sustainability

MDPI

Article

Life Cycle Assessment Applied to End-of-Life Scenarios of *Sargassum* spp. for Application in Civil Construction

Cristiane Bueno [1], João Adriano Rossignolo [2,*], Letícia Missiatto Gavioli [3], Camila Cassola Assunção Sposito [3], Fernando Gustavo Tonin [2], Mariana Matera Veras [4], Maria Júlia Bassan de Moraes [3] and Gabriela Pitolli Lyra [3]

1 Department of Civil Engineering, Federal University of São Carlos (UFSCAR), São Carlos 13565-905, Brazil
2 Department of Biosystems Engineering, Faculty of Animal Science and Food Engineering, University of São Paulo (USP), Pirassununga 13635-900, Brazil
3 Post-Graduation Program in Material Science and Engineering, Faculty of Animal Science and Food Engineering, University of São Paulo (USP), Pirassununga 13635-900, Brazil
4 Laboratory of Environmental and Experimental Pathology, LIM05 HC-FMUSP, School of Medicine, University of São Paulo (USP), São Paulo 05403-010, Brazil
* Correspondence: rossignolo@usp.br

Abstract: Environmental risks and vulnerabilities in coastal regions include the massive deposits of brown algae of the genus *Sargassum* in regions such as the Caribbean, Gulf of Mexico, and northern Brazil. Efforts have been made to turn this problem into an opportunity by seeking new uses for this biomass in the sectors of food, agriculture, health, biofuels, bioremediation, and civil construction. Thus, this study aimed to produce quantitative data for different end-of-life scenarios of the *Sargassum* algae, seeking for potential applications of this macroalgae in the civil construction sector. For this purpose, we conducted a life cycle assessment (LCA) study of the *Sargassum* algae, in its natural destination, and evaluated its potential impact. This evaluation was then compared to the possible impacts of alternatives to their end of life, such as landfill disposal, drying and grinding to use as fibers or particles, burning the biomass to generate energy and fly ash, using a consequential LCA and the indicators of the ReCiPe 2016 method. For each of the proposed scenarios, the functional unit of 1 kg of the three types of unprocessed *Sargassum* algae that are found in the Brazilian deposits (*natans I*, *natans VIII*, and *fluitans*) was considered separately, and also for a composition that is closer to that found in the Brazilian deposits (50% *fluitans*, 15% *natans I*, and 35% *natans VIII*). The results for both natural decomposition scenarios demonstrated a dominant contribution to the categories of impact for climate change, marine eutrophication, and land use, thus justifying the search for new initiatives for the use of the algae. The burning process showed a significant contribution to most of the indicators, with emphasis on the massive generation of particulate, inherent to the biomass burning process; however, it showed a reduction in the magnitude of climate change emissions from around 47% to less than 2%. Finally, the proposed scenario of processing *Sargassum* biomass to obtain particles presented prevalence of magnitude for potential impact in most of the proposed indicators, due to the processes with high electricity consumption, but keeping climate change emissions' relative reduction from 47% to 6%. Thus, new studies may further investigate the potential of application of these materials in different products and components of civil construction.

Keywords: life cycle assessment (LCA); *Sargassum*; *Sargassum* life cycle; biomass life cycle; *Sargassum* end of life

check for updates

Citation: Bueno, C.; Rossignolo, J.A.; Gavioli, L.M.; Sposito, C.C.A.; Tonin, F.G.; Veras, M.M.; Moraes, M.J.B.d.; Lyra, G.P. Life Cycle Assessment Applied to End-of-Life Scenarios of *Sargassum* spp. for Application in Civil Construction. *Sustainability* **2023**, *15*, 6254. https://doi.org/10.3390/su15076254

Academic Editor: Alberto Ferraro

Received: 22 February 2023
Revised: 21 March 2023
Accepted: 30 March 2023
Published: 5 April 2023

1. Introduction

Anthropogenic climate change is significantly affecting the world. Economic, social, and environmental impacts vary according to region—directly or indirectly, to a greater or lesser extent—they pose risks to the health of the population [1]. Direct health impacts are easily identified in episodes of extreme weather events (heat waves, floods, landslides, and drought), scarcity of drinking water, food insecurity, and circulation of diseases and their vectors [2]. Several articles show how temperature changes can affect health, increasing mortality and morbidity, emphasizing that the affects may vary according to age, gender, urbanization, and socioeconomic factors [3]. Indirect health impacts are not so easily perceived and require a more holistic analysis, for example, involuntary migration, proliferation of harmful algae, decreased demand and revenue from tourism, and local vulnerability of basic or critical service infrastructure [4,5].

The risks and vulnerabilities can be even greater in coastal regions; in addition to the rising sea levels and erosion, new challenges are impacting the health of local communities, such as the massive deposits of brown algae of the *Sargassum* genus, mostly present in the regions of the Caribbean, Gulf of Mexico, and Northern Brazil [6].

In Brazil, the appearance of pelagic species of *Sargassum* has been increasing since 2011 in the north and northeast regions [7]. The most recent occurrence happened in the state of Maranhão in May 2021, where the algae occupied an extension of about 4 km, totaling a mass of 200 tons [8].

In the last decade, these *Sargassum* algae events have become more frequent. Climate change (ocean warming) and changes in sea current regimes, combined with an increased influx of nutrients that reach the ocean through rivers due to deforestation and release of untreated sewage, create ideal conditions for the excessive growth of *Sargassum* algae [9].

Although not toxic, the accumulation and consequent decomposition of these algae on the beaches produce gases toxic to humans and other animals [10]. Efforts have been made to turn this problem into an opportunity by seeking uses for this biomass in the areas of food, agriculture, health, biofuels, bioremediation, and construction [11–19].

Considering the use of *Sargassum* biomass in construction products, the study developed by Rossignolo et al. (2022) [8] identified some potential applications, such as the use of *Sargassum* fibers or particles as reinforcement in composites (particulate panels and fiber cement) and the use of the fly ash from *Sargassum* algae burning (cogeneration) in Portland cement composites.

In addition to the studies on the technical use of *Sargassum* biomass in construction products, it is very important to understand the possible environmental impact of *Sargassum* algae deposits and the possible mitigative potentials when used. However, quantitative data that allow for a robust environmental analysis, such as life cycle evaluation (LCA), were not found in the recent literature.

Thus, this study aims to produce quantitative data for different end-of-life scenarios for *Sargassum* algae, focusing on the potential applications of this macroalgae in different forms in the construction sector by employing a sequential comparative LCA study.

2. Materials and Methods

The objective of this study is to apply attributional LCA to evaluate the impact potential of the *Sargassum* algae in their natural destination and compare it to the impacts of possible alternatives to their end of life, focusing on its use for civil engineering by applying consequential LCA. This study was mainly developed to quantify and, subsequently, mitigate the impacts to the marine ecosystems, human health areas, and ecosystems, due to the high concentrations of *Sargassum* algae deposited in sand strips, specifically the Brazilian coast, by seeking possible applications for its end of life.

Thus, our study also seeks to minimize the impact potentials of the life cycle of *Sargassum* algae, especially at the end of life, by verifying its application in materials and building components with lower potential for environmental impact, allowing the replacement of materials with high negative environmental impact.

2.1. Scope Definition

The functional unit adopted is 1kg of *Sargassum* algae deposited in a coastal area in Northern Brazil. For this functional unit, we evaluated its use according to the application and end-of-life alternatives to be compared:

(a) Natural decomposition on the beach (current reference scenario);
(b) Landfill disposal;
(c) Drying and grinding for use as fibers or particles;
(d) Generation of energy and fly ash from burning biomass.

For each of the proposed scenarios, LCA was performed for 1 kg of the 3 types of unprocessed *Sargassum* algae that compose the Brazilian deposits (natans I, natans VIII, and fluitans) separately, and also for a composition in 1kg of unprocessed *Sargassum* algae (50% fluitans, 15% natans I, and 35% natans VIII), which is closest to that found in Brazilian deposits, hereinafter Brazilian mix [8].

2.1.1. Life Cycle Inventory (LCI) Modeling Structure

This study will use the life cycle attributional model, which portrays its actual or predicted supply chain, incorporating the product system into a static technosphere for the control scenario, corresponding to the disposition and decomposition of *Sargassum* algae on the beach. Then, a sequential LCA will be carried out by the suggestion of a new end-of-life destination for *Sargassum* algae in order to evaluate the consequences of these scenarios considering potential environmental impacts.

The product systems evaluated in this LCA study are monofunctional, that is, for each system, there is only one final product. First, strategies on allocation and expansion of the system seemed unnecessary, which will be studied, as shown in Figures 1–4. The flowcharts contemplate only the main elementary processes, suppressing less significant intermediate processes. Similarly, elementary processes are known to have primary flows for input and emissions; however, not all of these flows are represented here for simplification purposes.

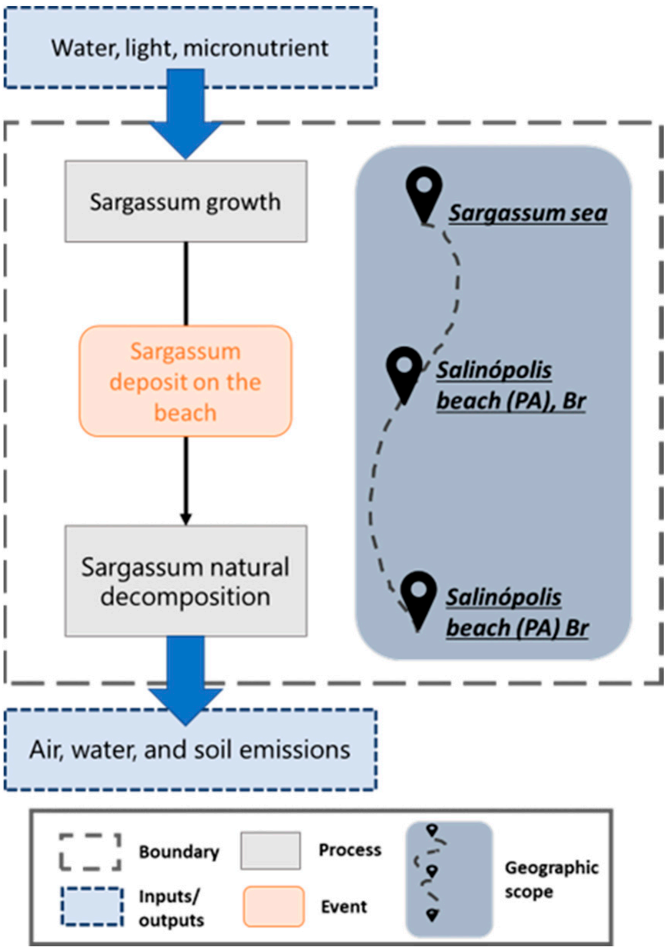

Figure 1. Natural decomposition of *Sargassum* algae on the beach.

