Techno-economic and environmental impact assessment of biogas production and fertiliser recovery from pelagic Sargassum

A biorefinery concept for Barbados

Thompson, Terrell M.; Ramin, Pedram; Udugama, Isuru; Young, Brent R.; Gernaey, Krist V.; Baroutian, Saeid

Published in:
Energy Conversion and Management

Link to article, DOI:
10.1016/j.enconman.2021.114605

Publication date:
2021

Document Version
Peer reviewed version

Citation (APA):
Thompson, T. M., Ramin, P., Udugama, I., Young, B. R., Gernaey, K. V., & Baroutian, S. (2021). Techno-economic and environmental impact assessment of biogas production and fertiliser recovery from pelagic *Sargassum*: A biorefinery concept for Barbados. *Energy Conversion and Management*, *245*, Article 114605. https://doi.org/10.1016/j.enconman.2021.114605

Techno-economic and environmental impact assessment of biogas production and fertiliser recovery from pelagic *Sargassum*: A biorefinery concept for Barbados

Terrell M. Thompson[a], Pedram Ramin[b], Isuru Udugama[b], Brent R. Young[a], Krist V. Gernaey[b], Saeid Baroutian[a,1]

[a] *Department of Chemical and Materials Engineering, The University of Auckland, Auckland, New Zealand*

[b] *Process and Systems Engineering Centre (PROSYS), Department of Chemical and Biochemical Engineering, Technical University of Denmark, Kgs, Lyngby, Denmark*

Abstract

Pelagic *Sargassum* inundation of coastlines across the North Atlantic is an ongoing challenge but presents new opportunities for value-added resource recovery. This study assessed the techno-economic feasibility and environmental impact of utilising these invasive brown seaweed, and food waste as feedstock for energy production and fertiliser recovery in Barbados. The biorefinery concept evaluated was designed with hydrothermal pretreatment (HTP) and anaerobic digestion (AD) technologies. Financial analyses of four varied feedstock and process scenarios (*S1*-*S4*) established a linear relationship between profitability and the sale of products (electricity and fertiliser). In all cases, simple sale of power generated to the national grid resulted in a negative cash flow and required the introduction of fertiliser sales to achieve positive cash flows. Moreover, the net loss in the electricity only scenarios exceeded that of the landfill disposal, the present operation employed on the island for *Sargassum* management. The addition of the solid digestate to the revenue stream increased the profit margin and financial attractiveness of the process. Maximum income generation could be attained through 100 % supply of the digestate to international markets. However, this approach provides zero support to local food security. The preferred option involves the 50/50 split utilisation of the solid digestate in local and international agricultural practice. While HTP is energy-intensive technology, the recirculation of waste heat generated by a combined heat and power unit for HTP reduced the input energy demand. It also lowered the potential environmental impact by more than 10-fold, relative to landfill disposal. Recycling of the liquid digestate also reduced the fresh water demand and its associated costs. Despite the promising results, process scale-up and commercialisation remain a main challenge, primarily due to the seasonality and variability of *Sargassum* seaweed for continuous bioprocessing.

Keywords: Anaerobic digestion; Environmental impact analysis; Food waste; Hydrothermal pretreatment; Pelagic *Sargassum*; Techno-economic assessment

---

[1] Corresponding author: Phone: +64 9 923 1424; E-mail: s.baroutian@auckland.ac.nz

1. Introduction

The recurring deluge of beaches in the North Atlantic Ocean with large, floating mats of *Sargassum* (90 % of *S. natans* and 10 % of *S. fluitans*) has reached crisis proportions, dating back to 2011 [1, 2]. These massive inundation events, also termed golden tides, are deemed “the single greatest threat” to the Caribbean [3] considering their adverse effect on the socio-economic and environmental stability of this fragile, tropical region [4, 5]. Tourism is the main sector in the Caribbean, generating over 80 % of the gross domestic product (GDP) [1]. In 2017, this industry amassed 57.1 billion U.S. dollar (USD) in onshore spending [6]. However, over the last decade, inundation events have led to reduced visitor arrivals caused by restricted ocean access for leisure activities, namely swimming, snorkeling and surfing. Beach-cast *Sargassum* is also an eyesore and has a very pungent odour [7-9]. The decay of these brown seaweeds produces hydrogen sulfide (H_2S), a corrosive and toxic gas with a rotten egg smell. Prolonged exposure to this pungent emission at low concentrations (< 20 ppm) can result in upper airways irritation, nausea, headaches and confusion in humans [7, 9, 10]. In extreme cases, hypoxic pulmonary, neurological, and cardiovascular disease have been reported [11]. Moreover, H_2S dissipates in the atmosphere to form sulfur dioxide and sulfuric acid, two precursors of acid rain [12]. Departments of Fisheries have been equally challenged by the influx of this biomass through extensive boat damage, net entanglements and mass fish and sea turtle kills [7-10].

Pelagic *Sargassum* originates in the Great Atlantic *Sargassum* Belt, a region of the tropical North Atlantic Ocean (8º-23º N and 89º-58 ºW) with aerial coverage of approximately 3,000 square kilometres (km) [13, 14]. At this growth location, the recent phenomena of mass *Sargassum* proliferation has been inextricably linked to global anthropogenic changes such as global warming, rising ocean temperatures, eutrophication from the Amazon, Orinoco and Congo rivers, and Sahara African dust emissions [15-17]. Annually, large quantities of pelagic *Sargassum* wash ashore in the Caribbean, Gulf of Mexico and West Africa. Peak deposition to the Caribbean of approximately 10,000 wet tonnes per day (t/d) was reported in 2015 [4, 18].

The clean-up of beach-cast *Sargassum* is necessary to restore the integrity of this invaluable ecosystem. In Mexico, Barbados and St. Lucia, *Sargassum* seaweeds have been repurposed as organic fertiliser in agricultural practice. More recently, scientists in Barbados began exploring bioactive compound extraction with a focus on application in cosmetic and skincare products [19]. However, it must be noted that these operations are small-scale, and thus exhibit negligible influence on annual inundation events. Overall, landfilling remains the primary approach to managing *Sargassum* seaweed influx across the Caribbean region. Nevertheless, this practice is expensive due to the large work-force demand for harvesting and high cost associated with the transportation of these wet seaweeds from beaches to the disposal site [1, 20]. In 2019, hoteliers in Cancún, Mexico, spent approximately USD 36.7 million to rid the beach of *Sargassum* seaweed, to accommodate tourists [21]. Similarly, the annual cost to rehabilitate beaches of Miami Dade County, USA was estimated at USD 35 million [22]. In the Caribbean alone, the cost of removing pelagic *Sargassum* from beaches is estimated at USD 120 million/year (a) [3]. Additionally, landfills are unsustainable and eco-unfriendly, posing a serious risk to human health through air, ground and water contamination [23, 24]. As a result, there is an urgent need to identify and implement alternative methods for the exploitation of these brown invasive seaweeds, preferably as feedstock for value-added resource recovery [1, 7, 9].

Anaerobic digestion (AD) is waste-to-energy technology which uses methanogenesis to convert organic matter in the absence of oxygen into biogas, a renewable fuel composed of methane (60-70 %) and carbon dioxide (CO_2) (30-40 %) [25, 26]. Biogas can be combusted for combined heat and power (CHP) generation, thus mitigating the demand for conventional fossil fuels in energy production [27]. The digestate recovered from biogas production is pathogen-free and nutrient-dense, revealing application in agricultural practice as an organic fertiliser or in soil amendment [28, 29]. Anaerobic digestion (AD) is mature and eco-friendly technology adopted worldwide for the treatment of biowaste streams such as municipal wastewater, food waste and sewage sludge [26, 30].

Brown seaweeds are promising feedstock for valorisation to biogas, given the rich polysaccharide content (40-60 % dry weight) and cell wall construction of negligible lignin and low cellulose [1, 5, 7, 25, 31]. However, in experimental study, the AD of mixed pelagic *Sargassum* mats yields biogas with negligible methane content. Thompson et al. [32] studied the AD of pelagic *Sargassum* from Barbados and achieved 29.29 % of the theoretical methane potential. Contrariwise, Milledge et al. [9] reported zero methanation from *Sargassum* seaweeds sampled from the Turks and Caicos Islands. The low biodegradation of this marine biomass was attributed to the high concentration of complex structural carbohydrates, salt, ammonia, sulphur, polyphenols and low carbon to nitrogen (C/N) ratio (< 20:1) [1, 7, 9, 25, 33].

Hydrothermal pretreatment (HTP) and co-digestion with various organic substrates may be used to combat several challenges of pelagic *Sargassum* single digestion. Hydrothermal pretreatment (HTP) is a green process that requires pressurised liquid hot water (120-200 ˚C) as the reaction medium. This technology accelerates biomass decomposition and the solubilisation of fermentable organic matter [31, 34, 35], thus enhancing methane production relative to the raw biomass [32, 36]. Additionally, HTP reduces the H_2S content of *Sargassum*-derived biogas from 3 % to 1 % [32]. This compositional change to the biogas product enhances its quality and marketability [32]. Alternatively, the anaerobic co-digestion of pelagic *Sargassum* with waste streams such as glycerol, frying oil and food waste can be utilised as a practical solution for achieving higher methane fermentation downstream [37, 38]. This approach improves digester performance by amending the C/N ratio to the suggested optimum range for AD (20-30:1), diluting salinity and increasing the tolerance to inhibitory compound accumulation [37, 39].

Despite the recent upsurge in the literature investigating the exploitation of pelagic *Sargassum* as feedstock for biogas production [1, 5, 7, 9, 31, 38, 40], no research has evaluated the full-scale design and optimisation of HTP and AD technologies for maximum conversion of this marine biomass to value-added products. The present study aims to fill that knowledge gap by assessing the economic feasibility and environmental impact of deploying, in Barbados, a *Sargassum*-based biogas plant, equipped with HTP for energy generation and fertiliser recovery. This study was sectionalised accordingly: (i) techno-economic analyses of four proposed scenarios, with various revenue streams; (ii) assessment of socio-technical readiness level to gauge societal project acceptance and technical feasibility; (iii) environmental sustainability analysis to determine potential environmental impacts (PEIs) for the proposed scenarios; and (iv) sensitivity (SA) and uncertainty analysis (UA) to identify the most influential factors and their impact on the cash flow. The novel integrated biorefinery concept evaluated in this work was proposed by Thompson et al. [7] as a practical Sargassum management strategy, mainly during inundation events.

