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Wood Waste Management from the Furniture Industry: The Environmental Performances of Recycling, Energy Recovery, and Landfill Treatments

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Abstract: Proper management of wood waste (WW) from the furniture industry has become an important issue. Life-cycle assessment (LCA) is a tool that is widely used for identifying environmental gains in WW management strategies. Thus, the aim of this research was to perform a comparative LCA, analyzing the environmental aspects and impacts of different WW management scenarios generated in the furniture industry in the state of Espirito Santo, Brazil. To conduct the study, five scenarios were designed: medium-density fiberboard (MDF) production (Scenario 1), medium-density particleboard (MDP) production (Scenario 2), solid ceramic brick production (Scenario 3), heat production in the ceramics industry (Scenario 4), and landfill disposal (Scenario 5). The results showed that compared to Scenarios 3 and 4, Scenarios 1 and 2 are potentially more favorable for disposing of WW. Scenario 1 achieved more environmental benefits in all of the impact categories evaluated. Notably, 1 m^3 of MDF stores 1080 kg CO_2 eq/m^3, which results in a net impact of −849 kg CO_2 eq/m^3 of MDF. Scenario 5 is the least favorable practice. This research designs scenarios that contribute to reductions in the demand for virgin sources and increases in environmental gains.

Keywords: life-cycle assessment; LCA; wood waste; furniture industry; circular economy

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1. Introduction

Furniture manufacturing is one of the oldest industrial activities worldwide, and technological advances have enabled its manufacturing system to evolve and increase in scale [1]. Worldwide, 77% of furniture production is concentrated in 10 countries, with Brazil being the 6th-largest producer [2,3]. This manufacturing sector generates a large volume of wood waste (WW) from the processes of cutting and sanding, for which the main raw materials are solid wood and wood panels. The Brazilian wood furniture industry represents 80% of the furniture production units in the country [4]. There were a total of 17,900 industries that produced 372 million pieces of furniture in 2022 [2]. Notably, approximately 30 million tonnes of WW is generated annually in Brazil [5]. Therefore, proper management of WW has become an important goal.

WW management should consider WW as an input for the production of materials and energy [6]. An analysis of 49 studies indicated that the generation of heat and electricity is common; in relation to wood products, reconstituted panels such as MDP (medium-density particleboard) and MDF (medium-density fiberboard) are the most investigated [7]. However many places in the world still send WW to landfills; this practice should not be prioritized, due to the accompanying generation of leachate, greenhouse gas (GHG) emissions, reduced landfill life, and wasted land use [8].

The circular economy (CE) is an economic model that describes practices whereby waste is avoided by encouraging its return to production processes or directing it toward new production cycles that can recover its value [9]. This process provides options for reusing and recycling materials. In this context, the concept of industrial symbiosis proposes a connection between production units in which the waste from one unit is adopted as a raw material by another unit [10]. In the study carried out by Cárcamo and Panãbaena-Niebles [11], Brazil stood out as the leader in the number of research projects in the Americas (81%), which is significant for an emerging economy. However, the contaminants in WW can hinder its use in a CE. To ensure quality, it is necessary to separate potential contaminants from potential materials [12]. In this way, the proper handling and classification of WW enhances its circularity.

Life-cycle assessment (LCA) is a widely used tool for identifying environmental gains in WW management strategies [8,13,14]. In this context, LCA is a methodology that supports CE and, thus, supports robust decision-making for a CE model.

Managers in the furniture industry in the state of Espírito Santo (ES), located in the southeastern region of Brazil, lack a systemic vision regarding the full value of this manufacturing sector. This includes knowledge of each stage of the product's life cycle, from the extraction of raw materials to final disposal [15]. The vast majority of companies in the state work in a linear production system, where their waste is disposed of in landfills or incinerated. This type of manufacturing is contained in a paradigm where the main stages are extraction, production, use, and disposal; this process is reaching its limit [9].

The furniture sector in Espírito Santo has 479 establishments, of which 417 produce furniture using predominantly wood materials. Another characteristic of this furniture segment is the number of small companies, which account for 55% of all manufacturing units in the state [16]. In the north-central area of the state, the spatial focus of this research is the furniture hubs of Colatina and Linhares, which together account for 75 industries [17]. The Linhares furniture center occupies a prominent position nationally in the manufacture of mass-produced furniture, while the Colatina furniture center traditionally focuses on the production of custom-made furniture. An annual generation of 80,000 tonnes of WW has been estimated for these two furniture hubs [17,18], which can vary from one year to the next due to market fluctuations [19]. Most of the waste generated is destined for firing in the kilns of the red ceramics industry. In addition, a wood panel industry is located in the far north of Espírito Santo, which is one of the main suppliers of raw materials to the furniture industry. This relationship supports connections between manufacturing units based on the concept of industrial symbiosis, which enables units to work together on a regional or local scale; synergies between industries are detectable and transport distances are feasible in technical and economic terms, thus allowing waste to substitute for natural resources [11].

The aim of this study was to carry out a comparative LCA, analyzing the environmental aspects and impacts of different WW management scenarios generated in the furniture industry of Espirito Santo, with the north-central area of the state as the spatial focus of the research. The following WW management scenarios were studied: MDF production, MDP production, solid ceramic brick production, heat production in the ceramics industry (current practice), and landfill disposal. In addition, the products and energy generation were compared with the predominant market scenarios that use virgin sources. To the best of the authors' knowledge, no other LCA study has provided a broad overview of different alternatives for managing WW from the furniture industry, projecting scenarios based on the industrial synergies of a given region. Furthermore, this research included wood panel waste in its analysis, which is still minimally studied. This research focuses on a Brazilian region, but it is intended to contribute to future studies to be conducted in other locations.

2. Theoretical Background

The basic raw materials of the wood furniture industry are solid wood and wood-based materials such as plywood, veneer, MDF, MDP, and OSB (oriented strand board) [20]. Part of these raw materials is lost in manufacturing in the form of waste, which is estimated at 10% of the total mass [21]. However, a study carried out at a medium-sized furniture industries in Espírito Santo showed a percentage loss of over 20% [22].

The technical feasibility of using WW has been proven by many studies. Buschalsky and Mai [23] investigated the recovery of wood fiber from post-use MDF waste via thermohydrolytic disintegration, which proved the viability of this process up to the third generation of panels. Teixeira [24] researched the combined use of MDP waste and fresh residual wood to manufacture new MDP panels, concluding that all of the product's properties remained preserved. Other studies have considered 100% natural WW as a raw material for the production of MDP [6,25]. In addition, Mori et al. [26] found that adding up to 11% WW was feasible without altering the technical properties of solid ceramic bricks.

Kim and Song [8] applied LCA to evaluate the performance of WW recycling systems for the production of particleboard and combined heat and power generation, and the results showed a greater benefit for the production of particleboard. Hossain and Poon [13] carried out an LCA of the current practice in Hong Kong of disposing of WW in landfills compared to three proposed scenarios that included the use of chipboard, wood–cement board, and energy production. The authors concluded that generating energy from WW was the best strategy for environmental gains when compared to generating energy from coal. Sormunen et al. [27] conducted a comparative study with various construction waste products, including wood, for the manufacturing of thermoplastic composites; this study covered environmental and economic aspects based on LCA and accounting principles, respectively. The results of the environmental analysis showed that the use of WW compared to plastic waste in the production of composites had lower benefits due to the lower impacts avoided from its disposal. In addition, Pinho and Calmon [7] conducted a broad critical review of the literature on the LCA of WW management systems. The results showed that although the research followed ISO standards, it was possible to verify the lack of standardization and clarity in relation to how the LCA methodology is applied in investigations centered on the environmental analysis of WW management systems. As a contribution, the article sought to provide a guideline proposal for conducting future research. Most of the authors mentioned have carried out LCAs of the management of WW from fresh wood, but some studies have used WW from panels [14,28].

3. Materials and Methods

LCA is a widespread method that supports waste management decision-making. The attributional LCA conducted in this study was based on the ISO 14040 [29] and ISO 14044 [30] standards for the following phases: (i) definition of purpose and scope, (ii) inventory analysis, (iii) life-cycle impact assessment, and (iv) interpretation.

3.1. Defining the Scope

The reference flow adopted for the analysis of the scenarios involving wood panels was 1 m^3 of MDF and MDP produced. In the scenarios involving the production of solid ceramic bricks and heat, 1 kg of ceramic bricks produced was adopted. For the landfill scenario, the reference flow was 1 kg of waste destined for the landfill.

The prevailing Brazilian market scenarios for producing wood panels (MDF and MDP) and bricks, which include inputs from virgin sources from the cradle to the factory gate, were compared to the WW-based scenarios. The length of the product system in the proposed scenarios was from the collection of the WW to its destination at the panel, brick, or landfill factory gate. The furniture hubs in Espírito Santo are Linhares, Colatina, and Grande Vitória. Figure 1 shows the region studied, with the locations of the furniture hubs for each municipality, points of interest for the proposed scenarios, and the relevant road distances for the analysis.

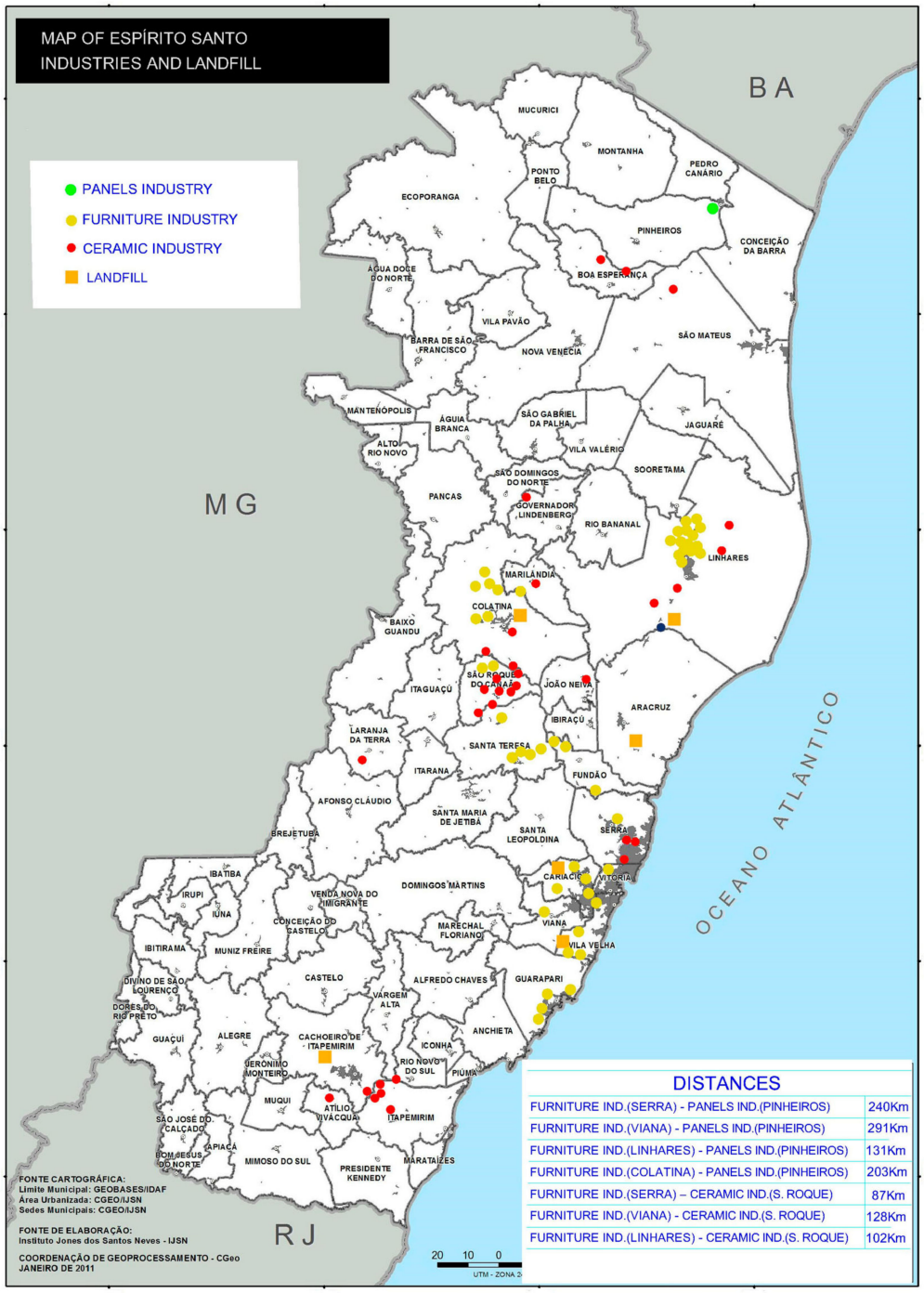

Figure 1. Map of the furniture, panel, ceramics, and landfill industries. Source: adapted by the author [31–33].