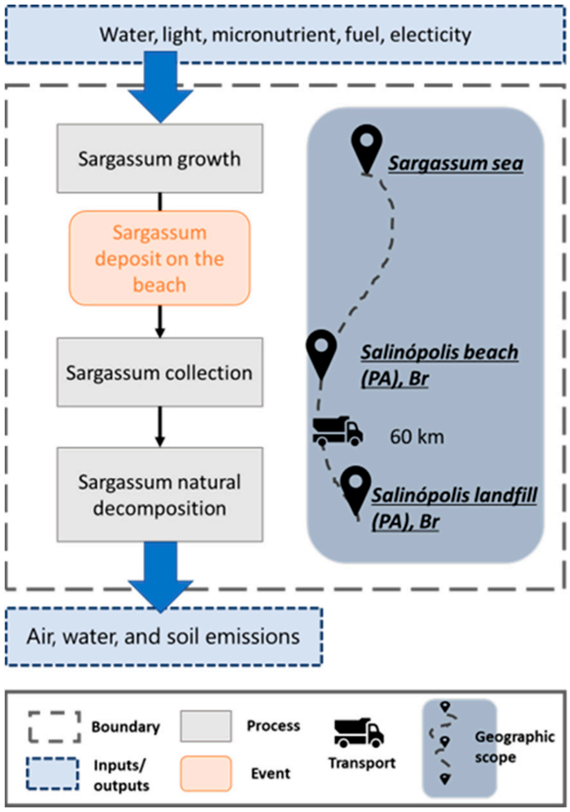

Figure 2. Natural decomposition of *Sargassum* algae on the landfill.

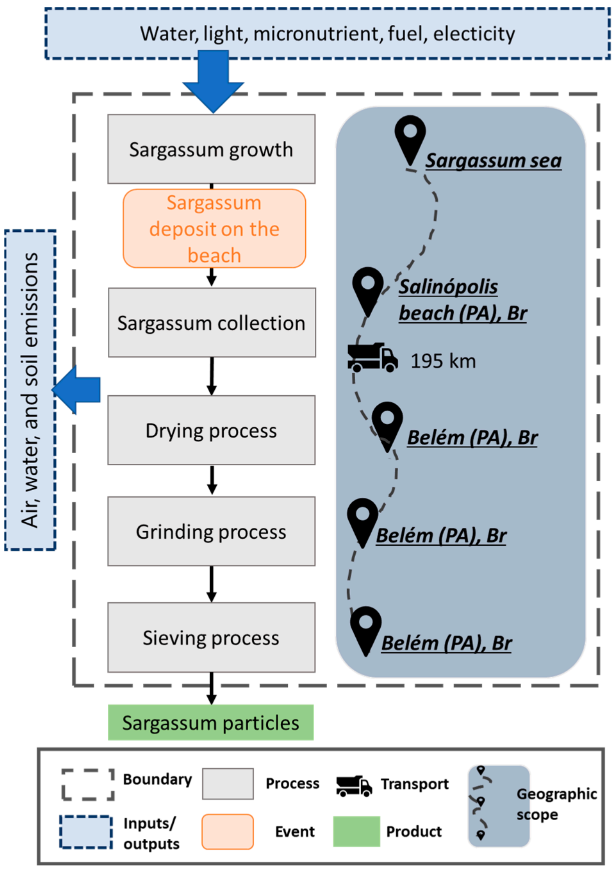

Figure 3. Biomass production with *Sargassum* algae (fibers/particles).

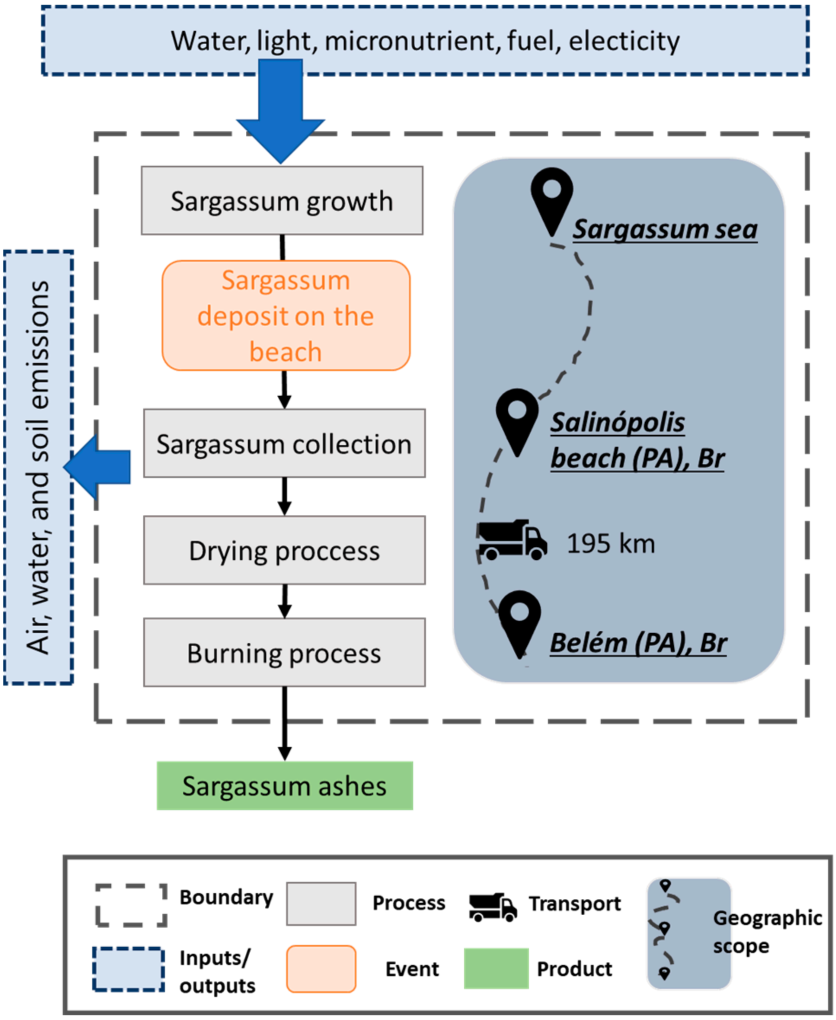

Figure 4. Energy/fly ash production with *Sargassum* algae.

The applied cut-off point considers that the main flows must include flows of water, energy, and mass; their exclusion will only be allowed if they prove to be less than 0.1% relevant to the results. Cut-off points were not applied to emissions to air, water, and soil, and all emissions identified were considered.

The technological scope of this study is considered to be up to date and static, and is directly related to the processes presented in the product system, as represented by the technologies currently used. Therefore, the data to be collected in the LCI phase must correspond to the inputs and outputs of these processes.

Regarding the geographical scope of the LCI data, the chemical analyses of the collected *Sargassum* samples were used to estimate the consumption of resources and the rate of emission according to stoichiometric analyses, secondary inventory data, and previous LCA studies conducted in these and other types of algae in order to fill the potential data gap in our object of study. Thus, the data collected for this study are a combination of regional primary and European secondary data, obtained from the chemical analyses of the collected *Sargassum* algae and from LCI databases, such as Ecoinvent 3.8.

For a more organized structuring of the inventory data, the systems analyzed in this study were subdivided according to their elementary processes. Inventory modeling was performed using the GaBi 6.0 software.

Figure 5 shows the composition of the Brazilian energy matrix, according to the Empresa de Pesquisa Energética [20], whose percentages were considered in this study.

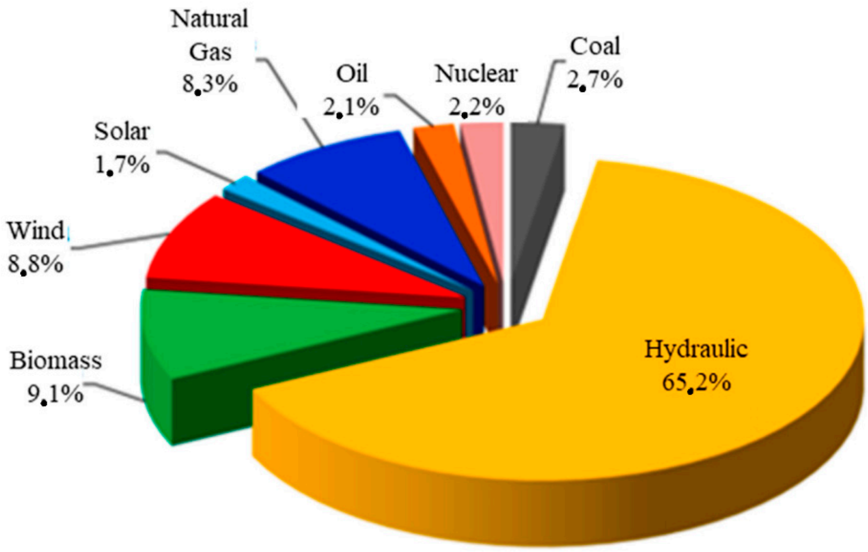

Figure 5. Brazilian electric matrix 2020 [20].

To elaborate the inventories of inputs and outputs related to the transport and distribution of *Sargassum* algae, the city of Salinópolis in the state of Pará was considered as the collection site since it is a recurrent point of deposit of these macroalgae [8,21]. Four different end-of-life scenarios were considered for the deposits of *Sargassum* algae, with different displacement characteristics: (1) Natural decomposition of *Sargassum* algae on the beach, without transportation; (2) Landfill decomposition, in which the distance considered in this study was 60 km between the coast of the city of Salinópolis and the landfill, located in the same city; (3) Biomass production from *Sargassum* algae, in which a distance of 195 km was considered for the transportation of the *Sargassum* algae to Belém (in the state of Pará), for drying and production of biomass; (4) The production of energy and fly ash from the burning of *Sargassum* algae, for which Belém was also considered as the treatment city, and the distance between collection and production was estimated at 195 km. For all distances used in this study, the inventory data for reference were used in t.km (ton per km).

All marginal processes in the inventory modeling, which used data from Ecoinvent 3.8, are listed in the Supplementary Material.

Sargassum Decomposition Emissions Inventory

According to Boyle (1977) [22], the maximum emissions from the anaerobic degradation of organic residues can be estimated by a stoichiometric model, expressed in Equation (1).

$$C_aH_bO_cN_dS_e + \left(a - \frac{b}{4} - \frac{c}{2} + \frac{3d}{4} + \frac{e}{2}\right)H_2O \\ \downarrow \\ \left(\frac{a}{2} + \frac{b}{8} - \frac{c}{4} - \frac{3d}{8} - \frac{e}{4}\right)CH_4 + \left(\frac{a}{2} - \frac{b}{8} + \frac{c}{4} + \frac{3d}{8} + \frac{e}{4}\right)CO_2 + dNH_3 + eH_2S \quad (1)$$

Boyle's equation is a modification of the equation originally proposed by Buswell and Symons (1933) [23] for carbohydrate degradation, allowing the estimation of ammonia and hydrogen sulfide emissions with the inclusion of nitrogen and sulfur in the biomass composition. Elemental analysis (carbon, hydrogen, oxygen, nitrogen, and sulfur) allows us to determine an empirical formula that represents biomass, and this model can be used to determine the maximum theoretical amount of the emissions of each gas [24]. This model considers that all organic material (C, H, O, N, and S) is converted into methane, carbon dioxide, ammonia, and hydrogen sulfide, i.e., it disregards the maintenance and anabolism of the microbial community involved in the process and the recalcitrance (resistance to degradation) of the biomass itself, which can lead to overestimated results [25]. According to Boyle (1977) [22], the estimation of methane emissions can be more realistic if the ratio between the experimental and theoretical methane production potential of the biomass to be degraded is considered.

Studies conducted in anaerobic biodigesters show that the biodegradability index for the genus *Sargassum* ranges from 27% to 46% [12,26]. In a more specific study on anaerobic biodigestion of the species *S. fluitans*, *S. natans* I, and *S. natans* VII, Milledge et al. (2020) [27] obtained individual degradability indices for the species equal to 29%, 17%, and 37%, respectively.

