstock co-digested with *S. Latissima* and the percentage increase for the measured SMP values are given in Table 3.

It can be seen from the Table 3 above that with the exception of BSG and Grass the SMP increased as a result of co-digesting *S. Latissima* with the organic feedstock. The highest % increase was observed for pig manure where a 32.3 % increase was observed.

Although the results of co-digestion suggest an increase in measured biogas yield the feedstock were mixed at a ratio of 70:30. According to Labatut et al. (2011) the increase or decrease in methane production as a result of co-digestion can be calculated by determining the difference between the measured SMP of the co-digested feedstock and the estimated SMP for co-digestion based on the ratios of mixed feedstock (Labatut et al., 2011). In this study, this calculation will only consider the specific methane production in co-digestion and will not be considering the biodegradability of the co-digested feedstock as to observe whether the co-digestion improved the digestion of either of the feedstock.

The percentage increase or decrease in measured specific methane production is calculated as per the equation below:

$$\frac{(\text{SMP in codigestion} - \text{SMP in monodigestion})}{(\text{SMP in monodigestion})}*100 \tag{i}$$

The estimated SMP for the co-digestion is calculated using the formula below:

$$\begin{aligned}&(0.7*\text{SMP organic feedstock in monodigestion}\\&\quad+0.3*\text{SMP macroalgae biomass in monodigestion})\end{aligned} \tag{ii}$$

From this calculation, the net percentage increase and decrease was

Table 3
Percentage increase for specific methane production in co-digestion.

Feedstock	Specific Methane Production (SMP) as L CH_4/kgVS					
	Wheat	Maize	Grass	SBV mix	Pig Manure	BSG
Mono-Digestion	0.393	0.391	0.395	0.292	0.130	0.421
Co-Digestion	0.472	0.397	0.395	0.373	0.172	0.404
% difference	21.9	1.01	0	27.7	32.3	−4.03

*SMP of S. Latissima in isolation 0.391 L $CH\ 4/kgVS$ added.

Table 1
Characteristics of *S. Latissima* used for semi continuous digestion.

Seaweed ID	Total Solids (%WW)	Volatile Solids (%WW)	VS (%TS)	Ash (%WW)	Moisture (%WW)	Calorific Values (MJ/kg)	SMP (L CH4/kg VS added)
Ventry Harbour	15.08	10.60	70.30	4.48	84.92	07.30	0.391

calculated as follows.

$$\frac{(\text{Measured SMP in codigestion} - \text{Estimated SMP in codigestion})}{(\text{Estimated SMP in codigestion})} * 100 \tag{iii}$$

These calculation was applied to the data and the results for net percentage increase or decrease in co-digestion are presented in Table 4 below.

From Table 4, it can be seen that *S. Latissima* when added as a co-digestion feedstock to Wheat resulted in the greatest percentage increase in methane yield 21.59 % based on estimated yields. In contrast the co digestion of *S. Latissima* with pig manure resulted in a decrease of 17 % in methane based on estimated yields.

3.5. Techno economic analysis

A Techno economic analysis was conducted based on the biochemical methane potential of macroalgae co-digested with agricultural crop residues, manure and brewery spent grain. The methodology was adapted from a model provided by the EnAlgae (Interreg IVb, EU) project (Parker et al., 2015; Sprujit, 2015). This techno-economic model (WP2A7.07) identified the political, economic, social and technological opportunities to promote the adoption of algal biomass within North-Western Europe. This model was specifically designed for considering the methane production from algae biomass and was therefore deemed appropriate for use in this study. The model was developed as a calculator to show the feasibility of AD for using algae biomass, and based on the findings from the EnAlgae report there existed a wide gap between a feasible business case and the AD of algae. Hence there was no verification study financed to verify the model as such. Rationale for the adaptation of the EnAlgae model for this study: The economic model considered co-digestion with products of either electricity with a combined heat and power (CHP) or green gas. The investment parameters considered in the economic model included:

- Cost of the digester,
- a CHP,
- a biogas process unit,
- A pre-treatment unit.

The substrates included in the model were predominantly for AD using co-digestion. Dairy manure was chosen as the base material and a maximum of 4 substrates could be chosen as co-digestion substrates. The full list of substrates is:

Base material:

- Dairy Cow manure

Co-materials:

- Glycerine
- Silage maize
- Wheat straw
- Sugar beet
- Beet leaves
- Pig manure
- Maize straw
- Algae paste

Table 4

Net percentage increase or decrease for co-digestion.

Feedstock	Measured SMP on co-digestion ($LCH_4/kgVS$)	Estimated SMP (based on 30:70 ratio) ($LCH_4/kgVS$)	Net Percentage increase or decrease (%)
S. Latissima	–	–	–
Wheat	0.472	0.388	21.59
Maize	0.397	0.392	1.17
Grass	0.395	0.394	0.30
SBV mix	0.373	0.322	15.95
Pig Manure	0.172	0.208	−17.43
Brewery spent grain	0.404	0.412	−1.94