2. Methodology

This study evaluated the material and energy requirements, capital expenditure (CAPEX) and annual operating cost (OPEX), in addition to potential environmental impacts and revenue generation from the commission of a *Sargassum*-based biorefinery in Barbados. The calculations were performed on spreadsheets (Microsoft Excel® software) and using the Waste Reduction

(WAR) Algorithm [41, 42]. The findings of experimentation by Thompson et al. [32, 37] provided the ultimate and proximate characterisations of the feedstock and inoculum inputs, process parameters, operation conditions and yields assumed in this study. The proposed biogas plant was assumed to operate for 330 d/a, over a lifespan of 10 years. Seaweed availability was assumed at 180 d/a. The system boundaries evaluated were set from raw material collection to final product (electricity and digestate).

2.1. Process description

This study evaluated four different feedstock scenarios for commercial biogas production and fertiliser recovery in Barbados. The first scenario, *S1*, examines the single digestion of raw pelagic *Sargassum,* while the second, *S2* explores the utilisation of hydrothermally pretreated *Sargassum* as the substrate for biogas production [32]. However, taking into account the seasonality and unpredictable availability of these brown invasive seaweeds for continuous energy production, scenario *S3* investigates the co-digestion of hydrothermally pretreated *Sargassum* and raw food waste at the weight ratio of 25:75. The final scenario studied, *S4*, examines a mixture of co-pretreated pelagic *Sargassum* and food waste (25:75 by mass) [37]. In both *S3* and *S4*, food waste is utilised as steady-state feedstock, and *Sargassum* added to the plant input depending upon availability [7]. In all scenarios, the total input of biomass slurry to the processing plant was 15,750 t/a, representing the mass of dried feedstock and fresh water utilised in HTP processing and AD. All equipment listed in the subsequent sections was chosen to achieve the desired plant processing capacity. Table 1 characterises the input materials and water ratios of the scenarios assessed [32, 37]. Fig. 1 presents process block diagrams to highlight the flow from feedstock to product.

The process block diagrams shown in Fig. 1 consist of five broad processing areas: feedstock harvesting and processing, HTP, AD, power and heat generation, and digestate separation and treatment. The solid lines in Fig. 1 indicate the flow from feedstock (*Sargassum*, food waste) to the products (electricity, heat, digestate). The dashed lines represent components recycled into the system i.e. heat and treated liquid effluent for HTP.

Table 1

Feedstock description.

Feedstock composition	Scenario				Unit
	S1	*S2*	*S3*	*S4*	
Wet *Sargassum**	9,000	9,000	1,800	1,800	t/a
Dried *Sargassum*	2,250	2,250	450	450	t/a
Food waste	0	0	4,200	4,200	t/a
Fresh water	13,500	13,500	11,100	11,100	t/a
Total plant input	15,750	15,750	15,750	15,750	t/a

*Mass harvested prior to processing

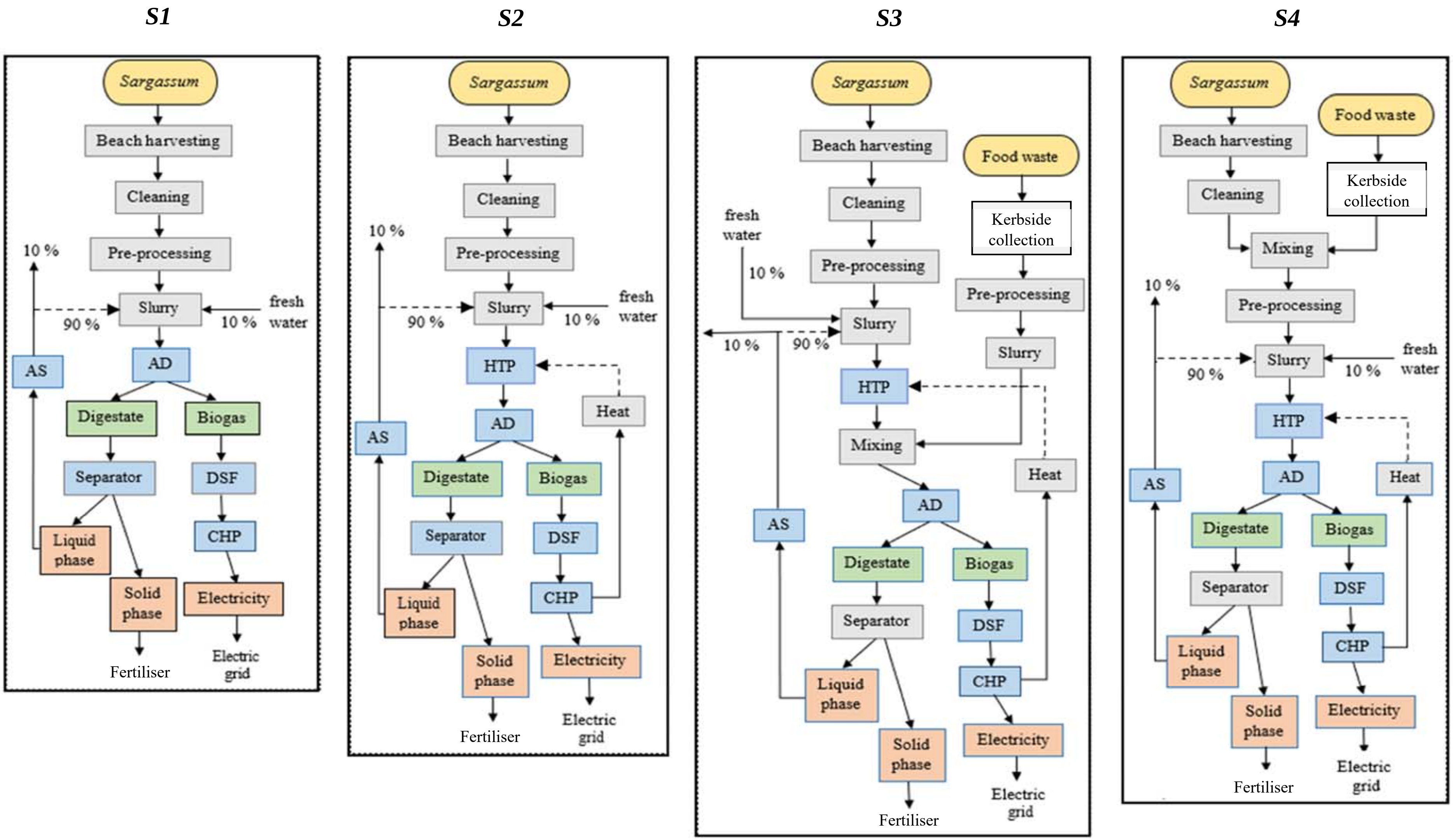

Fig. 1 - Process block diagrams of the four scenarios (*S1*-*S4*) evaluated and their defined system boundaries. (AD – anaerobic digestion; AS – ammonia stripping, DSF – desulfurisation; HTP – hydrothermal pretreatment; CHP – combined heat and power. Solid lines indicate flow from feedstock to product, while dashed lines represent recycled components).

2.1.1. Seaweed harvesting and preparation

In this study, *Sargassum* seaweed was collected from beaches (manually and mechanically via ocean harvester) and transported to the biorefinery for cleaning and pre-processing. A sifter of loading 25 t/h and power 6.5 kilowatts (kW) was used to remove sand and other undesirable particulates. The seaweeds were then sun-dried on locally designed seaweed racks for 7-14 d to 20 % moisture content [32]. *Sargassum* volume reduction through drying is assumed at 75 % (Table 1) [32, 37]. The dried seaweeds were conveyed to a shredder (loading 1 t/h; power 75 kW) for particle size reduction prior to hydrothermal processing, to increase the microbial bioconversion efficiency downstream. Thereafter, fresh water was mixed with the substrate to prepare a slurry. The biomass-to-water mass ratio varied with the feedstock (1:6 for *Sargassum* and 1:2 for food waste) to achieve a total solid content < 15 % for wet digestion. A fixed slurry throughput of 15,750 t/a. was assumed for HTP. Notably, in *S3* and *S4*, the ratio of *Sargassum* to food waste in the feedstock mixture was adjusted to maintain the input flow rate to AD. Hydrothermal pretreatment (HTP) was designed to operate in batch mode based on the work of Thompson et al. [32, 37]. Excess dried *Sargassum* was stored in a silo (capacity 1,500 t) until required for bioprocessing.

2.1.2. Hydrothermal pretreatment

To advance HTP from laboratory to commercial-scale, the four scenarios (Fig. 1) assumed the operational conditions and performances (temperature, pressure, retention time, product yield and composition) consistent with the literature values [32, 37]. Optimal process conditions were utilised to reduce the annual operating cost, while optimising system efficiency in full-scale applications. The proposed HTP reactor was a 1,000 litre (L) stirred batch pressure vessel, scaled-up from lab-level. Operating conditions were 140 ˚C temperature, 30 bar atmospheric pressure and 30 min reaction time [32, 37].

2.1.3. Anaerobic digestion

The digester considered was a batch stirred tank reactor (BSTR) of total volume 10,000 m^3 and 85 % working volume to facilitate expansion due to overhead pressure changes from biogas production. The digester volume was calculated based on feedstock and the annual number of batches (see below). The digester's design comprises a digester chamber, circulating pump, piping- and fittings. It was designed to operate in batch mode with an annual feed input of 15,750 t. Anaerobic digestion was conducted under mesophilic temperatures at approximately 35 ˚C. Barbados is a tropical island with an average ambient temperature of 28 °C, therefore the energy input required to achieve AD temperature was assumed to be negligible. The hydraulic retention time (HRT) of each batch was 21 d, and equipment cleaning and new batch preparation was assumed to be 9 d. Eleven (11) digestion cycles were anticipated annually, with the remaining 35 d allocated to equipment maintenance and plant downtime. The inoculum was sourced from the wastewater treatment plant and assumed to present no endogenous methane potential. In this study, biogas production from each scenario was deemed consistent with literature values at 147, 208, 371 and 421 millilitre per gram volatile solids (mL/g VS) for *S1*, *S2*, *S3* and *S4*, respectively, as reported by Thompson et al. [32, 37].