The study focuses on the north-central area of the state of Espírito Santo, where the furniture hubs of Linhares and Colatina are located. In addition, a significant number of red ceramics industries are located in Colatina and São Roque do Canaã, mainly in the area bordering the two municipalities. The potential industrial synergy among a wood panel factory in the municipality of Pinheiros, the furniture industry, and the ceramics industry was a determining factor in the direction of the study.

3.1.1. Wood Waste from the Furniture Industry

WW is part of the solid waste category and can be hazardous or nonhazardous according to NBR 10004 [34]. The residual mass from the furniture industry considered in this study is class II A solid waste (nonhazardous and non-inert) [22]. In terms of morphological characteristics, WW is classified as chips (maximum dimensions of 50 mm × 20 mm), shavings (waste larger than 2.5 mm), sawdust (dimensions between 0.5 mm and 2.5 mm), and dust (waste smaller than 0.5 mm) [35]. These sizes and nomenclature were used to designate the waste from the mills studied. In addition, the WW in this study was classified based on the British specification PAS 111:2012 and the German Waste Recovery and Disposal Ordinance: Grade A (GA) for natural solid wood without contamination and Grade B (GB) for wood-based panels (MDF and MDP) without surface coating that have not been treated with halogenated products, antifungals, paints, varnishes, or adhesives [36,37]. Taskhiri et al. [14] pointed out that this characterization (GB) meets the quality criteria for the manufacture of new panels.

3.1.2. Scenarios Evaluated

Five scenarios were evaluated: three material product production scenarios (MDF, MDP, and solid brick), one energy product production scenario (heat in the ceramics industry—the current practice), and one landfill disposal scenario. The 3 materials were compared to the predominant products on the market (made solely from virgin sources), and the energy product was compared to that made from virgin wood.

After being collected and transported to the material product manufacturing sites, the waste is treated before it can be used. In this way, the virgin resources are replaced by 20% in the panels and 11% in the ceramic brick on a mass basis (w/w). These percentages were defined according to technical research on the products [23,24,26]. Figure 2 shows the five scenarios evaluated for the disposal of WW.

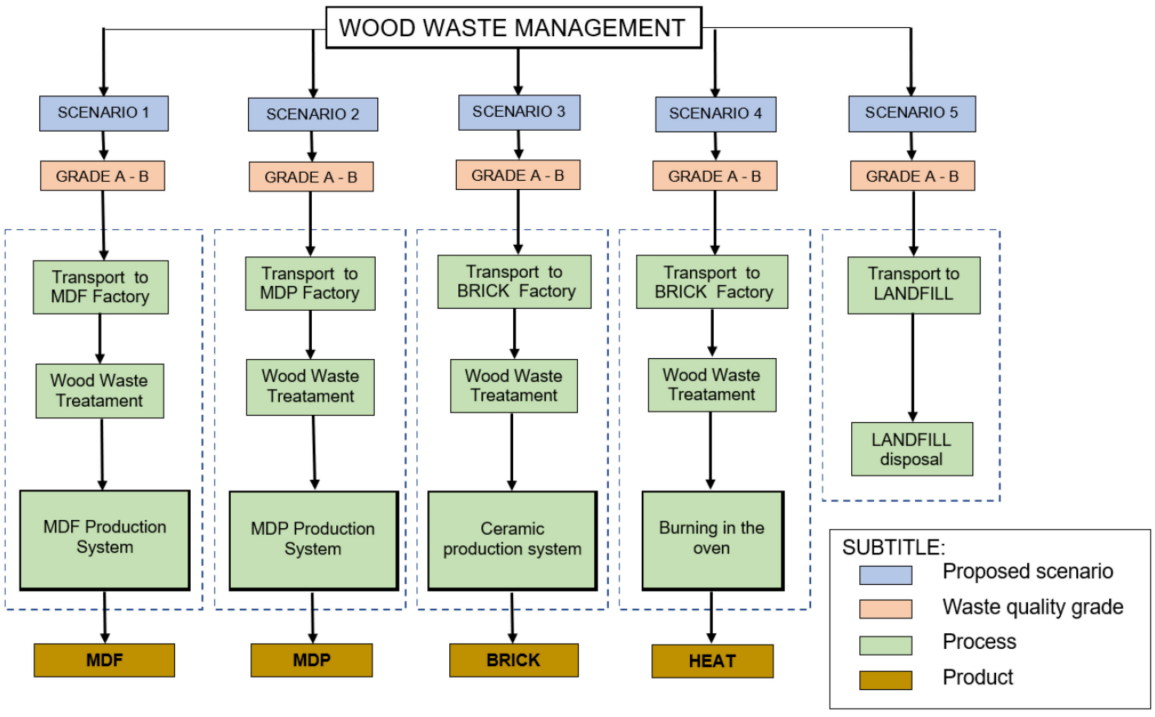

Figure 2. Extension of the foreground product system for the WW management scenarios.

As MDP is not yet manufactured in the region's panel factory, we considered its production data to be equal to MDF production, i.e., 1200 m^3 per day and 30,000 m^3 per month. For the production of ceramic bricks and heat, we considered the sum of the production of the industries belonging to the ceramic industry cluster in northern Espírito Santo, represented by the most important municipalities: Colatina and São Roque do Canaã. These municipalities border one another, and most of the industries are close to one another. Solid brick has a daily production of 13 tonnes [38,39]. To generate heat, the production of these industries averages 800 tonnes of ceramic products per day [38,40].

In the MDF and MDP manufacturing process, biogenic CO_2 emissions resulting from wood fuel in the boiler were assumed to be neutral, as eucalyptus, which has a short rotation time in Brazil, would have absorbed an equivalent amount of emissions during its growth process [6,41].

Regarding the transportation of supplies, CONAMA/2018 Resolution 490 [42], which was used to define the Euro 6 system as of January 2023, was adopted. This legislation aims to achieve significant reductions in pollutant emissions from diesel-powered vehicles.

The allocation procedure used in this study was process subdivision (also called cutoff criteria) in the generation of WW at the furniture factory to disregard the upstream environmental load.

The main characteristics of the scenarios studied are described below.

3.1.3. Scenario 1

The production of MDF with 20% *w*/*w* waste (S1-20% WW) was considered, with 10% GA and 10% GB, including virgin wood (80% *w*/*w*), and then compared to MDF produced with 100% virgin eucalyptus wood (S1-100% NW). The reference flow was the production of 1 m^3 of uncoated MDF with a thickness of 15 mm, an average density of 690 kg/m^3, and a moisture content of 8% *w*/*w*.

In this scenario, the furniture industry sorts the WW, determining the type and quantity of waste available for collection. The WW is then collected by trucks and taken to the panel factory in Pinheiros. The waste is deposited in a dry place and then sent for treatment. GA waste goes through an electric chipper and sieving to obtain wood chips. GB waste is recycled using the thermohydrolytic disintegration method, as described by Buschalsky and Mai [23]. After appropriate treatment, the waste is used as a raw material in the manufacture of MDF, according to the steps shown in Appendix A.

Primary data collection for the foreground inventory took place at the MDF factory in Pinheiros, with the managers responsible for each production area, in 2020 and 2022. A material flow analysis (MFA) was carried out to check the mass balance of the materials in the process via STAN software version 2.6.801. The difference between inputs and outputs was 1.36% *w*/*w*, which falls within the maximum range of 5% reported in the literature [43,44]. The data for the foreground inventory of MDF production were constructed using primary sources, which were collected directly from the industry. Emissions to air, land, and water were inventoried on the basis of emissions reports for the industry studied, made available by IBAMA [45], the Ministry of Cities [46,47], and Piekarski et al. [48]. Table 1 shows the parameters of the input and output flows for the manufacture of MDF. In Supplementary Materials, Table S1 provides information on: basic uncertainty, pedigree score and names of intermediate flows and elementary flows of MDF manufacturing in Espírito Santo.

Table 1. Foreground inventory of the production of 1 m^3 of MDF in Scenario 1.

INPUTS	Unit	Amount	Source	OUTPUTS	Unit	Amount	Source
Wood				**Emissions to air**			
Wood waste GA	kg	63	(3)	Carbon Dioxide, CO_2 (fossil)	kg	5.93	(6)
Wood waste GB (MDF)	kg	63	(3)	Carbon Monoxide, CO	kg	0.11	(5) (6)
Eucalyptus logs	m^3	1.15	(3)	Nitrogen oxides, NO_X	kg	0.12	(6)
Chemicals				Total VOCS	kg	1.06	(1) (6)
Urea-formaldehyde resin	kg	93.48	(4)	Particulate	kg	0.37	(5) (6)
Paraffin	kg	6.5	(4)	Formaldehyde, H_2CO	kg	0.10	(3)
Electricity				Water	L	539	(3)
Electricity	kWh	768	(4)	Sulfur Acid, H_2SO_4	kg	0.12	(1)
Fuels				Sulfur Oxides, Sox	kg	0.04	(5)
Lubricating oil	kg	0.018	(2)	**Emissions to land**			
Natural Gas	kg	0.1	(3)	Boiler Fly Ash	kg	2.2	(4)
Diesel	kg	1.89	(3)	Wood Waste	kg	4.2	(3)
Wood waste	kg	131.25	(4)	**Emissions to water**			
Transportation				Wastewater from MDF	L	86.3	(3)
Lorry > 32 ton	kg·km	477,757	(3)	Water	L	40	(3)
Water Use				**Product** (with wood waste)			
Water from Rio Itaúnas	L	666	(4)	Medium Density Fiberboard (MDF)	kg	690	
Water reuse (*)	L	200	(4)				

Note: (1) Piekaski et al. [48]; (2) Buchasky et al. [23]; (3) Estimated; (4) Collected on site; (5) IBAMA [45]; (6) Ministry of cities [46,47]. (*) Water closed circuit system. Emission not included.

3.1.4. Scenario 2

The production of MDP (particleboard) with 20% w/w waste (S2-20% WW) was considered, with 5% MDP waste, 15% solid WW, and virgin wood (80% w/w), and then compared to MDP produced with 100% virgin eucalyptus wood (S2-100% NW). The percentage of waste adopted for this analysis followed the Brazilian study by Teixeira [24]. The latter study also notes that, with a proportion of 5% MDP residue, new boards can be produced without changing the technology and losing their quality [24]. The two MDP panel scenarios analyzed used data from Silva et al. [41]. Waste from the Linhares and Colatina furniture industries is transported to the panel factory in Pinheiros, Espírito Santo. The reference flow is the production of 1 m^3 of uncoated MDP with a thickness of 15 mm, an average density of 630 kg/m^3, and a moisture content of 8% w/w.