In the developed EnAlgae model, a maximum of 4 co-substrates for the model could be chosen where the quantity of the co-materials should not exceed that of cow manure (Base material). The model assumes a ratio of 50–50 % of cow manure and co-material. The scale of the CHP is adjustable in the model for the desired CHP level. The price of the algae paste and the co material can also be adjusted according to the choice of the co material chosen. For this study, the model assumed a 52 % (CH_4 content) and 48 % (CO_2 content). A 36 % electric efficiency was assumed for the CHP unit. The operational hours of the digester per year was assumed to be 8000 h. The heating value of methane was approximated to be 36.5 MJ/m^3. An inflation rate of 2 % per year was considered for the cost parameters in the model. The digester was given a life span of 25 years, 10 years for CHP, and 10 years for green gas processor, and 15 years' life span for the pre-treatment unit in the model. The scale of the digester at 1,000,000m^3 of biogas for a digesting time of 30 days. The results from the economic model mainly focused on the return on investment percentage (ROI, %) and the payback time in years. The results also showed a comparison of the percentages of selling price and the cost price for the various substrates considered for co digestion. The results would also give the comparison of total returns and total costs. A financial return for every 100 Euro in costs will also be shown on the results table. The economics for *S. Latissima* harvested from three different locations, 4 different harvest times and wild and cultivated growth types were analysed in this study. The co-digestion feedstock of agricultural crop wastes, pig manure and brewery spent grain was analysed separately. The individual BMP of the co-digestion tests were inputted in to the model to estimate the effect of co-digestion on the biogas production unit of per gram of organic volatile solids digested.

3.6. Model assumptions and parameters

Techno economic analysis was conducted based on the biochemical methane potential of macroalgae *Saccharina latissima* species, co-digested with agricultural crop residues, manure and brewery spent grain. The study has utilised the Techno economic model (WP2A7.07 model methane V2.3) developed by Chris de Visser et al. as a part of the EnAlgae (Interreg IVb, EU) project (Spruijt et al., 2015). The basis of the new model including parameters, constants and the investments for the development of the model were derived from the work by Sinnott (2005). This techno-economic model identified the political, economic, social and technological opportunities to promote the adoption of algal biomass within North-Western Europe. This model was specifically designed to consider the methane production from algae biomass and was therefore deemed appropriate for use in this study. The economic model considered co-digestion with process outputs of either electricity with a combined heat and power (CHP) or green gas. The investment parameters considered in the economic model included the cost of the digester, a CHP, a biogas process unit, and a pre-treatment unit. The cost considerations included raw materials (organic feedstock costs), investment, depreciation, insurance, rent on capital, land costs, maintenance costs, land cost and labour cost. The total returns mainly involved the selling of the green gas into the grid unless the sale of digestate was considered as a route of income. The scale of the CHP was adjustable in the model for the desired CHP level. The price of the macroalgae biomass and the co-digested material could also be adjusted according to the choice of the co material chosen (Sinnott, 2005). The digester details are given in Table 5 below.

Once the parameters and digester details were defined, the next step was to define the system boundary. The system boundary for the study is

Table 5
Parameters and digester details (Adopted from Sinnott, 2005).

Parameters		Units
inflation	2.00 %	per year
life span digester	25	years
life span CHP	10	years
rent on debt capital	5.50 %	
Capacity biogas)	1,000,000	m^3/year
CHP electricity production	2520	MWh/year
Digesting time	30	days
Green Gas price	1.22	Euros

given in Fig. 1 below.

The boundary for the techno economic assessment system (shown by dotted lines) is assumed to start at the AD Plant (anaerobic digestion unit) where the wet biomass would be transported to the sites from the seaweed cultivation and processing units for digestion. The agricultural farm based unit will be producing the other organic waste feedstock such as the crop waste residues, brewery spent grain and pig manure which also will be transported to the AD unit for co-digestion. The digesting time for the feedstock was assumed to be 30 days. The two main products of an AD process; methane was utilised for CHP purposes and digestate was utilised as a fertiliser for CHP respectively.

The economic benefits of an AD plant are usually analysed using internal rate of return (IRR), return on investment (ROI) and payback period which vary with different AD plants. The results from this economic model mainly focus on the return on investment percentage (ROI, %) and the payback time in years. The economics for cultivated biomass of *S. Latissima* harvested during summer was analysed in this study as a single feedstock for AD purposes. The co-digestion feedstock of agricultural crop wastes, pig manure and brewery spent grain was analysed separately. This was to allow a real case scenario where macroalgae biomass would be abundantly available in the region during summer and digesting with other organic feedstock to reflect when the biomass was scarce. The individual BMP of the co-digestion tests were inputted in to the model to estimate the effect of co-digestion on the biogas production unit of per gram of organic volatile solids digested. All quantities are reported in tonnes and prices in euros.

Return on investment and payback time were calculated using the below formulae:

Return on investment

$$\frac{(\text{Total returns} - \text{Total costs}) - (\text{Depreciation of asset} - \text{Rent on debt capital})}{(\text{Total investment})} \tag{iv}$$

Payback time

$$\frac{(\text{Total investment})}{(\text{Total returns} - \text{Total costs}) + (\text{Rent on debt capital} + \text{Depreciation})]} \tag{v}$$

The results for the analyses are discussed in the following sections.

4. Results

4.1. Biochemical methane potential of S. Latissima

As described in the methods, the values for the techno-economic model were derived from the experimental results conducted as part of this research. The biochemical methane potential test results for *S. latissima* as a mono-digestion feedstock and on co-digestion with other organic feedstock are given in Table 6 below. The biomethane production potential for the feedstock is calculated on the basis of volatile

Table 6
0 Percentage increase for specific methane production in co-digestion.