2.1.4. Biogas desulfurisation and co-generation

The biogas cleaning system consists of a desulfurisation (DSF) unit equipped with pumps, piping and a condenser. The DSF unit operates at 90 kW power and biogas flow rate of 4,500 L/h. The scrubbed biogas will be forwarded to a CHP system, comprising two engines with a cumulative power of 300 kW, for electricity and heat generation. The electricity is sold to the national energy grid, while the heat is recycled to the HTP process via a heat exchanger to increase the input feed temperature from 40 ˚C to 100 ˚C. The thermal and electric efficiencies of biogas conversion assumed for the CHP system are 60 % and 40 %, respectively. The calorific value of biogas was assumed at 6 kilowatt hours per normal cubic meter (kWh/Nm^3) and 4 kWh/Nm^3, for heat and electricity production, respectively [43].

2.1.5. Digestate treatment and utilisation

The solid-liquid digestate undergoes phase separation and dewatering in a screw press separator of loading 180 cubic metres per hour (m^3/h) and power 7.1 kW. Solid digestate (3,150 t/a) and liquid digestate (12,600 t/a) are produced by this process. The solid fraction is stored for direct utilisation as a fertiliser, soil conditioner and livestock beddings. Alternatively, the liquid fraction was treated with aerated bubble ammonia stripping technology at intial pH 12 for 24-h (loading 80 m^3/h; power 100 kW) to ensure: (i) the prevention of ammonia accumulation and subsequent AD inhibition when reintroduced into the process flow for HTP and AD; (ii) the safe environmental disposal of this liquid effluent through the sewer system [44]. Treated wastewater (90%) was recirculated to dilute the input feed to the desired total solids content, thereby reducing water costs. The remaining 10 % was transported to the wastewater treatment plant for release into the sewer system. An equal quantity of fresh water (10 %) was added to the slurry to replace the volume disposed of, thereby restoring the process mass and energy balance.

2.2. Technology readiness level

The technology readiness level (TRL) is a 9-point metric system designed by NASA to evaluate the maturity of a given technology based on research, state of development and industrial deployment. This TRL matrix is a good indicator of a given technology's compatibility and market viability when compared to other technologies. The lowest score, TRL 1, is assigned when the technology is in its infancy with the basic principle observed and reported. On the other hand, the highest score, TRL 9, corresponds to highly developed successfully implemented technology in full-scale operation [45, 46].

The present work employed the modified TRL assessment framework outlined by Li et al. [47] to assign a TRL score to the studied technologies based on the following factors: process awareness (detailed understanding of the process phenomena), technical “knowhow” (ability to design and implement) and the number of occurrences in literature.

2.3. Economic assessment

The input data used in the economic analysis is shown in Table 1. The values were obtained from literature, industry stakeholders and government officials in Barbados. In this study, the economic performance of each scenario was assessed, accounting for the cost of raw materials, utilities, CAPEX, OPEX, as well as product revenue streams [48, 49]. The costs of the raw materials included the cost of harvesting seaweed and its transportation from beaches to the biorefinery. Annual seaweed availability was assumed at 180 d. Manual harvesting of this biomass was priced at 40 USD/d/person, while mechanically harvesting via an ocean harvester was slightly higher at 50 USD/d/person. These salary rates are for an 8-h work day and are above the country’s minimum wage of 4.25 USD/h [50]. The distance from the collection site to the processing plant was an estimated 10 km at the unit transportation cost of 1.22 USD/L [51]. Fuel consumption per truck was approximated at 0.64 USD/km. Noteworthy, food waste was assumed to be available at no additional cost since the management of this waste stream is the primary responsibility of the Government of Barbados [52]. Vehicle insurance was not considered in the calculations. Utilities include the cost of fresh water for biomass pretreatment, biogas DSF and liquid digestate ammonia stripping, as well as the electricity required to raise and maintain the

HTP reactor temperature at 140 ˚C. Commercial water rates in Barbados vary, as outlined in Table 2 and incur a 50 % sewage tariff [53]. Electricity was priced at 19.50 cents/kWh [54].

Table 2

Assumptions for the techno-economic assessment.

Parameter	Property	Value	Unit	Ref.
General	Analysis year	2021	-	-
	Construction year	2021	-	-
	Project lifespan	10	A	-
	Plant design + construction	1	A	-
	Operating time	330	d/a	-
	Pricing	-	USD	-
	Corporation tax rate	5.5	%/a	[55]
	Inflation rate	1.9	%/a	[56]
	Discount rate	10	%/a	
	Depreciation (Straight-line method)	-	-	[57]
	Depreciation rate (machinery)	10	%/a	
	Depreciation rate (building)	4	%/a	
Raw materials	Seaweed availability	180	d/a	-
	Seaweed harvesting (manual)	40	USD/d/person	-
	Seaweed harvesting (mechanical)	50	USD/d/person	-
Utilities	Commercial water rates	2.33 + sewage tariff	USD/m^3 (first 40 m^3)	[53]
		3.89 + sewage tariff	USD/m^3 (40-12000 m^3)	
		2.33 + sewage tariff	USD/m^3 (over 12000 m^3)	
	Sewage tariff	50	%	
	Electricity (input)	19.50	cents/kWh	[54]
	Fuel (diesel)	1.22	USD/L	[51]
CAPEX	Equipment*	-	-	-
OPEX	Manufacturing + labour	90,882	USD/a	[58]
	Administration + management	73,392	USD/a	
	Plant maintenance	3	% of CAPEX/a	-
Revenue	Electricity (sales)	22.125	cents/kWh	[59]
	Solid fertiliser (international)	581.40	USD/t	[60]
	Solid fertiliser (Barbados)	200.00	USD/t	-
	Liquid fertiliser*	2.30	USD/L	-
	Value-added tax (VAT) - Barbados	17.50	%	[61]
Waste disposal	Landfilling (tipping fee)	27.50	USD/t	[59]

*Average price based on quotations from international suppliers.

The CAPEX included plant construction, equipment purchase and installation (calculated for individual scenarios), whereas OPEX was sub-divided into labour, manufacturing, administration, management and maintenance costs. Total estimated revenue was calculated from the sale of electricity and distribution of the digestate locally and internationally. The assumption was that the electricity generated would be sold to the national energy grid at a cost of 22.125 cents/kWh through the feed-in-tariff (FIT) programme [59, 62]. In Barbados, the credits of electricity derived from biogas systems are regulated by the Barbados Fair Trading Commission and carries a higher rate than that supplied by the local power company, The Barbados Light & Power Company Limited. This incentivised FIT scheme was established to promote more decentralised forms of energy, thereby supporting the island's transition to 100 % renewable energy generation by 2030 as outlined in the Barbados National Energy Policy (BNEP) [63]. Alternatively, the heat generated from the CHP system would be recycled for the HTP process, thus mitigating the energy demand of this pretreatment technology. The solid fraction of the digestate was assumed to be potassium-rich [32, 37] and thus, generate international credits of 581.40 USD/t [60]. However, to encourage the consumption of this product as an organic fertiliser in local farming practice, the suggested sales price was reduced by approximately one-third to 200 USD/t. The scenarios presented in Fig. 1 assume that after ammonia stripping, the liquid effluent (10 %) was disposed of via the wastewater treatment plant. However, consideration was given to the redirection of this waste stream from disposal to utilisation as liquid fertiliser for an additional income of 2.30 USD/L. All revenue generated from the sale of electricity and fertiliser in Barbados is subjected to a value-added tax of 17.5 %, payable to the Government of Barbados [61]. Finally, comparison of the cumulative cash flow of each scenario was made against the current operation employed on island of seaweed landfill disposal to justify process feasibility.

2.4. Financial indexes calculation

The input values reported in Table 1 were used to determine the viability of each process scenario based on the following financial feasibility indicators: operating profit margin (OPM), net present value (NPV), internal rate of return (IRR), payback period (PBP) and return of investment (ROI) [64, 65]. These performance measures were calculated for the proposed 10 years lifespan of the biogas plant, which accounts for the macro-economic influences such as corporation tax, inflation, depreciation and the discount rates defined in Table 1. The financial indicators were calculated using the formula presented in the supplementary materials.

The cost of equipment was obtained from a conceptual equipment cost database [66] and adjusted to the plant construction year (2021). The size of the equipment was scaled up to meet the 15,750 m^3/a specification using Eq. 1 and 2, respectively.

$$\text{Cost in 2021} = \text{Base Cost}\left(\frac{\text{CEPCI}_{2021}}{\text{CEPCI}_{\text{Base}}}\right) \tag{1}$$

$$\text{Scaled up cost} = \text{Original cost}\left(\frac{\text{Scaled capacity}}{\text{Original capacity}}\right)^{\text{n}} \tag{2}$$

where, *n* is the scaling factor (0.6), and *CEPCI* is the chemical engineering plant cost index [67].

2.5. Sensitivity analysis

Sensitivity analysis (SA) is a quantitative method of ascertaining the association between every input variable and the robustness of process outcomes in mathematical financial models. This tool explores the sensitivity of system behaviour, efficiency, sustainability and output to changes in a single parameter within the specified process boundaries. Therefore, SA can be useful to improve model predictions and identify the variables with the most significant impact on the NPV. In this study, a SA was necessary to examine the effect of bioprocessing parameters, including the plant investment, feedstock supply and HTP energy costs.

The standardised regression coefficients (SRC) method was used for a global sensitivity analysis (SA) [68]. This method is based on Monte Carlo simulation, where a simple linear model is built from the original data. The model has the form:

$$sy_{ik} = b_{0k} + \sum_{j=1}^{M} b_{jk}\theta_{ij} + \varepsilon_k \tag{3}$$

Where sy_{ik} is single value of the output y for the i^{th} Monte Carlo simulation, b_{jk} is the linear regression coefficient for the parameter j and model output k, θ_{ij} is the input parameter, and ε_k is the error of the regression model. By transforming this equation to its standardised form, the following equation can be obtained:

$$\frac{sy_{ik} - \mu_{sy_k}}{\sigma_{sy_k}} = \sum_{j=1}^{M} \beta_{jk} \frac{\theta_{ij} - \mu_{\theta j}}{\sigma_{\theta j}} + \varepsilon_{ik} \tag{4}$$

Where μ is the mean and σ is the standard deviation, β_{jk} is the SRC of parameter j on output k. A parameter with a higher β value means that the parameter has a relatively higher contribution to altering the output. Positive and negative values of β indicate positive and negative correlations, respectively.

In this study, the SRC was calculated for the NPV, including CAPEX for each scenario. Parameters and their ranges considered for the SA are reported in Table 3.

Table 3

Parameters considered for sensitivity and uncertainty analysis with default values and the ranges for the analysis. The min/max values were chosen to determine how varying input variables would change the process outcomes.