In this scenario, the furniture industry sorts the WW, determining the type and quantity of waste available for collection. The WW is then collected by trucks and taken to the panel factory in Pinheiros. The waste is deposited in a dry place and then sent for treatment. The GA and GB waste goes through an electric chipper and sieving to obtain the appropriate particle size (2–20 mm) [44]. The waste is then used as a raw material in the MDP manufacturing process, as shown in Appendix B. For S2-20% WW and S2-100% NW, electricity consumption, raw materials, and chemical dosages were also adopted. In addition, Silva [49] and Silva et al. [41] indicated that 75.5 kg of waste is required to meet the boiler's energy needs per cubic meter of MDF; this research was conducted considering these data, which resulted in more environmentally friendly production results for the MDP studied, similar to those of the Brazilian MDF produced in the state of Espírito Santo. As MDP was not produced at the panel factory in this study, the foreground inventory was established based on the work of Silva et al. [41]. Table 2 shows the input and output flow parameters for the MDP manufacturing.

Table 2. Foreground inventory of the production of 1 m^3 of MDP in Scenario 2.

INPUTS	Unit	Amount	Source	OUTPUTS	Unit	Amount	Source
Wood				**Emissions to air**			
Wood waste GA	kg	103.08	(4)	Carbon Dioxide, CO_2 (fossil)	kg	5.38	(1)
Wood waste GB	kg	34.36	(4)	Carbon Monoxide, CO (fossil)	kg	0.21	(1)
Eucalyptus logs	m^3	1.16	(4)	Nitrogen oxides, NO_X	kg	0.25	(2)
Chemicals				Water	L	30.00	(1)
Ammonium sulfate	kg	1.38	(2)	Total VOCS	kg	0.36	(2)
Urea-formaldehyde resin	kg	71.7	(2)	Particulate < 2.5 µm	kg	0.02	(2)
Paraffin	kg	5.47	(2)	Particulate > 10 µm	kg	0.08	(2)
Electricity				Particulate > 2.5 µm and <10 µm	kg	0.08	(2)
Electricity	kWh	140.83	(2)	Sulfur Dioxide, SO_2	kg	0.00	(2)
Fuels				Formaldehyde, H_2CO	kg	0.15	(2)
Lubricating oil	kg	0.018	(2)	**Emissions to land**			
Diesel	kg	1.72	(2)	Boiler Fly Ash	kg	0.78	(2)
Wood waste	kg	75.00	(2)	Oils unspecified	kg	0.10	(2)
Transportation				Wood Waste untreated	kg	97.2	(2)
Lorry > 32 ton	kg·km	414,759	(3)	**Emissions to water**			
Water Use				Water	L	40.00	(1)
Water	L	90.40	(2)	Formaldehyde	kg	0.0001	(2)
				Suspended solids	kg	0.0244	(2)
				Wastewater from particleboard	L	6.00	(2)
				Product (with wood waste) Medium Density Particleboard (MDP)	kg	630	

Note: (1) Silva [49]; (2) Silva et al. [41]; (3) Estimated; (4) Teixeira [24].

3.1.5. Scenarios 3 and 4

Scenario 3 considers the production of ceramic bricks with 11% *w*/*w* waste (S3-11% WW), with the same proportions of GA and GB, and 89% *w*/*w* clay; these bricks are then compared to ceramic bricks produced with 100% clay (S3-100% NC). The firing fuel for the brick made with waste is also based on WW (GA + GB), while in the brick made with 100% clay, virgin eucalyptus is chosen as the energy source. WW from the Linhares and Colatina furniture industries is transported to the ceramics factories in Colatina and São Roque do Canaã, ES. The reference flow is the production of 1 kg of solid brick. The furniture industry sorts the WW, informing the ceramic factories of the type and quantity of waste available for collection. The WW is then collected by trucks and taken to the ceramics industries in São Roque do Canaã and Colatina. The waste is deposited in a dry place and then sent for treatment. Then, it is put through an electric chipper and sieved to obtain the appropriate particle size (between 0.5 mm and 2.5 mm), before being used as raw material in the brick manufacturing process, as shown in Appendix C.

Scenario 4 considers the production of heat (current scenario) from 100% WW (S4-100% WW), with the same proportions of GA and GB, and then compares the result to the heat produced with 100% virgin wood (S4-100% NW), accounting for the maximum emissions parameters established in CONSEMA Resolution 370/2017 on the use of uncontaminated MDF and MDP as a fuel source. This legislation aims to limit emissions of formaldehyde and volatile organic compounds that are highly harmful to human health. The resolution comes from the state of Rio Grande do Sul and was adopted in this study because the state of Espírito Santo does not yet have specific legislation on the subject. Thus, the results obtained are compared within the context of the controlled burning established in this legislation. WW from the furniture industries in Linhares and Colatina is transported to the brick factories in Colatina and São Roque do Canaã. The reference flow is the production

of 1 kg of ceramic. After the electric chipper stage, the waste is sent to the kilns as fuel for heat production. The foreground inventory was drawn up based on Vinhal [50]. The data on air emissions were sourced from IBAMA [45] reports, the maximum limits established by CONSEMA resolution 370/2017 [51], and Vinhal [50].

Table 3 shows the parameters of the input and output flows for the manufacture of solid ceramic bricks.

Table 3. Foreground inventory of the production of 1 kg of solid ceramic bricks in Scenario 3.

INPUTS	Unit	Amount	Source	OUTPUTS	Unit	Amount	Source
Feedstock				**Emissions to air**			
Steel	kg	0.00001	(3)	Total VOCs	kg	2.74×10^{-8}	(4)
Pallet	kg	0.00023	(1)	Particulate	kg	1.34×10^{-7}	(5)
Refractory	kg	0.01520	(1)	Formaldehyde, H_2CO	kg	5.49×10^{-9}	(4)
Polyethylene	kg	0.00096	(1)	**Product**			
Mine Clay	kg	0.97779	(1)	Bricks with wood waste	kg	1.00	
Wood fiber							
Wood waste	kg	0.12					
Electricity							
Electricity	kWh	0.05	(1)				
Diesel	Mj	0.07	(1)				
Wood chipping	kWh	0.02	(2)				
Fuels							
Lubricating oil	kg	0.00002	(1)				
Wood waste	kg	0.1200	(1)				
Transportation							
Lorry > 32 TON	kg·km	112.65	(2)				
Water Use							
Water from artesian well	L	0.00018	(1)				

Note: (1) Vinhal [50]; (2) Estimated with partial process data; (3) EcoInvent; (4) CONSEMA [51]; (5) IBAMA [45].

Biogenic CO_2 emissions from burning wood in the kilns were considered to be neutral.

In this study, regarding brick manufacturing, importantly, although the analysis was carried out separately for Scenarios 3 and 4, the use of waste occurred jointly in both the production and heating processes. Therefore, to avoid competition between the two applications, we believe that GB waste has great potential for inclusion in bricks. However, the behavior of this type of waste from MDF and MDP panels in bricks exposed to temperatures above 750 °C requires further investigation in terms of the resulting emissions.

Table 4 shows the transportation distances for acquiring the main raw materials for the scenarios studied.

Table 4. Transportation distances for purchasing the main raw materials.

Transportation Distances For Input Materials				
INPUT	**Adress (City-State)**	**Distance (km)**		
		MDF	**MDP**	**BRICK**
Wood Waste	Linhares/Colatina-ES	168	1687	71
Eucalyptus logs	Pinheiros/Pedro Canário/São Mateus-ES	130	130	130
Clay	São Roque do Canaã-ES	-	-	40
Plastic tape	Colatina-ES	-	-	28
Pallet	Santa Teresa-ES	-	-	33
Urea-formaldehyde	Curitiba-PR/Guarulhos-SP	1334.5	1334.5	-
Paraffin	Candeias/São Francisco do Conde-BA	829.5	829.5	-
Ammonium Sulfate	Pedro Canário-ES	-	5	-

3.1.6. Scenario 5

Scenario 5 considers the disposal of WW in a landfill, including transportation from the furniture industry to the landfill—an average distance of 30 km for the furniture industries in Colatina and Linhares. The reference flow is the disposal of 1 kg of waste. In this scenario, WW is collected by trucks and taken to landfills in Colatina and Linhares. The waste is then disposed of and sent for treatment. The Ecoinvent database version 3.6 was used for the LCI.

3.1.7. Research Limitations

The following premises were established for the analysis carried out in this study:

- The use and final destination phases were not adopted as the limits of this study, due to the difficulties of tracking product use and final destination. With regard to panels, Wilson [43] justified the exclusion of these phases due to the use of these materials in furniture and interior architecture, along with the various possibilities for final disposal.
- Water and sewage treatment systems in the panel industry were disregarded.
- Office supplies, transportation, and food for employees were not considered in this study.
- The production of ammonia was considered to take place at the same site as the manufacture of urea; thus, the transportation of ammonia was disregarded.
- This study used data from the manufacturing of MDF and MDP without coatings.
- The same amount of energy was considered for the process that used only virgin sources and for the process that used WW for the three products studied.
- To calculate the emissions from burning WW to produce heat, the maximum emissions determined in CONSEMA resolution 370/2017 on the use of uncontaminated MDF and MDP as a fuel source were accounted for. The results therefore refer to controlled burning.
- Scenario 5 (sanitary landfill) used the inventory "treatment of waste wood, untreated, sanitary landfill/waste wood, untreated/cutoff, U" from the Ecoinvent database version 3.6. This considers only WW from natural wood, so emissions from other components of MDF and MDP waste were not considered.

3.2. Life-Cycle Impact Assessment and Interpretation

The software used for the LCA was OpenLCA version 1.10 with the Ecoinvent database version 3.6 cutoff for the background inventory. The methodologies used for the LCA were IPCC 2013 (100 years), CML baseline, and USEtox for human toxicity. The six most studied environmental categories for WW management systems, as identified in the literature review carried out by Pinho and Calmon [7], were adopted for this analysis. This group includes global warming (GW), acidification potential (AC), eutrophication potential (EU), ozone depletion (OD), human toxicity–non-cancer (HT-NC), and human toxicity–cancer (HT-C).

The furniture industries in the state of Espírito Santo are mainly located in Colatina, Linhares, and Gran Vitória (Figure 1). As this research focuses on the furniture hubs of Linhares and Colatina, through sensitivity analysis, we sought to answer the following question: is it feasible to take the WW of the furniture factories in Gran Vitória to Pinheiros (panel factory) or to Colatina and São Roque do Canaã (ceramics factories)?

The feasibility of transportation distances for the use of furniture WW generated in the Gran Vitória region was therefore investigated in the proposed scenarios. A point located in the north and another in the south of the metropolitan region of Gran Vitória were considered to study the feasibility of acquiring WW. As part of the region analyzed is covered by a railway line, two analyses were carried out for each extreme point: one with the train associated with the cargo truck, and the other with just the truck as the means of transport. However, this analysis did not incorporate the loading and unloading operations

for the integration of the train and the truck, which may require energy and material consumption for conveyor belts, wagon turners, and lifting platforms, among others.

The reference flow of 1 t of WW collected from the furniture industry in Espírito Santo and managed was used to compare the scenarios evaluated. This comparative analysis was based on the environmental benefit obtained from using WW to produce MDF, MDP, ceramic bricks, and heat for pottery. Therefore, the first four scenarios were also calculated using only virgin sources, and the difference in impacts was the environmental benefit.

4. Results

The results presented in this section refer to the specific reference flow for each scenario described above. An analysis was also conducted in which the type and percentage of waste in the wood panels were varied. For this purpose, additional scenarios were considered for MDF and MDP made with 100% GA waste and MDF with 20% GB waste. For a broader analysis, the results were also associated with the management of 1 tonne of WW and the temporal production, referring to the day, month, and year of the panel factory and the ceramics industries studied.

