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A biorefinery concept for Barbados

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

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## 9 10

11 Abstract

Pelagic Sargassum inundation of coastlines across the North Atlantic is an ongoing challenge but 12 13 presents new opportunities for value-added resource recovery. This study assessed the technoeconomic feasibility and environmental impact of utilising these invasive brown seaweed, and 14 food waste as feedstock for energy production and fertiliser recovery in Barbados. The 15 biorefinery concept evaluated was designed with hydrothermal pretreatment (HTP) and 16 17 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 18 (electricity and fertiliser). In all cases, simple sale of power generated to the national grid 19 resulted in a negative cash flow and required the introduction of fertiliser sales to achieve 20 21 positive cash flows. Moreover, the net loss in the electricity only scenarios exceeded that of the 22 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 23 attractiveness of the process. Maximum income generation could be attained through 100 % 24 25 supply of the digestate to international markets. However, this approach provides zero support to 26 local food security. The preferred option involves the 50/50 split utilisation of the solid digestate 27 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 28 input energy demand. It also lowered the potential environmental impact by more than 10-fold, 29 relative to landfill disposal. Recycling of the liquid digestate also reduced the fresh water 30 demand and its associated costs. Despite the promising results, process scale-up and 31 32 commercialisation remain a main challenge, primarily due to the seasonality and variability of Sargassum seaweed for continuous bioprocessing. 33 Kevwords: Anaerobic digestion; Environmental impact analysis; Food waste; Hydrothermal 34 pretreatment; Pelagic Sargassum; Techno-economic assessment 35

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#### 37 **1. Introduction**

The recurring deluge of beaches in the North Atlantic Ocean with large, floating mats of 38 Sargassum (90 % of S. natans and 10 % of S. fluitans) has reached crisis proportions, dating 39 40 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-41 economic and environmental stability of this fragile, tropical region [4, 5]. Tourism is the main 42 43 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 44 last decade, inundation events have led to reduced visitor arrivals caused by restricted ocean 45 access for leisure activities, namely swimming, snorkeling and surfing. Beach-cast Sargassum is 46 also an eyesore and has a very pungent odour [7-9]. The decay of these brown seaweeds 47 produces hydrogen sulfide (H<sub>2</sub>S), a corrosive and toxic gas with a rotten egg smell. Prolonged 48 exposure to this pungent emission at low concentrations ( $\leq 20$  ppm) can result in upper airways 49 irritation, nausea, headaches and confusion in humans [7, 9, 10]. In extreme cases, hypoxic 50 51 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 52 [12]. Departments of Fisheries have been equally challenged by the influx of this biomass 53 54 through extensive boat damage, net entanglements and mass fish and sea turtle kills [7-10]. 55 Pelagic Sargassum originates in the Great Atlantic Sargassum Belt, a region of the tropical North Atlantic Ocean (8°-23° N and 89°-58 °W) with aerial coverage of approximately 3,000 square 56 kilometres (km) [13, 14]. At this growth location, the recent phenomena of mass Sargassum 57 proliferation has been inextricably linked to global anthropogenic changes such as global 58 59 warming, rising ocean temperatures, eutrophication from the Amazon, Orinoco and Congo

rivers, and Sahara African dust emissions [15-17]. Annually, large quantities of pelagic 60 Sargassum wash ashore in the Caribbean, Gulf of Mexico and West Africa. Peak deposition to 61 the Caribbean of approximately 10,000 wet tonnes per day (t/d) was reported in 2015 [4, 18]. 62 The clean-up of beach-cast *Sargassum* is necessary to restore the integrity of this invaluable 63 ecosystem. In Mexico, Barbados and St. Lucia, Sargassum seaweeds have been repurposed as 64 organic fertiliser in agricultural practice. More recently, scientists in Barbados began exploring 65 66 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 67 influence on annual inundation events. Overall, landfilling remains the primary approach to 68 69 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 70 transportation of these wet seaweeds from beaches to the disposal site [1, 20]. In 2019, hoteliers 71 72 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 73 Miami Dade County, USA was estimated at USD 35 million [22]. In the Caribbean alone, the 74 cost of removing pelagic Sargassum from beaches is estimated at USD 120 million/year (a) [3]. 75 76 Additionally, landfills are unsustainable and eco-unfriendly, posing a serious risk to human 77 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 78 seaweeds, preferably as feedstock for value-added resource recovery [1, 7, 9]. 79 Anaerobic digestion (AD) is waste-to-energy technology which uses methanogenesis to convert 80 organic matter in the absence of oxygen into biogas, a renewable fuel composed of methane (60-81 70 %) and carbon dioxide (CO<sub>2</sub>) (30-40 %) [25, 26]. Biogas can be combusted for combined heat 82

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 nutrientdense, 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].

