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Assessment of the energy potential as a solid biofuel of *Sargassum* spp. considering sustainability indicator

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Abstract. The present study evaluates the potential use of pelagic *Sargassum* spp. as a solid biofuel. Massive landings of these brown algae across the Atlantic have produced ecologic and economic problems since 2011. *Sargassum* biomass valorization could compensate for economic losses and reduce environmental impacts. The production of biofuels could be one of its applications. This research consists of two stages: (a) the physical-energy characterization: morphology, humidity, ash, volatiles, and calorific value, and (b) an estimate of the energy potential of these algae, considering their removal from 600 kilometers of coastline along the Mexican Caribbean coast. An analysis of sustainability indicators considering socioeconomic aspects shows the benefits of using this resource in comparison with other types of low-cost biofuels that produce low environmental impact. The results show the pertinence of using *Sargassum* spp. as an alternative energy resource with low cost, low environmental impact, high accessibility, and added value for localities along the Mexican Caribbean.

1. Introduction

It is expected that renewable energy sources in the coming years will have more installed power in a distributed manner and that they will diversify their production scheme, based on available local resources for energy generation and self-sufficiency. Solar, wind, and bioenergy industries could continue to show the highest growth and cost reduction in the future, as has occurred in recent years [1-3]. Bioenergy, in particular, offers different ways of using almost any organic resource, being it solid, liquid, or gaseous. Agricultural, timber, and marine residues are currently used for energy production through various mechanisms. Macroalgae, for example, have attracted for many years the interest of the scientific community for the generation of sustainable energy resources [4].

In recent years, macroalgae blooms have increased worldwide with those of the genera *Ulva* and *Sargassum* being the most notorious around the world [5-7]. Since 2011, pelagic *Sargassum* species have increased in abundance in the Atlantic Ocean and inundated coastlines in West Africa, northern Brazil, and the Caribbean with a distribution of just over 66 tons/ha, and although the growth rate is unstable to determine constant calculations of abundance, each year since 2015 an influx of tons per kilometer of the beach has been estimated each month [8-11]. Massive landings of these algae have resulted in the deterioration of coastal ecosystems [12,13], enhanced beach erosion [12], and affected the tourism industry [14].

In the Mexican Caribbean coast, the periodical massive beaching of thousands of tons of pelagic *Sargassum* spp. per kilometer of beach began in 2015 and in 2020, we report a monthly influx of $1.7X10^3$ m^3/km of beach in the Mexican Caribbean [15-17]. Macroalgae accumulation and decomposition on the beach has resulted in the mortality of seagrass beds and fauna [12] and drastically affected the tourist activity of the region [16-18], which is the most important activity for the local economy. Although these algae represent a harmful marine resource for many Atlantic countries, it also represents an opportunity for energy use with high potential that has been little-explored.

Therefore, this study aims to analyze the energy potential of pelagic *Sargassum* spp. as a solid biofuel through sustainable indicators. This work is a continuation of a previously published study that shows that these algae can provide a sustainable energy source alternative, which can contribute to the consumption matrix at the local level.

2. Materials and Methods

Pelagic *Sargassum* spp. fronds were collected from the three beaches along the Mexican Caribbean coast (Cancun, Puerto Morelos, and Tulum) in 2019. Samples were washed with tri-distilled water, sun-dried until moisture content reached approximately 20%, and later grounded in an agate mortar. The morphology of the algae was examined by scanning electron microscopy with a Jeol JSM 7600F model equipment with field emission. The calorific value as a solid fuel was evaluated through a LECO model AC600 isoperibol calorimeter. The contents of moisture, volatile material, and ash were determined using a standard UNE-EN 14774-1 [19], standard UNE-EN 15148 [20], standard UNE-EN 14775 [21], respectively. Also, an analysis of the energetic potential was carried out, based on the assumption of harvest of *Sargassum* spp. corresponding to 600 kilometers of beach on the coasts of the Mexican Caribbean, in the state of Quintana Roo, where this alga arrives. Although the amount of *Sargassum* spp that reaches different sites is variable, and better spatial and temporal monitoring is required [14], this research considered extrapolating the arrival of S*argassum* spp to Puerto Morelos Mexico (Quintana Roo) from an average month of 2019 reported in previous studies [17]. This study also considered a comparative analysis with sustainability indicators considering the national emissions inventory [22], the results of the characterization of *Sargassum* spp and other previously reported data for these algae [17], and the characterization data as biofuels of pine firewood (*Pinus* spp.) and oak firewood (*Quercus* spp) [23].