	Specific Methane Production (SMP) as L CH_4/kgVS					
Feedstock	Wheat	Maize	Grass	SBV mix	Pig Manure	BSG
SMP of *Saccharina Latissima* 0.391\ L\ CH_4/\ kgVS\ added						
Mono-Digestion	0.393	0.391	0.395	0.292	0.130	0.421
Co-Digestion	0.472	0.397	0.395	0.373	0.172	0.404
% difference	21.900	1.010	0.000	27.700	32.300	−4.030

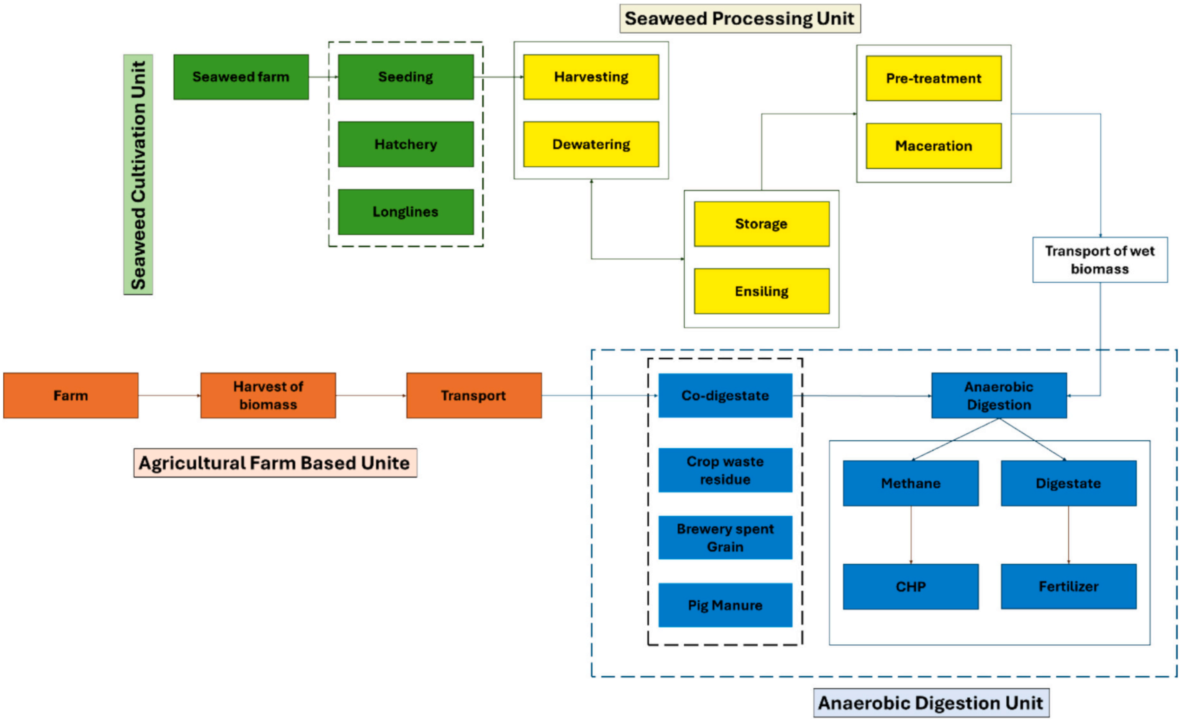

Fig. 1. The system boundary and process flow for the study.

solids.

It can be seen from the Table 6 above that with the exception of BSG and Grass the SMP increased as a result of co-digesting *S. Latissima* with the organic feedstock. The highest % increase was detected for pig manure where a 32.3 % increase was observed. The estimated SMP for the co-digestion is calculated using Eq. (ii) above.

4.2. Techno-economic assessment

The different scenarios assumed for the techno-economic analysis are broadly divided into three.

1. *Saccharina latissima* as a mono-digestion feedstock for AD
2. *Saccharina latissima* as a co-digestion feedstock for AD
3. Sensitivity analyses

The digester characteristics for the macroalgae biomass and the other organic feedstock were taken from the experimental data (BMP experiments. See Paul,(2018)) In northwest Europe the species is cultivated in long lines with a yield of 10 kg/m long line with a growing period of 20 weeks at sea. The price of electricity is assumed at 0.11 €/kWh which is the lowest of the electricity prices in a European member state (Eurostat, 2018).

4.2.1. S. Latissima as a mono-digestion feedstock for AD

For *S. Latissima* as a mono digestion feedstock, the economic viability were calculated with varying macroalgae biomass prices. The prices assumed for *S. Latissima* as a mono digestion feedstock 0, 50, 250 and 1000 Euros/t respectively. The prices represented the scenarios where macroalgae biomass was free (0 euros), 50 Euros (Cost of brown algae biomass dry basis per tonne in the literature (Dave et al., 2013), 250 Euros, (Price suggested by Crown Report if intended for bioenergy production) (Kelly and Dworjanyn, 2008) and 1000 Euros (price of biomass for high value products extraction, (Vandendaele, 2013)).

For the analysis of *S. Latissima* as a mono-digestion feedstock, results in this study showed that the only positive return on investment (2 %) for macroalgae biomass as a mono digestion feedstock was achieved when the feedstock was free (0 Euros/t). See Fig. 2. The values for ROI were calculated considering the total returns and total costs with depreciation of assets involved and rent on debt capital over the total investment for the technology. As expected, the values became increasingly negative as the prices were increased from 50 to 1000 Euros/t. This showed that the cost of macroalgae biomass was a critical factor affecting the economics of the technology involved.