89 Brown seaweeds are promising feedstock for valorisation to biogas, given the rich

90 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

92 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

94 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 ( $\leq 20:1$ ) [1, 7, 9, 25, 33].

98 Hydrothermal pretreatment (HTP) and co-digestion with various organic substrates may be used

99 to combat several challenges of pelagic *Sargassum* single digestion. Hydrothermal pretreatment

100 (HTP) is a green process that requires pressurised liquid hot water (120-200 °C) as the reaction

101 medium. This technology accelerates biomass decomposition and the solubilisation of

102 fermentable organic matter [31, 34, 35], thus enhancing methane production relative to the raw

biomass [32, 36]. Additionally, HTP reduces the H<sub>2</sub>S content of *Sargassum*-derived biogas from

104 3 % to 1 % [32]. This compositional change to the biogas product enhances its quality and

105 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 106 achieving higher methane fermentation downstream [37, 38]. This approach improves digester 107 performance by amending the C/N ratio to the suggested optimum range for AD (20-30:1), 108 diluting salinity and increasing the tolerance to inhibitory compound accumulation [37, 39]. 109 Despite the recent upsurge in the literature investigating the exploitation of pelagic Sargassum as 110 feedstock for biogas production [1, 5, 7, 9, 31, 38, 40], no research has evaluated the full-scale 111 112 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 113 the economic feasibility and environmental impact of deploying, in Barbados, a Sargassum-114 115 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 116 various revenue streams; (ii) assessment of socio-technical readiness level to gauge societal 117 project acceptance and technical feasibility; (iii) environmental sustainability analysis to 118 determine potential environmental impacts (PEIs) for the proposed scenarios; and (iv) sensitivity 119 (SA) and uncertainty analysis (UA) to identify the most influential factors and their impact on 120 the cash flow. The novel integrated biorefinery concept evaluated in this work was proposed by 121 122 Thompson et al. [7] as a practical Sargassum management strategy, mainly during inundation 123 events.

124

## 125 **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

130 (WAR) Algorithm [41, 42]. The findings of experimentation by Thompson et al. [32, 37]

131 provided the ultimate and proximate characterisations of the feedstock and inoculum inputs,

132 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

135 final product (electricity and digestate).

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137 2.1. Process description

138 This study evaluated four different feedstock scenarios for commercial biogas production and 139 fertiliser recovery in Barbados. The first scenario, S1, examines the single digestion of raw 140 pelagic Sargassum, while the second, S2 explores the utilisation of hydrothermally pretreated 141 Sargassum as the substrate for biogas production [32]. However, taking into account the seasonality and unpredictable availability of these brown invasive seaweeds for continuous 142 143 energy production, scenario S3 investigates the co-digestion of hydrothermally pretreated 144 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 145 both S3 and S4, food waste is utilised as steady-state feedstock, and Sargassum added to the 146 plant input depending upon availability [7]. In all scenarios, the total input of biomass slurry to 147 the processing plant was 15,750 t/a, representing the mass of dried feedstock and fresh water 148 utilised in HTP processing and AD. All equipment listed in the subsequent sections was chosen 149 to achieve the desired plant processing capacity. Table 1 characterises the input materials and 150 water ratios of the scenarios assessed [32, 37]. Fig. 1 presents process block diagrams to 151 152 highlight the flow from feedstock to product.

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

- **Table 1**
- 160 Feedstock description.

Foodstools composition		IInit				
reedstock composition	<i>S1</i>	S2 S3		<i>S4</i>	- Ollit	
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.
- 164 (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).