When consulting the Web of Science and Scopus databases in December 2022, no studies on the emissions from the decomposition of unprocessed *Sargassum* algae were identified. Thus, in the present study, the emissions were determined in a semi-empirical way. Initially, the elemental composition of individual samples (*S. fluitans*, *S. natans* I, and *S. natans* VII) collected in northeastern Brazil was experimentally determined. Next, the empirical formula of each species was calculated and Boyle's equation was applied to calculate the maximum theoretical emissions. The resulting values were corrected by the degradability indices determined by Milledge et al. (2020) [27] for each species, considering the same index for all gases. Once the emissions were obtained based on dry biomass (total solids), the emission values were converted to the unprocessed biomass (wet base, as collected on the beach) using the estimated moisture value of 87.5% at the time of collection. The values for the emissions of mixtures of more than one species were obtained by considering the emission of each of the species according to their percentage of mass in the mixture.

Sargassum Burning Emissions Inventory for Power Generation

When consulting the Web of Science and Scopus databases in December 2022, no publications were identified on the quantification of emissions of gases (carbon dioxide (CO_2), sulphur dioxide (SO_2), and nitrogen monoxide (NO)) from the burning of *Sargassum* algae specimens. Thus, the burning emission data were estimated based on mathematical models. Several mathematical models for the theoretical estimation of biomass combustion gas emissions have been developed, albeit with specific boundary conditions for each case study, such as boiler geomet [28], systems with parts developed to mitigate emissions [29], and the specific input of a type of biomass [30], hindering its application for the development of the LCI of algae.

On the other hand, the model described by Backa, Nosek, and Caja (2020) [31] and Channiwala and Parikh (2002) [32] requires, as data input, the elemental composition of biomass (carbon (C), hydrogen (H), oxygen (O), nitrogen (N), and sulfur (S)) and humidity of the samples. This model has complete or incomplete combustion as a boundary condition, having potential applicability to estimate the emissions of CO_2, SO_2, nitrogen (N_2), and oxygen (O_2) and the calorific value of each algae sample. In this sense, the study by Wang et al. (2018) [33] quantified the concentration of gases emitted in the burning of *Sargassum* natans in a fluized bed, and, from its results, it is possible to affirm that the combustion of the algae is at least 95% complete. This value was used as a boundary condition required by the theoretical method for estimating the chosen emissions.

The N_2 gas present in the combustion environment originates both from the nitrogen composition of the biomass itself and from the air introduced into the boiler to supply the oxygen needed for the complete combustion of the samples. Its disposal in the combustion system leads to the formation of thermal NO_x by the thermal dissociation of N_2 and O_2 at high temperatures [34].

According to Hayhurst and Vince (1980) [35], the type of fuel has no influence on the formation of pollutant gas NO, but rather the concentration of O_2 in the system and the temperature of the burning flame. According to the same authors, the reaction mechanism involves the set of chemical reactions presented in Figure 6.

$$O + N_2 \rightarrow NO + N$$

$$N + O_2 \rightarrow NO + O$$

Figure 6. Nitrogen and oxygen reaction mechanisms.

The formation of NO is much slower than the rate of combustion reactions, and most NO is formed only after complete combustion. Thus, as deduced by Bowman (1992) [36], it is possible to estimate the rate of thermal NO formation with Equation (2):

$$\omega_T = 1.45 \times 10^{17} \cdot T_{eq}^{-1/2} \cdot \exp\left(-\frac{69460}{T_{eq}}\right) \cdot [O_2]_{eq}^{1/2} \cdot [N_2]_{eq} \quad (2)$$

In which:

ω_T: Thermal NO formation rate per time (mol/cm^3.s)
T_{eq}: Temperature (K)
$[O_2]$: Oxygen concentration in mol/cm^3
$[N_2]$: Nitrogen concentration in mol/cm^3

Thus, to estimate the emissions of thermal NO gas, it was believed that during the first 60 s of burning there was NOx gas emission, according to the study by Wang et al. (2018) [33] for *Sargassum* natans. Then, this time was used to estimate the thermal NO formation rate (ω_T) of all the algae samples.

The density of gases was modeled on the basis of the ideal gas law, as considered by Medina et al. (2021) [30] in its specific study on wood combustion in a plancha-type cookstove.

The process of biomass self-combustion (such as sugarcane, wood waste, and rice husk) in boilers to obtain energy is already widely used in Brazil and corresponds to 9.8% of the internal energy supply in the country, according to recent data from the Ministry of Mines and Energy (2021) [20]. In the scenario modeled by this LCI study, the same current technology of self-combustion systems for the burning of the deposited algae will be considered. The energy efficiency of boilers results from the energy transferred from the biomass to the steam. In Brazil, it has a mean real value of 51% [37]. On the other hand, a technological maturation is expected until 2050 with the implementation of high efficiency boilers due to the growing interest in renewable energy sources, as observed by Souza et al. (2021) [38].

In this sense, the energy produced by the combustion of the evaluated algae samples is estimated in 51% (referring to the mean energy efficiency of Brazilian boilers) of the energy capacity obtained by estimating the calorific value described in the Channiwala and Parikh (2002) [32] model.

2.1.2. Life Cycle Impact Assessment (LCIA) and Interpretation

The ReCiPe 2016 method of the LCIA characterization was chosen, using the Hierarchist approach, since it presents the highest application representativeness, with its midpoint and endpoint approaches. Our study used its two levels of evaluation for sensitivity analysis. The ReCiPe 2016 methodology derived from an improvement of a set of methodologies, which justifies the greater application representativeness.

This methodology was chosen due to its regional scope directed to the average impacts of the European continent for all categories of impact, unlike other methods that are targeted to specific national contexts, resulting in a local coverage to their impact categories.

The results of the LCIA were presented for all processes by impact category. The characterization and standardization factors used in the AICV stage can be found in the bibliographic reference indicated for the method.

The interpretation was performed together with the presentation of the results, so that the impact potentials for each end-of-life scenario could be discussed in parallel, due to the relationship with its causes and consequences in the protection areas.

The normalization and weighting of the results were not addressed in this study for the purpose of impact assessment. However, for the analysis of the impact categories of greater significance for the studied end-of-life scenarios, normalization was used to compare its results to the non-normalized results in order to analyze if the impact categories of greater magnitude are consistent.

2.1.3. Method Limitations, Assumptions, and Impacts

A potential limitation of this study is related to the need to adopt assumptions and adaptations from the inventory data due to the difficulties in the collection of primary data from *Sargassum* algae. Thus, this study used a combination of primary and secondary data, obtained from the chemical analyses of the collected *Sargassum* algae; from the use of stoichiometry for the inventories of emissions associated with each end-of-life scenario; and from LCI databases, mostly European, applied to marginal processes, which may confer limitations for the application of the study results to the Brazilian context.

3. Results and Discussion

As described in the methodology, a comparative LCA study for the different end-of-life potentials of *Sargassum* algae was carried out using the GaBi 6.0 software, applying the ReCiPe 2016 method with a hierarchical approach, using Ecoinvent 3.8 inventory data for marginal processes, and data obtained through the methods previously described for the primary processes.

Table 1 shows the inventory data obtained and used for first-plan processes for each end-of-life approach studied, as well as their respective final AICV results by impact category and by *Sargassum* species.

Table 1. ReCiPe impact categories 2016.

Categories of Impact	Acronym
Climate change, default, excl biogenic carbon [kg CO_2 eq.]	CC—biogen
Climate change, incl biogenic carbon [kg CO_2 eq.]	CC + biogen
Fine particulate matter formation [kg PM2.5 eq.]	FPMF
Fossil depletion [kg oil eq.]	FD
Freshwater consumption [m^3]	FC
Freshwater ecotoxicity [kg 1,4 DB eq.]	FE
Freshwater eutrophication [kg P eq.]	FET
Human toxicity, cancer [kg 1,4-DB eq.]	HT cancer
Human toxicity, non-cancer [kg 1,4-DB eq.]	HT non cancer
Ionizing radiation [kBq Co-60 eq. to air]	IR
Land use [Annual crop eq.·y]	LU
Marine ecotoxicity [kg 1,4-DB eq.]	ME
Marine eutrophication [kg N eq.]	MET
Metal depletion [kg Cu eq.]	MD

Table 1. *Cont.*

Categories of Impact	Acronym
Photochemical ozone formation, ecosystems [kg NO_x eq.]	POF, E
Photochemical ozone formation, human health [kg NO_x eq.]	POF, H
Stratospheric ozone depletion [kg CFC-11 eq.]	OD
Terrestrial acidification [kg SO_2 eq.]	TA
Terrestrial ecotoxicity [kg 1,4-DB eq.]	TE

The categories of impact evaluated in this research and their respective acronyms of presentation in this article are also presented in Table 1.

3.1. End-of-Life Scenario I: Decomposition of Sargassum Algae on the Beach

The first end-of-life scenario studied for *Sargassum* algae was that of decomposition on the beach, since it is in the reference scenario, without human intervention, in which *Sargassum* algae decompose in the sand strips of coastal areas where they are naturally deposited.

To obtain inventory data, the empirical formula of each species of *Sargassum* algae was initially determined by means of elementary analysis (C, H, O, N, and S). Based on the empirical formula, the maximum GHGs emissions were determined using the Boyle equation, which were corrected by the degradability indices found by Milledge et al. (2020) [27] and converted to unprocessed emission (g GHG/Kg wet algae) by the moisture value determined at the time of collection. Tables 2 and 3 show the results obtained for the composition of the algae and their decomposition.

Table 2. Composition of *Sargassum* algae.

Parameter	*S. fluitans*	*S. natans I*	*S. natans VIII*
Carbon (% TS)	29.91	31.03	35.12
Hydrogen (% TS)	4.17	4.13	4.53
Nitrogen (% TS)	1.59	1.29	1.24
Oxygen (% TS)	32.53	31.09	39.96
Sulfur (% TS)	0.46	0.13	0.14
Moisture (%)	87.5	87.5	87.5
Empirical formula	$C_{2.49}H_{4.14}O_{2.03}N_{0.114}S_{0.014}$	$C_{2.58}H_{4.10}O_{1.94}N_{0.092}S_{0.004}$	$C_{2.92}H_{4.50}O_{2.50}N_{0.088}S_{0.004}$

Table 3. Estimative of *Sargassum* greenhouse gas emissions—TEB: theoretical emission according to Boyle's equation; CTEB: theoretical emissions corrected by the degradability index.

	S. fluitans			*S. natans I*			*S. natans VIII*		
GHG	**TE_B g/kg TS**	**CTE_B * g/kg TS**	**CTE_B ** g/kg (unprocessed)**	**TE_B g/kg TS**	**CTE_B * g/kg TS**	**CTE_B ** g/kg (unprocessed)**	**TE_B g/kg TS**	**CTE_B * g/kg TS**	**CTE_B ** g/kg (unprocessed)**
CH_4	194	56.2	7.02	206	35.0	4.37	219	81.1	10.1
CO_2	564	164	20.4	572	97.3	12.2	686	254	31.7
NH_3	19	5.6	0.70	16	2.7	0.33	15	5.6	0.70
H_2S	4.9	1.4	0.18	1.4	0.23	0.029	1.5	0.57	0.071

* Biodegradability index [26]—*S. fluitans*: 29%, *S. natans* I: 17%, *S. natans* VIII: 37%; ** CTE_B expressed in wet basis (as collected).

Based on these inventory data estimated for the foreground processing, the LCIA was performed separately for each species of the *Sargassum* algae, for the reference scenario, the results of which are shown in Figure 7.