The economic benefits of return on investment (ROI) and payback period vary with different AD plants. From the literature it is also seen that choice of feedstock is critical for the positive returns on any AD plant (Zamalloa et al., 2011). These parameters of ROI and payback time were chosen as this study focuses only on the selectivity of the best feedstock combination from the range of feedstock tested to produce the highest ROI in the shortest payback period. For an AD plant, an IRR higher than of 8 % was suggested to provide profits with a payback period of 17 years using the North Atlantic species of *Laminaria digitata* (Dave et al., 2013).

The price of seaweed has a limited effect on the payback time in consideration with the other cost factors and hence payback time is very small as shown in Fig. 2. In this study, the graph shows negative ROI, which can mean lower profits or negative returns during the initial years of the investment which is common at the start of any project. This also shows that for macroalgae biomass based mono-digestion, the process is not economically viable and a positive rate of return on investment of 2 % with payback time of less than a year is only possible when the macroalgae biomass is free of any cost. However, this can only be made possible if macroalgae is available in bulk and is cheaper to harvest, which at present is not practical.

4.2.2. S. Latissima as a co-digestion feedstock for AD

As mono-digestion of the biomass was shown not to be economically feasible, the second scenario was co-digestion with organic feedstock where macroalgae would be used at lower percentages (up to 30 %) to balance the economics. Co-digestion is a mechanism opted by the AD operators to enhance the AD either by increasing the biogas output or by modifying the digester conditions. Therefore, a base case scenario for co-digestion was to be considered in order to better understand the impact of macroalgae biomass co-digestion on the overall economics of the AD process. The assumptions made were as follows: -

- Macroalgae biomass price is 50 Euros/t
- The co-digestion percentage is 70 for organic feedstock and 30 for Macroalgae
- The other feedstock digested with macroalgae biomass are cost free (0 Euros/t)
- Digestate priced at 5 Euros/t

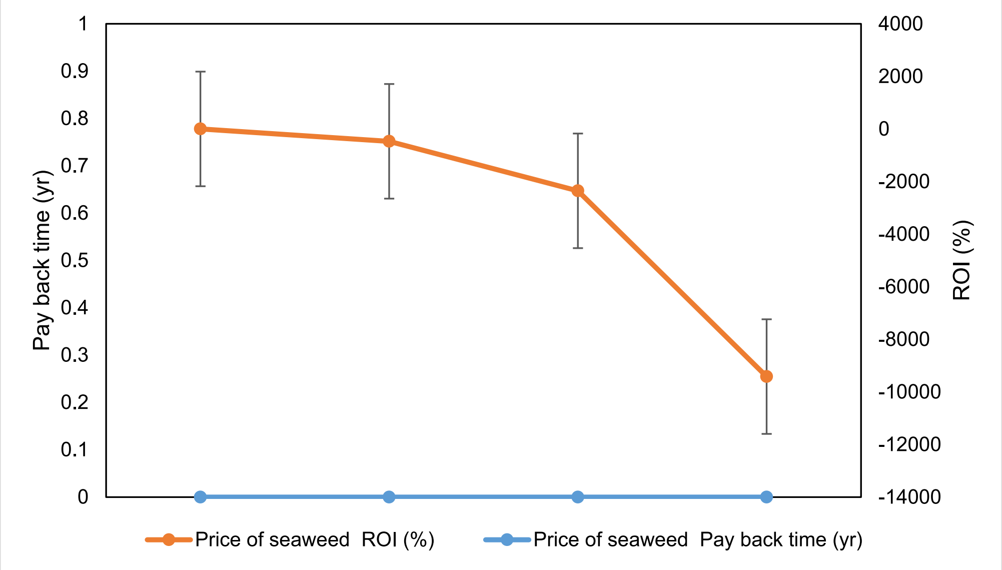

Fig. 2. Assessment of *S. Latissima* as a mono-digestion feedstock.

The results obtained for the base case scenario are given in Fig. 3 below.

It can be observed from the results above that such a scenario was also not economically favourable even when macroalgae biomass is co-digested with other organic feedstock. The only feasible co-digestion scenario was observed for wheat residues with a ROI of 2 % and a payback time of 2 years. Sensitivity tests were analysed for its effect on return on interest percentages for each co-digestion scenario without gate fees. The results are given Table 7 below.

As the base case scenario for co-digestion was considered to be not economically viable, modifications were made to the assumptions. The main feedstock (70 %) in co-digestion including the crop waste residues, brewery spent grain and pig manure are all organic wastes in nature. Typically, in an AD plant, where these wastes are admitted for digestion they are to be paid a price of (29 Euros/t, WRAP 2015) as gate fees unless they are being used in an on farm AD where the feedstock is in surplus. This information was included in the model to analyse any improvements to the economics of the whole system. The macroalgae biomass was still to be priced at 50 Euros/t and the digestate was priced at 5 Euros/t. The results are shown in Fig. 4 below.

As the assumptions were applied, it could be seen that the gate fees for the organic wastes provided a positive variation in the ROI, generating the highest returns for the sugar beet-vegetable mix (105 %), and the lowest for the pig manure (35 %). The payback time was lowest for the sugar beet-vegetable mix (0.7 years) and the highest for wheat (1.7 years).

