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The Use of Sargasso Seaweed as Lignocellulosic Material for Particleboards: Technical Viability and Life Cycle Assessment

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Abstract: There have been beaching events of the marine alga pelagic sargassum in coastal regions of the Caribbean Sea, West African countries, and the north-northeast region of Brazil since 2011. Its presence has caused environmental and socioeconomic impacts while several studies were conducted in order to understand the causes of this phenomenon, as well as alternatives to mitigate its impacts. The objective of this research was to evaluate pelagic sargassum biomass from beaching as a raw material for the manufacture of medium-density multilayer particleboards, aiming for an application that can reduce the impacts generated by the disposal of this seaweed on beaches and landfills. These are composed of 30% sargassum particles in their inner layer and 70% sugarcane bagasse particles on their outer layers, which are bonded with castor-oil-based polyurethane resin. A physical and chemical characterization was carried out in order to evaluate sargassum particles while physical and mechanical tests were carried out in order to evaluate the panels. Results were subsequently compared with indications from different particleboard standards. A life cycle assessment was carried out to complement the feasibility study of these panels and to compare their different manufacturing processes. The multilayer panels met the minimum requirements for physical and mechanical properties established by regulations, indicating that the *Sargassum* spp. biomass can be used as filling. The life cycle assessment study indicates that sargassum panels produced in the Belém, PA, Brazil, region present lower environmental impacts in four of seven evaluated categories when compared to conventional panels. Given the results obtained, the use of sargassum from beaching events as raw material for panels can be presented as an alternative for reducing social, economic, and environmental impacts in the regions affected by these events.

Keywords: sargassum; sugarcane bagasse; particleboard; biomass; LCA

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1. Introduction

The Sargassum Sea is composed predominantly by the holopelagic species Sargassum fluitans (morphotype III) and Sargassum natans (morphotypes I and VIII). It is a region of great ecological importance in the Atlantic Ocean, as its large floating biomass provides shelters, food, and substrates to several marine animals such as fish, invertebrates, birds, and turtles. It is, thus, a priority area for preservation [1,2].

Nevertheless, massive effluxes of pelagic sargassum began to cover a wider region since 2011, stretching from West Africa, passing through northern Brazil, and reaching the Gulf of Mexico; this new region is now called the "Great Atlantic Sargassum Belt

(GASB)" [3–5]. This belt is maintained due to the rapid proliferation of these phaeophycean seaweeds, which are sustained mainly by the increase in ocean surface temperatures, changes in the pattern of sea currents, and the increase in nutrient supply in the Amazon basins, Mississippi, and Congo rivers, as well as the resurgence and supply of sand from the Sahara Desert [4,6–10].

The expansion and changes in the displacement of large masses of these algae has caused beaching events, commonly called "Golden Tides" due to their color, and they reach coastal regions such as the Gulf of Mexico, the Caribbean, West Africa, and northern Brazil [11–14]. These could have catastrophic consequences for the affected coastal regions, both for the ecosystem and for human health [8].

Economic activities such as tourism and fishing are directly affected by these beaching events, which can also bring exotic species, causing problems for water quality and the development of native species [15–18]. Local population health can also be affected by the decomposition of stranded biomass due to the release of toxic gases such as methane, hydrogen sulfide, and ammonia, immediately imposing the removal of this biomass from beaches [16,19]. According to Davis et al. [20], when sargassum is washed ashore, it is collected mechanically and subsequently taken to a landfill; however, this practice generates costs. The authors also report estimates from the Caribbean Regional Fisheries Mechanism (CRFM), with around 210 million dollars having been spent on cleaning sargassum from the region's beaches in 2018.

Satellite imagery monitoring is a fundamental tool in order to understand the phenomena of pelagic sargassum blooms and attempt to correlate any changes in their occurrence patterns with bioclimatic factors [21]. In 2018, the GASB had just over 20 million tons of pelagic sargassum biomass dispersed across 8850 km [20], a significant increase when compared to the 5 million tons observed in 2011 from the OLCI imagery system (Ocean and Land Color Instrument) [12].

Several studies related to the problem of sargassum beaching seek to understand the secondary issues caused by these events. In this sense, a study by Arana et al. [22] evaluates the potential of microplastic transport caused by the movement of sargassum to beaches and how to mitigate these issues. Research such as Durand et al. [23] and Liranz-Gómez et al. [24] study the perception of populations affected by beaching events, the actions taken by the responsible government, and how this can affect actions to mitigate the problem. And also, there are studies correlated with the decrease in tourism and its negative impacts [25].

According to Amador-Castro et al. [26], other studies are looking for application alternatives that value *Sargassum* spp. biomass coming from beaching events in order to help mitigate the problem. Nevertheless, Rossignolo et al. [14] report that there is little work on the application of this biomass in civil construction, despite other algae already being used in some sectors of this area. Some research indicates the feasibility of its application in the particleboard sector, such as the study of fibers from the algae Kappaphycus alvarezii and Gracilariopsis longissima for the production of Medium-Density Fiberboard (MDF) [27] as well as Posidonia oceanica fibers in the production of composite panels [28,29].

Alamsjah et al. [27] developed a study where the feasibility of producing panels using algae fibers from aquaculture ponds was evaluated as alternatives to the use of wood, contributing to the preservation of forests in Indonesia and increasing the competitiveness of the fiber panels market. The panels produced were evaluated by physical–mechanical tests and compared with the Japanese industry's normative document for panels (JIS A 5905-2003). The research results showed that the treatment using 50% sawdust, 50% K. alvarezii fiber, and 12% adhesive met the normative document in both physical and mechanical parameters, indicating the potential of algae as a raw material for the production of panels.

Within this context, the introduction of sargassum in sugarcane bagasse medium-density particleboards may present an opportunity, given the range of studies demonstrating the viability of bagasse for this purpose already. As examples, here is Fiorelli, Bueno, and Cabral [30], who evaluated physical, mechanical, and thermal properties, and the durability of multilayer particleboards produced with green coconut fibers in their inner layer and sugarcane bagasse on the outer layers. Milagres et al. [31] evaluated the physical and mechanical properties of particleboards with sugarcane bagasse and compared the results with previous data on pine wood panels. Yano et al. [32] evaluated the physical and mechanical properties of medium-density panels (MDPs) using sawdust and sugarcane bagasse. Lastly, Duran et al. [33] evaluated physical and mechanical properties as well as moisture resistance in medium-density panels made of sugarcane bagasse particles.

MDP panels are characterized by having a density range between 550 and 750 kg/m^3 and can have a homogeneous or multilayer structure. Multilayer medium-density panels are commonly produced with a three-layer composition (inner layer or core and outer layers). The layers differ from each other, and the outer layers are composed of smaller particles and with a greater amount of resin, providing a better compression rate and density and, therefore, better physical and mechanical properties [30].

There is a growing concern in the industrial sector in reducing production system environmental impacts. For this, the life cycle assessment (LCA) methodology provides techniques for quantifying the inputs and outputs of a product system, identifying the most relevant environmental impacts as well as the main hotspots at each stage of the process. As such, it is possible to evaluate and present alternative ways that can minimize these impacts or present the alternative process that generates the least impact [34–36].