4.1. Scenario 1: MDF

In Scenario 1, the production of S1-20% WW was compared with the production of S1-100% NW (Figure 3).

Figure 3 shows that S1-20% WW in the GW category had the greatest environmental gain compared to the other impacts analyzed. The production of 1 m^3 of MDF in S1-100% NW generated 231.70 kg CO_2 eq, while S1-20% WW generated a total of 219.72 kg CO_2 eq. The forestry operation stage saw a 34% reduction in GW in Scenario 1 compared to MDF produced from virgin sources. In this category, UF resin accounted for more than 40% of the total impacts in the two processes analyzed (S1-100% NW and S1-20% WW). The production of ammonia, which is associated with the manufacturing of UF resin, was the most impactful process. However, the use of WW as a raw material for MDF enabled a reduction in GW related to UF. Electricity and the transportation of raw materials also stood out, with impact contribution percentages of over 19% and 18% in the two scenarios, respectively. Notably, 1 m^3 of MDF stores 1080 kg CO_2 eq/m^3, which results in a net impact of −849 kg CO_2 eq/m^3 of MDF. A similar result was found by Piekarski et al. [48], with 1235 kg CO_2 eq/m^3 for Brazilian MDF produced in São Paulo via technology that uses two species of wood: Eucalyptus and Pinus.

With regard to the environmental gains identified, the EU category also stood out. The forestry operation stage, whose main contributors to EU are the application of N-based fertilizers and the use of diesel during harvesting, showed significant reductions for Scenario 1. The production of UF resin accounted for more than 55% of both scenarios, mainly due to the emission of NO_x into the air and hydrocarbons into the water during the manufacture of methanol and urea [41].

The non-carcinogenic and carcinogenic toxicological impacts of the human toxicity (HT) categories were strongly influenced by formaldehyde emissions into the air. Although they are widely used, phenolic resins are highly hazardous to human health. Therefore, reductions in the amount of resin in MDF due to the incorporation of WW brought environmental benefits for human health. For HT-C, UF resin accounted for 90% of the contribution.

Urea–formaldehyde resin (UF) stands out as having the greatest contribution in the categories evaluated. In MDF made from 100% virgin wood (S1-100% NW), the amount of resin was 14% of the total weight of the board, but in S1-20% WW it was 13.5% due to the use of recycled MDF (10% *w*/*w*), which is higher than in the study by Buschalsky and Mai [23], which used 10% resin to manufacture MDF from fibers recovered during the thermohydrolytic disintegration process. However, the impacts relating to transportation as a whole were slightly increased as a result of the average distances adopted for the WW. The greatest reductions observed were in emissions from eucalyptus forestry operations. Figure 3 shows that S1-20% WW showed reductions in all of the impact categories evaluated.

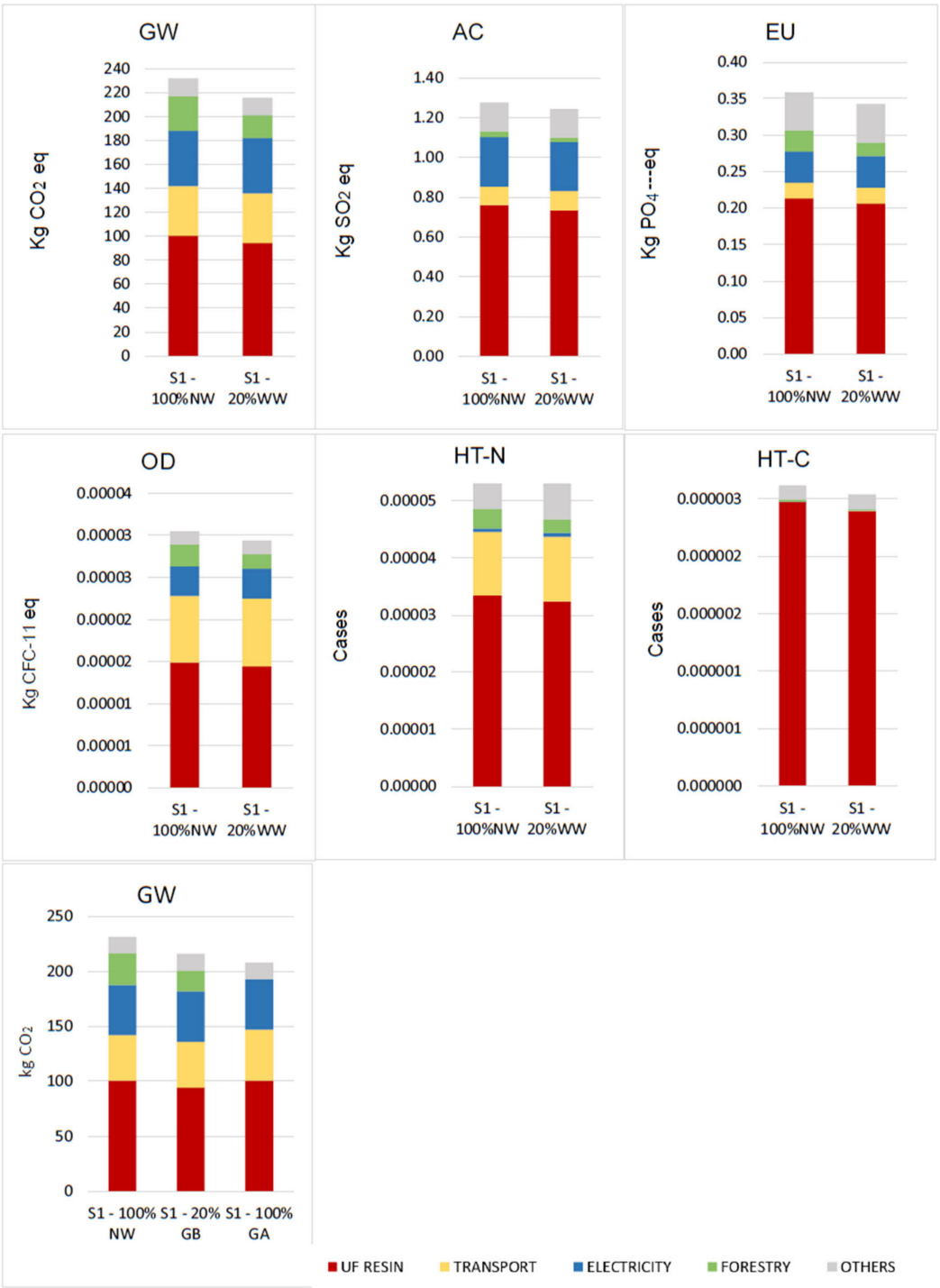

Figure 3. Environmental impacts for the production of 1 m^3 of MDF from virgin sources compared to MDF produced with 20% *w*/*w* WW, with 20% *w*/*w* GB WW, and with 100% *w*/*w* GA WW in Scenario 1.Notes: Subtitle: S1-100% NW-SCENARIO 1 with 100% natural wood; S1-20% WW-SCENARIO 1 with 20% wood waste. Impact categories: global warming (GW); acidification potential (AC); eutrophication (EU); ozone layer depletion (OD); human toxicity–non-cancer (HT-N); human toxicity–cancer (HT-C). Others (more significant): paraffin, untreated waste wood, and wastewater from MDF.

Additionally, as shown in Figure 3, MDF produced with virgin sources was compared with MDF produced with 20% *w*/*w* GB WW and with 100% *w*/*w* GA WW.

MDF incorporating 20% *w*/*w* fiber recovered from panels showed a 7% reduction in impacts for GW compared to MDF produced with 100% natural wood. There was a small increase in the contribution from transport, but the notable reduction in the contributions from UF resin and forestry operations strongly favored the better performance of this proposal. In the MDF produced with 100% *w*/*w* GA waste, it was possible to achieve a GW result 10% lower than that of the reference MDF. Although the percentage of UF resin (14% *w*/*w*) was the same as that used in MDF produced from virgin sources, and transportation increased significantly, the forestry operation stage strongly influenced the environmental benefit achieved.

4.2. Scenario 2: MDP

In Scenario 2, the production of S2-20% WW was compared with the production of S2-100% NW (Figure 4). Based on the literature consulted, the two scenarios analyzed appear to be very similar in terms of energy consumption and inputs [8,13,52].

Figure 4 shows that S2-20% WW in the GW category had the greatest environmental gain compared to the other impacts analyzed. The production of 1 m^3 of MDP in S2-100% NW generated 199.41 kg CO_2 eq, while S2-20% WW generated a total of 194.25 kg CO_2 eq. For the GW category, the lowest GHG emissions in Scenario 2 were associated with eucalyptus forestry operations. Emissions related to transport were increased (3%) due to the distances adopted for the wood residue, but the results of the total emissions showed that this category had a greater environmental gain than the others analyzed. It was also possible to see that the carbon dioxide emissions related to transporting UF resin (9%) were a critical factor, which emphasizes the need to look for alternatives for purchasing resin closer to the panel factory. As with MDF, biogenic emissions from the boiler process were not accounted for. Notably, 1 m^3 of the studied MDP stores 1174 kg CO_2 eq/m^3, resulting in a net impact of −975 kg CO_2 eq/m^3 of MDP. Similar values were found in the study of Silva et al. [41] (1290 kg CO_2 eq/m^3) and Wilson [43] (1268 kg CO_2 eq/m^3).

The OD category also stood out in terms of the environmental benefit achieved. A significant impact contribution was related to UF (45%) and the transportation of raw materials (28%).

In the categories relating to human toxicity, most of the impacts are from the gate-to-gate system (GTOG), with HT-NC accounting for 38% and HT-C accounting for 50% in S2-100% NW. These figures are mainly due to formaldehyde emissions during the manufacture of MDP.

UF resin represented a significant percentage of all of the impact categories evaluated. This indicates the need for greater efforts to replace this raw material in panel production. Resin options from renewable sources such as tannin, lignin, and castor oil are examples that deserve more in-depth studies, encompassing environmental, economic, and social aspects [53]. Figure 4 shows that all of the categories evaluated showed environmental gains compared to S2-20% WW.

In addition, as shown in Figure 4, MDP produced with virgin sources was compared with MDP produced with 100% *w*/*w* GA.

In the MDF produced with 100% *w*/*w* GA waste, it was possible to achieve a GW result 10.5% lower than that of the reference MDF. An increase of 5% occurred in the transportation stage, but the difference from the forestry operations stage led to an improvement in environmental performance. The study carried out by Hossain and Poon [13] for Hong Kong showed a 6% lower result for MDP made from virgin wood for GW compared to MDF made from 100% *w*/*w* GA waste.