4.3. Sensitivity analyses - price of the macroalgae biomass with gate fees

This sensitivity analysis involved varying the price of the macroalgae biomass with gate fees attached for the main feedstock and observing the return on investment for each co-digestion scenario. The changes on payback time was also monitored using the sensitivity analyses (See Table 9 below). The gate fees were fixed at 29 Euros/t for all of the feedstock and the price of the macroalgae biomass was varied from 0, 50, 250 and 1000 Euros/t. The sensitivity tests were analysed for its effect on return on interest percentages for each co-digestion scenario with gate fees fixed for the main organic feedstock at 29 Euros/t. The results are given in Table 8 below.

Table 7
Sensitivity analysis of varying macroalgae prices with no gate fees.

Price of macroalgae biomass	Return on investment, ROI (%) Gate fees 0 €/t					
	Maize	Grass	Wheat	SBV mix	BSG	Pig Manure
0 €/tonne	2	2	2	1	2	2
50 €/tonne	−2	−2	2	−5	−3	0
250 €/tonne	−16	−14	0	−30	−22	−8
1000 €/tonne	−70	−63	−8	−125	−96	−39

As observed in Table 8 above, even with the gate fees for the organic feedstock, high feedstock costs associated with the price of macroalgae biomass is prohibitive for the overall economic feasibility of the AD plant AD with co-digestion practices. Ideally, it could be recommended that the price of the macroalgae biomass should be between 50 and 250 Euros for a positive ROI if intended to perform co-digestion with macroalgae biomass for these main feedstock. Sugar beet – vegetable mix (105 %) demonstrated the highest methane production yield while wheat residues demonstrated the lowest with the ROI percentages (11 %). All of the feedstock had positive ROI when cost of the macroalgae biomass is free (as expected) however only wheat had a positive ROI for the highest macroalgae biomass price (1000 Euros/t).

4.3.1. Effect of varying macroalgae prices on payback time

This sensitivity analyses produced the pattern of payback time (years) for each co-digestion with gate fees fixed for the main organic feedstock at 29 Euros/t.

As the macroalgae biomass price increased, the payback time also increased for each substrate in co-digestion. Among the substrates, wheat residue exhibited the least variability in payback time 1.7 and 2.1 years across the various macroalgae biomass prices. Sugar beet-vegetable mixture was found to have the lowest payback time for the price of 0, 50 and 250 Euros (macroalgae biomass) however the highest payback time of 3.2 years if the macroalgae biomass is priced at 1000 Euros/t.

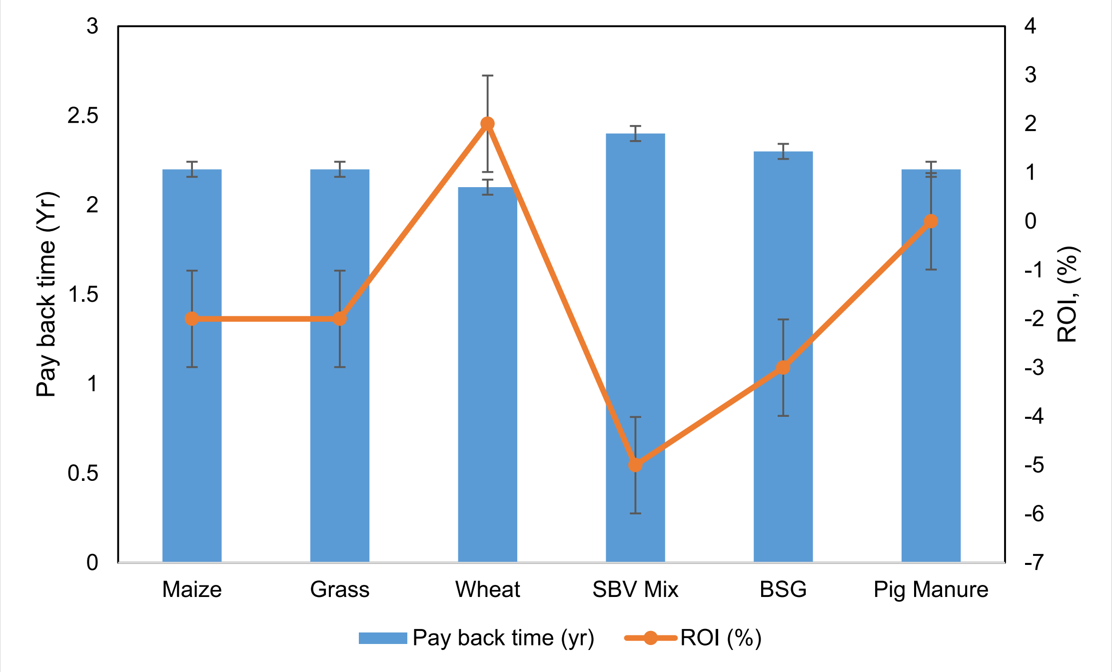

Fig. 3. *S. Latissima* as a co-digestion feedstock for AD (base case scenario - no gate fee for the main feedstock).