Silva et al. [35] developed an LCA study in the production of MDP using sugarcane bagasse and wood. The study covered the process from cradle to gate that evaluates everything from the acquisition of raw materials to the production of the final product, with a design that encompassed three subsystems: bagasse generation, bagasse distribution, and panel production. Potential environmental impacts were assessed using the CML and USEtox methods. According to the authors, the main identified hotspots were related to a panel production subsystem, highlighting the great contribution of urea-formaldehyde resin used to agglomerate particles. The conclusion of the work indicates that replacing wood with bagasse provides a better environmental performance.

The objective of this work is the technical evaluation and LCA of multilayer panels composed of sugarcane bagasse on their outer layers and sargassum particles in their inner layers, and agglomerated with castor-oil-based polyurethane resin (castor PU). The development of this work seeks to evaluate the feasibility of using sargassum biomass from beaching events in order to minimize the impacts caused by these events.

2. Materials and Methods

Dried algae of the genus *Sargassum* spp. collected in May 2021 in the municipality of Carutapera, Maranhão (Brazil), and sugarcane bagasse supplied by a sugar and alcohol plant located in the region of Pirassununga, São Paulo (Brazil), were used to produce the medium-density multilayer panels.

The resin used to agglomerate the particleboards was the commercial two-component castor-oil-based polyurethane resin (PU castor oil), free of solvents (100% solids), with mass loss only above 210 °C, at a content of 12% for the inner layer and 15% for the outer layers in accordance with the recommendations by Fiorelli, Bueno, and Cabral [30].

2.1. Chemical and Anatomical Characterization of Particles

The chemical characterization of sargassum fibers followed the recommendations of Van Soest [37], determining the levels of lignin, cellulose, hemicellulose, and extractives. The bromatological test was carried out by separating the cellular content, using the technique of solubilizing, first in a neutral detergent solution and then acid detergent; finally, the lignin is separated from the rest of the material by filtration.

The anatomical characterizations of sugarcane bagasse and sargassum were performed through scanning electron microscopy images, using a low-vacuum TM-3000 Hitachi microscope.

2.2. Multilayer Panel Production

The steps for multilayer particle panel production followed the guidelines established by Fiorelli, Bueno, and Cabral [30]. After collection, the sargassum and sugarcane bagasse were dried in an oven with air circulation, processed in a knife mill, and sieved in a mechanical shaker, resulting in particles with lengths ranging from 0.3 to 1.0 mm (outer layers) and 1.0 to 4.0 mm (inner layer).

The castor PU resin was sprayed onto the particles in a proportion of 12% of the inner layer (sargassum) and 15% of the outer layer (sugarcane bagasse) in a planetary mixer. After mixing, the material was inserted into a mattress-forming mold in a thermo-hydraulic press.

Pressing took place at a pressure of 5 MPa, at 100 °C for 10 min [38]. The panels measuring 40 × 40 cm and 15 mm thick were stored in an air-conditioned room with a controlled temperature and humidity (20 ± 3 °C and 65 ± 5% RH) until a constant mass was obtained. Three multilayer panels were produced with 30% sargassum particle mass in the inner layer and 70% sugarcane bagasse particles in the outer layer (35:30:35) (Figure 1).

Figure 1. Sugarcane bagasse and sargassum particleboard sample (50 × 50 mm).

2.3. Characterization of the Panels

The panels were evaluated through physical and mechanical tests following the guidelines adapted from NBR 14810-2:2018—Medium density particleboards (in Portuguese) [39], using 10 test samples for each analysis: 24h thickness swelling, three-point bending (modulus of rupture and modulus of elasticity), and perpendicular tensile (internal bond). Samples measuring 50 × 50 mm were used for the thickness swelling and internal bond tests and 350 × 50 mm for the bending test. Mechanical evaluations were carried out through a universal testing machine, from the BioPdi brand, which has a load capacity of 10 KN (test speed of 8 mm/min for bending test and 4 mm/min for perpendicular tensile).

The results of the physical and mechanical tests were compared to recommendations of the NBR 14810-2:2018—Medium density particleboards (in Portuguese) [39] and ISO 16893:2016—Wood-based panels—Particleboard standard [40]. The arithmetic mean was used as a trend measure, while the standard deviation was used as a measure of dispersion.

Microstructural characterization was carried out through a Hitachi TM-3000 low-vacuum scanning electron microscope. The images aimed to record particle agglomeration and the presence of voids in particleboards.

2.4. Life Cycle Assessment

ISO 14040: Environmental Management—Life Cycle Assessment—Principles and Framework [41] and 14044: Environmental Management—Life Cycle Assessment—Requirements and Guidelines [42] were followed for the life cycle assessment (LCA). This study presents a comparative attributional LCA of four multilayer particleboards: Eucalyptus + UF (urea-formaldehyde) resin (CP), sugarcane bagasse + UF resin (BUFP), sugarcane bagasse + PU resin (BPUP), and sugarcane bagasse + sargassum + PU resin (BSP). The aim is to recommend raw materials with less environmental impact in the production of these composite panels.

The function of the studied systems was established for MDP for non-structural applications in dry environments, in accordance with the NBR 14810-2:2018 standard [39], and for general use and furniture production in dry conditions and non-structural use meeting the ISO 16893-2016 requirements. Thus, the functional unit defined for this study was the production of 1 m^3 of medium-density multilayer panels, with a 15 mm thickness, and a density between 700 and 750 kg/m^3. The durability of the panels was considered the same, as there are no studies on the degradation of panels with the use of polyurethane resin from castor oil, sugarcane bagasse, and sargassum.

The reference flows of this study are presented in Table 1. The quantities presented for the BUFP and BPUP reference panels were obtained from the referenced articles, while the BSP was obtained in a laboratory.

Table 1. Composition of multilayer particleboards.

Panels	Panel Composition					Reference
	Eucalyptus (kg)	Sugarcane Bagasse (kg)	Sargassum (kg)	Urea-Formaldehyde Resin (UF) (kg)	Castor Bean Polyurethane Resin (PU) (kg)	
CP	630	-	-	70	-	Faria et al. [43]
BUFP	-	640	-	60	-	Ribeiro et al. [44]
BPUP	-	651	-	-	99	Duran et al. [33]
BSP	-	447	198	-	106	This study

The cradle-to-gate system was adopted, and encompasses the production, acquisition, transportation, and preparation of raw materials, and production. The main activities of the agricultural or forestry phase in the case of Eucalyptus and sugarcane bagasse raw materials are the cultivation of seedlings, soil preparation, planting seedlings, management, harvesting, and transportation. For sargassum, deposition on the beach, collection, and transportation are considered. All raw materials are dried, chipped or ground, and classified. From there, the molding and pressing along with resins takes place and is followed by a finishing phase. As there are no studies of particleboards with sugarcane bagasse and sargassum, the stage of use and end of life was considered the same for all different panels; therefore, it was disregarded in this research.

The geographic scope of this study presents two evaluation scenarios, one of them in Pirassununga, SP, Brazil—a region close to the sugarcane bagasse supply industry—while the other is in Belém, PA, Brazil—a region close to sargassum landfalls—as shown in Figure 2. As such, transport was considered for the main raw materials: Eucalyptus, sugarcane bagasse, sargassum, UF resin, and castor PU resin.

Allocation was avoided for all production stages, except for the sugarcane bagasse, where the current Ecoinvent 3.7.1 process already presents its mass allocation impacts.