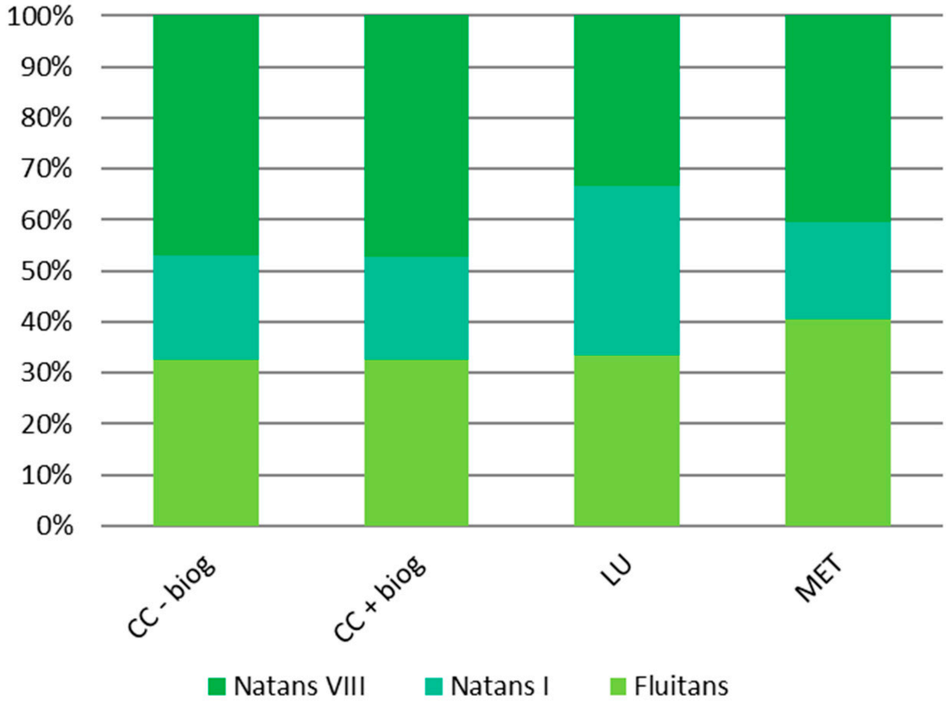

Figure 7. Decomposition on the beach—comparison of each alga.

The theoretical results obtained for the reference scenario show that, regarding the indicators of climate change, the species *S. natans* VIII has higher emission potential—almost corresponding to the sum of emissions of other species—followed by the species fluitans.

For the marine eutrophication impact category, the impact potentials of the species *S. natans* VIII and *S. fluitans* are similar, and both have twice the impact potential of the algae *S. natans* I, which, for every impact category evaluated, always showed the lowest contribution, proving to be the species with the lowest impact potential.

Finally, for the category land use, the contributions of the three species are equivalent since the same functional unit of 1kg of unprocessed algae is considered for all, which, thus, occupy the same space and impact the same soil area regardless of the species.

It is important to note that, for the reference scenario in which the natural decomposition of *Sargassum* algae on the beach was considered, only four of the indicators (out of the 18 evaluated) herein shown presented potential for impact, without contribution to other categories.

3.2. End-of-Life Scenario II: Decomposition of Sargassum Algae in Landfill

The second scenario constitutes the removal of *Sargassum* algae from the beach with appropriate machinery and transportation to the landfill.

For this scenario, the composition used was of 50% *S. fluitans*, 15% *S. natans* I, and 35% *S. natans* VIII, in 1 kg of unprocessed *Sargassum* algae, the Brazilian mix. Figure 8 shows the results of the LCIA.

In this simulation, we can evaluate the potential for impact contribution of *Sargassum* algae retrieval and transportation processes compared to the reference scenario. Thus, we first observed no change for the indicator of marine eutrophication, which confirms the hypothesis that the destination of *Sargassum* algae has no influence on its previous potential for eutrophication.

For the categories referring to climate change, the results showed a slight contribution from the transportation process, which, however, presents less than 5% of the magnitude of potential impacts related to the decomposition of algae.

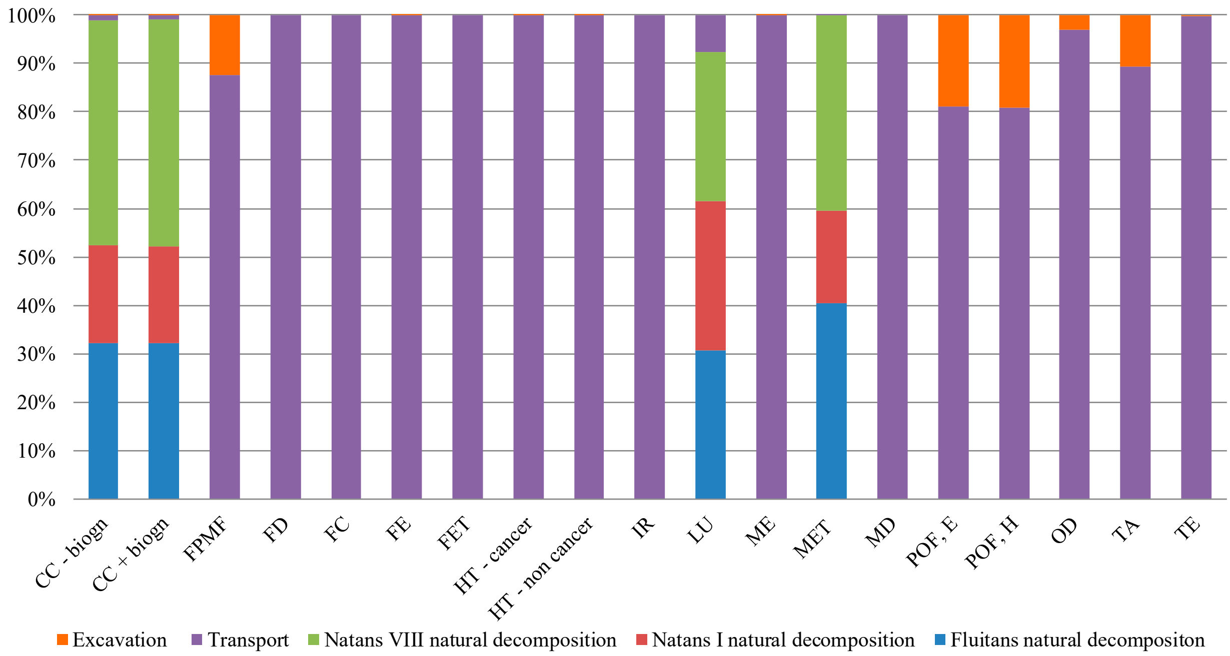

Figure 8. Percentage contribution of potential impacts for Scenario II—landfill.

Finally, for the land use category, the contribution of the transportation process reaches 20% of the magnitude of impact potential, representing a more significant participation.

For the other impact categories, which did not present potentials in the reference scenario, the transportation process showed a more significant contribution, mostly due to the more ostentatious use of fuels and emissions from the burning.

The excavation process appears with contributions of some significance only in the categories of particulate formation and soil acidification, due to the movement of collateral land by the removal of *Sargassum* algae, and in the categories related to stratospheric ozone formation and ozone depletion due the characteristic emissions of the machinery used in the process.

3.3. End-of-Life Scenario III: Processing Sargassum Algae for Use as Fibers or Particles

For the third scenario, in which we aim to observe the impact potentials related to the drying and grinding processes of *Sargassum* algae for later use of its fibers, the same situation described in the previous scenario is observed; the *Sargassum* species has no influence on the results since the impact potentials of the processes involved vary according to the *Sargassum* mass processed. Moreover, in this case, the product of such processes—fibers of *Sargassum* algae—is not intended for decomposition, but potentially for use in industrial products.

Thus, the results of the LCIA of the Brazilian mix (shown in Figure 5) were used to observe the potential contributions of each of the processes to the evaluated indicators.

The patterns observed in Figure 9 show the great contribution of electricity consumption in most categories of impact due to the use of machinery for the various processes (knife mill and vibrating sieve machine operation). This observation is of great importance since it shows that, more than the equipment used for the processing of the *Sargassum* algae, the energy matrix has proven to be of great relevance for the results of this scenario; a factor which should be carefully evaluated before expanding this study data to other geographical scopes.

The contribution chart shows that the impacts arising from the collection of the *Sargassum* algae on the beach are less significant than the impacts of the transportation and processing stages of the *Sargassum* algae.

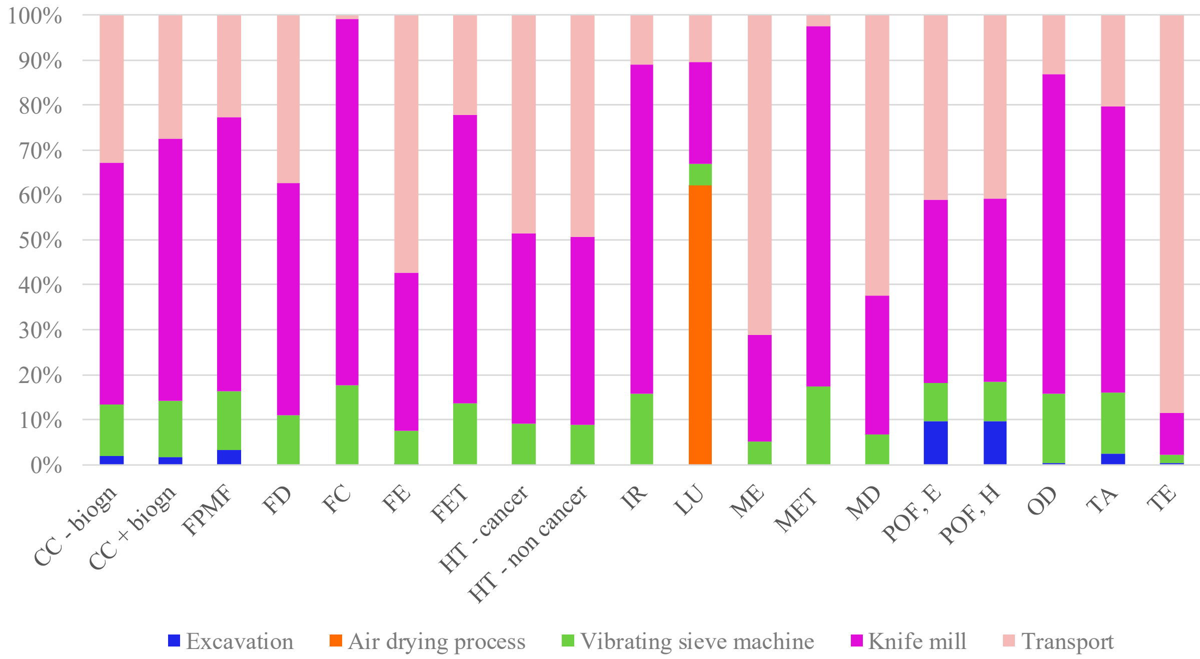

Figure 9. Percentage contribution of potential impacts in the process of obtaining fibers of *Sargassum* algae.

For the drying process of the *Sargassum* algae, the natural drying process was considered, without the use of technologies or equipment for forced drying. Thus, this process presented potential for impact only for the soil use indicator, due to the area required for the drying of the *Sargassum* algae.

Moreover, the high-energy consumption from the processes of sieving in an agitator and grinding in the knife mill presented the most significant contributions to the potential impact on climate change with the use of fossil fuels (due to the contributions of the mixed energy considered), leading to ozone depletion and stratospheric ozone formation. In addition, they also presented the most important contributions to the indicators of particulate formation and eutrophication of both fresh and marine water due to the residues from the separation process of the *Sargassum* algae.

Water consumption also proved to be very relevant in this process, which also explains the eutrophication indicators, since the large volume of water consumed also generates a large volume of wastewater.

Finally, the transportation impacts presented a great contribution in most of the indicators, representing then a point of sensitivity for the management of the environmental data of the scenarios. Considering that the processes of transportation and energy consumption are those with the greatest potential for impact in the scenario (Figures 9 and 10), the sensitivity of the results to the delimitation of the geographic scope of the study must be highlighted, since changes in the energy mix and transportation distances can be decisive for the environmental performance of the proposed solution.