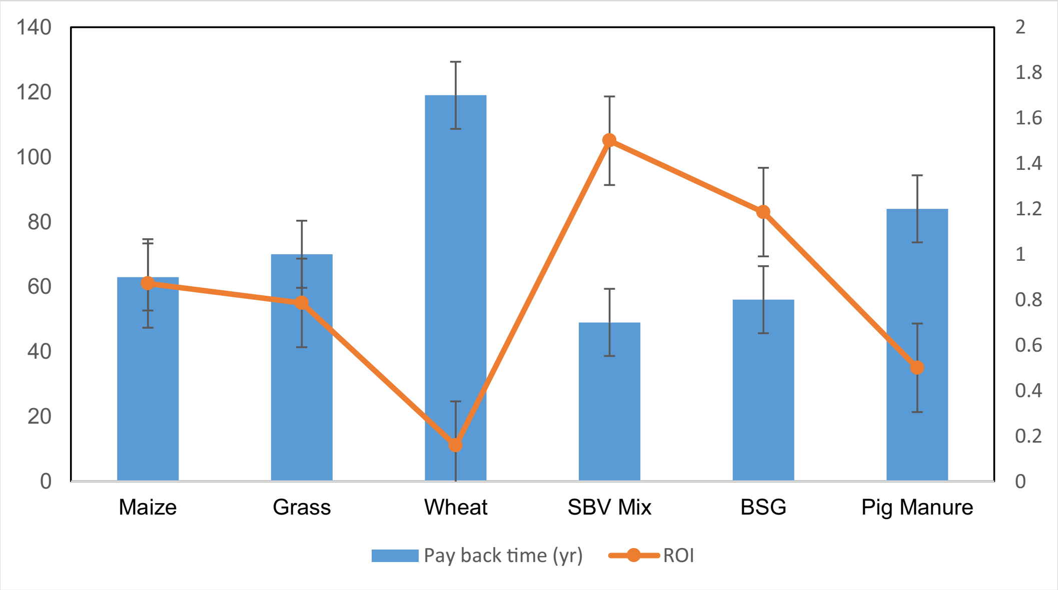

Fig. 4. Scenario for macroalgae biomass priced at 50 Euros/t (29 Euros gate fee).

Table 8
ROI for varying macroalgae prices with gate fees at 29 Euros/t.

Price of macroalgae biomass	Return on investment, ROI (%) Gate fees 29 €/tonne					
	Maize	Grass	Wheat	SBV mix	BSG	Pig Manure
0 €/tonne	64	58	11	111	88	38
50 €/tonne	61	55	11	105	83	35
250 €/tonne	46	42	9	80	63	27
1000 €/tonne	−8	−7	1	−15	−10	−3

Table 9
Payback time for varying macroalgae prices with gate fees at 29 Euros/t.

Price of macroalgae biomass	Pay Back time (years) With gate fees at 29 €/tonne					
	Maize	Grass	Wheat	SBV mix	BSG	Pig Manure
0 €/tonne	0.9	1	1.7	0.6	0.7	1.2
50 €/tonne	0.9	1	1.7	0.7	0.8	1.2
250 €/tonne	1.1	1.1	1.8	0.8	0.9	1.4
1000 €/tonne	2.6	2.5	2.1	3.2	2.8	2.3

5. Discussion

5.1. *Impact of feedstock variability on process economics*

The process economics of macroalgae biomass utilisation (as the single feedstock for AD) was found to be economically unviable. Even when macroalgae biomass was priced at 0 Euros/t, an ROI of only 2 % could be generated. As the price of macroalgae biomass increased, the ROI demonstrated increasingly negative values (up to −9000 %). This is in agreement with the literature where macroalgae with lesser solids content is shown to require more quantities in wet weight to feed the digester which will be reflected in higher feedstock costs resulting in negative rates on investment if used for biogas production. In addition, there is little established data on long term anaerobic digestion of macroalgae biomass and little agreement on the yields of macroalgae biomass per hectare per annum which differs by geographical location, and related environmental conditions, nutrient levels, methods of cultivation and harvest type (Murphy et al., 2015). To improve the digester economics, co-digestion of different feedstock was considered in this study. The agricultural crop waste residues analysed included wheat, maize, sugar beet – vegetable mix, and grass. Pig manure pellets and brewery spent grain was also analysed in this techno-economic study. A base case scenario where macroalgae biomass was priced at 50 Euros per tonne (Dave et al., 2013) was chosen for all the scenarios considered and compared in this study.

5.1.1. *Waste feedstock and macroalgae biomass*

When the feedstock was compared assuming macroalgae biomass price is 0 Euros/t, wheat residues, sugar beet mix, maize and grass demonstrated a 2 % on ROI with a payback time of 2 years. In the base case scenario where macroalgae biomass is priced at 50 Euros/t, among the agricultural crop wastes, only wheat was observed to have a positive ROI (2 %) with a payback time of 2 years. This can be linked to the characteristics of wheat biomass with its higher volatile solids content (84%WW) and lower ash content of 1.4%WW. All the other feedstock had negative ROI values with a payback time between 2 and 3 years. In addition, as macroalgae biomass price increased from 50 to 250 and 1000 Euros, the scenarios became less economically viable with negative returns and longer payback times. Agricultural crop wastes include the non-food based portion including the leaves, stalks, cobs trimmings, husk and straw, grasses and animal waste. A large quantity of crop waste is produced annually around the world and is disposed of in the open environment. The disposal of the crop waste residues is not considered a sustainable practice and direct combustion of biomass results in emission of 1599 kg CO_2 per tonne of dry biomass (Chandra et al., 2012). Therefore, with the aid of co-digestion practices these wastes can be utilised to extract their energy potential with a potential of application in on farm AD facilities.