The production process data for all panels are considered similar, only with a variation in energy consumption in the preparation of raw materials.

Secondary data extracted from a database were used for the life cycle inventory (LCI) phase, with predominant information on the European context. The LCA was carried out with GaBi 6 software, using secondary databases, with Eucalyptus production and the MDP panel production inputs and output taken from the "SICV Brasil" LCA database [https://sicv.acv.ibict.br/] (accessed on 6 February 2024). The processing for sargassum was taken from Bueno et al. [45] and the other Ecoinvent 3.7.1 processes. Table 2 presents the secondary data used for multilayer particleboards' LCA.

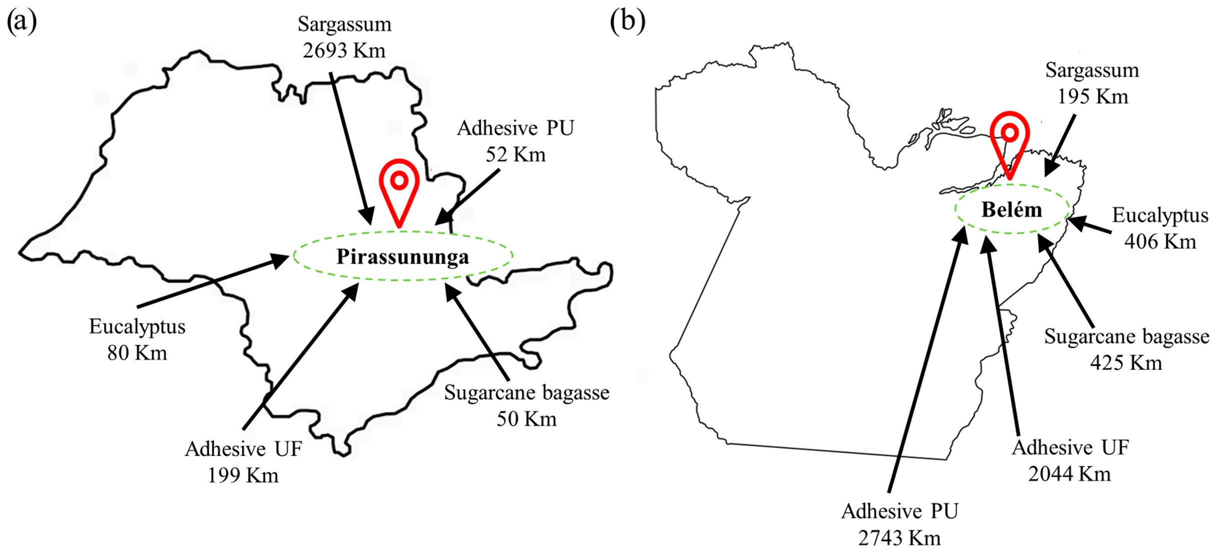

Figure 2. The geographic scope of this study. (**a**) Pirassununga, SP, Brazil, and (**b**) Belém, PA, Brazil.

Table 2. Secondary data and respective sources used for multilayer particleboards.

Processes' Inputs and Outputs	Data Source
Inputs	
Materials	
Sargassum particle	Bueno et al. [45]
Eucalyptus	SICV Brazil
Sugarcane bagasse; BR: market for bagasse, from sugarcane	
Castor-oil-based polyurethane resin; EU-28: 2-component PUR adhesive based on polyether and castor oil (modified energy consumption based on a Brazilian industry)	Ecoinvent 3.7.1
Urea-formaldehyde resin; RER: melamine formaldehyde resin production	
Lubricating oil; RER: lubricating oil production	
Diesel; BR: diesel, import from Row	
Heavy fuel oil; BR: heavy fuel oil, import from Row	
Transport	
Transport; RoW: transport, freight, lorry, all sizes; EURO3 to generic market for transport, freight, lorry, and unspecified.	Ecoinvent 3.7.1
Electricity consumption	
Electricity; BR: electricity, high voltage, production mix	Ecoinvent 3.7.1
Outputs	
Medium-density multilayer panels	-

Recipe 2016 was the life cycle inventory analysis (LCIA) method used in this study, which is one of the most recent and current methods available. There currently is no consolidated Brazilian methodology. Seven of the most impactful categories in the panel production process were evaluated. These are climate change (including biogenic carbon), fossil depletion, freshwater consumption, human toxicity (cancer and non-cancer), land use, and terrestrial ecotoxicity.

3. Results

3.1. Chemical and Anatomical Properties of Particles

A quantification of the particles' lignocellulosic composition contributed to the interpretation of the physical and mechanical properties of this product, given that the fiber tensile strength is closely related to the internal structure and chemical composition [46].

Table 3 presents the lignocellulosic composition of sargassum particles, sugarcane bagasse, and *Pinus* spp.—a wood commonly used in the commercial production of particleboards.

Table 3. Lignocellulosic composition of Sargassum and agro-industrial waste.

Waste	Cellulose (% *)	Hemicellulose (% *)	Lignin (% *)	Source
Pelagic Sargassum	**41.48**	**3.21**	**16.94**	**This study**
Sugarcane bagasse	50.47	30.56	10.74	Fiorelli et al. [47]
Pinus spp.	51.13	15.10	27.29	Fiorelli et al. [47]

* Percentage by mass.

The sargassum holocellulosic composition values (cellulose + hemicellulose) are close to those presented in a study carried out by Borines, De Leon, and Cuello [48], which indicated the holocellulosic composition of *Sargassum* spp. at 46.08%. On the other hand, the values are below those presented by Ali and Bahadar [49], which were at 63.7%.

According to Borines, De Leon, and Cuello [48], variation in sargassum chemical composition may be related to several environmental factors such as water, temperature, salinity, light, and amount of nutrients available. These factors stimulate or inhibit the biosynthesis of various compounds, and vary depending on the location and season, with values differing from one year to the next.

It is worth highlighting that the value obtained for sargassum lignin content in this study differs from what is seen in the literature. According to John et al. [50] and Wi et al. [51], the cell wall of algae contained low levels of lignin (less than 1%). This probably occurred because the methodology differed from those applied in the aforementioned studies, which focus on the production of biofuels. The result of around 16% lignin must be related to other materials being similar to lignin. This can be seen in Alzate-Gaviria et al.'s study [52], who observed the presence of compounds similar to lignin in *Sargassum* spp. biomass from the Caribbean region.

Sargassum particles showed lower levels of cellulose, hemicellulose, and lignin compared to other agro-industrial residues that have been used in the studies of unconventional panels. According to Fengel and Wegener [53], the high cellulose content contributes to wood resistivity, while the high lignin content improves rigidity, providing better mechanical properties to the panels. As such, particles of this algae are not similar to the wood lignocellulosic composition of *Pinus*—mainly with regard to lignin content—which can impact the physical and mechanical performance of the particleboards.

Still within this context, lignin is a component that acts as a sealing agent and, therefore, holds an extremely important binding property, providing a better agglomeration of particles in the panels in addition to its hydrophobic characteristic [54]. The low lignin content in algae creates a need for higher resin levels in order to ensure adequate particle agglomeration and less thickness swelling.

