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Environmental Sustainability Assessment of Tissue Paper Production

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Abstract: The environmental performance of tissue paper varies greatly based on factors such as the type of fibre used as the raw material, the production process and the fuels used to meet the energy requirements. One possible strategy to decrease greenhouse gas emissions in tissue production is the integration of pulp and paper mills and their energy systems at the same site. However, the environmental trade-offs associated with this strategy are still unclear. Therefore, this study aimed (i) to assess for the first time the environmental impacts of tissue paper produced at a typical industrial site in Portugal using slush and market pulp as the main raw material, and (ii) to assess the environmental effects of the integration of bioenergy produced in the pulp mill in tissue production. A life cycle assessment was conducted from cradle to gate using real data from the production of eucalyptus wood, eucalyptus pulp and tissue paper. The results showed that energy consumption in tissue paper production is the main hotspot for most impact categories. When bioenergy is used in tissue production, the environmental impacts decrease by up to 20% for categories other than marine eutrophication and mineral resource scarcity. These results are relevant to support decision making concerning sustainable practices not only for the pulp and paper industry but also for the authorities in charge of defining environmental policies, incentives and tax regulations.

Keywords: bioeconomy; carbon footprint; industrial symbiosis; life cycle assessment; pulp and paper; sustainability

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1. Introduction

Globally, the pulp and paper (P&P) industry accounted for approximately 6% of the global industrial energy consumption in 2020, but the share of energy provided by fossil fuels is only about 30% [1]. This sector presents the potential to contribute to the decarbonisation of national economies. Among the major strategies to address decarbonisation is the substitution of fossil fuel with bioenergy, as this sector presents a natural aptitude for using forest biomass co-products [2]. However, the environmental sustainability gains associated with this strategy are still unclear.

Tissue products such as toilet paper, facial tissue, napkins, kitchen towels and other sanitary tissues (e.g., medical tissues) are widely demanded for hygiene purposes and are considered to be of major importance for human health [3]. In this context, their consumption is expected to grow at an average rate of 6% between 2022 and 2026 as a result of population and economic growth [4]. A likely consequence of the increased consumption of tissue products is an increase in the global environmental impacts. To be cost-effective, tissue products should be based on short supply chains. Thus, it is important to place tissue mills close to the production sites of raw materials (e.g., forests and pulp mills) and energy supply systems to minimise the transportation costs. Additionally, process integration in tissue production systems, by installing P&P mills at the same industrial site, may contribute to industrial symbiosis and the implementation of a circular economy.

Process integration allows for the transfer of slush pulp (in a water suspension) from the pulp mill to the tissue mill, displacing market pulp (dried and sold in bales) and thus avoiding the environmental burdens associated with pulp transport and drying. Moreover, process integration enables bioenergy transfer from the pulp mill to the tissue mill, reducing the energy produced from fossil fuels. However, currently, most of the tissue mills are not integrated with pulp mills and consume market pulp; consequently, they do not take advantage of the environmental benefits of the integration of the P&P production processes.

Life cycle assessment (LCA) is a methodological tool used to assess the environmental impacts associated with a product or service over its entire life cycle by identifying and quantifying the energy, materials and wastes released into the environment [5]. LCA is an adequate methodology to evaluate the environmental sustainability of products because it provides a holistic, systemic and rigorous assessment of the environmental performance of products [6]. Hence, it is particularly useful, for example, to support decision making, product development and/or environmental labels and declarations [5,7]. LCA may also play a relevant role in the achievement of the 2030 Agenda for Sustainable Development defined by the United Nations [8].