#### 166 *2.1.1. Seaweed harvesting and preparation*

In this study, Sargassum seaweed was collected from beaches (manually and mechanically via 167 168 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 169 particulates. The seaweeds were then sun-dried on locally designed seaweed racks for 7-14 d to 170 171 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 75 172 kW) for particle size reduction prior to hydrothermal processing, to increase the microbial 173 bioconversion efficiency downstream. Thereafter, fresh water was mixed with the substrate to 174 prepare a slurry. The biomass-to-water mass ratio varied with the feedstock (1:6 for Sargassum 175 and 1:2 for food waste) to achieve a total solid content < 15 % for wet digestion. A fixed slurry 176 throughput of 15,750 t/a. was assumed for HTP. Notably, in S3 and S4, the ratio of Sargassum to 177 food waste in the feedstock mixture was adjusted to maintain the input flow rate to AD. 178 179 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 180 required for bioprocessing. 181

182

#### 183 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].

#### 191 2.1.3. Anaerobic digestion

The digester considered was a batch stirred tank reactor (BSTR) of total volume 10,000 m<sup>3</sup> and 192 85 % working volume to facilitate expansion due to overhead pressure changes from biogas 193 production. The digester volume was calculated based on feedstock and the annual number of 194 batches (see below). The digester's design comprises a digester chamber, circulating pump, 195 196 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 35 197 °C. Barbados is a tropical island with an average ambient temperature of 28 °C, therefore the 198 199 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 200 was assumed to be 9 d. Eleven (11) digestion cycles were anticipated annually, with the 201 remaining 35 d allocated to equipment maintenance and plant downtime. The inoculum was 202 203 sourced from the wastewater treatment plant and assumed to present no endogenous methane 204 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, 205 S2, S3 and S4, respectively, as reported by Thompson et al. [32, 37]. 206

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#### 208 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<sup>3</sup>) and 4 kWh/Nm<sup>3</sup>, for
heat and electricity production, respectively [43].

218

#### 219 2.1.5. Digestate treatment and utilisation

The solid-liquid digestate undergoes phase separation and dewatering in a screw press separator 220 of loading 180 cubic metres per hour  $(m^3/h)$  and power 7.1 kW. Solid digestate (3,150 t/a) and 221 liquid digestate (12,600 t/a) are produced by this process. The solid fraction is stored for direct 222 utilisation as a fertiliser, soil conditioner and livestock beddings. Alternatively, the liquid 223 fraction was treated with aerated bubble ammonia stripping technology at intial pH 12 for 24-h 224 225 (loading 80 m<sup>3</sup>/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 226 227 environmental disposal of this liquid effluent through the sewer system [44]. Treated wastewater 228 (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 229 release into the sewer system. An equal quantity of fresh water (10%) was added to the slurry to 230 replace the volume disposed of, thereby restoring the process mass and energy balance. 231

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233 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 implementedtechnology 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.

245

246 2.3. Economic assessment

The input data used in the economic analysis is shown in Table 1. The values were obtained from 247 literature, industry stakeholders and government officials in Barbados. In this study, the 248 economic performance of each scenario was assessed, accounting for the cost of raw materials, 249 250 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 251 biorefinery. Annual seaweed availability was assumed at 180 d. Manual harvesting of this 252 253 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 254 the country's minimum wage of 4.25 USD/h [50]. The distance from the collection site to the 255 processing plant was an estimated 10 km at the unit transportation cost of 1.22 USD/L [51]. Fuel 256 consumption per truck was approximated at 0.64 USD/km. Noteworthy, food waste was assumed 257 to be available at no additional cost since the management of this waste stream is the primary 258 responsibility of the Government of Barbados [52]. Vehicle insurance was not considered in the 259 calculations. Utilities include the cost of fresh water for biomass pretreatment, biogas DSF and 260 261 liquid digestate ammonia stripping, as well as the electricity required to raise and maintain the

262 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].