Samples of sugarcane bagasse (Figure 3A) and sargassum particles (Figure 3B) were ran through scanning electron microscopy (SEM) to comparatively evaluate their morphological structure, as well as pore anatomy between particles.

Figure 3A illustrates how sugarcane bagasse particles present surface pores at different diameters. This trait contributes to resin dispersion between the particles, positively affecting the panels' physical and mechanical properties [47].

Figure 3B shows sargassum particles with a "spongy" appearance. This differs from sugarcane bagasse particles, as porosity does not occur superficially. The presence of these large voids contributes to greater water absorption, leading to damages in the panels' physical and mechanical properties.

This corroborates what happened in another application described by Ahmed et al. [55], who developed nylon membranes associated with sargassum biomass for removing heavy metals in water treatment systems. According to the authors, the addition of 30% sargassum biomass to the membrane provided an increase in the porosity and absorption capacity, contributing to an increase in the efficiency of the material.

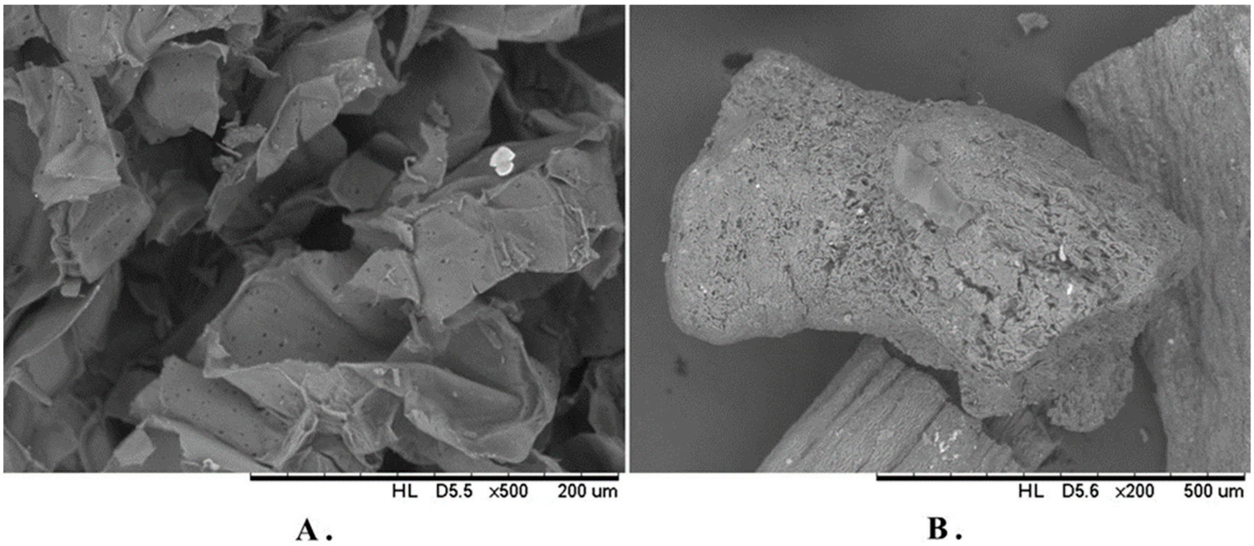

Figure 3. Images of sugarcane bagasse and sargassum particles obtained by SEM. (**A**) Sugarcane bagasse particles at 500× magnification. (**B**) sargassum particles at 200× magnification.

Initially, it is concluded that these chemical and anatomical characteristics of sargassum particles do not improve the physical and mechanical performance of particleboards and are more suitable when used as a filler in the production of these composites.

3.2. Panel Physical and Mechanical Properties

Table 4 presents the average values of the physical and mechanical properties of sugarcane bagasse and sargassum particleboards, from scientific works and regulatory guidelines.

Table 4. Mean values of the physical and mechanical properties in sugarcane bagasse and sargassum particleboards. Values derive from scientific works and normative guidelines.

Medium-Density Panels	ρ (kg/m^3)	Adhesive	TS (%)	MOR (MPa)	MOE (MPa)	IB (MPa)	Source
			24 h				
Sugarcane bagasse and *Sargassum*	**750**	**PU**	**19.81**	**16.31**	**2162**	**0.49**	**This study**
(sd)			0.84	1.30	273.25	0.15	
Sugarcane bagasse	700	UF	9.9	15.6	2021	0.48	Ribeiro et al. [44]
Sugarcane bagasse	750	PU	14.99	15.48	1885	1.02	Duran et al. [33]
Eucalyptus	700	UF	11.50	18.71	1841	0.65	Faria et al. [43]
NBR 14810-2:2018—Non-structural use in dry conditions (P2)	551–750		22	11	1600	0.35	
ISO 16893-2016—General purpose for use in dry conditions	-		-	10	-	0.24	
ISO 16893-2016—Furniture grade for use in dry conditions	-		-	11	1600	0.35	

ρ: density; **TS**: thickness swelling; **MOR**: rupture modulus; **MOE**: elasticity modulus; **IB**: internal bond; **(sd)**: standard deviation; **UF**: urea-formaldehyde; **PU**: castor-oil-based two-component PU resin.

The physical and mechanical results from the sugarcane bagasse and sargassum panels indicate technical feasibility for non-structural applications in a dry environment in accordance with the NBR 14810-2:2018 standard. It also meets all the ISO 16893-2016 requirements for general use in dry conditions and for furniture production in dry conditions.

Duran et al. [33] produced MDP from sugarcane bagasse and PU castor resin with different proportions between layers (20:60:20). The multilayer panel with sargassum in its inner layer presented higher mean values for MOR and MOE than those obtained for panels composed only of sugarcane bagasse. Nevertheless, there were lower IB and TS mean values. It is worth noting that the sargassum panel was produced with a higher resin content in its outer layers.

In the research by Rammou et al. [29], P. oceanica particles and sawdust were used to produce particle panels, varying content between 0 and 50%. According to the authors, the increase in the content of P. oceanica particles reduced panel mechanical resistance values. Nevertheless, the swelling of these panels was opposite to that observed in panels with sargassum particles.

Figure 4 shows sugarcane bagasse and sargassum particle panels before (A) and after (B) immersion in water for 24 h. From image (B), it is possible to see that sargassum particles expanded more than those of sugarcane bagasse. This is related to the anatomical characteristics of the alga (high porosity and low lignin content).

A. B.

Figure 4. Sargassum particleboard sample (50 × 50 mm). (**A**) Before thickness swelling test. (**B**) After thickness swelling test.

Although it met the minimum TS requirement established by the normative, this greater expansion of sargassum particles when subjected to the test corroborates the chemical and anatomical analysis carried out previously; however, these evaluated particleboards have characteristics that enable their use as thermal or acoustic insulators.

3.3. Particleboard Microstructural Analysis

Figure 5 shows a transition region between the external (sugarcane bagasse) and the internal (sargassum) layer of the particleboard. The internal layer presents more voids when compared to the external layer. Additionally, there is also the "spongy" characteristic of sargassum particles—a trait related to the TS results, which were higher due to its hygroscopicity.

The presence of these voids also indicates less compaction between the sargassum particles, which can directly influence the mechanical performance. However, using a 30% algae content only in the inner layer of the panels, the mechanical performance maintained results adequate to the established standards, given that the load requests from the three-point bending test are greater in the outer layers.