3. Results and Discussions

The *Sargassum* spp. samples collected from the Mexican Caribbean coast (Figure 1a) had a morphology (Figure 1b) consistent with pelagic *Sargassum* reported in previous investigations [17]. The scanning electron microscopy images showing the components of these algae (leaves, vesicles, and stem) can be seen in figures 1c, 1d, and 1e. With solar drying, 84.90% of moisture was removed (Standard deviation, SD: 0.14%), which is acceptable for its use as a solid biofuel. The volatile matter content was 84.59% (SD: 0.072%), and the ash content was 21.64% (SD: 1.46%). Compared to other solid biofuels, these algae have high volatility and high ash content [23].

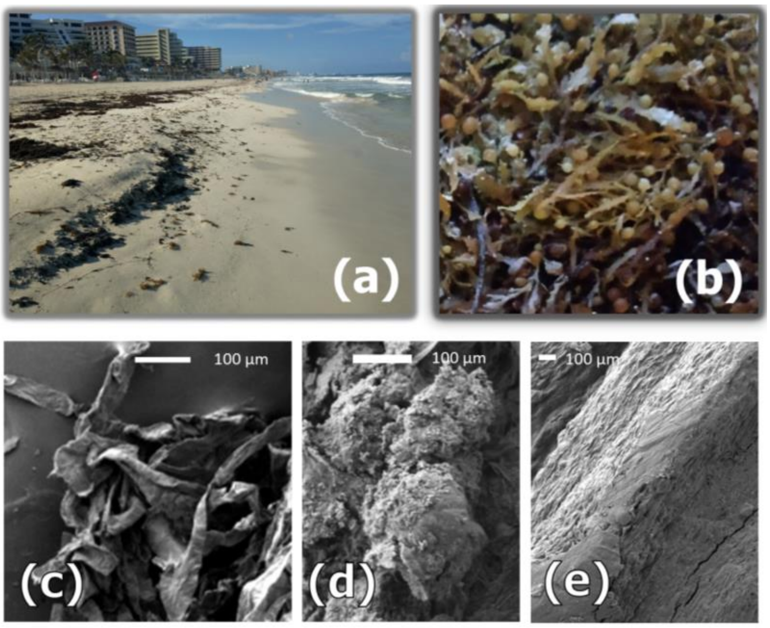

Figure 1. (a) Harvest of *Sargassum* spp. from the Mexican Caribbean coast, (b) close-up of *Sargassum* spp. collected from the shore. Scanning Electron Microscopy morphology analysis: (c) leaves, (d) vesicles, and (e) stem.

The calorific value was 13.65 MJ/kg (SD: 0.46), and we have previously reported that due to the influx of *Sargassum* spp. it is possible to have an energy generation potential of 0.61 TJ/km/month [17], with the use of 11% per cubic meter of matter removed from the coasts (due to the loss of moisture, sand content, and other adhered marine resources) [17]. An energy use scenario has been built on the coasts of the Mexican Caribbean, considering the removal of *Sargassum* spp. in 600 km of coastline during a month (Figure 2a and 2b), under the assumption of energy generation/kilometer/month mentioned above. It also shows the equivalent in tons of LP gas, firewood, and coal, of energy produced by the exploitation of this amount of *Sargassum* spp., based on the calorific value of these fuels (Figure 2c).

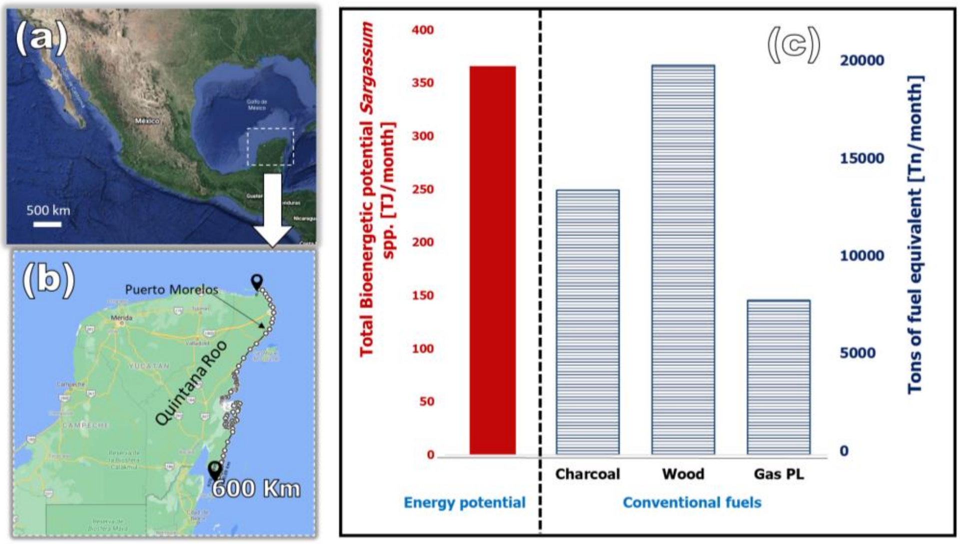

Figure 2. (a) y (b) identification of the territorial extension of exploitation of *Sargassum spp*. (c) potential for energy use and equivalence with other fuels.