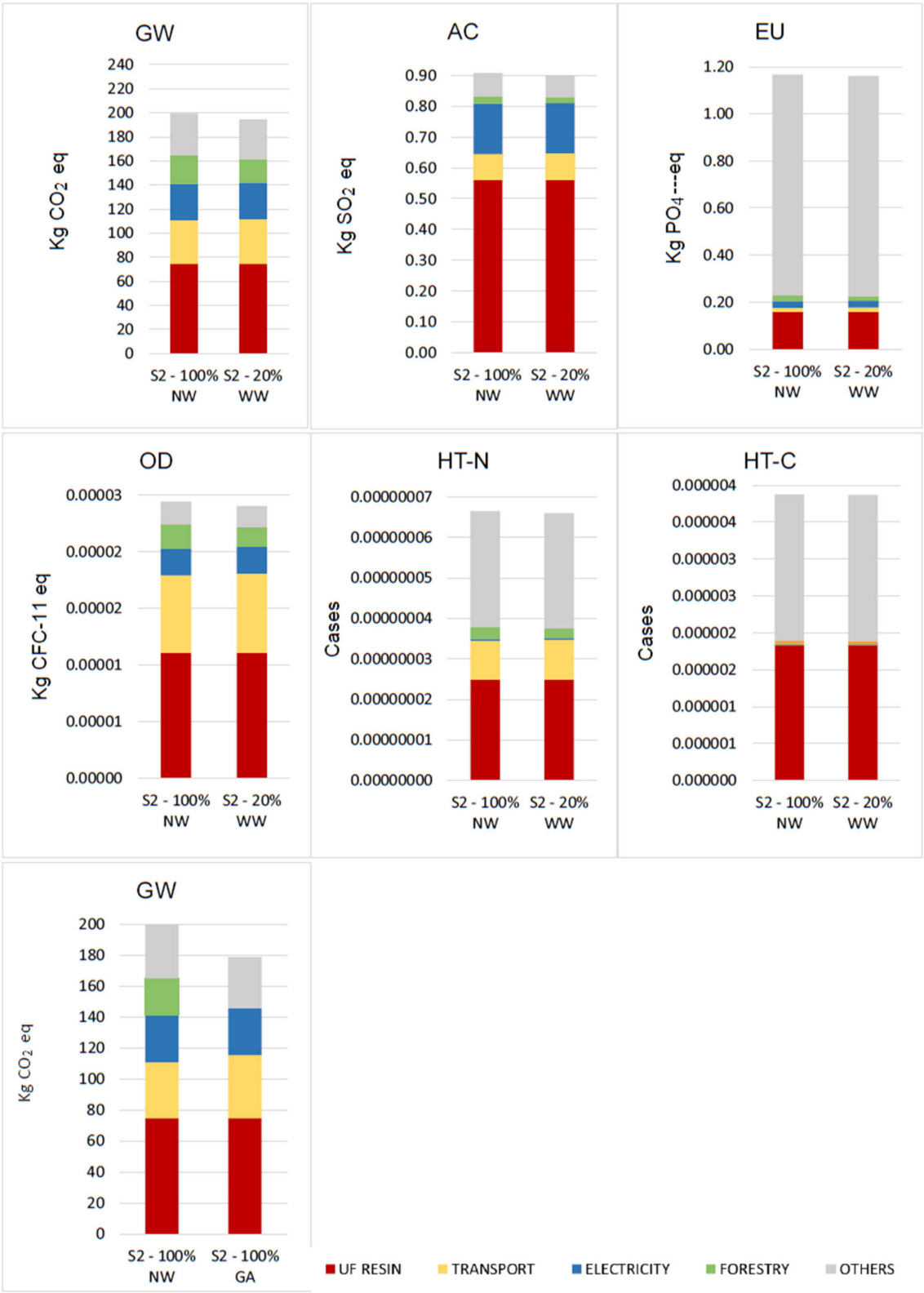

Figure 4. Total impact per category for the production of 1 m^3 of MDP with 20% *w*/*w* WW and with 100% *w*/*w* GA WW in Scenario 2. Note: Subtitle: S2-100% NW-Scenario 2 with 100% natural wood; S2-20% WW-Scenario 2 with 20% WW. Others (more significant): paraffin, untreated waste wood, and wastewater from MDP.

4.3. Scenarios 3 and 4: Ceramic Bricks and Heat

In Scenario 3, the production of ceramic bricks incorporating 11% *w*/*w* GA and GB waste (S3-11% WW) was compared with the production of bricks made with 100% clay (S3-100% NC). Scenario 4 (the current scenario) compared the environmental impacts of using virgin eucalyptus to generate heat (S4-100% NW) with those of using WW from the GA and GB furniture industries (S4-100% WW). Scenarios 3 and 4 are presented together, as they pertain to the production of the same product (Figure 5).

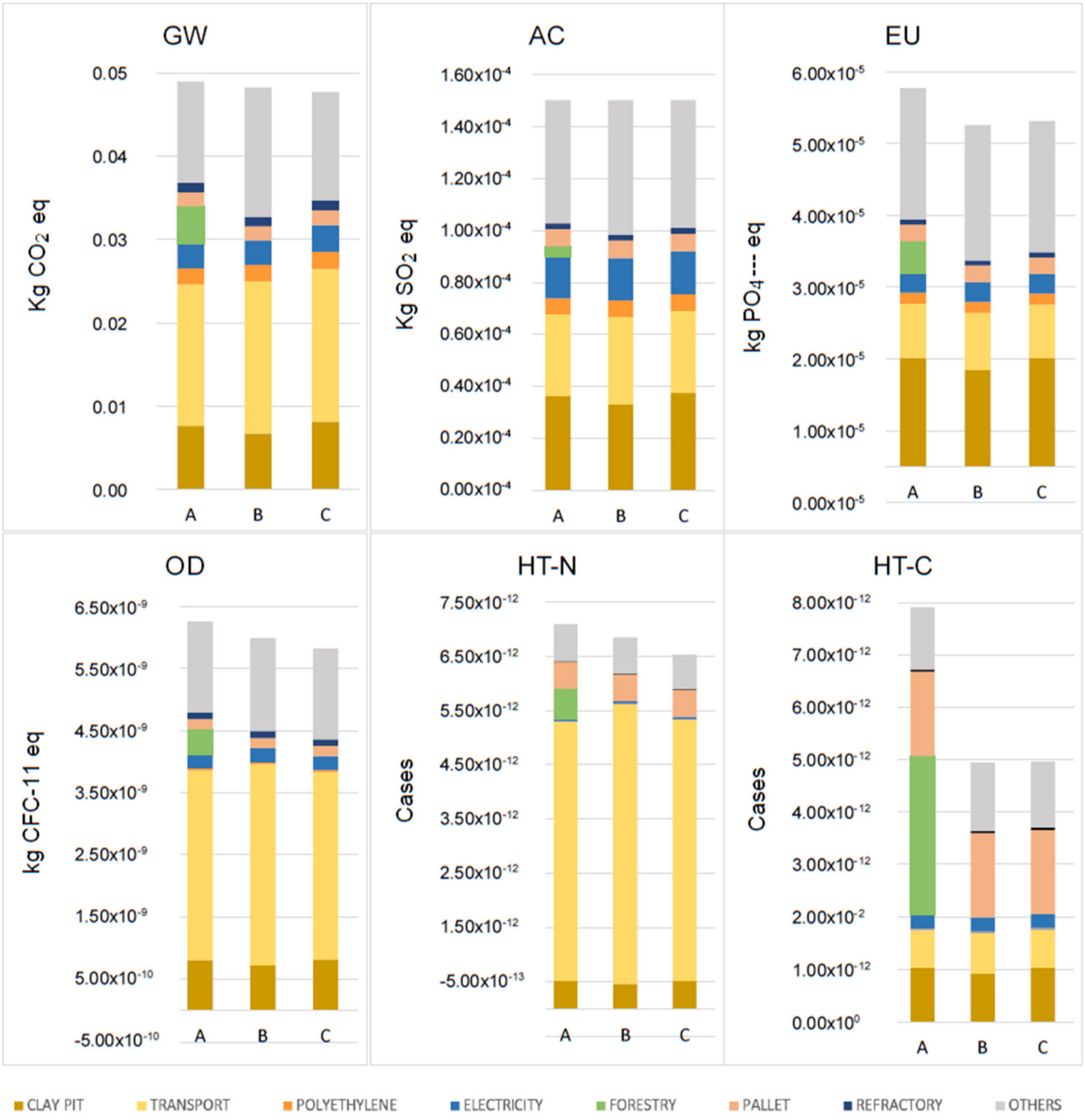

Figure 5. Total impact of GW for the production of 1 kg of ceramic bricks. Note: A—S3-100% NC and S4-100% NW for heat (SCEN3 and 4); B—S3-11% WW and S4-100% WW for heat (SCEN3); C—S3-100% NC and S4-100% WW for heat (SCEN4). Others (more significant): diesel, steel, and lubricant oil.

The greatest environmental gains observed (38%) occurred in the HT-C category for Scenario 3 and Scenario 4 due to the use of natural wood for burning in Scenario A (Figure 5). Bricks made from virgin wood sources are significantly impacted by forestry operations (40%). The chainsaw-related process used in the felling stage was the most important impact value for HT-C. With a 100% reduction in forestry impacts, Scenarios B and C achieved significant gains for human health. Another process with an important contribution to HT-C was pallet production, which also uses phenolic resins as a raw material, with the largest impact contributions from this supplier.

The EU category also showed the greatest reductions in the analysis carried out. For Scenario A, forestry operations accounted for 8.5% of the impacts of this category, while in Scenarios B and C these operations were reduced by 100%. In Scenario B, there was also a considerable environmental gain for the clay extraction stage.

The analysis of GW showed that this category was significantly influenced (over 27% in all three scenarios) by emissions from the transportation of raw materials. However, the 100% reduction in forestry operations led to environmental gains in Scenarios B and C. Lower emissions were also achieved in clay extraction in Scenario B.

Figure 5 shows that in all three scenarios, raw material transportation makes significant contributions to all of the impact categories evaluated. An increase in transportation impacts related to brick production and firing occurred due to the distance associated with acquiring WW as a raw material. However, the reduction in demand for clay extraction in Scenario 3, and especially the forestry stage in Scenarios 3 and 4, contributed to significant reductions in all of the impact categories assessed.

4.4. Scenario 5

In Scenario 5, WW was sent to the landfill, which is up to 30 km from the Colatina and Linhares furniture hubs. Table 5 shows the impacts associated with the disposal of WW at the landfill.

Table 5. Total amount per impact category for the disposal of 1 kg of wood waste to landfill.

		Landfill	
Impact Category	**Simbol**	**Impact Result**	**Unit**
Global Warning	GW	8.37×10^{-2}	kg CO_2 eq
Acidification	AC	5.35×10^{-5}	kg SO_2 eq
Eutrophication	EU	2.61×10^{-3}	kg PO_4 eq
Ozone Layer Depletion	OD	4.27×10^{-9}	kg CFC-11 eq
Human Toxicity NC	HT-N	2.10×10^{-9}	Cases
Human Toxicity C	HT-C	5.95×10^{-9}	Cases

Transportation played a significant role in the impact results. In particular, for OD, 40% of the results were associated with transportation.

Figure 6 shows the contribution of transporting WW for the four projected scenarios for the GW category compared to landfill disposal (Scenario 5). The amount of kg CO_2 eq for Scenario 5 was higher than that of all of the other scenarios analyzed, due to the processing operations required at the landfill.

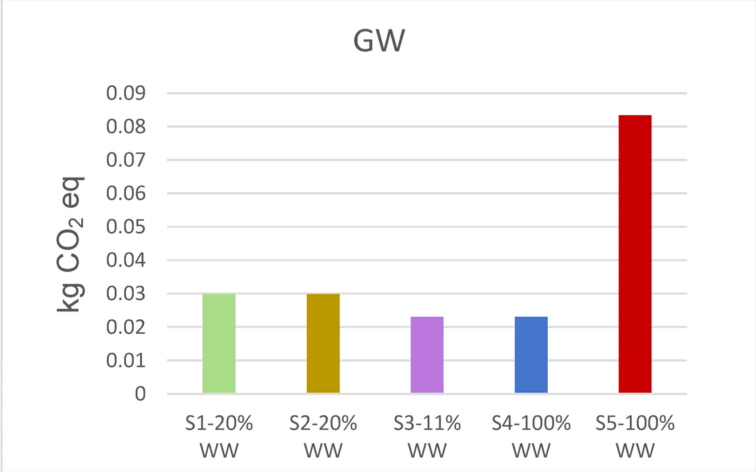

Figure 6. Amount of transportation in kg CO_2 eq for the GW category of 1 kg of WW to the mills (Scenarios 1–4) compared to Scenario 5.