LCA has been applied to tissue paper produced with virgin and secondary fibres. For example, Joseph et al. [3] assessed paper towels made from 100% recycled paper in a cradle-to-gate LCA, whereas Ingwersen et al. [9] also focused on paper towels, but produced from virgin fibre, and adopting a cradle-to-grave approach. Another example is the study by Brito et al. [10], who addressed bath tissue produced from virgin fibre in a cradle-to-gate assessment. In the LCA studies of tissue paper, both the impacts and the processes with the largest contributions to the impacts (i.e., the hotspots) present high variability, depending on factors such as the type of fibre used as the raw material, the technology implemented and the mix of energy sources. None of these studies focused on tissue products produced in Portugal, which use eucalyptus kraft pulp as the main raw material; however, the impacts and effects of using alternative energy sources to fulfil the energy requirements of paper production have been analysed in some LCA studies. Silva et al. [11] assessed different scenarios of energy production during offset paper production, as alternatives to the baseline scenario, in which thermal energy is produced on site from biomass and diesel. Corcelli et al. [12] addressed office and magazine paper production using energy produced on site and energy from the national grid and simulated a scenario where all the energy is produced from the national grid. Finally, Puschnigg et al. [13] studied alternatives based on the virtual battery concept for the current energy production (based on on-site production from natural gas and electricity from the grid) in the production of super-calendered and lightweight coated paper grades. These alternatives include, for example, substituting electricity produced on site from natural gas with electricity from the grid in times of high local renewable generation. However, to the best of the authors' knowledge, none of the available studies evaluated the implications of the integration of bioenergy produced in the pulp mill to reduce the use of fossil fuels in the paper mill. This is a significant gap in the scientific literature regarding possible improvements to enhance decarbonisation and sustainability in the P&P industry.

To fill these knowledge gaps, there were two main objectives for this study:

- To assess the environmental impacts of tissue paper produced at a typical industrial site in Portugal semi-integrated with eucalyptus pulp production to identify the main hotspots;
- To assess the effects on the environmental impacts of bioenergy integration in tissue production, to quantify the associated greenhouse gas (GHG) emission reductions and to determine whether other environmental impacts also decrease.

The LCA methodology was selected to evaluate the environmental impacts in this study because it provides comprehensive, systematic and rigorous results [6], as mentioned above, which are pivotal to support industrial strategies as well as public policies.

2. Materials and Methods

The environmental impacts of tissue paper were evaluated by applying the LCA methodology based on the ISO 14040 and ISO 14044 standards [5,14]. LCA modelling was performed with SimaPro software (version 9.2.0.2).

2.1. Scenarios, Functional Unit and System Boundaries

This study evaluated two scenarios. They are schematically illustrated in Figure 1 and described below:

- S1 consists of a semi-integrated pulp and tissue production system where most of the pulp is integrated with tissue production, but market pulp is also consumed due to operational reasons. Therefore, the origin of the pulp is as follows: 60% eucalyptus slush pulp, 10% eucalyptus market pulp and 30% softwood market pulp. On-site energy production occurs in a recovery boiler and a biomass boiler that supply the eucalyptus pulp mill with steam and electricity; in addition, a natural gas boiler supplies the tissue mill with steam. The remaining electricity requirements of the pulp and tissue production are fulfilled with electricity from the grid. Of note, natural gas is also used in the tissue mill to produce hot air for tissue paper drying;
- S2 consists of a semi-integrated pulp and tissue production system similar to that of S1 but with a different configuration of the energy sources. On-site energy production occurs in a recovery boiler that supplies the eucalyptus pulp mill with steam and electricity. In addition, a biomass boiler supplies the eucalyptus pulp mill and tissue mill with steam and 33% of the electricity requirements. The remaining electricity requirements of the pulp and tissue production are fulfilled with electricity from the grid. The consumption of natural gas in the tissue mill to produce hot air for tissue paper drying remains unchanged.