In this case, the multilayer panel structure presents an efficient design for the introduction of sargassum particles, since in the inner layer, the load requests are lower and the sargassum can fill this zone in the panel.

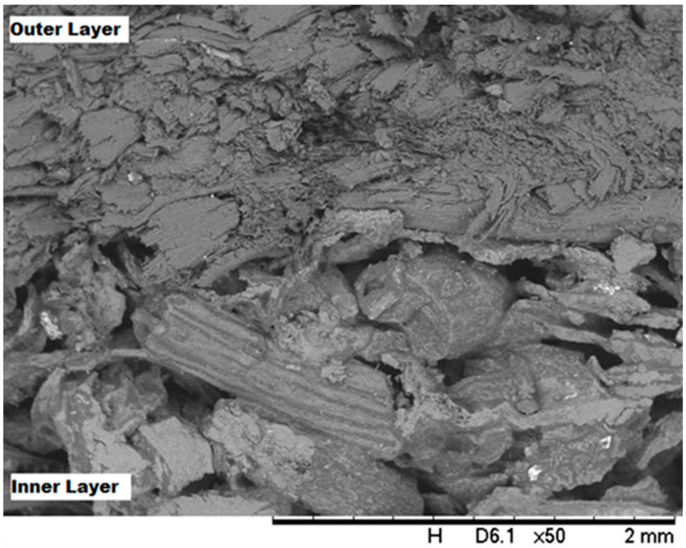

Figure 5. Images of sugarcane bagasse and sargassum particleboard outer and inner layers. Image was obtained with SEM at 50× magnification.

3.4. Life Cycle Assessment

This item presents the comparative life cycle assessments of the four different multilayer particleboards: CP, BUFP, BPUP, and BSP. Production took place in the Brazilian cities of Pirassununga, SP, Brazil, and Belém, PA, Brazil, and the six impact categories were evaluated.

Figure 6 presents the potential impacts on the climate change category (including biogenic carbon) for the production of panels in (a) Pirassununga, SP, Brazil, and (b) Belém, PA, Brazil. These graphs show that CP panels presented the best environmental performance in both locations. Conventional particleboards have a positive impact for this category, which outweighs the negative due to the CO_2 absorbed by Eucalyptus forests through the photosynthetic process. It is estimated that these forests absorb two times more CO_2 than they emit, which contributes to mitigating climate change [56].

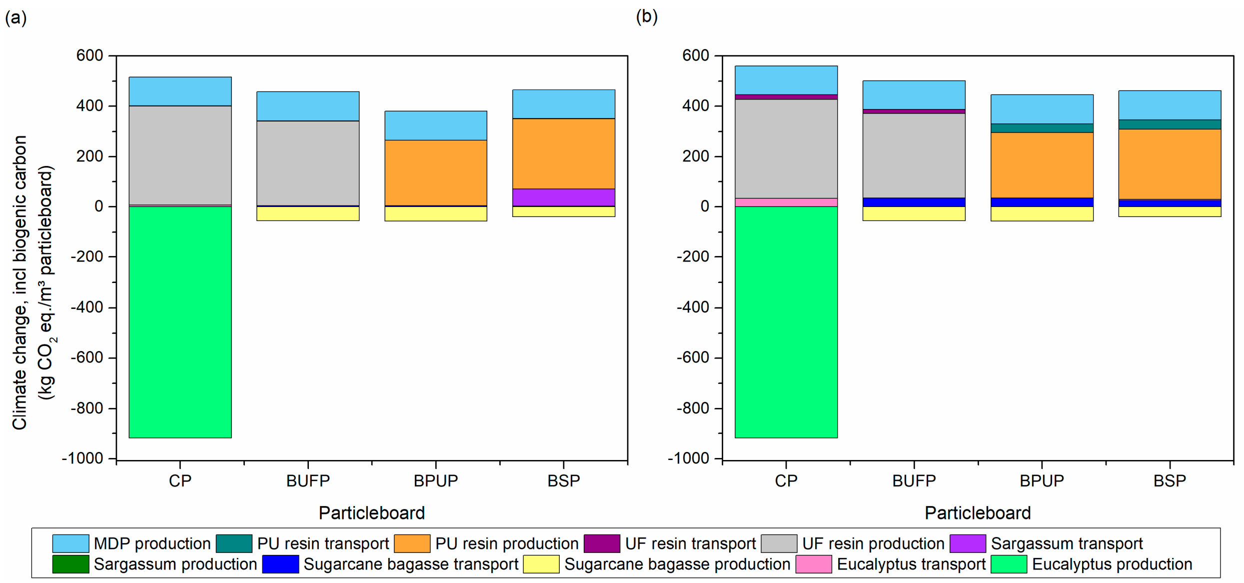

Figure 6. Environmental impact of multilayer particleboard production on the climate change category; (**a**) Pirassununga, SP, Brazil, and (**b**) Belém, PA, Brazil.

Despite sugarcane bagasse also having a positive environmental impact from photosynthesis, it is inferior to Eucalyptus due to the emissions from planting and harvesting. These result in a greater consumption of fossil fuels such as diesel for agricultural equipment and trucks.

The most important negative impacts come from the BSP panel production in the Pirassununga region, and BUFP panels for the Belém region. In the case of the BSP panel, there is a significant contribution from the transport of sargassum from the north of Brazil to Pirassununga, SP, which contributes to the increase in CO_2 emissions. For the BUFP panel, UF resin has a greater impact when compared to PU resin. When compared to production between the city of Belém and the city of Pirassununga, the transport of sugarcane bagasse and resin has a greater contribution to the increase in equivalent CO_2 emissions in the northern region of Brazil, given the long-distance transport to production facilities.

Resin production is primarily responsible for negative environmental impacts on climate change. UF resin contributes approximately 70% to 83% of impacts, while PU resin can contribute between 6% and 80%, depending on panel composition. The use of compounds derived from fossil raw materials and the use of non-renewable sources for generating electricity are the factors that mostly contribute to these impacts. The lowest contribution, which is observed in PU resin, occurs due to the partial replacement of the adhesive composition with vegetable polyurethane based on castor oil. When UF resin is used, methanol and urea are generated in its production, contributing to climate change [34].

The second stage that most contributes to potential negative impacts is the production of multilayer particleboards, corresponding to approximately 20% to 35%, mainly due to electricity from non-renewable sources and the use of heavy fuel oils.

Figure 7 presents the potential impacts on the fossil depletion category for panels produced in (a) Pirassununga, SP, Brazil, and (b) Belém, PA, Brazil. This figure shows that CP panels exert the greatest negative impact on the fossil depletion category, followed by BUFP panels in both locations. The production of UF resin is the stage that most contributes to this category due to the use of mineral coal and natural gas in its urea-formaldehyde production processes. These present a relative contribution of approximately 76% to 85% for the different panels using this resin.