5. Discussion

5.1. Comparison of the Results with the Literature Consulted

Although the environmental impacts of manufacturing reconstituted panels (MDF and MDP) and ceramic bricks can be influenced, for example, by differences in technology, fleet characteristics and transportation distances, or percentage of resin, it was possible to verify that the results obtained were consistent with the literature consulted (Table 6).

Table 6. Comparison of the results of the products studied with those in the literature consulted.

ID	Study	Location	System Boundary	Sources of Wood Material	Global Warming Potential (kg CO_2 eq)
Scenario 1 MDF (1 kg)	Puettmann et al. [54]	USA	CTOG	100% GA	0.760
	Piekarski et al. [48]	BRASIL (SP)	CTOG	VIRGIN	0.290
	This Study	BRASIL (ES)	CTOG	VIRGIN	0.330
	This Study	BRASIL (ES)	CTOG	20% GA + GB	0.310
Scenario 2 MDP (1 kg)	AWC [55]	CANADA	CTOG	VIRGIN	0.440
	Silva et al. [41]	BRASIL (SP)	CTOG	VIRGIN	0.560
	This Study	BRASIL (ES)	CTOG	VIRGIN	0.320
	This Study	BRASIL (ES)	CTOG	20% GA + GB	0.300
Scenario 3 BRICK (1 kg)	Vinhal [50]	BRASIL (SP)	CTOG	VIRGIN	0.026
	Vinhal [50]	BRASIL (SP)	CTOG	VIRGIN	0.026
	This Study	BRASIL (ES)	CTOG	VIRGIN	0.049
	This Study	BRASIL (ES)	CTOG	11% GA + GB	0.045

Note: CTOG = cradle to gate.

The MDF studied in Scenario 1 used a higher percentage (14% and 13.5% *w*/*w*) of resin in its composition than that in the study by Piekarski et al. [48], which used 10.3% *w*/*w*; this material is a relevant factor in the increase in emissions observed in the panels.

Silva et al. [41] conducted a cradle-to-grave study in Brazil, but heavy fuel oil was the main boiler fuel, which contributed to a higher GW value. The replacement of heavy fuel oil with more environmentally friendly inputs in industrial production can result in better environmental performance of the MDP [41]. The analysis of MDP in Scenario 2 adopted WW as the boiler fuel, which led to better environmental performance of the product.

Vinhal [50] carried out two studies in Brazilian ceramic brick factories that also used WW as fuel for the kilns, but the transportation distance of some raw materials was close to the ceramic factories, in contrast to the distances in this study. For example, clay, which is the main raw material, is extracted an average of 40 km from the factories studied. In the analysis by Vinhal [50], this distance was not accounted for. In both studies carried out by the author, the clay extraction process was carried out by the ceramics industry itself.

5.2. Comparative Analysis

Table 7 shows the environmental benefit achieved by impact category in Scenarios 1, 2, 3, and 4 for the reference flow of 1 tonne of WW and for the production quantity of the industries in the region studied at different timescales (i.e., day, month, year). Table 7 shows that in terms of recovering 1 tonne of WW, MDF has the greatest environmental benefit in all of the categories evaluated. This advantage also occurs when the production quantities of MDF are associated with time.

Table 7. Environmental benefits of the evaluated scenarios compared to those of the conventional scenarios regarding the quantity of production in the chosen industries.

	Impact Category	Benefit/ 1 t Wood Waste	Benefit/ Day	Benefit/ Month	Benefit/ Year	Unity
MDF Scenario 1	GW	94.90	14,348.88	3.59×10^5	4.3×10^6	kg CO_2 eq
	AC	0.25633	38.757	968.927	11,627.13	kg SO_2 eq
	EU	0.12600	19.05	476.28	5,715.36	kg PO_4 eq
	OD	0.00001	0.00139	0.03474	0.41686	kg CFC-11 eq
	HT-N	1.56×10^{-8}	2.36×10^{-6}	5.90×10^{-5}	7.08×10^{-4}	Cases
	HT-C	6.83×10^{-7}	1.03×10^{-4}	2.58×10^{-3}	3.10×10^{-2}	Cases
MDP Scenario 2	GW	37.408	6,170.08	1.54×10^5	1.82×10^6	kg CO_2 eq
	AC	0.056	9.237	230.916	2.77×10^3	kg SO_2 eq
	EU	0.044	7.200	179.991	2.16×10^3	kg PO_4 eq
	OD	2.76×10^{-6}	4.55×10^{-4}	0.01138	0.13656	kg CFC-11 eq
	HT-N	3.26×10^{-9}	5.38×10^{-7}	1.34×10^{-5}	1.61×10^{-4}	Cases
	HT-C	2.52×10^{-8}	4.16×10^{-6}	1.04×10^{-4}	1.25×10^{-3}	Cases
BRICK Scenario 3	GW	28.990	47.167	1415.00	1.698×10^4	kg CO_2 eq
	EU	0.04217	0.02745	0.82350	9.88202	kg PO_4 eq
	OD	2.19×10^{-6}	1.43×10^{-6}	4.29×10^{-5}	5.14×10^{-4}	kg CFC-11 eq
	HT-N	1.74×10^{-9}	1.13×10^{-9}	3.39×10^{-8}	4.07×10^{-7}	Cases
	HT-C	2.43×10^{-8}	21.58×10^{-8}	4.47×10^{-7}	5.70×10^{-6}	Cases
Energy for Bricks Scenario 4	GW	37.499	3599.86	107,995.68	1.30×10^6	kg CO_2 eq
	EU	0.03800	3.648	109.440	1.313×10^3	kg PO_4 eq
	OD	3.61×10^{-6}	3.467×10^{-4}	1.04×10^{-2}	0.12480	kg CFC-11 eq
	HT-N	4.29×10^{-9}	4.114×10^{-7}	1.234×10^{-5}	1.48×10^{-4}	Cases
	HT-C	2.46×10^{-8}	2.365×10^{-6}	7.09×10^{-5}	8.51×10^{-4}	Cases

Notes: Calculation Methods for each scenario are explained in Appendix D. For Scenario 3 and 4 the AC category had very small benefits, thus disregarded.

With regard to Scenario 4, which considers the production of heat in the ceramics industry (current practice), the benefits by category over time are closer to those of Scenario 2 (MDP) but are still lower. Only in relation to Scenario 3 does the environmental benefit of Scenario 4 show a greater advantage in all of the categories evaluated.

As part of a more detailed analysis of GW, Figure 7 shows the quantity of this category for all of the scenarios evaluated, considering the environmental benefit of managing 1 tonne of WW and the impact of disposing of it in a landfill. Figure 8 shows the benefits achieved with the annual production of these products.

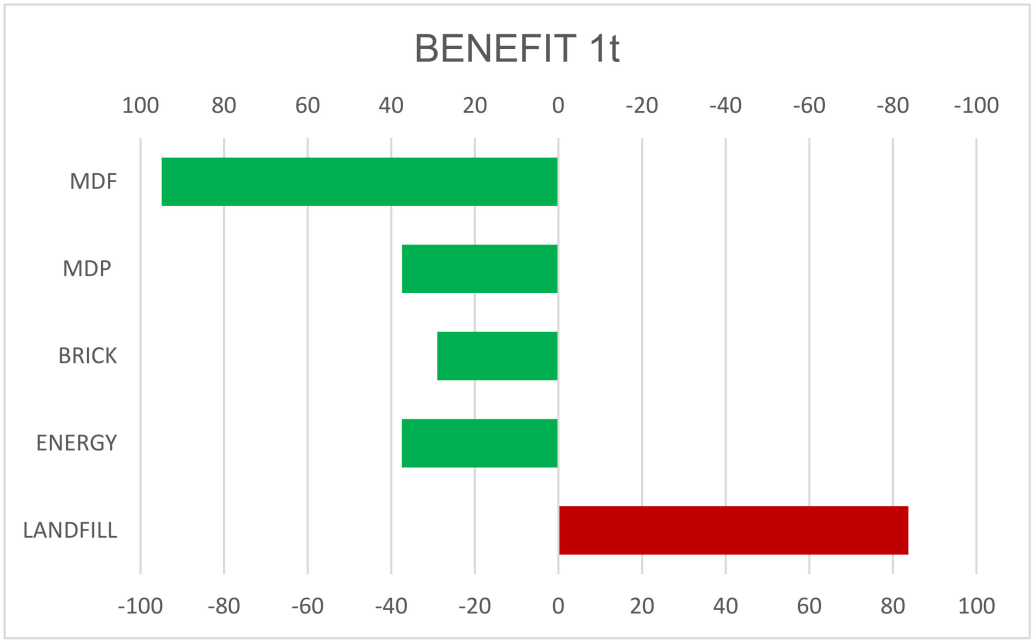

Figure 7. Environmental benefit for the GW category for the recovery of 1 tonne of WW.

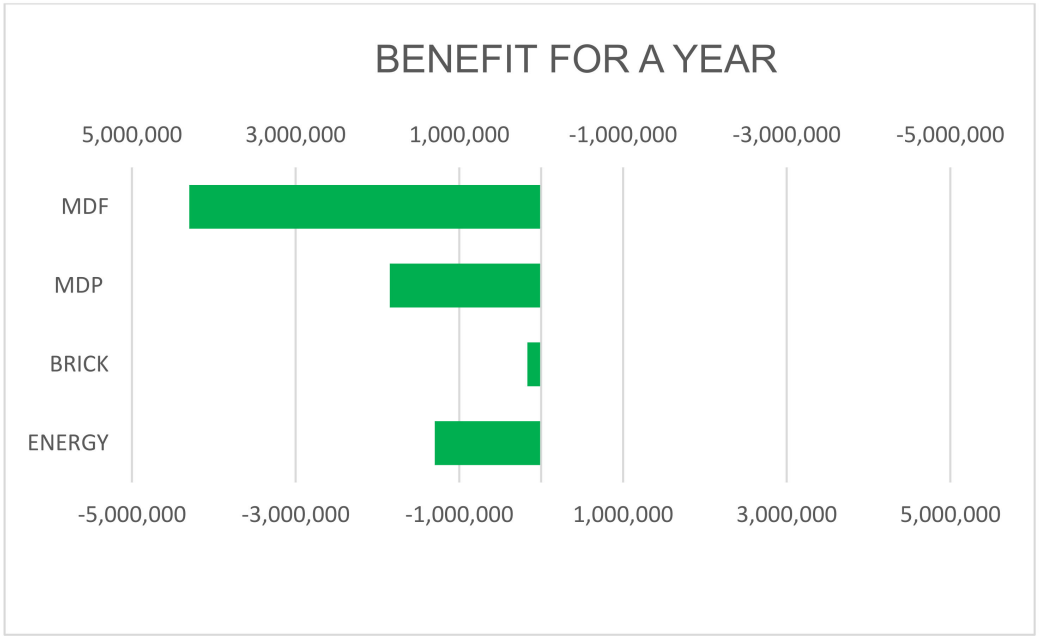

Figure 8. Environmental benefit for the GW category considering the annual production of MDF, MDP, ceramic bricks, and heat.

In Figure 7, MDF (Scenario 1) stands out as having the highest environmental benefit values for GW. It also indicates that for 1 tonne of waste, the disposal scenarios for MDP (Scenario 2), brick (Scenario 3), and heat production (Scenario 5) show environmental benefits of between 20 and 40 kg CO_2 eq. However, when analyzing annual production (Figure 8), the figures show greater advantages for MDF and MDP in relation to brick production and energy production. In addition, in the research by Buschalsky and Mai [23], MDF was recovered up to the third generation of panels by using the thermohydrolytic disintegration process; furthermore, Kim and Song [8] stated that MDP can be recycled up to 16 times after use, which demonstrates the potential circularity of these products prior to being sent to landfills or incinerated.