Although *Sargassum* spp. has a lower calorific value than LP gas, coal, and wood, its cost as a marine product at this time is zero, as it is being disposed of as waste. Due to the necessity to remove it from the beaches to prevent ecological and economic impacts, this potential pollutant could be used and have an added energetic and economic value (Figure 3a). The use of *Sargassum* spp. as fuel may be viable because the massive landing of these algae to Atlantic coasts appears to be the new "normal". As a solid fuel for the residential sector, *Sargassum* spp. can be used in micro-gasifiers containing specialized filters to inhibit pollutant emissions and optimize the combustion process [24]. Compared with other conventional fuels, the use of the full monthly energy potential of *Sargassum* spp. (Figure 2 c), for the 600 km harvest scenario, represents significant mitigation of tons of CO_2 regarding those fuels (Figure 3b).

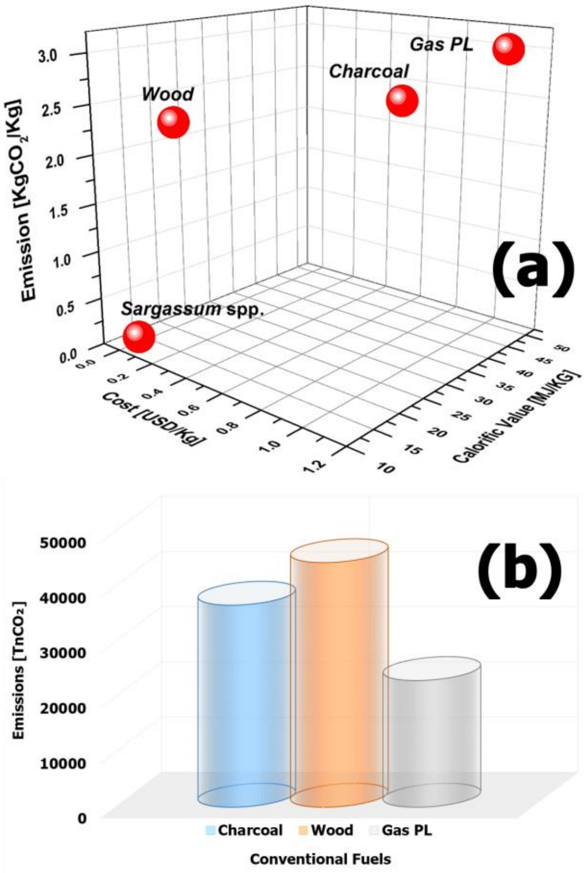

Figure 3. Multivariate analysis of various fuels compared to *Sargassum* spp.: (a) comparison of different fuels in terms of their calorific value, emissions and costs (b) equivalent emissions of other fuels concerning the energy potential of S*argassum* spp collected in 600 km.

To evaluate the local exploitation potential of this marine resource, we consider knowing the per capita consumption of firewood in the state of Quintana Roo, Mexico (where the algae are harvested), which is, 2 kg/day [25]. Thus, the more than 350 TJ/month of usable energy of *Sargassum* spp. could satisfy represent the satisfaction of the annual bioenergetic needs of approximately 79,163 inhabitants, which is an important way shows the local exploitation potential of this marine resource.

In addition, a multi-criteria analysis has been carried out with sustainability indicators shown in table 1. For each one of the above indicators, we considered maximum and minimum values to define the best- and worst-case scenarios. Values are assigned to these indicators according to databases, research carried out, or technical reports. The indicators are frames of reference to evaluate different case studies in a comparative way.

Table 1. Parameters and indicators utilized in the multi-criteria analysis.

Parameter	Indicator	Minimum value	Maximum value
Energy	Calorific power (MJ/kg)	0	20.92 [26]
Physicochemical	Moisture content (%)	0	56 [26]
	Lignin content (%)	0	35 [26]
	Ash content (%)	0	21.64 (Present research)
Economic-environmental	Unitary production cost ($/kg)	0	80 [23]
	Amount of first-use wood (kg)*	0	1 [23]

*First-use wood is considered because its only application is the generation of heat, which does not happen with *Sargassum* spp. which is a waste.