No.	Parameter	Unit	Default	Min	Max
1	Seaweed availability	d	180	-20%	+20%
2	Biogas to power	kWh/Nm^3	4	-20%	+20%
3	Recycling liquid digestate	%	90	50	100
4	Temperature output	°C	100	-20%	+20%
5	Chemical fertiliser K (export)	USD/t	581.4	-20%	+20%
6	Chemical fertiliser (domestic)	USD/t	200	-20%	+20%
7	CAPEX	%	100	-50%	+100%

2.6. Uncertainty analysis

Uncertainty analysis (UA) was performed to assess the accuracy of the process model calculations. The UA considers a range of possible outputs depending on variations in the inputs for management purposes. In this work, the Monte Carlo method was applied. This methodology relies on computation to estimate uncertainty in a calculation and provides greater accuracy than first-order analysis of budgets. The parameters and ranges considered for the UA are shown in Table 3.

2.7. Environmental impact assessment

The potential environmental impacts (PEI) of producing biogas and fertiliser from pelagic *Sargassum* via HTP and AD were analysed and compared by the WAR Algorithm [41, 42]. This algorithm is a tool designed by the United States Environmental Protection Agency (USEPA) for the calculation of possible threats posed by a chemical process to the environment, utilising the mass and energy balances derived in Section 2.1. The WAR algorithm evaluates the four local toxicological impacts: human toxicity potential by ingestion (HTPI), human toxicity potential by exposure (HTPE), aquatic toxicity potential (ATP), terrestrial toxicity potential (TTP), and four global atmospheric impacts: global warming potential (GWP), ozone depletion potential (ODP), photochemical oxidation potential (PCOP), and acidification potential (AP). The eight PEI categories listed above were summed into a single PEI index expressed per hour (PEI/h) [41, 69]. Processes designed with low PEI index values are considered environmentally desirable. In this study, natural gas was assumed to be the energy source for HTP, while fresh water was chosen for the pretreatment process. The greenhouse gas (GHG) emissions were calculated using the default CO_2 emissions conversion factor of 56,100 kg CO_2 equivalent per terajoule ($CO_{2\ eq.}$/TJ) for natural gas combustion, in accordance with the 2006 Intergovernmental Panel on Climate Change (IPCC) guidelines for National GHG inventories [70].

3. Results and discussion

3.1. Process economic comparisons

Fig. 2 compares the four studied scenarios based on the following parameters: (a) estimated CAPEX and OPEX; (b) CHP product yield. Fig. 2a highlights a marginal differential of approximately USD 25,000 between the scenario CAPEX values, due solely to the incorporation of biomass pretreatment into the process design. On the contrary, the OPEX exhibited greater fluctuation resulting from the costly *Sargassum* harvesting and substrate pretreatment. In both *S1* and *S2*, the removal of 9,000 tonnes of wet *Sargassum* for bioprocessing was priced at USD 317,730/a. This valuation represents 55 % and 42 % of the annual total operating costs of the respective scenarios. Reducing the volume of wet *Sargassum* gathered from 9,000 to 1,080 t/a. and adding food waste to the input feed as proposed in *S3* and *S4*, resulting in savings of 244,579

USD/a (Fig. 2) since the Government of Barbados holds the portfolio for food waste collection [52]. One other consideration of interest is the utilisation of HTP for biomass pretreatment. This technology is energy-intensive and requires considerable water input for feedstock dilution prior to operation, primarily due to the physicochemical properties of pelagic *Sargassum* [32, 37]. In this study, the incorporation of HTP in the process design (Fig. 1) increased the annual operating costs of the plant by USD 30,292 - 144,461 (Fig. 2) in direct proportion to the volume of substrate pretreated. *S2* which involved the harvesting of 9000 tonnes of wet pelagic *Sargassum* and included HTP and AD technologies in the process, presented the highest OPEX of USD 753,039/a.

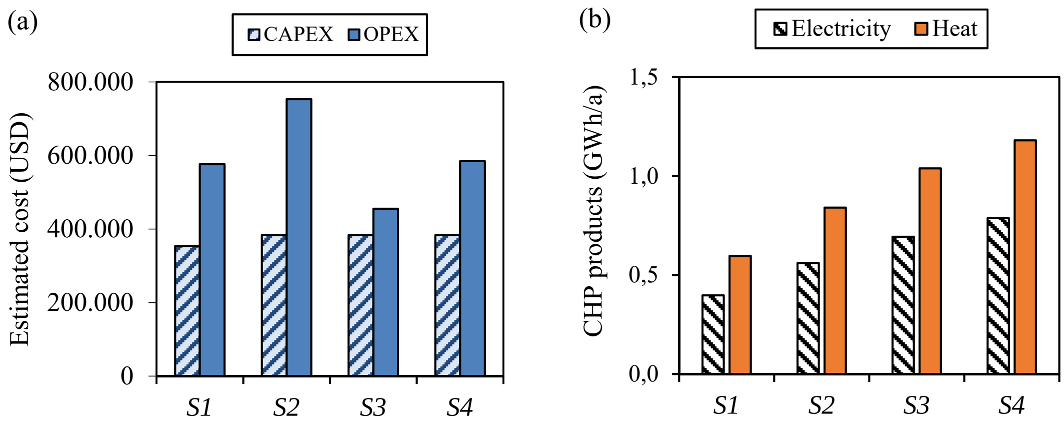

Fig. 2. Scenario comparison (*S1*-*S4*) of the (a) CAPEX and OPEX; (b) CHP products (electricity and heat).

Fig. 2b shows the annual production rate of up-scaled AD products, from lab to industry-scale, according to literature data. Based on the proposed plant design (Table 1), electricity generation increased linearly from 0.39 gigawatt hours per year (GWh/a) in *S1* to 0.79 GWh/a in *S4*. Similarly, heat production doubled from 0.60 GWh/a in *S1* to 1.18 GWh/a in *S4*. Enhancement of power generation was attributed to the high efficiency of HTP at accelerating *Sargassum* solubilisation for microbial bioconversion downstream [32]. Additionally, food waste supplied the seaweed feed with a rich source of organic matter which improved biogas productivity [37]. In all the scenarios evaluated, digestate recovery was assumed to be constant at 15,750 t/a, with a solid-to-liquid ratio of 20:80.

3.2. Profitability assessment

Total income generation from the AD plant is given in Fig. 3, assuming different product sale streams. In all the scenarios evaluated, the revenue derived from the sale of electricity was insufficient to cover the breakeven costs of the processes. Interestingly, these negative cash flows exceed current Government expenditure to landfill dispose of beach-cast *Sargassum* seaweeds (9000 wet tonnes). Therefore, the operation of the AD plant for the sole purpose of electricity production would not be an economically viable approach.

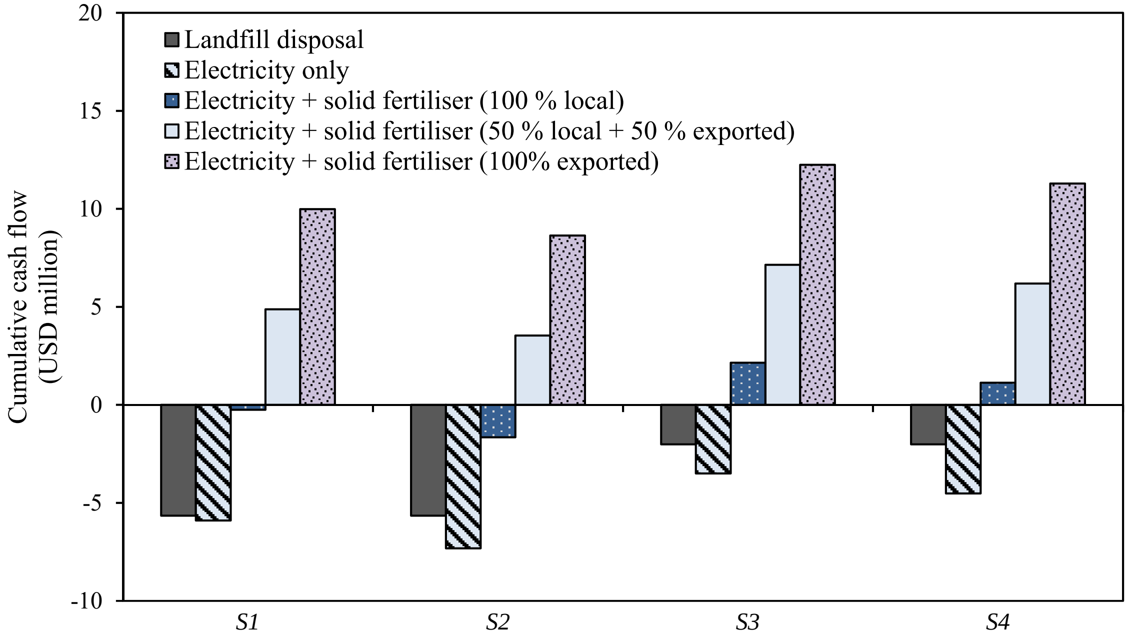

Fig. 3. Income accumulated over the lifespan (10 a) of the AD plant from different revenue streams. NB. The cash flow includes corporation tax, inflation, depreciation and discount rates.

The sale of the solid digestate as a potassium-rich biofertiliser can improve the economic feasibility of the process (Fig. 3). Annual financial profit of approximately USD 1.83 million can be achieved through 100 % export to foreign markets, based on high pricing of the organic fertiliser products on the international market (Table 1). However, this practice would be ill-advised for Barbados as it offers no support to the sustainability of the local agricultural sector. From the economic assessment conducted (Fig. 3), the preferred option would involve the split (50/50) utilisation of the solid fertiliser domestically (Barbados) and internationally. While this process design would reduce financial earnings by approximately USD 590,705/a, it would prove beneficial for crop improvement, thereby contributing to the enhancement of food security in the country. Repurposing the treated liquid effluent (10 %) from disposal to utilisation as a liquid fertiliser could create equal opportunity and an estimated USD 2.90 million/a additional income.

Recirculation of heat produced by the CHP unit to hydrothermal processing via a heat exchanger proved advantageous at reducing the overall process energy demand and operation costs. In Barbados, the average ambient temperature is 28 °C. Based on our calculations, the heat derived from CHP would sufficiently raise the temperature of the input slurry from 28 °C to 100 °C, resulting in reduced expenditure cost on electricity required to achieve the desired HTP temperature of 140 °C.