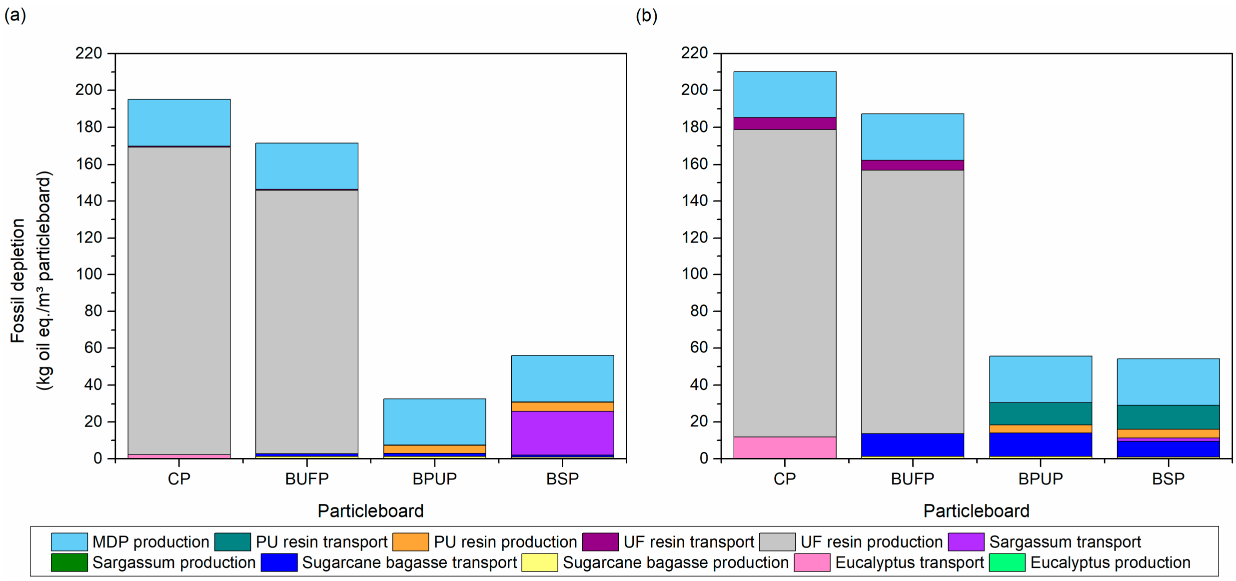

Figure 7. Environmental impact of multilayer particleboard production on the fossil depletion category; (**a**) Pirassununga, SP, Brazil, and (**b**) Belém, PA, Brazil.

The manufacture of MDP panels is the second process that contributes to this category given the use of heavy fuel oil as a source of thermal energy, diesel for internal transport, and fossil sources for the production of a portion of Brazilian electricity; currently, 14% of energy comes from fossil sources [57].

This contribution varies approximately from 12% to 76% depending on panel composition; as for panels that use PU, this is the stage with greatest contribution.

Comparing the two regions, we found that the distance of the raw materials to the MDP factory interferes with the results. Sargassum when used in Pirassununga, SP, Brazil, and Eucalyptus, sugarcane bagasse, and resins when used in Belém, PA, Brazil, contribute negatively to fossil depletion because of transport distances, and consequently, there is greater diesel consumption. The BPUP panel is the composition with the lowest impact for the fossil depletion category, as it uses PU resin and short-distance transport.

Figure 8 presents the potential impacts on the freshwater consumption category for panels produced in (a) Pirassununga, SP, Brazil, and (b) Belém, PA, Brazil.

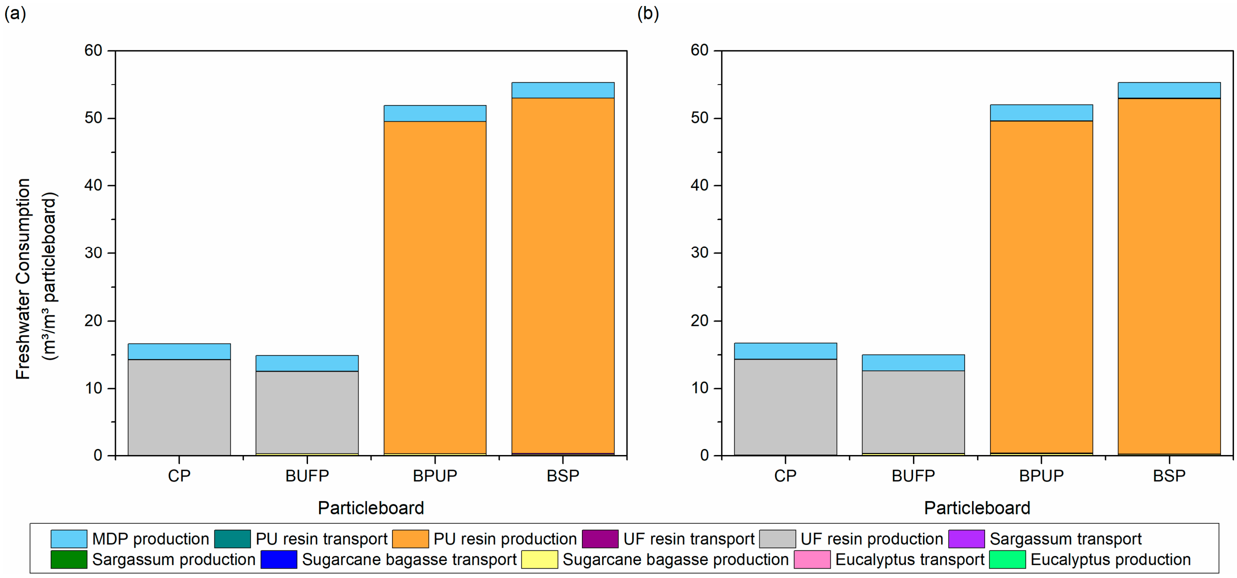

Figure 8. Environmental impact of multilayer particleboard production on the freshwater consumption category for (**a**) Pirassununga, SP, Brazil, and (**b**) Belém, PA, Brazil.

The biggest negative impacts in this category occurred in BSP panels, followed by BPUP, for both regions. This occurred because both panels use castor PU resin as a binder, and the production of this resin increases 94% to 95% of the emissions that contribute to this category. PU resin has high freshwater consumption due to the irrigation of castor beans during cultivation, and the water used in the resin production process. Furthermore, the production of electrical energy in Brazil contributes to the water consumption category, as over 60% of the Brazilian energy matrix comes from hydroelectric plants [57].

The BUFP panel composition has the lowest negative environmental impact, as it uses UF resin in smaller quantities when compared to CP panels.

Figure 9 presents the results of potential impacts on the human toxicity (cancer) category for panels produced in (a) Pirassununga, SP, Brazil, and (b) Belém, PA, Brazil.

According to the graphs, the panels with the greatest negative impact for this category are CP followed by BUFP. This is goes to the UF resin production stage, which presents the greatest negative impact due to formaldehyde emissions during the manufacturing process. The resin presents an approximate relative contribution between 64% and 73% for the different panels that use this type of resin.

The second stage with a greater contribution is the production of MDP panels due to the consumption of fossil fuels for transport and the generation of thermal and electrical energy. It represents 23% to 88% of the relative contribution depending on the panel, as this is the step with the greatest contribution in processes that do not use UF resin.