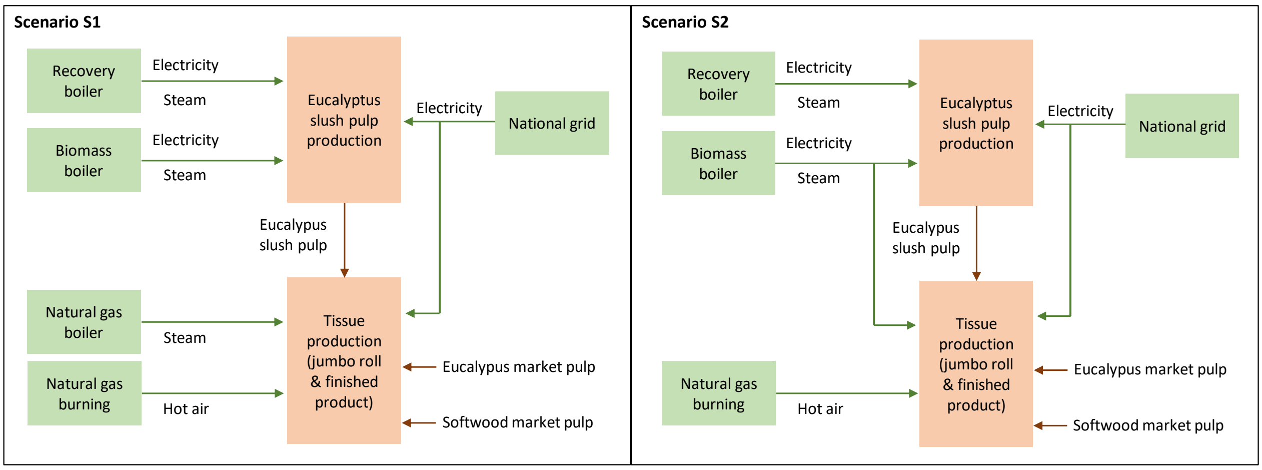

Figure 1. The two scenarios considered in the assessment.

The functional unit is the production of 1 ton of tissue paper that is ready to be distributed. The tissue paper consists of 25% of wet-strength products (e.g., multipurpose rolls, kitchen rolls and napkins) and 75% of non-wet-strength products (e.g., toilet paper).

The system boundary defines the processes along the value chain included in the LCA. The full value chain is addressed up to the gate of the industrial site that produces the tissue paper. Therefore, the following life cycle stages, shown in Figure 2, are considered:

- Forest (includes the production of eucalyptus wood and softwood used as raw materials to produce pulp; the production of forest biomass used to produce energy in the biomass boiler in the pulp mill is considered at the stage at which this energy is consumed);
- Pulp production (refers to the production of eucalyptus market and slush pulp and imported softwood market pulp);

- Jumbo roll production (includes jumbo roll tissue paper production);
- Finished product production (includes finished tissue paper product production in converting lines).

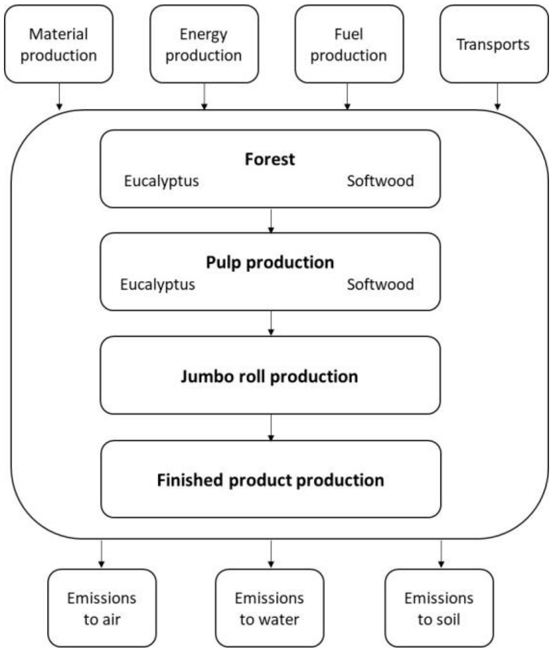

Figure 2. System boundary of the tissue paper product systems.

Besides the abovementioned processes, each stage includes additional processes, such as transport, the production of chemicals, packaging materials, the energy from the national grid and fuels. Additionally, to simplify data collection, a cut-off criterion was defined for the processes based on primary data, that is, eucalyptus pulp production, jumbo roll production and finished product production. For these processes, the production of the materials and the treatment of wastes whose flows represent <0.5% of the mass of the finished product production (i.e., <5 kg per functional unit) were left outside the system boundaries.

2.2. Multifunctionality and Allocation

In the forest stage, eucalyptus forest management is a multifunctional process that produces several co-products, in particular, wood for the wood-based industry and other biomass for bioenergy (logging residues, bark and stumps). A mass allocation (on a dry basis) was adopted to allocate the environmental burdens between wood and biomass for the bioenergy that leaves the forest, following Dias [15]. An environmental burden was not allocated to the forest biomass that is left in the forest ground due to ecological reasons and technical restrictions; it was assumed to be half of the logging forest residues and stumps produced [15]. Therefore, 75.3% of the total environmental burdens of forest management was allocated to wood, 10.3% to logging residues, 10.0% to bark and 4.4% to stumps.