Table 4 summarises the profitability ratios of the project proposals achieved over the plant 10 year lifespan. In all scenarios assessed, the OPM increased linearly with revenue generation, primarily due to the sale of the solid digestate on the global market. The NPV calculations indicate that investors can only achieve net positive value and gain surplus on their investment through diversification of the revenue stream. Notably, the highest NPV was obtained at total supply (100 %) of solid digestate on the international market. The trend of the NPV is comparable to that observed for the IRR. Overall, projects with net positive NPV and high IRR values (20 %) can be undertaken. The maximum PBP for projects with a positive cash flow was estimated to be 2.03 years. The ROI is a key performance indicator for investors as projects with ROI values greater than 15 % show financial benefit and are deemed acceptable for implementation. From Table 4, it should be noted that all scenarios exhibited ROI > 15 % and are significantly profitable when at least 50% of the fertiliser produced is exported. Even with a 100% local sale approach, *S3* and *S4* show a positive operating income. Nevertheless, it must be stressed that the ROI takes an investment view of the expected cash flow stream but does not measure uncertainty or risk.

Table 4

Profitability indicators of the process proposals for the 10 year lifespan of the biogas plant.

Scenario		Financial indicator				
		OPM (%)	NPV (USD million)	IRR (%)	PBP (a)	ROI (%)
S1						
A	Electricity only	- 703.33	- 3.37	N/A	N/A	- 1,671.72
B	Electricity + solid fertiliser (100 % local)	1.63	- 0.29	N/A	N/A	- 70.29
C	Electricity + solid fertiliser (50 % local + 50 % exported)	46.44	2.98	144.58	0.70	1,456.67
D	Electricity + solid fertiliser (100 % exported)	63.20	6.25	284.81	0.35	2,983.64
S2						
A	Electricity only	- 623.29	- 4.21	N/A	N/A	- 1,914.57
B	Electricity + solid fertiliser (100 % local)	- 19.01	- 0.78	N/A	N/A	- 436.41
C	Electricity + solid fertiliser (50 % local + 50 % exported)	33.76	2.49	99.76	1.02	973.02
D	Electricity + solid fertiliser (100% exported)	54.11	5.76	229.65	0.44	2,382.45
S3						
A	Electricity only	- 227.17	- 1.90	N/A	N/A	- 7.38
B	Electricity + solid fertiliser (100 % local)	35.95	1.53	60.01	1.65	560.79
C	Electricity + solid fertiliser (50 % local + 50 % exported)	63.75	4.80	191.80	0.53	1,970.22
D	Electricity + solid fertiliser (100% exported)	74.72	8.08	321.14	0.31	3,379.65
S4						
A	Electricity only	- 264.97	- 2.51	N/A	N/A	-1,182.81
B	Electricity + solid fertiliser (100 % local)	20.95	0.92	36.18	2.72	295.36
C	Electricity + solid fertiliser (50 % local + 50 % exported)	54.75	4.19	167.41	0.6	1,704.79
D	Electricity + solid fertiliser (100% exported)	68.31	7.5	296.79	0.34	3,114.22

N/A – not applicable

Overall, *S3* reveals the best performance and profitability across all financial conditions (Table 4) and is therefore the favoured option for implementation.

3.3. Technology readiness level

The combination of hydrothermal processing and anaerobic digestion for the purpose of manufacturing biogas and fertiliser from *Sargassum*/food-based feedstock introduces a novel process. However, when analysing the key components that make up the overall production process, the following observations can be made:

1. Hydrothermal processes (HTP) are currently implemented at a commercial scale for treatment of similar types of organic waste, mainly, wastewater treatment sludge.
2. Anaerobic digestion (AD) units are commercially utilised in wastewater treatment plants for waste that is similar in characterisation to *Sargassum* and food waste.
3. For *Sargassum*, laboratory-scale experiments have been performed at simulated *Sargassum*-based waste conditions where the proposed combined HTP and AD process has successfully yielded both biogas and fertiliser products.

Taking these outcomes into consideration, it can be concluded that the TRL of the proposed production process ranges from 7-9. Therefore, an initial commercial-scale production process can be introduced to further fine-tune the processes. The knowledge gained during this process will guide technology maturity to a TRL of 9.

3.4. Environmental analysis

The annual landfill disposal of *Sargassum* (9,000 wet tonnes) has the potential to generate 0.33 kg $CO_{2\ eq.}$/kg *Sargassum* [71]. This is due to high atmospheric GHG emissions, which negatively influence environmental stability by increasing the GWP. Waste degradation in landfills also produces leachate, which poses a potential risk to public health [72]. By comparison to landfilling, the carbon footprint of the proposed projects was significantly lower at 0.005, 0.023, 0.022 and 0.042 kg $CO_{2\ eq.}$/kg *Sargassum*/food waste for *S1*, *S2*, *S3* and *S4*, respectively.

The WAR algorithm was applied to the project proposals to evaluate their environmental impact (Fig.4). Across all cases, the PEI of feedstock harvesting was assumed to be constant, and hence, the system boundaries were redefined for stand-alone technology comparison. For HTP, the use of water as a solvent had zero effect on the PEI. Similarly, AD exhibited negligible influence on the process PEI as: (i) the biogas produced is directly utilised for CHP generation; (ii) zero energy input is required to achieve the desired AD mesophilic condition given the tropical climate of Barbados. In turn, these variables reduce individual impacts by HTPE, ODP and PCOP. The main environmental effect came from extensive power usage for machinery operation as fossil fuel combustion increases the AP through production of acid rain precursory compounds [73]. In this study, *S1* had the lowest PEI of 905 PEI/h (Fig. 4) due to the absence of hydrothermal processing in the process design. In scenarios employing HTP, PEI reductions were achieved through heat recovery from CHP and its recirculation to hydrothermal processing. Nevertheless, future consideration may be given to the installation of solar panels to satisfy the project's energy needs and surplus injected into the national energy grid for added income. Wastewater from the wastewater treatment facility may also be redirected from ocean disposal to the biorefinery for seaweed cleaning and HTP, thereby reducing seaweed corrosion of equipment and compounding savings on fresh water utilisation.

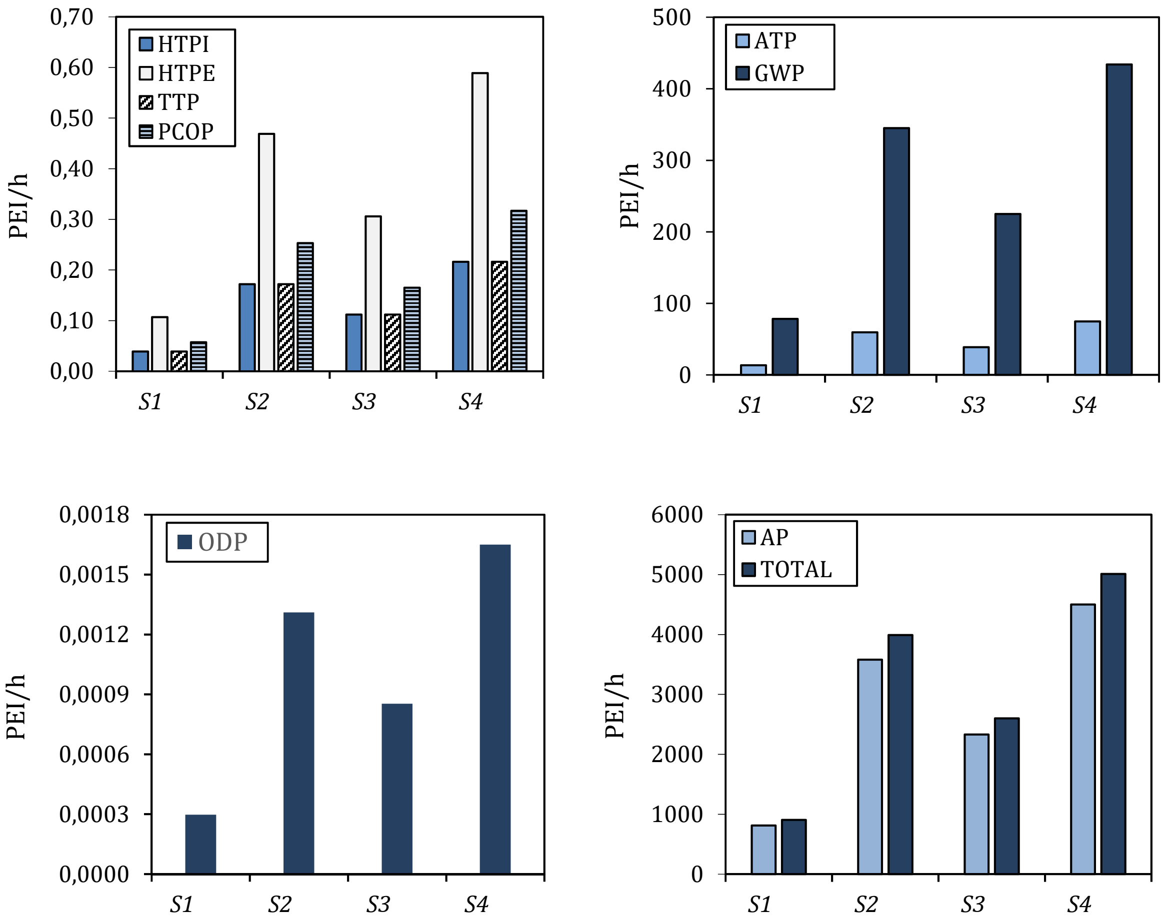

Fig. 4. The potential environmental impacts (PEIs) in the biogas plant (technology comparison only).

3.5. Sensitivity analysis

Following 10,000 Monte Carlos simulations with Latin Hypercube Sampling (LHS), a linearised model could be achieved for each scenario ($R^2 > 0.98$), as shown in Fig. 5. From the parameter settings (Table 3), the sale price of the solid chemical fertiliser (USD/t) (parameter 5 for export and parameter 6 for domestic fertiliser sale) and seaweed availability (d) (parameter 1) are ranked as the most sensitive parameters in all scenarios. Other parameters showed lower sensitivities. Moreover, most parameters showed a positive correlation with the NPV.