The multi-criteria methodology is not a tool per se of evaluation, consists of carrying out a comparative analysis, so we analyzed the three biofuels mentioned previously: (1) *Sargassum spp*.; (2) pine firewood (*Pinus* spp.); and (3) oak firewood (*Quercus spp*). The results of the evaluation of these indicators for the three cases are shown in Table 2.

Table 2. Real values of the indicators.

Indicator	*Sargassum* spp.	Pine [23]	Oak [23]
Calorific power (MJ/kg)	13.65	17.8	19.5
Moisture content (%)	15.10	32.0	25.0
Lignin content (%)	9.6 [17]	28.0	24.59
Ash content (%)	21.64	3.0	0.95
Unitary production cost ($/kg)	0.0	0.4	0.5
Amount of first-use wood (kg)	0.0	1.0	1.0

The values in Table 2 were then normalized with those in Table 1 to establish a scale of 0-10, where 0 and 10 represent, respectively, the worst and best possible scenarios. Table 3 shows the normalized values.

Table 3. Normalized values of the indicators.

Indicator	*Sargassum* spp.	Pine	Oak
Calorific power (MJ/kg)	6.52	8.51	9.32
Moisture content (%)	7.3	4.29	5.54
Lignin content (%)	2.74	8.0	7.03
Ash content (%)	0.0	8.61	9.56
Unitary production cost ($/kg)	10.0	9.95	9.94
Amount of first-use wood (kg)	10.0	0.0	0.0

An integrated analysis of the data, carried out using the MULTIBERSO software, shows that *Sargassum* spp. has advantages in the unitary production cost, regarding moisture and the amount of first-use wood when compared to pine and oak, although it qualifies lower regarding calorific power, lignin content, and ash contents (Figure 4). The high generation of ash after the combustion process of *Sargassum* spp. represents an area of opportunity for bio-construction, which we will address in other investigations.

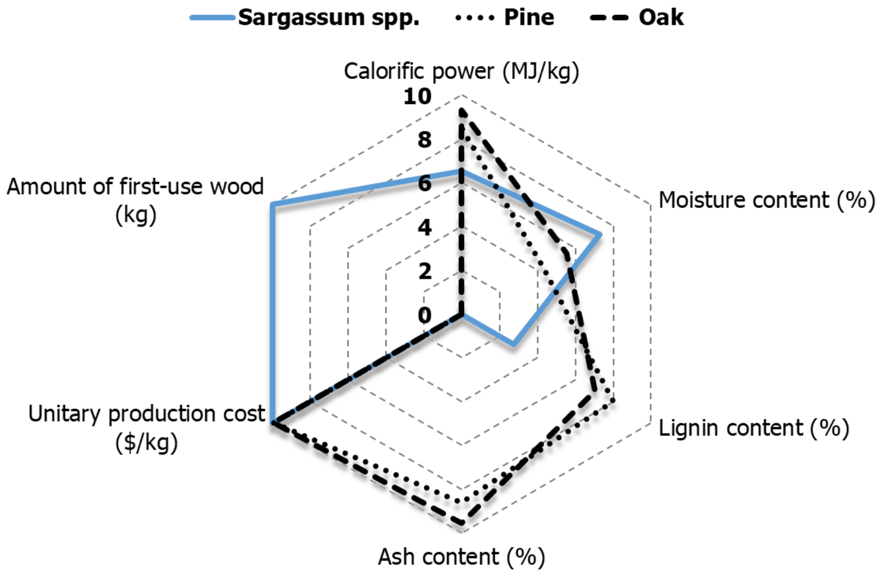

Figure 4. Multi-criteria analysis considering sustainability indicators

The high generation of ash after the combustion process of *Sargassum spp.* represents an area of opportunity for bio-construction, which we will address in other investigations.

4. Conclusions

Pelagic *Sargassum* spp., has the potential for energy use as a biofuel, considering its use in efficient end-use technologies and mitigation of emissions such as micro-gasifiers.; the high influx beaching of these algae in the Mexican Caribbean coast in recent years has made it possible to estimate that its removal of only one month from 600 km of coastline that can could theoretically supply the annual bioenergetic needs of residential heat of 79,163 inhabitants in said region. Its viability as a solid biofuel, considering a comparative analysis with other bioenergetic fuels, is shown through potential benefits in terms of costs and emission generation, because it is a marine residue with an imperative need for removal. With proper transformation management, *Sargassum* spp. could be converted into densified materials such as briquettes or pellets, generating a new market in the bioenergy industry.

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