3.4. End-of-Life Scenario IV: Biomass Burning for Power/Fly Ash Generation

To obtain inventory data for the algae combustion process for energy generation, we used the methodology described in item 3.1.1.2 of this article, which resulted in the data of power generation and emissions for 1kg of unprocessed *Sargassum* algae (Table 4).

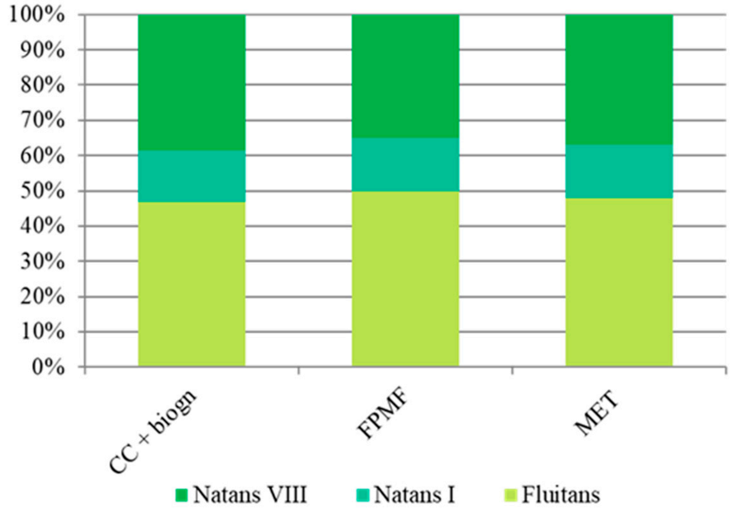

Figure 10. Comparative percentage of the potential impact among algae—burning.

Table 4. Emissions from *Sargassum* biomass (kg/kg of algae).

S. natans I					
CO_2	**CO**	**SO_2**	**N_2**	**O_2**	**NO**
2.91×10^{-01}	1.20×10^{-02}	6.43×10^{-04}	7.48×10^{-01}	2.29×10^{-01}	2.46×10^{-12}
Energy produced by boilers (MJ/Kg of algae)					
5.51×10^{-01}					
S. fluitans					
CO_2	**CO**	**SO_2**	**N_2**	**O_2**	**NO**
2.81×10^{-01}	1.16×10^{-02}	2.46×10^{-03}	7.20×10^{-01}	2.20×10^{-01}	2.37×10^{-12}
Energy produced by boilers (MJ/Kg of algae)					
5.26×10^{-01}					
S. natans VIII					
CO_2	**CO**	**SO_2**	**N_2**	**O_2**	**NO**
3.30×10^{-01}	1.36×10^{-02}	7.72×10^{-04}	7.94×10^{-01}	2.43×10^{-01}	2.61×10^{-12}
Energy produced by boilers (MJ/Kg of algae)					
5.80×10^{-01}					

Some of the inventoried emissions for the process of burning and energy generating showed no variation since it refers only to the mass of the processed *Sargassum* algae, as is the case of the impact from the algae collection, transportation, and drying.

The burning process—for which the emissions can be measured per species of *Sargassum* algae—contributed to three impact indicators: climate change, particulate formation, and marine eutrophication. For particulate formation, no variation among the different species was observed. Both for climate change and for the potential of marine eutrophication, an emission pattern can be identified; *S. natans* VII showed the greatest potential for impact, followed by *S. natans* I and *S. fluitans*, respectively.

From these inventory data estimated for the foreground process, the LCIA was performed separately for each species of *Sargassum* algae (Figure 10).

For a better observation of the relative impact potentials of the processes within a single-product system, the contribution for the Brazilian mix was analyzed (Figure 11).

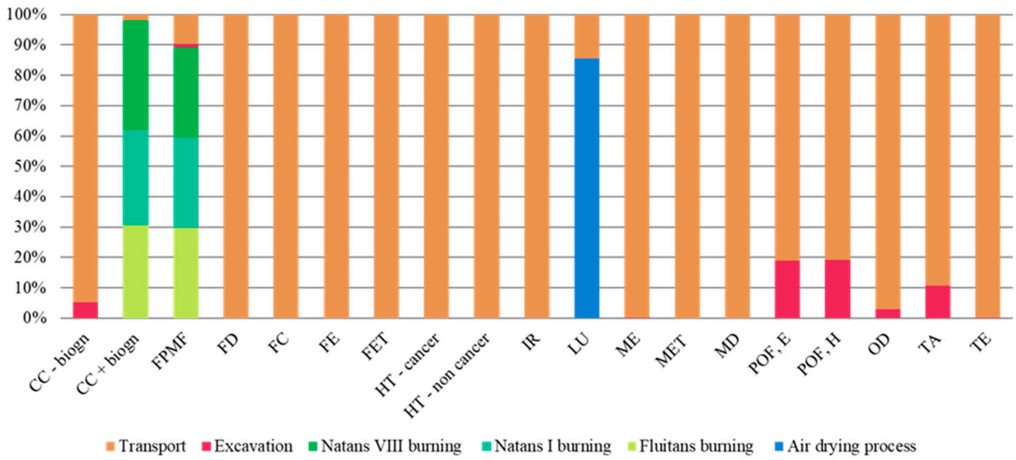

Figure 11. Percentage contribution of potential impacts to produce biomass by burning process for power generation.

Notably, the transportation of *Sargassum* algae follows the prevailing contribution pattern to most of the indicators for environmental impact, except for land use, in which the drying of the *Sargassum* algae prevails—as already discussed in the fiber production scenario—and the indicators of climate change and particulate formation, in which the contributions of the burning process of the *Sargassum* algae is predominant. Especially in the climate change indicator, the greatest contribution of CO_2 emissions from the burning of *Sargassum* algae compared to the use of fossil fuels in the transportation process is evident.

3.5. Comparison among Scenarios

Given the observation and discussion of contributions for each of the scenarios studied, Figures 12 and 13 show, respectively, an overview of the results for all scenarios, followed by a comparative graph of the contributions of each scenario for each indicator of impact potential. These comparative analyses were performed considering the emissions data from the Brazilian mix to properly observe the variations of the impact potential of the proposed geographic scope.

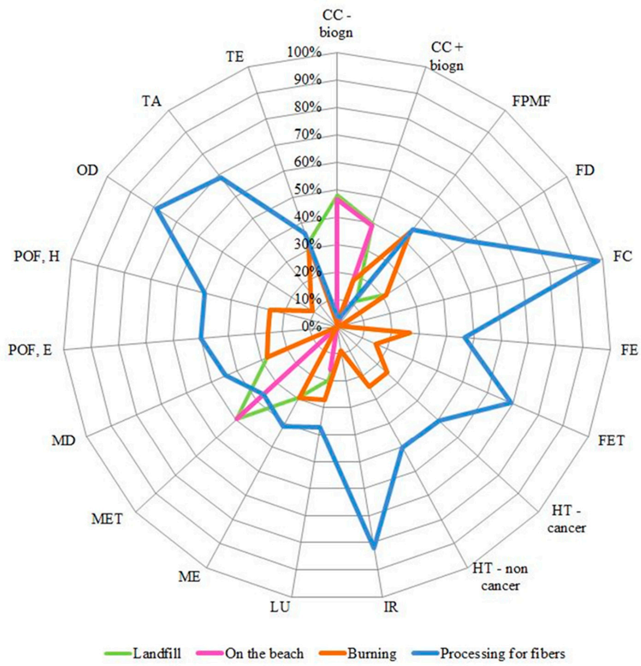

Figure 12. Comparison among *Sargassum* end-of-life scenarios.

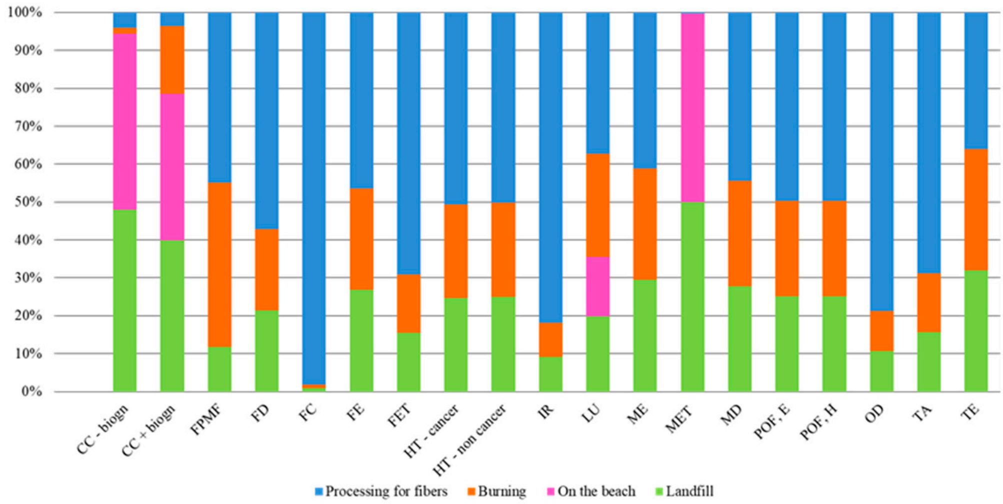

Figure 13. Percentage contribution of potential impacts from different scenarios of *Sargassum* end-of-life.

The general graph of total impact potentials for each scenario studied (Figure 11) show quite clearly the greater scope and magnitude of impact potentials resulted from the process of obtaining *Sargassum* fibers by grinding compared to the other scenarios. The burning process also has great scope among the different categories of impact, in general, with lower magnitude. Finally, the natural decomposition on the beach (reference) and in the landfill scenarios present contributions of impact potential in more specific categories, albeit with significant magnitude.

Thus, Figure 13 shows more clearly the relative contributions of each scenario for the 19 impact categories evaluated.

Both scenarios of natural decomposition, on the beach or in the landfill, have equivalent and dominant contribution to the categories of impact on climate change, evidencing the high potential of CO_2 emissions equivalent to the decomposition process of *Sargassum* algae, thus justifying initiatives to use this material for industrial products and processes to improve its environmental destination.

The same prevalence can be observed in the marine eutrophication impact category, possibly due to the low contributions of other processes, but also, especially when compared with the reference scenario, to the proximity of the decomposition region with marine ecosystems.

The contribution of these processes to the land use category are due to the areas directly occupied and affected by the process of natural decomposition of the end of life of algae.

The burning process presents a significant contribution to most indicators; however, it does not overcome, the impacts of the process of obtaining *Sargassum* fibers in any of the indicators, except for climate change (more biogenic carbon), in which it represents much less significant impact potential than that of the natural decomposition of *Sargassum* algae. The generation of particulate matter stands out in the burning scenario inherent to the biomass burning process, which can be the focus of mitigative actions.

Finally, the proposed scenario of drying, separating, and grinding the *Sargassum* algae to obtain fibers for use in other industrial processes, which showed the greatest magnitude in potential contribution for most of the proposed indicators, as observed earlier, is composed by processes of high electricity consumption, which is its highest point of sensitivity and mitigating potential. Thus, the change in the energy matrix is a great point of sensitivity since it has a great potential for both mitigating or worsening the impact potentials identified.

In order to better evaluate the magnitude of the impact potentials observed, especially for the use of biomass from *Sargassum* algae for the production of fibers, particles, and fly ash, this study compared such indicators, for similar applications, to the use of sugarcane biomass.