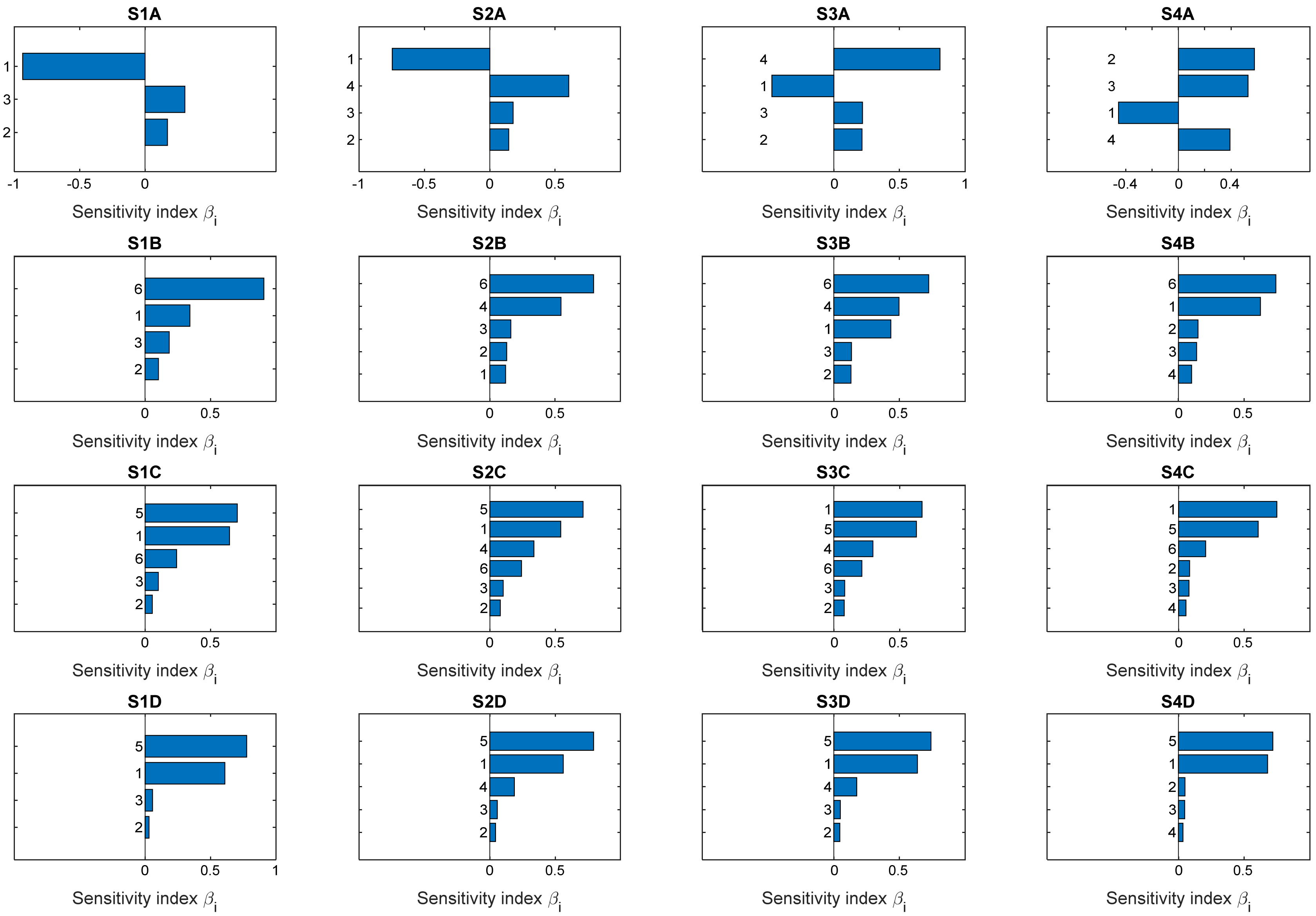

Fig. 5. Parameter importance ranking based on the sensitivity indices for predicting NPV for each scenario. The numbers on the y axis indicate the parameter number defined in Table 3.

3.6. Uncertainty analysis

Monte Carlo simulation (10,000) with LHS sampling was used to calculate the values of NPV, including CAPEX for each scenario. The distribution (histogram) of these NPV values for each scenario with different revenue streams (Table 4) is shown in Fig. 6. The wider distribution, the higher is the uncertainty. Moreover, the skewing/shifting of the distribution to the right is an indication of higher viability. Higher viability and higher uncertainty are apparent for the situation where the revenue is generated by selling electricity and 100% export of the solid fertiliser.

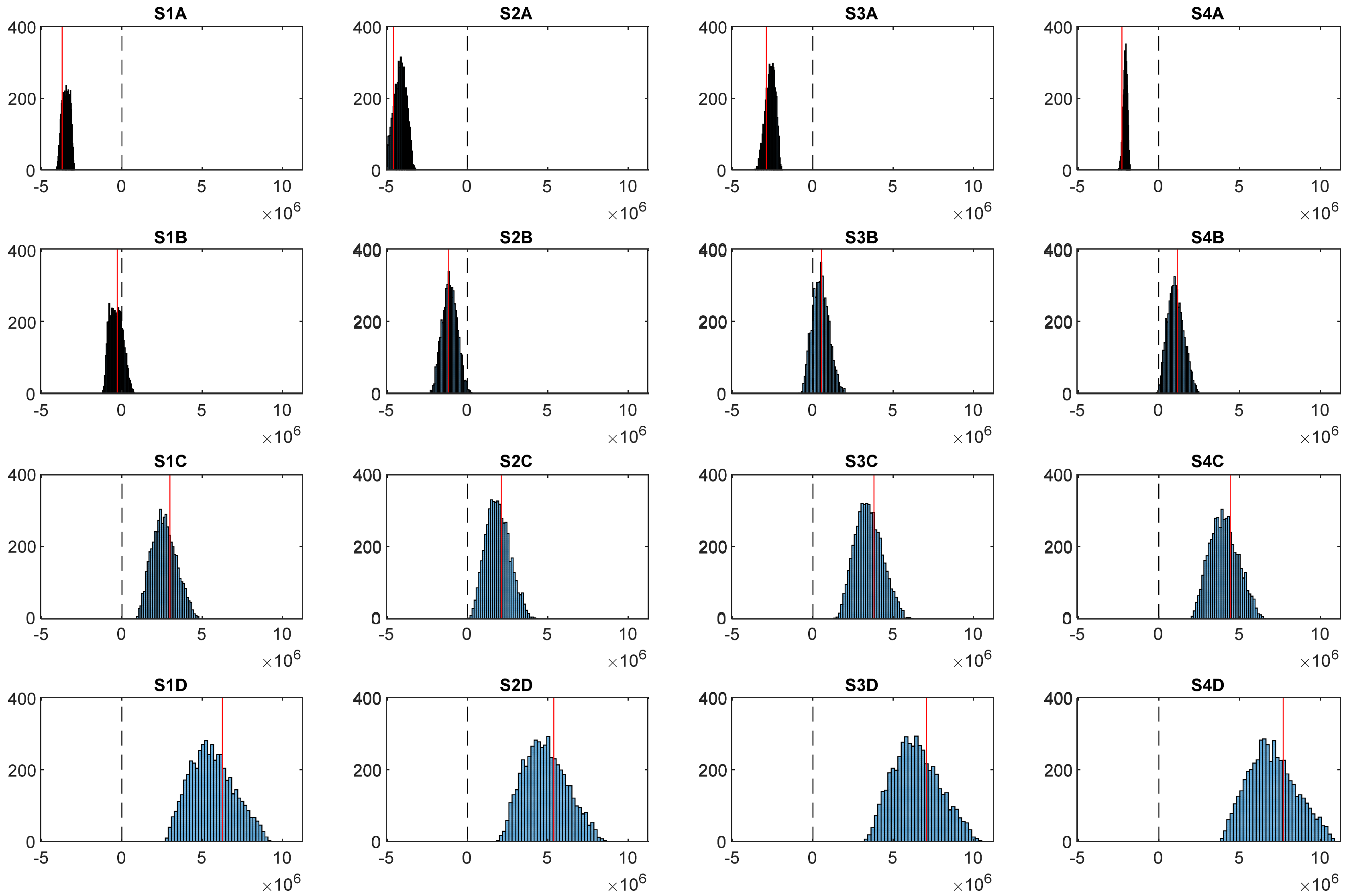

Fig. 6. Distribution of NPV for different scenarios following uncertainty analysis. Red vertical lines indicate average values as reported in Table 4.

3.7. Societal readiness level

3.7.1. Sargassum removal

Tourism is a key contributor to the overall GDP in Barbados, with 88.7% coming from the supply of goods and services [1, 74]. Beach-cast *Sargassum* directly impacts this industry, particularly considering its natural bio-degradation process that makes inundated beaches unpleasant. The fisheries sector also suffers during inundation events from increased fish kills and equipment failure [7, 23]. As such, if the proposed project takes *Sargassum* from beaches and uses it as a raw material for resource recovery, there are definite positive societal benefits to all of Barbados, such as: (i) restoration of the natural coastal aesthetics of beaches; (ii) industry and infrastructural development; (iii) job creation; (iv) waste management; (v) economic growth; (vi) sustainability of the tourism and fisheries sectors. Importantly, food waste utilisation in the input feed mitigates sole dependence on this seasonal marine biomass for continuous energy generation and supports process viability.

3.7.2. Energy and fertiliser independence

Currently, Barbados is heavily reliant on imports for both its fertiliser and power generation needs [63]. In all scenarios listed, the implementation of such a project will allow Barbados to reduce its energy related imports and become either self-sufficient or a net exporter in terms of fertiliser production [7]. Collectively, the aforementioned would contribute to the development of a sustainable green economy as detailed in the BNEP [63] and promote food security through increased crop production in agriculture [7].

3.7.3. Environmental sustainability

Fossil fuel combustion for electricity generation is an environmentally harmful practice emitting vast quantities of GHGs into the atmosphere. Redirection of *Sargassum* from landfill disposal to feedstock in bioprocessing would reduce GHG emissions and the island’s carbon footprint [75], thus reaffirming its pledge to fight climate change through ratification of the Paris Agreement [76].

3.7.4. Economic diversification and upskilling

Presently, less than 10% of the Barbados economy is driven by industry [74]. While the proposed project will not significantly impact these statistics at a regional level, many other islands in the Caribbean face similar *Sargassum* and energy issues [7]. Consequently, the engineering knowhow and operational experience gathered from this project can be leveraged to develop hydrothermal and biological processing technical services in Barbados.

4. Conclusions

The introduction of a *Sargassum*-based biorefinery equipped with hydrothermal pretreatment (HTP) and anaerobic digestion (AD) technologies would offer many socio-economic and environmental advantages to Barbados. Presently, the Government of Barbados spends an estimated USD 62.80/t *Sargassum* for landfill disposal. This practice is also eco-unfriendly, given its high potential environmental impact (PEI) of 0.33 kg $CO_{2\ eq.}$/kg *Sargassum.* Redirection of these invasive seaweeds from landfill disposal to feedstock in a biogas plant would support diversification of the national energy matrix and positively contribute to local food security through the production of a potassium-rich organic fertiliser.