## 264 **Table 2**

265 Assumptions for the techno-economic assessm	ient.
---	-------

Parameter	Property	Value	Unit	Ref.
General	Analysis year	2021	-	-
	Construction year	2021	-	-
	Project lifespan	10	А	-
	Plant design + construction	1	А	-
	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 <sup>3</sup> (first 40 m <sup>3</sup> )	[53]
		3.89 + sewage tariff	USD/m <sup>3</sup> (40-12000 m <sup>3</sup> )	
		2.33 + sewage tariff	USD/m <sup>3</sup> (over 12000 m <sup>3</sup> )	
	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 267 individual scenarios), whereas OPEX was sub-divided into labour, manufacturing, 268 269 administration, management and maintenance costs. Total estimated revenue was calculated from the sale of electricity and distribution of the digestate locally and internationally. The 270 assumption was that the electricity generated would be sold to the national energy grid at a cost 271 272 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 273 274 Commission and carries a higher rate than that supplied by the local power company, The 275 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 % 276 renewable energy generation by 2030 as outlined in the Barbados National Energy Policy 277 (BNEP) [63]. Alternatively, the heat generated from the CHP system would be recycled for the 278 HTP process, thus mitigating the energy demand of this pretreatment technology. The solid 279 280 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 281 product as an organic fertiliser in local farming practice, the suggested sales price was reduced 282 283 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 284 plant. However, consideration was given to the redirection of this waste stream from disposal to 285 286 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 %, 287 288 payable to the Government of Barbados [61]. Finally, comparison of the cumulative cash flow of 289 each scenario was made against the current operation employed on island of seaweed landfill disposal to justify process feasibility. 290

291

292 2.4. Financial indexes calculation

The input values reported in Table 1 were used to determine the viability of each process 293 scenario based on the following financial feasibility indicators: operating profit margin (OPM), 294 295 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 10 296 years lifespan of the biogas plant, which accounts for the macro-economic influences such as 297 corporation tax, inflation, depreciation and the discount rates defined in Table 1. The financial 298 indicators were calculated using the formula presented in the supplementary materials. 299 The cost of equipment was obtained from a conceptual equipment cost database [66] and 300 adjusted to the plant construction year (2021). The size of the equipment was scaled up to meet 301 302 the 15,750  $\text{m}^3/\text{a}$  specification using Eq. 1 and 2, respectively. Cost in 2021 = Base Cost  $\left(\frac{CEPCI_{2021}}{CEPCI_{Base}}\right)$ 303 (1) Scaled up cost = Original cost  $\left(\frac{\text{Scaled capacity}}{\text{Original capacity}}\right)^n$ 304 (2) 305 where, n is the scaling factor (0.6), and *CEPCI* is the chemical engineering plant cost index [67]. 306 307 2.5. Sensitivity analysis 308 309 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 310 tool explores the sensitivity of system behaviour, efficiency, sustainability and output to changes 311 in a single parameter within the specified process boundaries. Therefore, SA can be useful to 312 improve model predictions and identify the variables with the most significant impact on the 313 NPV. In this study, a SA was necessary to examine the effect of bioprocessing parameters, 314 including the plant investment, feedstock supply and HTP energy costs. 315

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:

319 
$$sy_{ik} = b_{0k} + \sum_{j=1}^{M} b_{jk}\theta_{ij} + \varepsilon_k$$
(3)

Where  $sy_{ik}$  is single value of the output y for the *i*<sup>th</sup> Monte Carlo simulation,  $b_{jk}$  is the linear regression coefficient for the parameter *j* and model output *k*,  $\theta_{ij}$  is the input parameter, and  $\varepsilon_k$  is the error of the regression model. By transforming this equation to its standardised form, the following equation can be obtained:

324 
$$\frac{sy_{ik} - \mu_{sy_k}}{\sigma_{sy_k}} = \sum_{j=1}^M \beta_{jk} \frac{\theta_{ij} - \mu_{\theta j}}{\sigma_{\theta j}} + \varepsilon_{ik}$$
(4)

325

326 Where  $\mu$  is the mean and  $\sigma$  is the standard deviation,  $\beta_{jk}$  is the SRC of parameter *j* on output *k*.

327 A parameter with a higher  $\beta$  value means that the parameter has a relatively higher contribution

to altering the output. Positive and negative values of  $\beta$  indicate positive and negative

329 correlations, respectively.