Scenario 3 shows that the inclusion of 1 tonne of waste as a raw material in the manufacturing of bricks, compared to those produced with 100% clay, resulted in a reduction of 29.0 kg CO_2 eq. Considering that a brick masonry wall can remain in a building for more than 40 years, the carbon storage time before recycling or final disposal would also be 40 years [56].

In Scenario 4, energy production (heat) in the brick factory was evaluated using 1 tonne of WW as a burning fuel, replacing virgin eucalyptus. A reduction of 37.5 kg CO_2 eq was found. This scenario (reference) is the usual waste disposal practice adopted by the furniture industry. However, in the analysis carried out considering the annual production of the region's ceramics industry (Figure 7), the environmental gains were smaller when compared to those of Scenarios 1 and 2.

In Scenario 5, emissions from the disposal of WW in landfills were associated with 83.74 kg of CO_2 eq per GW for managing 1 tonne of WW. The emissions from this landfill were calculated using the Ecoinvent database version 3.6, which considers only WW from natural wood. The inventory used was "treatment of waste wood, untreated, sanitary landfill/waste wood, untreated/cutoff, U". It was therefore not possible to account for emissions from components of MDF and MDP waste, such as those resulting from UF resin. This indicates that the environmental burden may be greater.

In view of the above, Scenarios 1 and 2 are potentially more favorable for waste disposal compared to Scenario 4. Scenario 3 has a lower environmental gain compared to Scenario 4 but could be a promising alternative for disposing of GB waste. Scenario 1 appears to be the best option, and its environmental benefit for managing 1 tonne of waste exceeds the second option by 60% (heat) in relation to GW (Figure 6).

Considering the amount of waste needed to meet the monthly production of the projected scenarios (Appendix D) and the estimated monthly generation of WW (6700 tonnes) in the Colatina and Linhares furniture hubs, more than one scenario could be used. For example, Scenario 1 could be considered together with Scenario 4. However, the quantity of WW is sensitive to market demand. In addition, correct sorting is crucial for the best use. Therefore, the creation of data-sharing platforms between industries, with information on sorting and the amount of waste available to support supply and demand planning, is an important factor in the development of a CE in the region studied.

5.3. Sensitivity Analysis

Figure 9 shows the sensitivity analysis in relation to transportation distances for the three products studied: MDF, MDP, and ceramic bricks. This figure also shows that for each base case (i.e., product with virgin source inputs), purchasing WW is viable throughout Gran Vitória. Importantly, the point located in the south of GV for Scenario 3 (ceramic bricks) exceeds the base case. However, the option that integrates the train with a freight truck shows a significant reduction. The destination of GV waste for the manufacturing of bricks proved to be more attractive with the use of transport that integrates trains and trucks, because the red ceramics factories are close (28 km) to the Colatina train station. As a result, the journey to the ceramics factories by freight truck was shorter than for MDF and MDP.

Within the context analyzed, integration of the train and freight truck for completing the necessary journeys achieved lower emissions for the three products at the two points analyzed in the GW category.

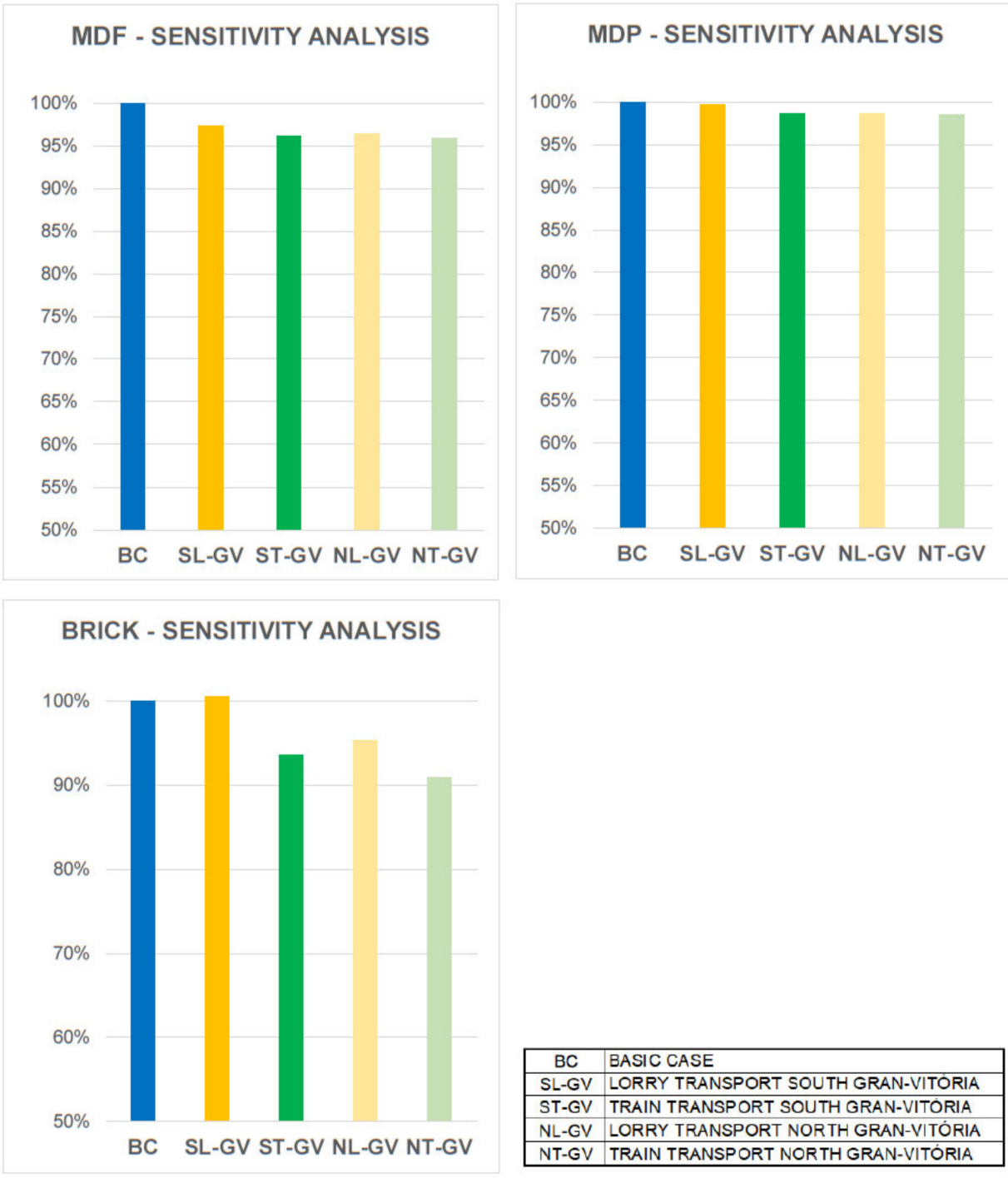

Figure 9. Sensitivity analysis for the distance and mode of transportation of WW from the furniture industry in the Metropolitan Region of Gran Vitória, considering the GW category.

6. Conclusions

In this study, a comparative LCA was carried out to evaluate the environmental performance of different scenarios for the disposal of WW generated by the furniture industry of Espirito Santo, with the central-northern area of the state as the spatial focus of the research. To assess the environmental impacts, five WW management scenarios were studied: MDF production, MDP production, solid ceramic brick production, heat production in the ceramics industry (current practice), and landfill disposal. The results showed that Scenario 1 (MDF) achieved more environmental benefits in all of the evaluated impact categories compared to the base scenario without using waste materials. The categories studied included GW, AC, EU, OD, HT-NC, and HT-C. Notably, 1 m^3 of MDF stores 1080 kg CO_2 eq/m^3, which results in a net impact of −849 kg CO_2 eq/m^3 of MDF. In relation to MDP, 1 m^3 of the studied panel stores 1174 kg CO_2 eq/m^3, resulting in a net impact of −975 kg CO_2 eq/m^3 of MDP.

Scenario 5 (landfill disposal) is the least favorable practice, and its emissions are associated with 83 kg of CO_2 eq in the GW category for 1 tonne of WW. With regard to Scenario 4 (current practice), only when compared to Scenario 3 (ceramic bricks) is its environmental benefit greater in all of the evaluated categories. It is therefore possible to see that Scenarios 1 and 2 are potentially more favorable for disposing of WW than Scenarios 3 and 4. Scenario 3 has a lower environmental gain compared to the other scenarios but could be a promising alternative for disposing of wood panel waste (Grade B). With regard to panels, notably, the literature highlights the potential circularity of these products before they are sent to landfills or incinerated. For example, MDP can be recycled up to 16 times after use [8].

The results of the sensitivity analysis in relation to transportation distances support the environmental viability of purchasing WW from companies in Gran Vitória to manufacture the studied products. However, Scenarios 3 and 4 show the greatest benefits, especially when rail use is included in the journey.

Based on quality, WW from the furniture industry can be used in different scenarios, thus avoiding competition between them. However, most of the furniture companies surveyed do not separate their waste carefully, which is a limiting factor for using it in new cycles that add value to the waste. The creation of platforms for sharing data between industries is also necessary; these should include information on the classification and quantity of waste available to support supply and demand planning. In addition, the government must promote and strengthen policies that encourage and promote solid foundations for the development of the CE.

This study sought to provide a broad overview of different alternatives for reducing environmental impacts, while presenting efficient and possible solutions for managing WW. The scenarios were constructed by detecting existing synergies and bringing local industries together, with the aim of building a network of value for stakeholders. Finally, it is hoped that the analyses carried out in this research will be of interest to industries in the area, entities linked to the furniture sector, and public policymakers, as these bodies can help in the decision-making processes on WW management, especially at a regional scale, as addressed in this research. The scenarios in this study describe possible ways to use WW as a raw material for manufacturing new products, thus reducing the demand for virgin sources and increasing environmental gains.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su152014944/s1, Table S1: Basic uncertainty, pedigree score, and names of the intermediate flows and elementary flows of Scenario 1 (manufacturing of MDF in Espírito Santo).

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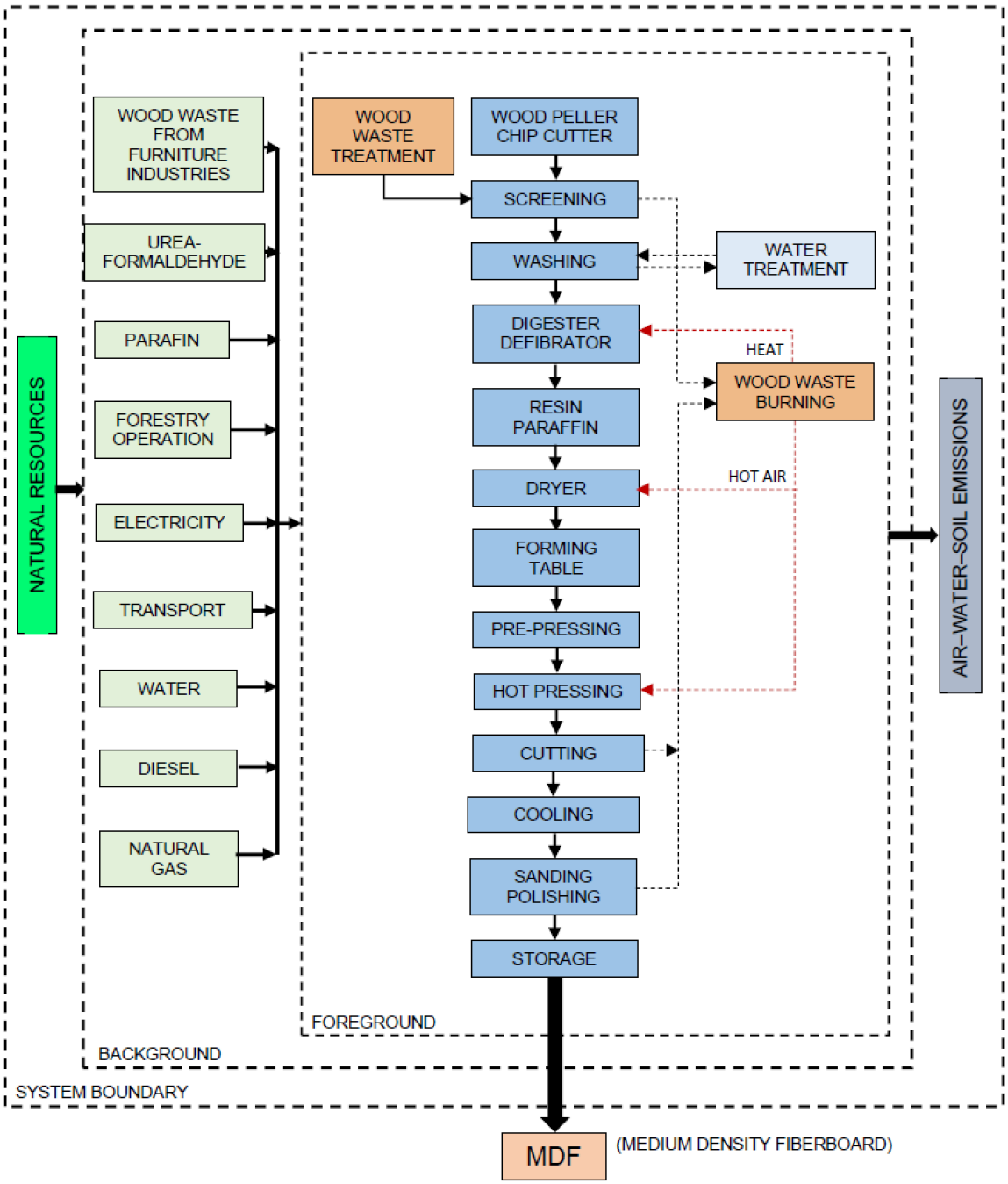
Acronyms