Annually, the feed input of 15,750 t of hydrothermally pretreated *Sargassum*/raw food waste (mass ratio of 25:75) can yield 0.69 GWh of electricity, 1.04 GWh of heat and 15,750 t solid-liquid digestate. Maximum potential income of USD 12.76 million can be amassed through the supply of electricity to the national energy grid and 100 % exportation of the biofertiliser to foreign markets. However, this option offers zero support to sustainability of the local agricultural sector. Preference should be given to the 50/50 split utilisation of the solid digestate in local and international farming practices (*S3*C). While this scenario reduces revenue generation by approximately 40 %, environmental sustainability stands to benefit through a lower PEI of 0.022 kg $CO_{2\ eq.}$/kg *Sargassum* and greenhouse gas emissions. The NPV, OPM and ROI of project proposal *S3*C are USD 4.80 million, 63.75%, 1970.22 %, respectively, further indicating the operation's financial health and long-term viability. The system breakeven period is 0.53 years. Addition of the liquid fraction of the digestate to the product revenue stream would increase the gross profit margin and shorten the project PBP.

Overall, the findings of this study suggest potential economic benefit to countries negatively impacted by the annual influx of pelagic *Sargassum*. There is also great opportunity for process scale-up given the maturity and wide-spread commercialisation of HTP and AD technologies globally for various organic substrates. Notwithstanding this, the primary bottleneck to full-scale application of the above-mentioned technologies for pelagic Sargassum bioprocessing remains the seasonal availability of this feedstock. Future work should therefore focus on *Sargassum* storage techniques and the development of regulatory policies and frameworks for pilot-scale studies.

Acknowledgements

The authors acknowledge Ministry of Foreign Affairs and Trade (MFAT) for providing the New Zealand Development Scholarship Programme.

References

[1] Milledge JJ, Harvey PJ. Golden tides: Problem or golden opportunity? The valorisation of Sargassum from beach inundations. J Mar Sci Eng 2016;4:60. https://doi.org/10.3390/jmse4030060.

[2] Ryther JH. The Sargasso Sea. Sci Am 1956;194:98-108.

https://doi:10.1038/scientificamerican0156-98.

[3] MercoPress. Sargassum seaweed, 'greatest single threat to the Caribbean tourism industry', http://en.mercopress.com/2015/08/19/sargassum-seaweed-greatest-single-threat-to-the-caribbean-tourism-industry; 2015 [accessed 16 May 2018].

[4] Smetacek V, Zingone A. Green and golden seaweed tides on the rise. Nature 2013;504:84-8. https://doi.org/10.1038/nature12860.

[5] CPI. Anaerobic Digestion Economic Feasibility Study: Generating energy from waste, sewage and sargassum seaweed in the OECS, https://www.uk-cpi.com/reports/anaerobic-digestion-economic-feasibility-study-generating-energy-waste-sewage-sargassum-seaweed-oecs; 2017 [accessed 14 July 2018].

[6] WTTC. Travel & Tourism Economic Impact 2017 Caribbean, https://www.wttc.org/-/media/files/reports/economic-impact-research/regions-2017/caribbean2017.pdf; 2017 [accessed 4 June 2018].

[7] Thompson TM, Young BR, Baroutian S. Pelagic Sargassum for energy and fertiliser production in the Caribbean: A case study on Barbados. Renew Sust Energ Rev 2020;118:109564. https://doi.org/10.1016/j.rser.2019.109564.

[8] Rodríguez-Martínez RE, Roy PD, Torrescano-Valle N, Cabanillas-Terán N, Carrillo-Domínguez S, Collado-Vides L, et al. Element concentrations in pelagic Sargassum along the Mexican Caribbean coast in 2018-2019. PeerJ 2020;8:e8667. https://doi.org/10.7717/peerj.8667.

[9] Milledge JJ, Maneein S, Lopez EA, Bartlett D. Sargassum inundations in Turks and Caicos: Methane potential and proximate, ultimate, lipid, amino acid, metal and metalloid analyses. Energies 2020;13:1523. https://doi:10.3390/en13061523.

[10] van Tussenbroek BI, Arana HAH, Rodríguez-Martínez RE, Espinoza-Avalos J, Cizales-Floresa HM, González-Godoy CE, et al. Severe impacts of brown tides caused by Sargassum spp. on near-shore Caribbean seagrass communities. Mar Pollut Bull 2017;122:272-81. https://doi.org/10.1016/j.marpolbul.2017.06.057.

[11] Lim E, Mbowe O, Lee ASW, Davis J. Effect of environmental exposure to hydrogen sulfide on central nervous system and respiratory function: a systematic review of human studies. Int J Occup Environ Health 2016; 22:80-90. https://doi.org/10.1080/10773525.2016.1145881.

[12] Ma Rubright SLM, Pearce LL, Peterson J. Environmental toxicology of hydrogen sulfide. Nitric Oxide 2017;71:1-13. https://doi.org/10.1016/j.niox.2017.09.011.

[13] Wang M, Hu C, Barnes BB, Mitchum G, Lapointe B, Montoya JP. The great Atlantic Sargassum belt. Science 2019;365:83-7. https://doi.org/10.1126/science.aaw7912.

[14] Chávez V, Uribe-Martínez A, Cuevas E, Rodríguez-Martínez RE, van Tussenbroek BI, Francisco V, et al. Massive Influx of Pelagic Sargassum spp. on the Coasts of the Mexican Caribbean 2014–2020: Challenges and Opportunities. Water 2020;12:2908. https://doi.org/10.3390/w12102908.

[15] Gower J, Young E, King S. Satellite images suggest a new Sargassum source region in 2011. Remote Sens Lett 2013;4:764-73. https://doi.org/10.1080/2150704X.2013.796433.

[16] Gower JFR, King SA. Distribution of floating Sargassum in the Gulf of Mexico and the Atlantic Ocean mapped using MERIS. Int J Remote Sens 2011;32:1917-29. https://doi.org/10.1080/01431161003639660.

[17] Djakouré S, Araujo M, Hounsou-Gbo A, Noriega C, Bourlè B. On the potential causes of the recent pelagic Sargassum blooms events in the tropical North Atlantic Ocean. Biogeosci Discuss. https://doi.org/10.5194/bg-2017-346 (in review 2017).

[18] Wang M, Hu C. Mapping and quantifying Sargassum distribution and coverage in the Central West Atlantic using MODIS observations. Remote Sens Environ 2016;183:350-67. https://doi.org/10.1016/j.rse.2016.04.019.

[19] Jesumani V, Du H, Aslam M, Pei P, Huang N. Potential use of seaweed bioactive compounds in skincare - A review. Mar Drugs 2019;17:688. https://doi.org/10.3390/md17120688.

[20] Cox S, Oxenford HA, McConney P. Summary report on the review of draft national sargassum plans for four countries in the Eastern Caribbean, https://www.cavehill.uwi.edu/cermes/projects/sargassum/docs/cc4fish/d20_review_of_draft_national_sargassum_plans.aspx; 2019 [accessed 10 March 2020].

[21] BBC. Mexico's top Caribbean beaches hit by seaweed infestation, https://www.bbc.com/news/world-latin-america-48756500#:~:text=Some%201%2C000km%20(621%20miles,Roo%20state%2C%20local%20officials%20say; 2019 [accessed 10 March 2020].

[22] Steir R. Sargassum seaweed: A source of economic opportunity, https://www.frontlinewaste.com/sargassum-seaweed-a-source-of-economic-opportunity; 2019 [accessed 10 March 2020].

[23] Hinds C, Oxenford H, Cumberbatch J, Fardin F, Doyle E, Cashman A. Golden tides: Management best practices for influxes of Sargassum in the Caribbean with a focus on clean-up, https://www.cavehill.uwi.edu/cermes/getdoc/123bf91c-1565-414d-8e21-e59fb6f7ca2d/cermes_sargassum_management_brief_2016_08_24.aspx; 2016 [accessed 6 June 2018].

[24] DCNA. Prevention and clean-up of Sargassum in the Dutch Caribbean, https://www.dcnanature.org/wp-content/uploads/2019/02/DCNA-Sargassum-Brief.pdf; 2019 [accessed 10 March 2020].

[25] Montingelli ME, Tedesco S, Olabi AG. Biogas production from algal biomass: A review. Renew Sust Energ Rev 2015;43:961-72. https://doi.org/10.1016/j.rser.2014.11.052.

[26] Rodriguez C, Alaswad A, Mooney J, Prescott T, Olabi A. Pre-treatment techniques used for anaerobic digestion of algae, Fuel Process Technol 2015;138:765-79. https://doi.org/10.1016/j.fuproc.2015.06.027.

[27] Passos F, Uggetti E, Carrère H, Ferrer I. Pretreatment of microalgae to improve biogas production: A review, Bioresour Technol 20147;172:403-12. https://doi.org/10.1016/j.biortech.2014.08.114.

[28] Al Seadi T, Lukehurst C. Quality management of digestate from biogas plants used as fertiliser, IEA Bioenergy, https://www.ieabioenergy.com/wp-

content/uploads/2012/05/digestate_quality_web_new.pdf; 2012 [accessed 15 November 2019].

[29] Al Seadi T, Drosg B, Fuchs W, Rutz D, Janssen R. Biogas digestate quality and utilisation. In: Wellinger A, Murphy J, Baxter D, editors. The Biogas Handbook, Science, Production and Applications, Woodhead Publishing Ltd; 2013, p. 267-301. https://doi.org/10.1533/9780857097415.2.267.

[30] Ariunbaatar J, Panico A, Esposito G, Pirozzi F, Lens PNL. Pretreatment methods to enhance anaerobic digestion of organic solid waste. Appl Energ 2014;123:143-56.

[31] Thompson TM, Young BR, Baroutian S. Advances in the pretreatment of brown macroalgae for biogas production. Fuel Process Technol 2019;195:106151. https://doi.org/10.1016/j.fuproc.2019.106151.

[32] Thompson TM, Young BR, Baroutian S. Efficiency of hydrothermal pretreatment on the anaerobic digestion of pelagic Sargassum for biogas and fertiliser recovery. Fuel 2020;279:118527. https://doi.org/10.1016/j.fuel.2020.118527.