330 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.
- 332

#### 333 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

336 would change the process outcomes.

No.	Parameter	Unit	Default	Min	Max
1	Seaweed availability	d	180	-20%	+20%
2	Biogas to power	kWh/Nm <sup>3</sup>	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%

337

#### 338 2.6. Uncertainty analysis

339 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.

345

346 2.7. Environmental impact assessment

347 The potential environmental impacts (PEI) of producing biogas and fertiliser from pelagic

348 *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 351 toxicological impacts: human toxicity potential by ingestion (HTPI), human toxicity potential by 352 exposure (HTPE), aquatic toxicity potential (ATP), terrestrial toxicity potential (TTP), and four 353 global atmospheric impacts: global warming potential (GWP), ozone depletion potential (ODP), 354 photochemical oxidation potential (PCOP), and acidification potential (AP). The eight PEI 355 356 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 357 study, natural gas was assumed to be the energy source for HTP, while fresh water was chosen 358 359 for the pretreatment process. The greenhouse gas (GHG) emissions were calculated using the default CO<sub>2</sub> emissions conversion factor of 56,100 kg CO<sub>2</sub> equivalent per terajoule (CO<sub>2 eq.</sub>/TJ) 360 for natural gas combustion, in accordance with the 2006 Intergovernmental Panel on Climate 361 Change (IPCC) guidelines for National GHG inventories [70]. 362

363

#### **364 3. Results and discussion**

365 3.1. Process economic comparisons

Fig. 2 compares the four studied scenarios based on the following parameters: (a) estimated 366 CAPEX and OPEX; (b) CHP product yield. Fig. 2a highlights a marginal differential of 367 approximately USD 25,000 between the scenario CAPEX values, due solely to the incorporation 368 of biomass pretreatment into the process design. On the contrary, the OPEX exhibited greater 369 fluctuation resulting from the costly Sargassum harvesting and substrate pretreatment. In both S1 370 371 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 372 respective scenarios. Reducing the volume of wet Sargassum gathered from 9,000 to 1,080 t/a. 373 374 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 375 [52]. One other consideration of interest is the utilisation of HTP for biomass pretreatment. This 376 technology is energy-intensive and requires considerable water input for feedstock dilution prior 377 to operation, primarily due to the physicochemical properties of pelagic Sargassum [32, 37]. In 378 this study, the incorporation of HTP in the process design (Fig. 1) increased the annual operating 379 380 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 381 and included HTP and AD technologies in the process, presented the highest OPEX of USD 382 383 753,039/a.



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

395

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.
- 399 Similarly, heat production doubled from 0.60 GWh/a in S1 to 1.18 GWh/a in S4. Enhancement
- 400 of power generation was attributed to the high efficiency of HTP at accelerating Sargassum
- 401 solubilisation for microbial bioconversion downstream [32]. Additionally, food waste supplied





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 418 feasibility of the process (Fig. 3). Annual financial profit of approximately USD 1.83 million can 419 be achieved through 100 % export to foreign markets, based on high pricing of the organic 420 fertiliser products on the international market (Table 1). However, this practice would be ill-421 advised for Barbados as it offers no support to the sustainability of the local agricultural sector. 422 423 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 424 process design would reduce financial earnings by approximately USD 590,705/a, it would prove 425 426 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 427 fertiliser could create equal opportunity and an estimated USD 2.90 million/a additional income. 428 Recirculation of heat produced by the CHP unit to hydrothermal processing via a heat exchanger 429 proved advantageous at reducing the overall process energy demand and operation costs. In 430 Barbados, the average ambient temperature is 28 °C. Based on our calculations, the heat derived 431 from CHP would sufficiently raise the temperature of the input slurry from 28 °C to 100 °C, 432 resulting in reduced expenditure cost on electricity required to achieve the desired HTP 433 temperature of 140 °C. 434

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 441 values (20 %) can be undertaken. The maximum PBP for projects with a positive cash flow was 442 estimated to be 2.03 years. The ROI is a key performance indicator for investors as projects with 443 444 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 445 are significantly profitable when at least 50% of the fertiliser produced is exported. Even with a 446 100% local sale approach, S3 and S4 show a positive operating income. Nevertheless, it must be 447 stressed that the ROI takes an investment view of the expected cash flow stream but does not 448 measure uncertainty or risk. 449