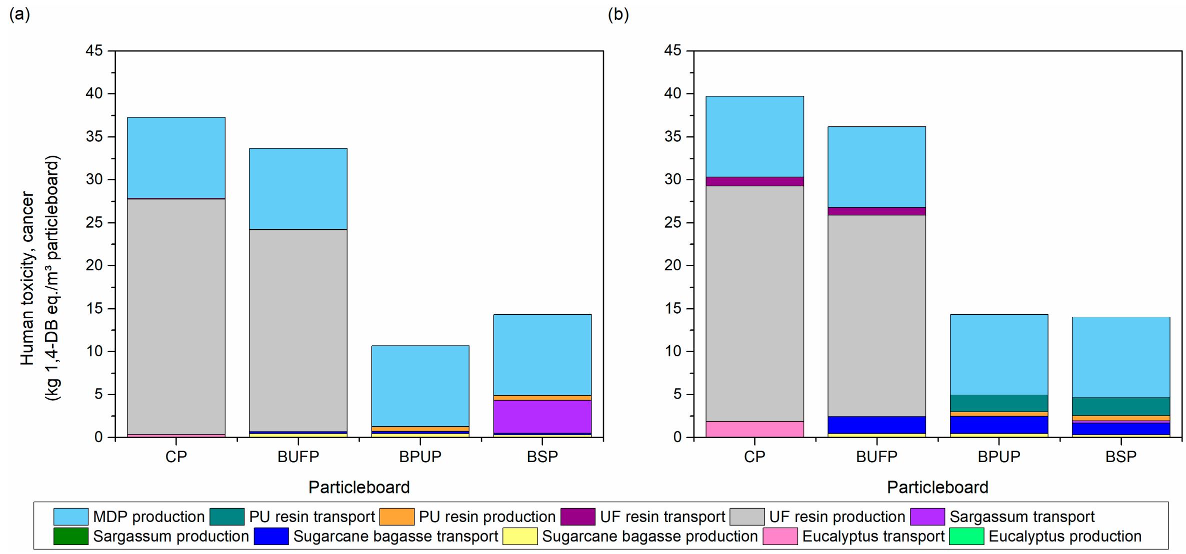

Figure 9. Environmental impact of multilayer particleboard production on the human toxicity, cancer category; (**a**) Pirassununga, SP, Brazil, and (**b**) Belém, PA, Brazil.

Long-distance transport contributes significantly to this category, with the transport of sargassum having an impact on the region of Pirassununga, SP, and the transport of resins and bagasse to the region of Belém, PA.

Thus, the lowest observed impact is for the composition of sugarcane bagasse + PU resin (BPUP) produced in the Pirassununga, SP, region.

Figure 10 presents the results of potential impacts on the human toxicity (non-cancer) category for panels produced in (a) Pirassununga, SP, Brazil, and (b) Belém, PA, Brazil.

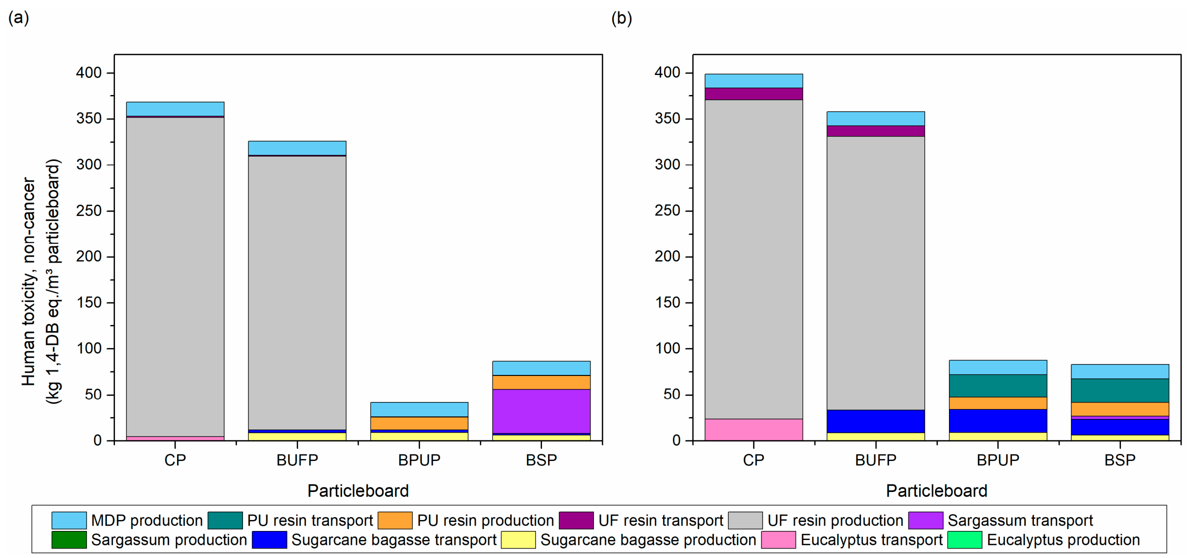

Figure 10. Environmental impact of multilayer particleboard production on the human toxicity, non-cancer category; (**a**) Pirassununga, SP, Brazil, and (**b**) Belém, PA, Brazil.

Similar to the human toxicity category with carcinogenic effects, the non-carcinogenic effect category presents the greatest negative impacts for CP and BUFP panels in both locations. This occurs due to the use of UF resin, which presents a contribution of approximately 83% to 94% on panels that use it in their composition. The production of this adhesive emits toxic substances during its processing, presenting high emissions for this category [36].

Transport over long distances is the second most significant emission source, as we observed that the transport of sargassum to the region of Pirassununga, SP, Brazil, and the transport of sugarcane bagasse and resins to the region of Belém, PA, Brazil, are the ones with the highest emissions.

BPUP panels produced in the Pirassununga, SP, Brazil, region presented the best environmental performance due to the raw materials used and short-distance transport.

Figure 11 presents the impacts on the land use category from panels produced in (a) Pirassununga, SP, Brazil, and (b) Belém, PA, Brazil. The graphs indicate that agricultural crops are the ones that contribute the most to this category.

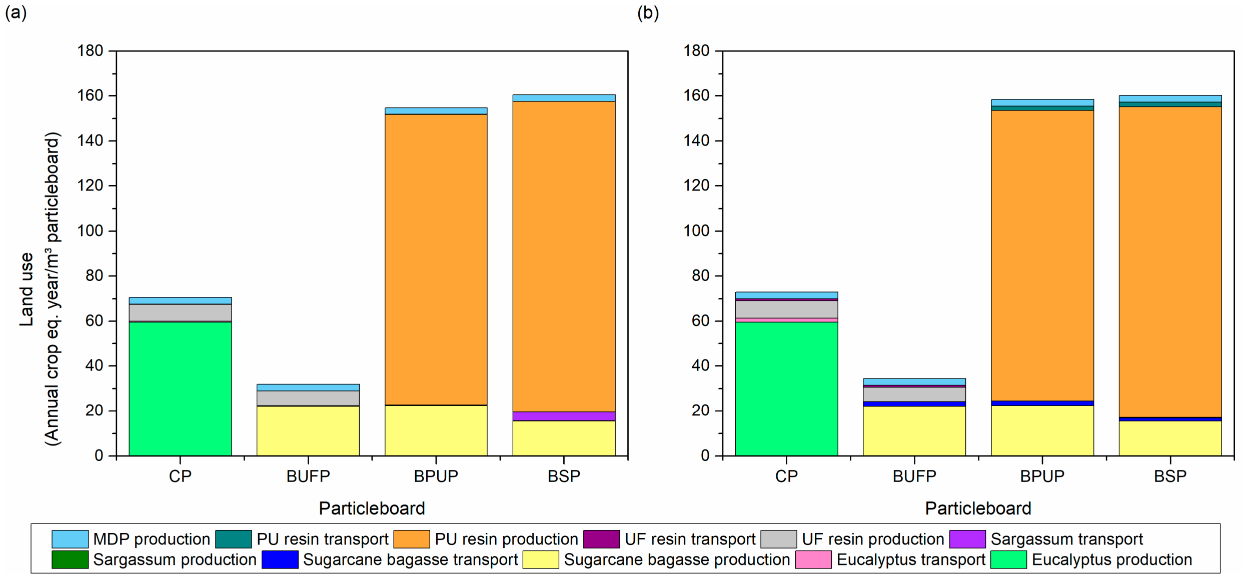

Figure 11. Environmental impact of multilayer particleboard production on the land use category; (**a**) Pirassununga, SP, Brazil, and (**b**) Belém, PA, Brazil.