3.6. Comparative Analysis of Environmental Impact Potentials of Particle Production from Biomass of Sargassum Algae and Sugarcane

Sargassum dry biomass, among some possibilities, may be used as an alternative raw material for particleboard production. To produce the particles, the biomass suffers two more processes in addition to drying: grinding in a knife mill and sieving in vibrating sieves. Thus, for the comparison of the processes and distances used in the geographical scope, Figure 14 shows the information used in the comparative LCA of both materials.

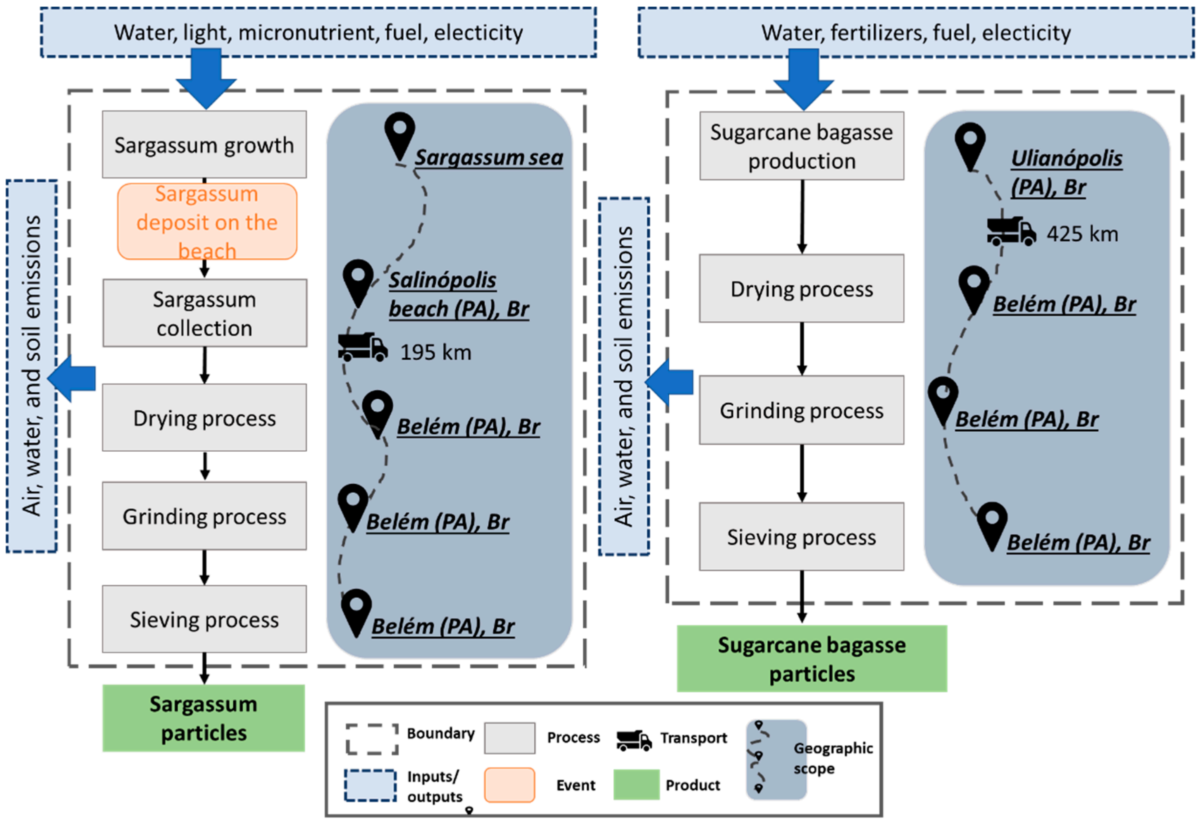

Figure 14. *Sargassum* versus Sugarcane bagasse particle production processes.

In the scenarios presented for each particle production, the same processes are presented: drying, cutting, and sieving. In these processes, energy consumption stands out, which was based on equipment used on a laboratory scale for processing. The drying processing of 1 kg of *Sargassum* algae generates 0.15 kg of particles, which was then considered a functional unit. The functional unit of 0.15 kg was adopted for sugarcane bagasse particles (SB) for comparison; however, according to Driemeier et al. (2018) [39], in the sugar–alcohol industry, sugarcane bagasse comes out of processing with approximately 50% moisture, so the entry of 0.3 kg of SB was considered before drying.

For both particles, the same energy consumption values were considered. The first process (drying) was considered a mixed process, in which outdoor pre-drying was performed, followed by drying in an oven with hot air circulation for six hours. For this process, the energy consumption was 7.91 MJ. Then, 0.238 MJ was considered consumption of the knife mill; finally, 0.0511 MJ was considered consumption for the sieving of the material.

Figure 15 shows that the production of sugarcane bagasse (SB) and *Sargassum* algae (SAR) particles presents similar values of environmental potential impact for all categories of impact, with slightly lower values to SAR particles. The percentage values of potential impact are in the range between 45.1% and 56.6% for SB particles and between 43.4% and 54.9% for SAR particles. Despite the range of similar values, the potential impact related to transport is higher for SB particles, mainly due to the large distance between the sugarcane plant and Belém, where processing takes place. Nonetheless, the potential impact values of SAR particles are similar to the SB values due to the excavation impact considered in the algae process.

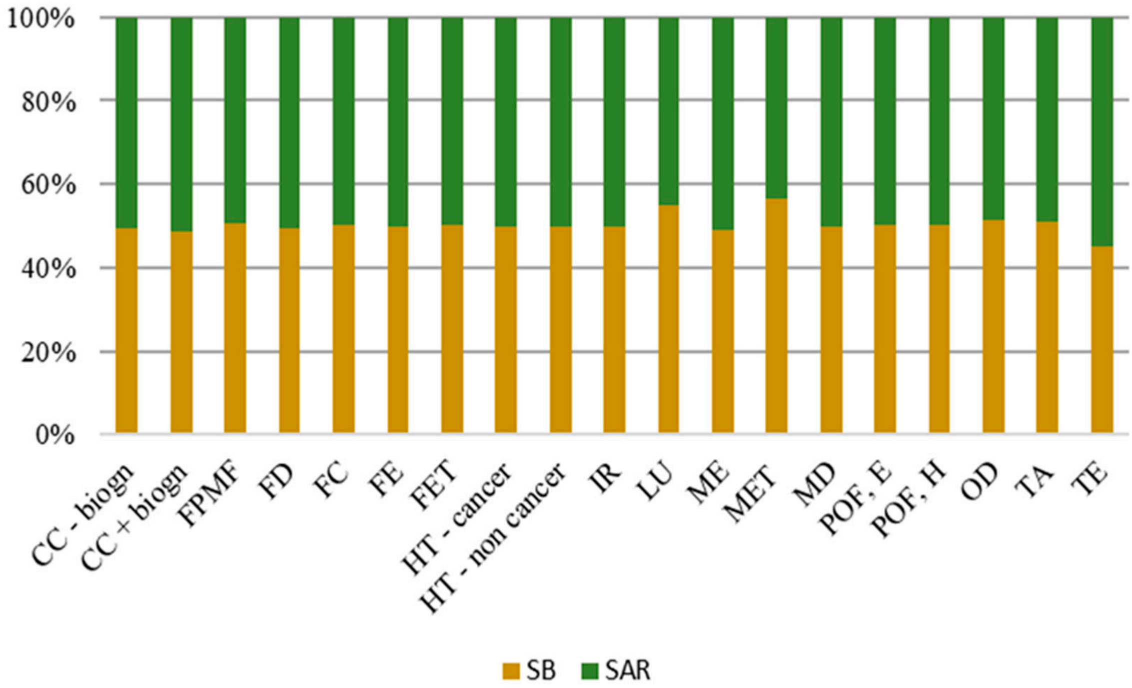

Figure 15. Comparison between percentage contribution of potential impacts *Sargassum* particles and sugarcane bagasse for particle board production.

The geographical scope of each product system can either worsen or mitigate the potential impacts of the product. In this case, the Brazilian northern region has a lower concentration of sugar–alcohol plants than the central-south axis, which results in greater distances for the transportation of bagasse and, consequently, in greater environmental impacts.

The impact category that presents the highest difference between particles is terrestrial ecotoxicity (TE), in which the production of 1kg of SB and *Sargassum* particles can generate approximately 13 kg of 1.4-DB eq., and 8.3 kg of 1.4-DB eq., respectively. The higher values of SB particles can be explained by the fertilizers and pesticides used in the agricultural cultivation.

Thus, for this scenario, the use of *Sargassum* particles presents a slightly lower potential for environmental impact. A possible destination for the particles produced would be the use in particle panels, which has already been studied with the use of [40–42]. However, no studies have been found in the literature on the production of particle panels with *Sargassum* algae. Therefore, although the environmental performance of *Sargassum* particles for this geographical scope is compared to that of sugarcane bagasse particles, their functional performance must be further explored, so that the particles can be considered as total or partial substitutes for conventionally used particles.

3.7. Comparative Analysis of Environmental Impact Potentials among Sargassum Fly Ash, Sugarcane Bagasse Fly Ash, and Limestone

Sargassum fly ash (SSA) has potential as a mineral filler in cementitious composites or alkali-activated composites due to its chemical composition (36–81% calcium) and the ash content of the algae (34–47% of its dry weight) [8]. The burning of the algae species natans I, natans VIII, and fluitans yields 32.3%, 19.0%, and 31.3%, respectively.

Sugarcane bagasse fly ash (SBA) is widely investigated as a renewable material alternative to sand [43] and limestone [44] in composites such as concrete and mortars. Thus, we propose a comparative LCA among SSA, SBA, and limestone to evaluate the environmental potential for the application of SSA in composites conventionally manufactured with limestone. The SSA used is a mix of the three species evaluated (15% of *S. natans* I, 35% *S. natans* VIII, and 50% *S. fluitans*).

The functional unit is one kilogram of inert material, and the geographic scope of SBA and limestone are presented along with the boundary of the systems in Figure 16.

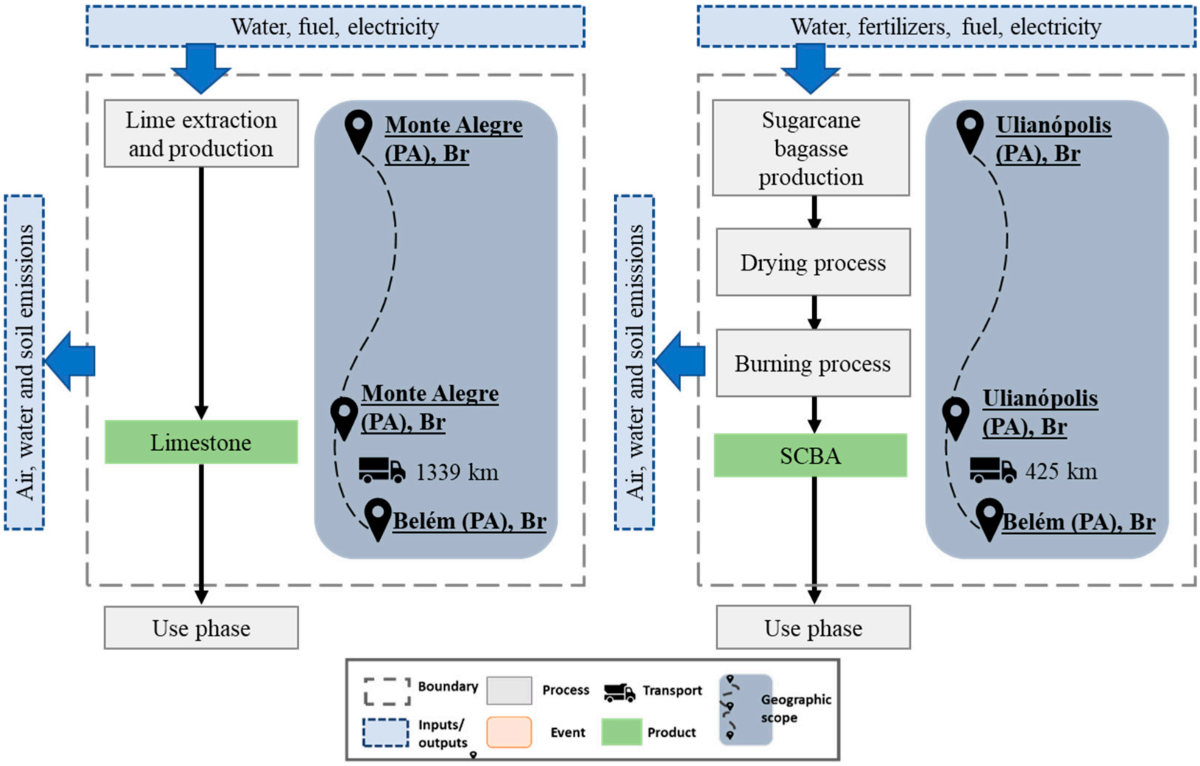

Figure 16. SCBA generation versus limestone extraction and production system boundaries.