## 450 **Table 4**

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

			Financial indicator				
Scen	ario	OPM (%)	NPV (USD million)	IRR (%)	PBP (a)	ROI (%)	
<i>S1</i>							
А	Electricity only	- 703.33	- 3.37	N/A	N/A	- 1,671.72	
В	Electricity + solid fertiliser (100 % local)	1.63	- 0.29	N/A	N/A	- 70.29	
С	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	
<i>S2</i>							
А	Electricity only	- 623.29	- 4.21	N/A	N/A	- 1,914.57	
В	Electricity + solid fertiliser (100 % local)	- 19.01	- 0.78	N/A	N/A	- 436.41	
С	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	
<i>S3</i>							
А	Electricity only	- 227.17	- 1.90	N/A	N/A	- 7.38	
В	Electricity + solid fertiliser (100 % local)	35.95	1.53	60.01	1.65	560.79	
С	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	
<i>S4</i>							
А	Electricity only	- 264.97	- 2.51	N/A	N/A	-1,182.81	
В	Electricity + solid fertiliser (100 % local)	20.95	0.92	36.18	2.72	295.36	
С	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 453 4) and is therefore the favoured option for implementation. 454

455

462

3.3. Technology readiness level 456

The combination of hydrothermal processing and anaerobic digestion for the purpose of 457 manufacturing biogas and fertiliser from Sargassum/food-based feedstock introduces a novel 458 process. However, when analysing the key components that make up the overall production 459

460 process, the following observations can be made:

1. Hydrothermal processes (HTP) are currently implemented at a commercial scale for 461 treatment of similar types of organic waste, mainly, wastewater treatment sludge.

463 2. Anaerobic digestion (AD) units are commercially utilised in wastewater treatment plants for waste that is similar in characterisation to Sargassum and food waste. 464

3. For *Sargassum*, laboratory-scale experiments have been performed at simulated 465

Sargassum-based waste conditions where the proposed combined HTP and AD process 466

has successfully yielded both biogas and fertiliser products. 467

Taking these outcomes into consideration, it can be concluded that the TRL of the proposed 468

production process ranges from 7-9. Therefore, an initial commercial-scale production process 469

can be introduced to further fine-tune the processes. The knowledge gained during this process 470

will guide technology maturity to a TRL of 9. 471

472

3.4. Environmental analysis 473

474 The annual landfill disposal of Sargassum (9,000 wet tonnes) has the potential to generate 0.33

kg CO<sub>2 eq.</sub>/kg Sargassum [71]. This is due to high atmospheric GHG emissions, which negatively 475

influence environmental stability by increasing the GWP. Waste degradation in landfills also 476

477 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,

479 0.022 and 0.042 kg CO<sub>2 eq.</sub>/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 480 (Fig.4). Across all cases, the PEI of feedstock harvesting was assumed to be constant, and hence, 481 the system boundaries were redefined for stand-alone technology comparison. For HTP, the use 482 of water as a solvent had zero effect on the PEI. Similarly, AD exhibited negligible influence on 483 the process PEI as: (i) the biogas produced is directly utilised for CHP generation; (ii) zero 484 energy input is required to achieve the desired AD mesophilic condition given the tropical 485 climate of Barbados. In turn, these variables reduce individual impacts by HTPE, ODP and 486 487 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 488 compounds [73]. In this study, S1 had the lowest PEI of 905 PEI/h (Fig. 4) due to the absence of 489 hydrothermal processing in the process design. In scenarios employing HTP, PEI reductions 490 were achieved through heat recovery from CHP and its recirculation to hydrothermal processing. 491 Nevertheless, future consideration may be given to the installation of solar panels to satisfy the 492 project's energy needs and surplus injected into the national energy grid for added income. 493 Wastewater from the wastewater treatment facility may also be redirected from ocean disposal to 494 495 the biorefinery for seaweed cleaning and HTP, thereby reducing seaweed corrosion of equipment and compounding savings on fresh water utilisation. 496



498

497

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

501

502 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.