The compositions that present the highest land use are BSP and BPUP due to the use of castor PU resin, which represents 81% to 86% of land use. Compared to other crops, Eucalyptus, bagasse, and castor beans have the lowest production per area, thus presenting a greater occupation, vacancy, and soil transformation. Next, there is the production of Eucalyptus and sugarcane. Furthermore, there is the contribution of the electrical energy during the production of the PU resin itself, which makes significant use from hydroelectric plants, with these requiring large areas for their operation.

As such, BUFP panels presented the lowest negative impact for this category, as they contain sugarcane bagasse and UF resin in their composition.

Figure 12 presents the results of potential impacts on the terrestrial ecotoxicity category for panels produced in (a) Pirassununga, SP, Brazil, and (b) Belém, PA, Brazil. The graphs indicate that long-distance transport is what mostly contributes to emissions in this category, with the use of diesel-emitting toxic substances into the soil.

For the Pirassununga, SP, Brazil, region, the production process with the worst environmental performance was BSP panels, due to the transport of sargassum from the northern region of Brazil, contributing to 77.47% of emissions. For Belém, PA, Brazil, the panels showed very similar results, with high emissions mainly originating from long transport distances. The panel with the highest emission was CP due to the transport of Eucalyptus, as well as the transport and production of UF resin, which contribute 36.73%, 40.26%, and 20.15%, respectively.

Thus, BPUP panels from the Pirassununga, SP, Brazil, region presented the best environmental performance due to the use of PU resin and short-distance requirement to acquire raw materials.

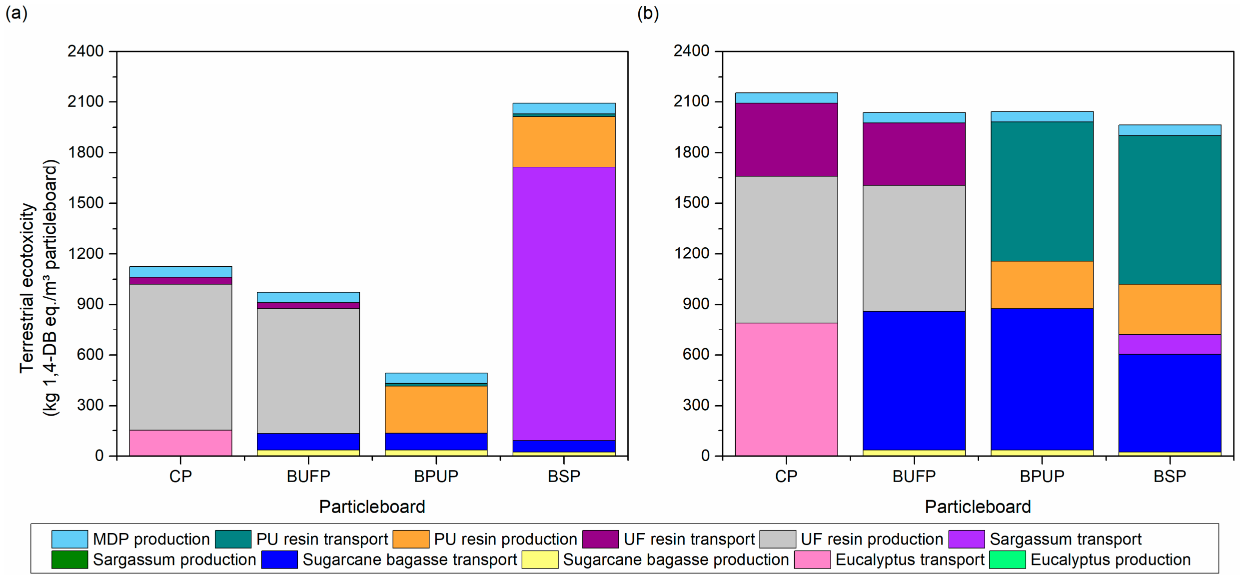

Figure 12. Environmental impact of multilayer particleboard production on the terrestrial ecotoxicity category; (**a**) Pirassununga, SP, Brazil, and (**b**) Belém, PA, Brazil.

Among all the categories compared to conventional panel production, BSP panels presented better environmental impact potential for three of them in Pirassununga, SP, Brazil, and four in Belém, PA, Brazil. Nevertheless, when compared to BPUP panels produced in Pirassununga, SP, Brazil, panels that use only sugarcane bagasse had the lowest potential environmental impact among them all.

It is important to notice that sargassum itself almost does not contribute to emissions for all the presented categories. The problem of BSP panel production is related to the transportation of raw materials. In regards to the region of Pirassununga, SP, Brazil, the transport of sargassum impacts emissions, whereas when production takes place in Belém, PA, Brazil, the transport of PU resin and sugarcane bagasse affects the negative environmental impacts.

The main limitations in this study stem from the use of secondary data for both resins (PU and UF), which come from European databases, due to the lack of national data. The production of focus panels in this study occurred at a laboratory scale; therefore, data from other panel production processes were used to assume a commercial scale. Even so, this assessment is extremely important to allocate sargassum arriving on beaches while aiming to reduce their economic, social, and environmental problems.

4. Conclusions

This work produced quantitative data on the use of sargassum as a raw material in the production of particleboards with different applications, evaluating the technical performance and their respective potential environmental impacts while aiming to present an alternative way of using this biomass.

The introduction of an internal layer of pelagic sargassum in sugarcane bagasse particleboards results in problems of dimensional instability and increased thickness swelling. Nevertheless, the 30% sargassum composition in the inner layer of the panel meets all the minimum requirements required by NBR 14810-2:2018 standards and ISO 16893:2016 for furniture in dry conditions.

Most of the potential negative environmental impacts are related to the use of fossil fuels and the production of UF resin. Thus, the BSP panel can replace the conventional Eucalyptus panel, as it presents lower impacts for most of the categories when produced in the Belém, PA, Brazil, region. This also comes in addition to avoiding toxic gas emissions that occur when sargassum decomposes on beaches or landfills. Ideally, sargassum should be processed in regions close to collection sites. It is also important to identify waste that can replace sugarcane bagasse such as local biomass, and assess whether resins are manufactured in these regions.

Considering the problem of sargassum beaching events, which are causing economic and environmental impacts, and the use of its particles as filler in particleboards can be an alternative to mitigating this problem.

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