The transportation of materials to the downtown of Belém is carried out by the same means (road); however, the supply distances are much different. The nearest limestone supplier is 1339 km from Belém, while the nearest sugar–alcohol plant is 425 km, and the distance traveled by *Sargassum* algae to the burning and use site is 195 km. The LCI process used for transportation was the use of 32 t maximum cargo trucks from the Ecoinvent 3.8 database. For the generation of sugarcane bagasse and the production of limestone, secondary LCI data from the Ecoinvent 3.8 database were used.

The multifunctionality between SBA and the energy produced by cogeneration in the sugar–alcohol plant was solved by the total allocation of the impacts of the burning to the main product (electricity). Due to the low calorific value of the dry algae (5.10 MJ/kg of *Sargassum* mix), the possibility of generating marketable energy by the cogeneration process was not considered; therefore, our main product—the SSA—carries 100% of the impacts of burning emissions.

Figure 17 shows the results of the comparison among the three materials. SBA presented the greatest impacts in most of the categories of environmental impact. These results are due to the stage of cultivation and generation of sugarcane bagasse, steps inexistent in the generation of SSA. The SSA, in turn, appears as the worst option only for the categories of CC + biogen, which makes it an option with positive environmental potential to be considered in scientific research on the development of new composites.

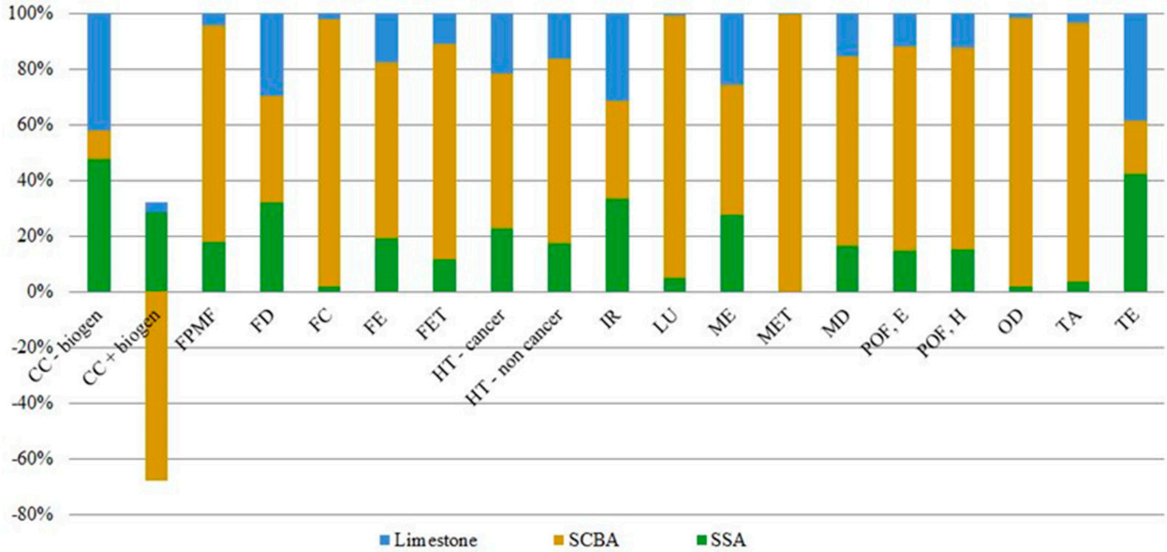

Figure 17. Comparison between percentage contribution of potential impacts of *Sargassum* particles and sugarcane bagasse for particle board production.

The CC + biogen impact category considers the CO_2 absorption capacity during any stage of the life cycle of each material. Thus, SBA appears to have positive impacts due to the cultivation of sugarcane, since the crop has a stock of 19.4% carbon [45], and therefore, a large CO_2 sequestration capacity [46].

Furthermore, the results of limestone and SSA LCIA have as a hotspot the transport of supply to the city of Belém and, as previously discussed for *Sargassum* particles, the choice of geographic scope can worsen or mitigate the potential environmental impacts.

Except for the CC + biogen category, SSA appears as an option with environmental potential for use as an inert material in new composites.

4. Conclusions

This study produced quantitative data on the possible environmental impact from different end-of-life scenarios of *Sargassum* algae to evaluate the feasibility of alternative applications of macroalgae in the civil construction sector.

Initially, we observed the different end-of-life scenarios of the *Sargassum* algae. Both scenarios of natural decomposition demonstrated a dominant contribution to the categories of impact for climate change (related to the decomposition process of *Sargassum* algae), marine eutrophication (possibly due to the proximity of the decomposition region to marine ecosystems), and land use (due to the areas affected by the natural decomposition process of the end of life of algae), thus justifying the search for new initiatives of algae use.

The burning process showed a significant contribution to most of the indicators, especially the massive particulate generation inherent to the biomass burning process, which may be the focus of mitigative actions.

The proposed scenario of biomass processing of *Sargassum* algae to obtain particles showed a prevalence of potential impact magnitude for most of the proposed indicators due to processes of high consumption of electricity—thus becoming the greatest focus of sensitivity and mitigative potential.

Despite the significant impact potentials for the mentioned categories presented by the proposed scenarios for the application of *Sargassum* biomass, these scenarios have the potential to significantly mitigate the high impact on climate change observed in the reference scenarios. Such decision-making should consider the main areas of sensitivity identified for each situation and application.

The comparative analyses performed between the results obtained for the application scenarios of *Sargassum* algae and sugarcane for particle and ash production also corroborate the results of this study. In both scenarios, we observed a lower potential impact of the use of *Sargassum* biomass compared to the other sources, thus evidencing the potential for mitigating environmental impacts with macroalgae use.

Both comparative studies, however, showed high sensitivity to the results on transportation distances, leading to the conclusion that the environmental potential of the use of different types of biomasses is directly linked to the geographical scope of the product system. Therefore, in regions where sugarcane production predominates, the use of sugarcane biomass seems to be the best alternative from an environmental perspective. On the other hand, the use of *Sargassum* algae has a greater potential for mitigating impacts in regions closer to the places where such deposits are found.

As potential limitations of the research, we highlight the lack of data on the composition and end-of-life emissions of *Sargassum*. Faced with this gap, the present research has enabled the production of greenhouse gas emissions data, not considering, however, other emissions such as NOx and VOCs. In conclusion, the main objective of comparative analysis was achieved, since our study demonstrated the quantitative and qualitative environmental potential and feasibility of the use of *Sargassum* biomass for particle and fly ash production. Thus, based on this feasibility analysis, studies can further investigate the potential for the application of these materials in different products and components for civil construction, replacing the materials with a high environmental impact potential.

Thus, we emphasize that the main contribution of this work to the field of knowledge consists of verifying the environmental viability of processing *Sargassum* biomass for potential uses in several industries, with a special focus on the civil construction industry.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su15076254/s1.

Author Contributions: Conceptualization, C.B., J.A.R.; methodology, C.B., F.G.T., L.M.G. and C.C.A.S.; formal analysis, C.B., L.M.G. and C.C.A.S.; investigation, F.G.T., L.M.G. and C.C.A.S.; writing—original draft preparation, C.B., L.M.G. and C.C.A.S.; writing—review and editing, C.B., M.M.V., M.J.B.d.M. and G.P.L.; supervision, C.B. and J.A.R.; project administration, J.A.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by FAPESP—Fundação de Amparo à Pesquisa do Estado do São Paulo grant number 2019/21007-0.

Data Availability Statement: Not applicable.

Acknowledgments: The authors thank the Fundação de Amparo à Pesquisa do Estado do São Paulo, Process nº 2019/21007-0 (FAPESP), for financial support. This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior—Brasil (CAPES)—Finance Code 001. MMV were supported by FAPESP (Project 2019/21047-1). J.A.R. was supported by CNPq (grant no 307921/2021-2).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Pörtner, H.-O.; Roberts, D.C.; Tignor, M.; Poloczanska, E.S.; Mintenbeck, K.; Alegría, A.; Craig, M.; Langsdorf, S.; Löschke, S.; Möller, V.; et al. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. In *Climate Change 2022: Impacts, Adaptation, and Vulnerability*; IPCC: Geneva, Switzerland, 2022; ISBN 9789291691586.
2. Haines, A.; Kovats, R.S.; Campbell-Lendrum, D.; Corvalan, C. Climate Change and Human Health: Impacts, Vulnerability and Public Health. *Public Health* **2006**, *120*, 585–596. [CrossRef]
3. Patz, J.A.; Frumkin, H.; Holloway, T.; Vimont, D.J.; Haines, A. Climate Change. *JAMA* **2014**, *312*, 1565. [CrossRef] [PubMed]
4. Trainer, V.L.; Moore, S.K.; Hallegraeff, G.; Kudela, R.M.; Clement, A.; Mardones, J.I.; Cochlan, W.P. Pelagic Harmful Algal Blooms and Climate Change: Lessons from Nature's Experiments with Extremes. *Harmful Algae* **2020**, *91*, 101591. [CrossRef] [PubMed]