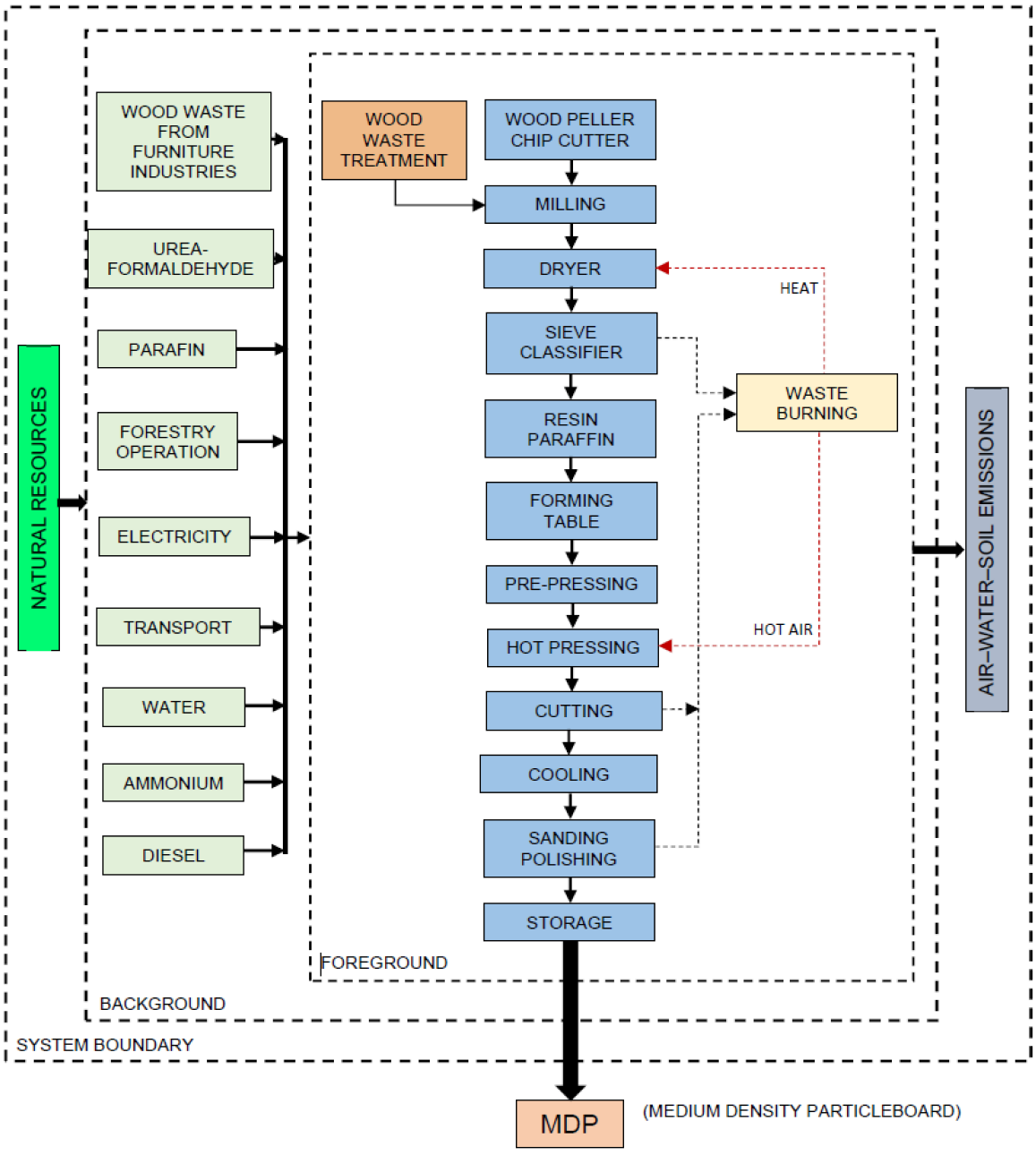
Adopted Acronyms

LCA	Life Cycle Assessment
WW	Wood Waste
MDF	Mediun Density Fibreboard
MDP	Medium density Particle Board
CE	Circular Economy
GA	Solid Wood Waste
GB	Panel Waste
w/w	Weight per Weight
NW	Natural Wood
NC	Natural Clay
UF	Urea Formaldehyde
GW	Global Warming
AC	Acidification
EU	Eutrophication
OD	Ozone Layer Depletion
HT-N	Human Toxicity-non cancer
HT-C	Human Toxicity-cancer
GV	Grand Vitoria Region

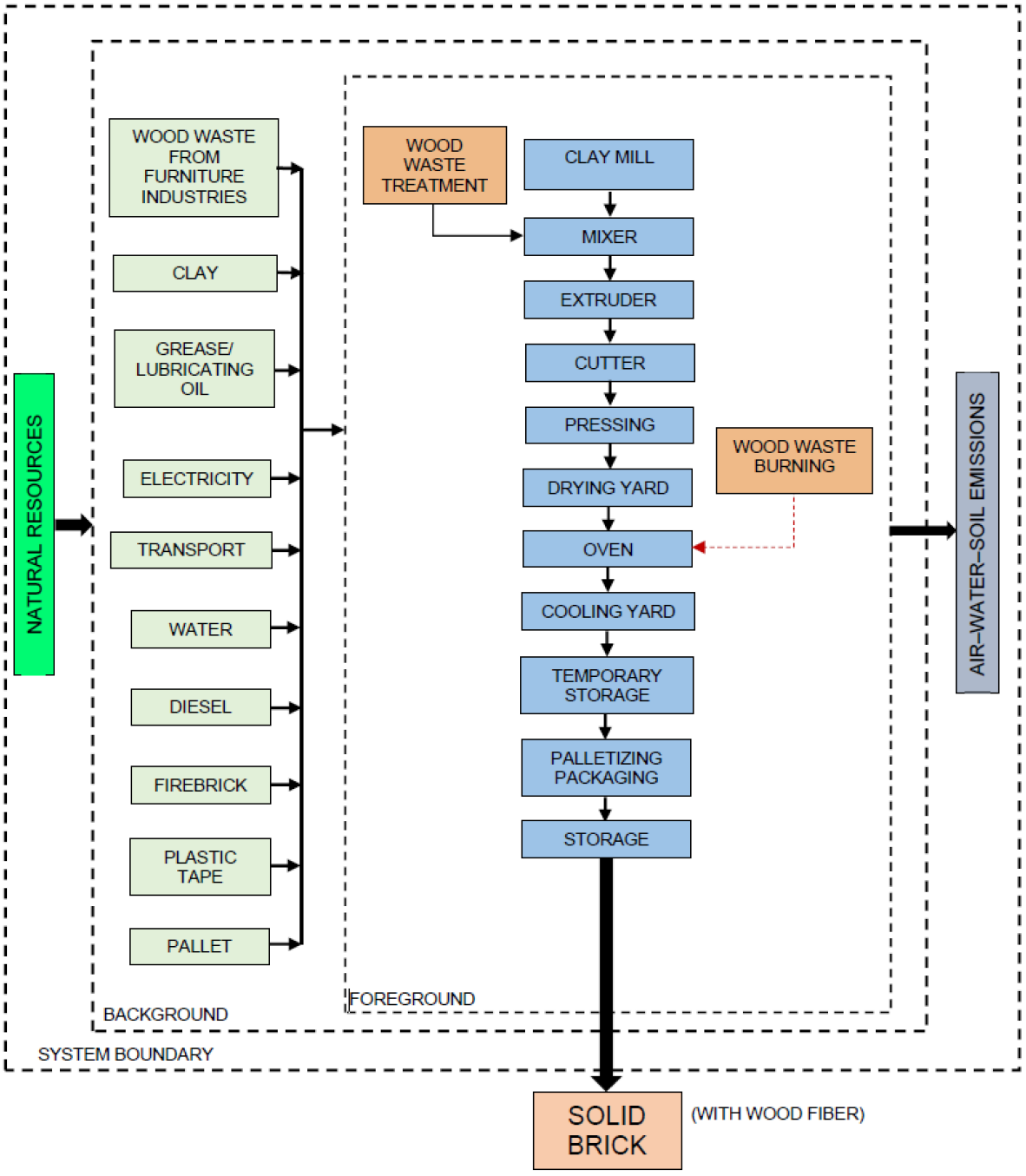
Appendix A. MDF Panel System Boundary (Cradle to Gate)



Appendix B. MDP Panel System Boundary (Cradle to Gate)



Appendix C. Ceramic Brick System Boundary (Cradle to Gate)



Appendix D. Method of Calculating the Data in Table 7

	Calculation Method for Environmental Benefits in Time
MDF	Environmental benefit/m^3: MDF with 20% wood waste − natural wood MDF (BA = PR − PV) Exemple GW: 126 kg wood waste has benefit 11.96 kg CO_2 eq (1 t wood waste × 11.96)/126 = 94.9 kg CO_2 eq 1200 m^3 MDF/day uses 1000 × 0.126 t = 151.2 t/day Benefit/day: Benefit 1 t × 151.0 t Month = 25 days of production
MDP	Enviromental benefit/m^3: MDP with 20% wood waste − natural wood MDP (BA = PR − PV) 1200 m^3 MDP/day uses 1200 × 0.137 t = 164.94 t/day Benefit/day: Benefit 1 t × 164.94 Month = 25 days of production
BRICK	Environmental benefit/1 kg: clay with 11.11% wood waste − 100% natural clay (BA = PR − PV) Production/Day = 13,330 kg bricks × 0.1221 kg waste = 1627 kg/day − Benefit 1 t × 1627/1000 = 1.627 Month = 30 days of production
ENERGY for Bricks	Environmental benefit/1 kg: 100% natural brick − wood waste for heat Production/Day = 800,040 kg ceramics × 0.12 kg waste = 96,005 kg/day − Benefit 1 t × 96,005/1000 = 96 Month = 30 days of production

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