512 3.6. Uncertainty analysis

513 Monte Carlo simulation (10,000) with LHS sampling was used to calculate the values of NPV,

514 including CAPEX for each scenario. The distribution (histogram) of these NPV values for each

- 515 scenario with different revenue streams (Table 4) is shown in Fig. 6. The wider distribution, the
- 516 higher is the uncertainty. Moreover, the skewing/shifting of the distribution to the right is an
- 517 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
- 519 fertiliser.
- 520



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

#### 525 3.7. Societal readiness level

#### 526 3.7.1. Sargassum removal

Tourism is a key contributor to the overall GDP in Barbados, with 88.7% coming from the 527 supply of goods and services [1, 74]. Beach-cast Sargassum directly impacts this industry, 528 particularly considering its natural bio-degradation process that makes inundated beaches 529 530 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 531 and uses it as a raw material for resource recovery, there are definite positive societal benefits to 532 533 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; 534 (vi) sustainability of the tourism and fisheries sectors. Importantly, food waste utilisation in the 535 input feed mitigates sole dependence on this seasonal marine biomass for continuous energy 536 generation and supports process viability. 537

538

## 539 *3.7.2. Energy and fertiliser independence*

540 Currently, Barbados is heavily reliant on imports for both its fertiliser and power generation 541 needs [63]. In all scenarios listed, the implementation of such a project will allow Barbados to 542 reduce its energy related imports and become either self-sufficient or a net exporter in terms of 543 fertiliser production [7]. Collectively, the aforementioned would contribute to the development 544 of a sustainable green economy as detailed in the BNEP [63] and promote food security through 545 increased crop production in agriculture [7].

546

#### 547 *3.7.3. Environmental sustainability*

548 Fossil fuel combustion for electricity generation is an environmentally harmful practice emitting

549 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].

- 553
- 554 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.

560

#### 561 **4.** Conclusions

562 The introduction of a *Sargassum*-based biorefinery equipped with hydrothermal pretreatment

563 (HTP) and anaerobic digestion (AD) technologies would offer many socio-economic and

environmental advantages to Barbados. Presently, the Government of Barbados spends an

s65 estimated USD 62.80/t Sargassum for landfill disposal. This practice is also eco-unfriendly,

566 given its high potential environmental impact (PEI) of 0.33 kg CO<sub>2 eq.</sub>/kg Sargassum.

567 Redirection of these invasive seaweeds from landfill disposal to feedstock in a biogas plant

568 would support diversification of the national energy matrix and positively contribute to local

569 food security through the production of a potassium-rich organic fertiliser.

570 Annually, the feed input of 15,750 t of hydrothermally pretreated *Sargassum*/raw food waste

571 (mass ratio of 25:75) can yield 0.69 GWh of electricity, 1.04 GWh of heat and 15,750 t solid-

572 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

574 foreign markets. However, this option offers zero support to sustainability of the local

575	agricultural sector. Preference should be given to the 50/50 split utilisation of the solid digestate
576	in local and international farming practices (S3C). While this scenario reduces revenue
577	generation by approximately 40 %, environmental sustainability stands to benefit through a
578	lower PEI of 0.022 kg CO <sub>2 eq.</sub> /kg Sargassum and greenhouse gas emissions. The NPV, OPM and
579	ROI of project proposal S3C are USD 4.80 million, 63.75%, 1970.22 %, respectively, further
580	indicating the operation's financial health and long-term viability. The system breakeven period
581	is 0.53 years. Addition of the liquid fraction of the digestate to the product revenue stream would
582	increase the gross profit margin and shorten the project PBP.
583	Overall, the findings of this study suggest potential economic benefit to countries negatively
584	impacted by the annual influx of pelagic Sargassum. There is also great opportunity for process
585	scale-up given the maturity and wide-spread commercialisation of HTP and AD technologies
586	globally for various organic substrates. Notwithstanding this, the primary bottleneck to full-scale
587	application of the above-mentioned technologies for pelagic Sargassum bioprocessing remains
588	the seasonal availability of this feedstock. Future work should therefore focus on Sargassum
589	storage techniques and the development of regulatory policies and frameworks for pilot-scale
500	

591

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595

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