[33] Song M, Pham HD, Seon J, Woo HC. Marine brown algae: A conundrum answer for sustainable biofuels production. Renew Sust Energ Rev 2015;50:782-92. https://doi.org/10.1016/j.rser.2015.05.021.

[34] Yousefifar A, Baroutian S, Farid MM, Gapes DJ, Young BR. Fundamental mechanisms and reactions in non-catalytic subcritical hydrothermal processes: A review. Water Res 2017;123:607-22. https://doi.org/10.1016/j.watres.2017.06.069.

[35] Munir MT, Mansouri SS, Udugama IA, Baroutian S, Gernaey KV, Young BR. Resource recovery from organic solid waste using hydrothermal processing: Opportunities and challenges. Renew Sust Energ Rev 2018;96:64-75. https://doi.org/10.1016/j.rser.2018.07.039.

[36] Lin R, Deng C, Ding L, Bose A, Murphy JD. Improving gaseous biofuel production from seaweed Saccharina latissima: The effect of hydrothermal pretreatment on energy efficiency, Energy Convers Manag 2019;196:1385-94. https://doi.org/10.1016/j.enconman.2019.06.044.

[37] Thompson TM, Young BR, Baroutian S. Enhancing biogas production from caribbean pelagic Sargassum utilising hydrothermal pretreatment and anaerobic co-digestion with food waste. Chemosphere 2021;275:130035. https://doi.org/10.1016/j.chemosphere.2021.130035.

[38] Oliveira JV, Alves MM, Costa JC. Optimisation of biogas production from Sargassum sp. using a design of experiments to assess the co-digestion with glycerol and waste frying oil. Bioresour. Technol 2015;175:480-5. https://doi.org/10.1016/j.biortech.2014.10.121.

[39] Angelidaki I, Karakashev D, Alvarado-Morales M. Anaerobic co-digestion of cast seaweed and organic residues. Technical University of Denmark: Lyngby, Denmark 2017;1:6. https://energiforskning.dk/sites/energiforskning.dk/files/slutrapporter/12097_slutrapport-12097.pdf.

[40] Tapia-Tussell R, Avila-Arias J, Domínguez Maldonado J, Valero D, Olguin-Maciel E, Pérez-Brito D, et al. Biological pretreatment of Mexican Caribbean macroalgae consortiums using Bm-2 Strain (Trametes hirsuta) and its enzymatic broth to improve biomethane potential. Energies 2018;11:494. https://doi.org/10.3390/en11030494.

[41] Young D, Scharp R, Cabezas H. The waste reduction (WAR) algorithm:environmental impacts, energy consumption, and engineering economics,Waste Manage (Oxford) 2000;20:605–15. http://dx.doi.org/10.1016/S0956-053X(00)00047-7.

[42] Young DM, Cabezas H. Designing sustainable processes with simulation: The waste reduction (WAR) algorithm; Comput Chem Eng 1999;23:1477-91. https://doi.org/10.1016/S0098-1354(99)00306-3.

[43] Kaparaju P, Rintala J. Generation of heat and power from biogas for stationary applications: boilers, gas engines and turbines, combined heat and power (CHP) plants and fuel cells. In: Wellinger A, Murphy J, Baxter D, editors. The Biogas Handbook, Science, Production and Applications, Woodhead Publishing Ltd; 2013, p. 404-27. https://doi.org/10.1533/9780857097415.3.404.

[44] Yuan M-H, Chen Y-H, Tsai J-Y, Chang C-H. Removal of ammonia from wastewater by air stripping process in laboratory and pilot scales using a rotating packed bed at ambient temperature. J Taiwan Inst Chem 2016; 60:488-95. https://doi.org/10.1016/j.jtice.2015.11.016.

[45] Rybicka J, Tiwari A, Leeke GA. Technology readiness level assessment of composites recycling technologies. J Clean. Prod 2016;112:1001-12. https://doi.org/10.1016/j.jclepro.2015.08.104.

[46] NASA. Technology readiness level, https://www.nasa.gov/directorates/heo/scan/engineering/technology/txt_accordion1.html, 2012 [accessed 4 June 2018].

[47] Li B, Udugaman I, Mansouri SS, Yu W, Baroutian S, Gernaey KV, et al. An exploration of barriers for commercialising phosphorus recovery technologies, J Clean Prod 2019;229:1342-54. http://dx.doi.org/10.1016/j.jclepro.2019.05.042.

[48] Essien S, Udugama I, Young B, Baroutian S. Recovery of bioactives from kānuka leaves using subcritical water extraction: Techno-economic analysis, environmental impact assessment and technology readiness level, J Supercrit Fluid 2021;169:105119. https://doi.org/10.1016/j.supflu.2020.105119.

[49] Xing X, Dell K, Udugama IA, Young BR, Baroutian S. Transforming biomass pyrolysis technologies to produce liquid smoke food flavouring, J Clean Prod 2021;294:125368. https://doi.org/10.1016/j.jclepro.2020.125368.

[50] CNW. Barbados new minimum wage takes effect, https://www.caribbeannationalweekly.com/caribbean-breaking-news-featured/barbados-new-minimum-wage-takes-effect/#:~:text=Prime%20Minister%20Mia%20Mottley%20confirmed; 2021 [accessed 7 July 2018].

[51] Ministry of Energy, Small Business and Entrepreneurship of Barbados. Changes to the

prices of petroleum products, https://commerce.gov.bb/price-list-of-petroleum- products; 2021 [accessed 7 July 2018].

[52] PMCU. Barbados waste characterisation study: Final report, https://www.barbadosparliament.com/uploads/sittings/attachments/b7fafa53eab7cd2cb9f2368bbb2aff5a.pdf; 2015 [accessed 7 July 2018].

[53] BWA. Billing calculations, http://barbadoswaterauthority.com/?page_id=192; 2014 [accessed 7 July 2018].

[54] GPP. Barbados electricity prices, https://www.globalpetrolprices.com/Barbados/electricity_prices/; 2021 [accessed 7 July 2018].

[55] BRA. Income tax, https://bra.gov.bb/About/Tax-Types/Income-Tax/Corporations.aspx; 2021 [accessed 7 July 2018].

[56] Trading Economics. Inflaion rate, https://tradingeconomics.com/barbados/inflation-rate; 2021 [accessed 7 July 2018].

[57] FTC. Decision on depreciaton policy, https://www.ftc.gov.bb/library/2009-02-25_commission_decision_depreciation_policy_bl&p.pdf; 2009 [accessed 7 July 2018].

[58] Paylab. Salaries on positions in Barbados, https://www.paylab.com/bb/salaryinfo; 2021 [accessed 7 July 2018].

[59] BGIS. Decision & order on feed-in-tariffs for renewable technologies, https://gisbarbados.gov.bb/download/decision-order-on-feed-in-tariffs-for-renewable-energy-technologies/; 2019 [accessed 7 July 2018].

[60] Li Y, Han Y, Zhang Y, Luo W, Li G. Anaerobic digestion of different agricultural wastes: A techno-economic assessment, Bioresour Technol 2020;315:123836. https://doi.org/10.1016/j.biortech.2020.123836.

[61] Trading Economic. Tax rate, https://tradingeconomics.com/barbados/sales-tax-rate; 2021 [accessed 7 July 2018].

[62] FTC. Decision on feed-in-tariffs for renewable energy technologies above 1 MW and up to 10 MW, https://www.ftc.gov.bb/library/2020-09-29_commission_decision_blandp_feed-in-tariff_1-10MW.pdf; 2020 [accessed 7 July 2018].

[63] Division of Energy and Telecommunications. Barbados national energy policy (2017 - 2037), https://www.greengrowthknowledge.org/sites/default/files/downloads/policy-database/BARBADOS)%20Barbados%20National%20Energy%20Policy%20(2017-2037).pdf.; 2018 [accessed 7 July 2018].

[64] Cristobal J, Caldeira C, Corrado S, Sala S. Techno-economic and profitabilityanalysis of food waste biorefineries at European level, Bioresour Technol 2018;259:244–52. http://dx.doi.org/10.1016/j.biortech.2018.03.016..

[65] Dursun D, Koulouris A, Dalgıc ̧AC. Process simulation and techno economic analysis of Astaxanthin production from agro-industrial wastes, Waste Biomass Valori 2018;11:943–54. http://dx.doi.org/10.1007/*S1*2649-018-0439-y.

[66] Matches. Matches' process equipment cost estimates, https://www.matche.com/equipcost/EquipmentIndex.html; 2014 [accessed 7 July 2018].

[67] Chemical Engineering. The chemical engineering plant cost index, https://www.chemengonline.com/pci; 2019 [accessed 10 November 2020].

[68] Cabezas H, Bare JC, Mallick SK. Pollution prevention with chemical process simulators: the generalised waste reduction (WAR) algorithm - full version, Comput Chem Eng 1999;23:623–34, http://dx.doi.org/10.1016/S0098-1354(98)00298-1.

[69] IPCC, in: Eggleston HS, Buendia L, Miwa K, Ngara T, T.K (Eds), IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, IGES, Japan, 2006. 2006.

[70] Cosenza A, Mannina G, Vanrolleghem PA, Neumann MB. Global sensitivity analysis in wastewater applications: A comprehensive comparison of different methods. Environ Model Softw 2013;49:40-52. https://doi.org/10.1016/j.envsoft.2013.07.009.

[71] EPA. Energy and the environment, https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references; 2021 [accessed 7 July 2018].

[72] Loizidou M, Kapetanios EG. Effect of leachate from landfills on underground water quality. Sci Total Environ 1993;128:69-81. https://doi.org/10.1016/0048-9697(93)90180-E.

[73] Keller F, Lee RP, Meyer B. Life cycle assessment of global warming potential, resource depletion and acidification potential of fossil, renewable and secondary feedstock for olefin production in Germany. J Clean Prod 2020.;250:119484. https://doi.org/10.1016/j.jclepro.2019.119484.

[74] The World Factbook. Barbados. https://www.cia.gov/the-world-factbook/countries/barbados/; 2021 [accessed 23 June 2018].

[75] Moore W, Alleyne F, Alleyne Y, Blackman K, Blenman C, Carter S. Green economy scoping study Barbados, http://www.un-page.org/files/public/barbados_gess_study_web2.pdf; 2014 [accessed 23 June 2018].

[76] UNTC. Environment - Paris Agreement, https://treaties.un.org/Pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXVII-7-d&chapter=27&lang=_en&clang=_en; 2015 [accessed 3 August 2018].