5.1.2. *Pig manure and macroalgae biomass*

For pig manure, when the organic feedstock is free, a ROI of 2 % with a payback time of 2.1 years was observed When the base case scenario is considered, pig manure has a 0 % ROI with a payback time of 2.2 years, and as price of macroalgae biomass increased, (for 250 euros - −8 %, 2.2 years; for 1000 euros - −39 % and 13.4 years) negative returns are observed with longer payback times. Pig slurry pellets used in this study are very different to the traditional animal slurry used for digestion. The total solids content in a slurry is 0.9%WW where as in pellets used in this study is observed to be 90%WW. Even though separation of solid and liquid fraction in a pig slurry is recommended for slurry management, anaerobic digestion of solid fraction is found to be inhibited due to its high solids content (Campos et al., 2008). Therefore, it could be suggested that pig manure pellets are not an appropriate substrate to be mixed with macroalgae biomass and if intended for co-digestion, C/N ratio should be balanced for the optimum process efficiency. This will reflect on the overall methane production from the mix and thereby making the process economically viable.

5.1.3. Brewery spent grain and macroalgae biomass

Brewery spent grain is an emerging potential feedstock for AD, and therefore considered for co-digestion with macroalgae biomass. For Brewery Spent Grain, 2 % ROI with 2 years' payback time is observed when the macroalgae biomass is free. For the base case scenario, −3 % ROI with a payback time of 2.2 years is observed. The pattern observed for other feedstock is repeated for BSG as −22 % ROI and 4 years 'payback time is observed when macroalgae biomass is 250 Euros/t and − 96 % ROI when macroalgae biomass is 1000 Euros/t. This could suggest that, for effective co-digestion of feedstock such as BSG, more research is required to optimise effective digestion of the biomass. BSG is currently perceived as a waste that brewers want to dispose due to their environmental challenges of odours with disintegration and increase in rodents in their premises however biovalerisation of BSG is found to hold a strategic economic position in the EU due to its availability and various potential uses in food industry (Vitanza et al., 2016). Currently it is used as an animal feed which most of the breweries sell to the farmers with no cost. However the farmers will be responsible for transporting the wet BSG to the farms which upon analysis can cost up to £38/t in the UK market (Ben-Hamed et al., 2011). So utilising for AD can be a better option for economic as well as environmental benefits however BSG is predominantly a ligno-cellulosic biomass which could potentially be a limiting factor for full utilisation of the biomass for AD and pre-treatment may be required to enhance the digestibility of the biomass. However, from an economical point of view, addition of a pre-treatment technology can only lead to an increase in the investments which can challenge the economic viability of the process.

5.2. Impact of market price on the economics of macroalgae biomass co-digestion

The prices adopted in this study were 0, 50, 250, and 1000 Euros/t as previously mentioned. For mono-digestion of macroalgae, the process was not found economically viable if the biomass itself is costed into the model due to negative return percentages and longer payback times. A positive return was observed when macroalgae biomass is free, however this is not currently achievable where macroalgae biomass is specifically cultivated for energy due to the high capital and operational cost of the cultivation/harvest techniques. Hence, in our study the most economically viable and realistic price range for the macroalgae biomass was found to be between 50 and 250 Euros for positive returns. Macroalgae biomass for high value products can achieve a market price of approximately 1000 Euros/t. This is the case for biomass which is utilised for human consumption or pharma/nutraceutical grade products. However, the literature (The Crown Estate Report) suggests that if macroalgae biomass is to be used for bioenergy generation the price of the biomass should be less than 250 Euros/t (Kelly and Dworjanyn, 2008). This is also in agreement with other studies conducted on brown algae biomass for species *Laminaria digitata* by Dave et al. (2013). Since *S. Latissima* is also a brown algae biomass, economic feasibility with positive return on investment using AD can be possible only if the price is below 250 Euros. Other techno economic feasibility studies on the biofuel production from macroalgae biomass has reported that adopting a biorefinery approach with understanding in the growth factors of the biomass and better management of aquaculture systems are essential for efficient biofuel production utilising the biomass (Roesijadi et al., 2008). Therefore by lowering production costs and increasing area under cultivation, biofuel production from macroalgae biomass can be made economically feasible (Soleymani and Rosentrater, 2017). The price of macroalgae biomass for bioenergy purposes can be reduced by having two harvests one in early spring for the biomass where high quality biomass can be sold for high value products manufacture and use the later summer harvests with epiphytic growth for bioenergy production (Spruijt et al., 2015). Utilising summer harvests can be very advantageous for AD due to the higher percentage of storage carbohydrates in the biomass which would result in higher methane production in AD (Manns et al., 2017). In addition, studies on *S. Latissima* have also shown that biomass which are fouled with epiphytes can still be used for methane production, therefore there may be an opportunity to capture this poorer quality/wasted biomass for AD. Even though properties of macroalgae biomass residues after transesterification were found to be a suitable material as fuel pellets, cost effective utilisation of these residues using AD are still needed and yet to be explored after other biofuel processes such as fermentation and extraction of chemicals from the biomass (Wei et al., 2013; Maceiras et al., 2011).