5. Arabadzhyan, A.; Figini, P.; García, C.; González, M.M.; Lam-González, Y.E.; León, C.J. Climate Change, Coastal Tourism, and Impact Chains—A Literature Review. *Curr. Issues Tour.* **2021**, *24*, 2233–2268. [CrossRef]
6. Resiere, D.; Mehdaoui, H.; Névière, R.; Mégarbane, B. *Sargassum* Invasion in the Caribbean: The Role of Medical and Scientific Cooperation. *Rev. Panam. Salud Pública* **2019**, *43*, 1. [CrossRef]
7. Sissini, M.N.; de Barros Barreto, M.B.B.; Széchy, M.T.M.; de Lucena, M.B.; Oliveira, M.C.; Gower, J.; Liu, G.; de Oliveira Bastos, E.; Milstein, D.; Gusmão, F.; et al. The Floating *Sargassum* (Phaeophyceae) of the South Atlantic Ocean—Likely Scenarios. *Phycologia* **2017**, *56*, 321–328. [CrossRef]
8. Rossignolo, J.A.; Felicio Peres Duran, A.J.; Bueno, C.; Martinelli Filho, J.E.; Savastano Junior, H.; Tonin, F.G. Algae Application in Civil Construction: A Review with Focus on the Potential Uses of the Pelagic *Sargassum* spp. *Biomass. J. Environ. Manag.* **2022**, *303*, 114258. [CrossRef]
9. Oviatt, C.A.; Huizenga, K.; Rogers, C.S.; Miller, W.J. What Nutrient Sources Support Anomalous Growth and the Recent *Sargassum* Mass Stranding on Caribbean Beaches? A Review. *Mar. Pollut. Bull.* **2019**, *145*, 517–525. [CrossRef]
10. Resiere, D.; Mehdaoui, H.; Florentin, J.; Gueye, P.; Lebrun, T.; Blateau, A.; Viguier, J.; Valentino, R.; Brouste, Y.; Kallel, H.; et al. *Sargassum* Seaweed Health Menace in the Caribbean: Clinical Characteristics of a Population Exposed to Hydrogen Sulfide during the 2018 Massive Stranding. *Clin. Toxicol.* **2021**, *59*, 215–223. [CrossRef]
11. Milledge, J.; Harvey, P. Golden Tides: Problem or Golden Opportunity? The Valorisation of *Sargassum* from Beach Inundations. *J. Mar. Sci. Eng.* **2016**, *4*, 60. [CrossRef]
12. Thompson, T.M.; Young, B.R.; Baroutian, S. Efficiency of Hydrothermal Pretreatment on the Anaerobic Digestion of Pelagic *Sargassum* for Biogas and Fertiliser Recovery. *Fuel* **2020**, *279*, 118527. [CrossRef]
13. de Souza Coracao, A.C.; Dos Santos, F.S.; Duarte, J.A.D.; Lopes-Filho, E.A.P.; De-Paula, J.C.; Rocha, L.M.; Krepsky, N.; Fiaux, S.B.; Teixeira, V.L. What Do We Know about the Utilization of the *Sargassum* Species as Biosorbents of Trace Metals in Brazil? *J. Environ. Chem. Eng.* **2020**, *8*, 103941. [CrossRef]
14. Abdullah, M.A.; Ahmad, A.; Shah, S.M.U.; Shanab, S.M.M.; Ali, H.E.A.; Abo-State, M.A.M.; Othman, M.F. Integrated Algal Engineering for Bioenergy Generation, Effluent Remediation, and Production of High-Value Bioactive Compounds. *Biotechnol. Bioprocess Eng.* **2016**, *21*, 236–249. [CrossRef]
15. Kalia, V.C.; Prakash, J.; Koul, S. Biorefinery for Glycerol Rich Biodiesel Industry Waste. *Indian J. Microbiol.* **2016**, *56*, 113–125. [CrossRef]
16. Puspita, M.; Setyawidati, N.A.R.; Stiger-Pouvreau, V.; Vandanjon, L.; Widowati, I.; Radjasa, O.K.; Bedoux, G.; Bourgougnon, N. Indonesian *Sargassum* Species Bioprospecting: Potential Applications of Bioactive Compounds and Challenge for Sustainable Development. In *Advances in Botanical Research*; Academic Press: Cambridge, MA, USA, 2020; pp. 113–161.
17. López-Sosa, L.B.; Alvarado-Flores, J.J.; Corral-Huacuz, J.C.; Aguilera-Mandujano, A.; Rodríguez-Martínez, R.E.; Guevara-Martínez, S.J.; Alcaraz-Vera, J.V.; Rutiaga-Quiñones, J.G.; Zárate-Medina, J.; Ávalos-Rodríguez, M.L.; et al. A Prospective Study of the Exploitation of Pelagic *Sargassum* spp. as a Solid Biofuel Energy Source. *Appl. Sci.* **2020**, *10*, 8706. [CrossRef]
18. Desrochers, A.; Cox, S.; Oxenford, H.; Van Tussenbroek, B. *Sargassum Uses Guide: A Resource for Caribbean Researchers, Entrepreneurs and Policy Makers Lead*; Food and Agriculture Organization: Rome, Italy, 2020.
19. Amador-Castro, F.; García-Cayuela, T.; Alper, H.S.; Rodriguez-Martinez, V.; Carrillo-Nieves, D. Valorization of Pelagic *Sargassum* Biomass into Sustainable Applications: Current Trends and Challenges. *J. Environ. Manag.* **2021**, *283*, 112013. [CrossRef]
20. EPE (Empresa de Pesquisa Energética). *Brazilian Energy Balance 2021 Year 2020/Empresa de Pesquisa Energética*; EPE: Rio de Janeiro, Brazil, 2021.
21. Martinelli Filho, J.E.; Morais, L.M.S.; Aviz, D. Can the Invertebrate Fauna Associated to Pelagic *Sargassum* Landings in the Brazilian Amazon Coast Aid Us to Understand Its Origin and Dispersion? In Proceedings of the Sixty Eighth Annual Gulf and Caribbean Fisheries Institute, Panama, Central America, 9–15 November 2016; pp. 14–17.
22. Boyle, W.C. Energy Recovery from Sanitary Landfills—A Review. In *Microbial Energy Conversion*; Elsevier: Amsterdam, The Netherlands, 1977; pp. 119–138.
23. Symons, G.E.; Buswell, A.M. The Methane Fermentation of Carbohydrates 1,2. *J. Am. Chem. Soc.* **1933**, *55*, 2028–2036. [CrossRef]
24. Channiwala, S.A.; Parikh, P.P. A Unified Correlation for Estimating HHV of Solid, Liquid and Gaseous Fuels. *Fuel* **2002**, *81*, 1051–1063. [CrossRef]
25. Wang, S.; Cao, B.; Abomohra, A.E.-F.; Hu, Y.; Wang, Q.; He, Z.; Xu, S.; Feng, Y.; Bernard, U.B.; Jiang, X. Comparative Study of Combustion Properties of Two Seaweeds in a Batch Fluidized Bed. *Combust. Sci. Technol.* **2018**, *190*, 755–769. [CrossRef]
26. Achinas, S.; Euverink, G.J.W. Theoretical Analysis of Biogas Potential Prediction from Agricultural Waste. *Resour. Technol.* **2016**, *2*, 143–147. [CrossRef]
27. Allen, E.; Wall, D.M.; Herrmann, C.; Xia, A.; Murphy, J.D. What Is the Gross Energy Yield of Third Generation Gaseous Biofuel Sourced from Seaweed? *Energy* **2015**, *81*, 352–360. [CrossRef]
28. Bird, K.T.; Chynoweth, D.P.; Jerger, D.E. Effects of Marine Algal Proximate Composition on Methane Yields. *J. Appl. Phycol.* **1990**, *2*, 207–213. [CrossRef]
29. Milledge, J.J.; Maneein, S.; Arribas López, E.; Bartlett, D. *Sargassum* Inundations in Turks and Caicos: Methane Potential and Proximate, Ultimate, Lipid, Amino Acid, Metal and Metalloid Analyses. *Energies* **2020**, *13*, 1523. [CrossRef]
30. Mousavi, S.M.; Fatehi, H.; Bai, X.-S. Numerical Study of the Combustion and Application of SNCR for NO Reduction in a Lab-Scale Biomass Boiler. *Fuel* **2021**, *293*, 120154. [CrossRef]

31. Horvat, I.; Dović, D.; Filipović, P. Numerical and Experimental Methods in Development of the Novel Biomass Combustion System Concept for Wood and Agro Pellets. *Energy* **2021**, *231*, 120929. [CrossRef]
32. Medina, P.; Núñez, J.; Ruiz-García, V.M.; Beltrán, A. Experimental and Numerical Comparison of CO_2 Mass Flow Rate Emissions, Combustion and Thermal Performance for a Biomass Plancha-Type Cookstove. *Energy Sustain. Dev.* **2021**, *63*, 153–159. [CrossRef]
33. Backa, A.; Nosek, R.; Čaja, A. The Analytical Model of Biomass Combustion. *MATEC Web Conf.* **2020**, *328*, 04003. [CrossRef]
34. Martins, C.A.; Ferreira, M.A. Considerações Sobre a Formação de NOx Na Combustão. In Proceedings of the VI National Congress of Mechanical Engineering, Campina Grande, Brazil, 18–21 August 2010; pp. 18–21.
35. Hayhurst, A.N.; Vince, I.M. Nitric Oxide Formation from N2 in Flames: The Importance of "Prompt" NO. *Prog. Energy Combust. Sci.* **1980**, *6*, 35–51. [CrossRef]
36. Bowman, C.T. Control of Combustion-Generated Nitrogen Oxide Emissions: Technology Driven by Regulation. *Symp. Combust.* **1992**, *24*, 859–878. [CrossRef]
37. Kravetz, C. *Estudo do Desempenho Energético das Caldeiras da Indústria de Polpa Celulósica Kraft*; Universidade de São Paulo: São Paulo, Brazil, 2018.
38. La Picirelli de Souza, L.; Rajabi Hamedani, S.; Silva Lora, E.E.; Escobar Palacio, J.C.; Comodi, G.; Villarini, M.; Colantoni, A. Theoretical and Technical Assessment of Agroforestry Residue Potential for Electricity Generation in Brazil towards 2050. *Energy Rep.* **2021**, *7*, 2574–2587. [CrossRef]
39. Driemeier, C.E.; Ling, L.Y.; Yancy-Caballero, D.; Mantelatto, P.E.; Dias, C.S.B.; Archilha, N.L. Location of Water in Fresh Sugarcane Bagasse Observed by Synchrotron X-ray Microtomography. *PLoS ONE* **2018**, *13*, e0208219. [CrossRef]
40. Mendes, R.F.; Mendes, L.M.; Oliveira, S.L.; Freire, T.P. Use of Sugarcane Bagasse for Particleboard Production. *Key Eng. Mater.* **2014**, *634*, 163–171. [CrossRef]
41. Silva, D.A.L.; Lahr, F.A.R.; Pavan, A.L.R.; Saavedra, Y.M.B.; Mendes, N.C.; Sousa, S.R.; Sanches, R.; Ometto, A.R. Do Wood-Based Panels Made with Agro-Industrial Residues Provide Environmentally Benign Alternatives? An LCA Case Study of Sugarcane Bagasse Addition to Particle Board Manufacturing. *Int. J. Life Cycle Assess.* **2014**, *19*, 1767–1778. [CrossRef]
42. Silva, M.R.; Pinheiro, R.V.; Christoforo, A.L.; Panzera, T.H.; Lahr, F.A.R. Hybrid Sandwich Particleboard Made with Sugarcane, Pínus Taeda Thermally Treated and Malva Fibre from Amazon. *Mater. Res.* **2017**, *21*. [CrossRef]
43. Khawaja, S.A.; Javed, U.; Zafar, T.; Riaz, M.; Zafar, M.S.; Khan, M.K. Eco-Friendly Incorporation of Sugarcane Bagasse Ash as Partial Replacement of Sand in Foam Concrete. *Clean. Eng. Technol.* **2021**, *4*, 100164. [CrossRef]
44. de Siqueira, A.A.; Cordeiro, G.C. Properties of Binary and Ternary Mixes of Cement, Sugarcane Bagasse Ash and Limestone. *Constr. Build. Mater.* **2022**, *317*, 126150. [CrossRef]
45. Barbosa, L.D.S.N.S.; Hytönen, E.; Vainikka, P. Carbon Mass Balance in Sugarcane Biorefineries in Brazil for Evaluating Carbon Capture and Utilization Opportunities. *Biomass Bioenergy* **2017**, *105*, 351–363. [CrossRef]
46. Spósito, C.C.A.; Fazzan, J.V.; Rossignolo, J.A.; Bueno, C.; Spósito, F.A.; Akasaki, J.L.; Tashima, M.M. Ecodesign: Approaches for Sugarcane Bagasse Ash Mortars a Brazilian Context. *J. Clean. Prod.* **2023**, *385*, 135667. [CrossRef]