5.3. Gate fees for the organic waste feedstock and its impact on the process economics

A gate fees of 29 Euros was used for studying the effect of gate fees on the process economics. According to the literature, gate fees have decreased in the last few years from 40 Euros/t to 29 Euros/t (Dick et al., 2016). This techno-economic study only considered a fixed rate for gate fees of 29 Euros and the variation of gate fees was not studied. This was because in the current political scenario with most of the subsidies being reduced for AD, it was subject to change in near future where majority of the farms will be forced to be even charging less or nothing as gate fees. However, having gate fees at an AD facility was found to be the best feasible scenario for co-digestion with *S. Latissima* in our study. The sensitivity analyses showed that co-digestion was highly favourable with high rates of returns when the price of macroalgae biomass was 50 Euros/t. The most favourable combination for of co-digestion identified in this study was *S. Latissima* plus sugar beet-vegetable mix with a ROI of 105 % and a payback time of 0.7 years. The second most favourable combination was BSG with 83 % ROI and 0.8 years of payback time. The lowest ROI (11 %) and highest payback time (1.7 years) was observed for wheat residues. The results are promising, illustrating that given optimised gate fees (29Euros/t) a profitable scenario can be achieved for co-digestion of *S. Latissima* with sugar beet-vegetable mix (a traditional AD feedstock) as well as newly emerging biomass sources such as Brewery spent grain. In the UK, BSG has shown an availability of 250 million tonnes per year (Kerby and Vriesekoop, 2017; Thomas and Rahman, 2006) and already Sugar beet is used for AD as a whole crop or from residues after sugar processing. A total volume of 500,000 t are currently produced in the UK alone from the sugar processing waste (Suhartini et al., 2018). Sugar beet is a root crop very similar to parsnip and is grown widely in the temperate climates of Europe and North America (Sugar). This also suggests that seasonal feedstock such as macroalgae biomass if intended for bioenergy production can produce high rates of methane using the co-digestion mechanisms.

Even though a variety of techno-economic studies have focused on the co-digestion of traditional feedstock, fewer studies have focused on the techno-economics of co-digestion with newer feedstock such as macroalgae biomass. There are, therefore, limited studies to compare against the results obtained in this study.

5.4. Effect on stakeholder

Cost was a predominant factor for macroalgae biomass cultivators (e.g. Queen's University Belfast (QUB), Scottish Association for Marine Sciences (SAMS), and Dingle Bay farm) as it determined the route to market and overall economics generated from the biomass. According to the macroalgae biomass farmers, the biomass that is currently intended for human consumption or nutrition products provides a higher economic yield (Paul, 2018). However, if the biomass is intended for bioenergy generation, the stakeholders held the opinion that the market price would need to be lowered (to approximately less than 50 Euros/t) from currently around 100 Euros per kilo. At both QUB and SAMS, macroalgae biomass is grown only for research purposes, therefore commercial level information on the economics could not be retrieved for the purpose of this study. Vale green Energy supported the concept of co-digestion of macroalgae biomass with agricultural crop wastes as they currently practice co-digestion of various different crops and wastes generated from the farm. The energy generated on site is currently utilised for various purposes and the site operators were keen to test the probability of using a seasonal feedstock such as macroalgae biomass. However, large scale AD users such as Minworth were more cautious of the proposed approach to co-digestion predominantly because of the scale of its application. They recommended pilot scale adoptions of the technology prior to large scale AD. With regards to the digestate, vale green energy was supportive as they currently used AD digestate as fertiliser on their site. However, currently the price of digestate is considered low in the market therefore the stakeholders agreed that specific high value *N*, *P*, *K* (Nitrogen, Phosphorus and Potassium respectively) should be extracted from the digestate first to enhance the overall process economics. Macroalgae biomass cultivators also held the opinion that if macroalgae biomass waste was utilised as a fertiliser in IMTA (integrated multi trophic aquaculture) systems, it could generate more income for the macroalgae biomass cultivators and fish and oyster farmers equally. SAMS (2017) have previously published a number of studies for the ideal IMTA system with combined macroalgae biomass cultivation.

6. Conclusions

This study analysed the process economics of utilisation of macroalgae biomass, *Saccharina latissima* as a single and co-digestion feedstock for AD. Biochemical methane potential tests confirmed that AD of *S. Latissima* have comparable methane potentials to energy crops in this study and is also feasible as a co-digestion feedstock. However, even when macroalgae biomass was free, a lower ROI of only 2 % could be generated showing that AD of *S. Latissima* as a mono-digestion feedstock is economically not viable. As the price of macroalgae biomass increased, the ROI demonstrated increasingly negative values suggesting that the price of the biomass is a critical factor. The economics favoured co-digestion with *S. Latissima* suggesting a better way of utilising newer biomass if intended for bioenergy production.

Limitations to this study include that the study boundary did not consider transportation or cultivation costs into the system boundary. Therefore, for future environmental and economic assessment of bioenergy production from macroalgae biomass, it is recommended to adopt a biorefinery model considering factors such as the transportation, and other options from the biomass such as high value products to further develop the macroalgae industry in a sustainable fashion. Moreover, the techno-economic study in this paper only considered a fixed gate fee of 29 Euros and a variation of gate fees could be adopted in future studies. Although the economic benefits of an AD plant analysed here are based on the ROI and payback time, future research could look into the annual rate of growth that stakeholders might expect using internal rate of return (IRR).

CRediT authorship contribution statement

Roshni Paul: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Lynsey Melville:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Aminu Bature:** Writing – review & editing, Visualization, Validation, Software, Resources, Project administration, Methodology, Data curation. **Michael Sulu:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Formal analysis, Conceptualization. **Sri Suhartini:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization.

Declaration of competing interest

The authors have no relevant financial or non-financial interests to disclose. The authors declare no conflict of interest.

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Data availability

Data will be made available on request.

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