Furthermore, multifunctionality also occurs in the eucalyptus pulp production processes because some solid wastes (e.g., sludge from the wastewater treatment plant) undergo further valorisation, which has two functions: to treat the waste from the eucalyptus pulp production and to produce a new product. Thus, a procedure to partition the environmental burdens between the eucalyptus pulp production and the valorisation process must be defined. In this case, a cut-off approach was adopted, meaning that the environmental burdens of the valorisation process were excluded from the assessment, as well as any environmental benefits that arose from that valorisation.

2.3. Inventory Analysis

2.3.1. Forest

The forest stage includes the eucalyptus forest in Portugal and abroad, as well as the softwood forest in Central and Northern Europe. It also includes the transport of pulpwood from forest sites to the pulp mills.

Eucalyptus Forest

The eucalyptus forest in Portugal consists of *Eucalyptus globulus* plantations that provide 97.5% of the total eucalyptus wood consumed in tissue production. The remaining 2.5% of eucalyptus wood is produced abroad in Uruguay and Mozambique. Due to the lack of specific information for these countries, the inventory data were considered to be the same as those for the wood produced in Portugal. However, imported wood undergoes an additional chipping operation near the harvesting sites. According to measured data, this process consumes 31.08 kWh of energy per ton of wood.

This study adopted the methodological approach for compiling inventory data for eucalyptus wood production described by Dias and Arroja [16]. The inventory data comprise the consumption of fuels and lubricating oil used in mechanised operations, the consumption of fertilisers and herbicides, and emissions to air and soil from fuel combustion and fertiliser application. All operations carried out during site preparation, stand establishment, stand tending, logging and infrastructure establishment were considered. This study excluded operations such as seedling production at nurseries, the transport of workers, machinery and materials to and from forest work sites and the production and maintenance of capital goods (e.g., machinery).

Four types of current management models were considered: (i) intensively managed forests with terraces (20%), (ii) intensively managed forests without terraces (14%), (iii) forests extensively managed by smallholders (33%) and (iv) abandoned forests (33%). The share of each management model is representative of the eucalyptus wood supplied to produce the tissue paper under assessment. In all cases, eucalyptus forest is exploited according to three coppice rotations of 12 years each. Table 1 describes the operations carried out and their respective frequencies over one revolution (36 years) for the production of eucalyptus wood in Portugal for the four management models.

In intensively managed forests with terraces, site preparation includes the construction of terraces and the manual preparation of the soil. In intensively managed forests without terraces and forests extensively managed by smallholders, site preparation includes the control of spontaneous vegetation through harrowing and soil mobilisation through subsoiling. In all managed forests, site preparation also includes fertilising with ternary fertiliser (11% N, 12% P_2O_5 and 9% K_2O) and superphosphate (45% P_2O_5). In abandoned forests, no operations are carried out regarding site preparation. In all forest management models, planting is a manual operation.

Stand tending includes fertilising with the application of ternary fertiliser (20% N, 10% P_2O_5 and 10% K_2O) once in the first rotation and twice in the second and third rotations in forests under intensive management, and once in the third rotation in forests extensively managed by smallholders. In forests under intensive management, ammonium sulphate (30% N) is also applied once in the first rotation. In forests under intensive management, stand tending also includes herbicide application (eight times per rotation) and the selection of coppice stems with a chainsaw (once in the second and third rotations). Moreover, stand tending encompasses the control of spontaneous vegetation through tilling and harrowing in two management models. This operation is implemented six times in intensively managed forests without terraces and four times in forests extensively managed by smallholders. Herbicide is applied 24 times in forests under intensive management. Finally, in all management models other than abandoned forests, the selection of coppice stems is carried out with a chainsaw at the second and third rotations.

Table 1. Operations carried out and their respective frequencies over one revolution of 36 years for the production of eucalyptus wood in Portugal.

		Intensively Managed		Extensively Managed	
		With Terraces	Without Terraces	By Smallholders	Under Abandonment
		Frequency Over One Revolution			
Site preparation	Stump removal	1	1	1	-
	Clearing (harrowing)	-	1	1	-
	Ripping + subsoiling	-	1	1	-
	Localized fertilizing	1	1	-	-
	Fertilizing (with subsoiling)	1	1	1	-
Stand establishment	Planting (manual)	1	1	1	1
Stand tending	Clearing (harrowing)	-	6	4	-
	Fertilizing (manual)	6	6	2	-
	Herbicide application	24	24	-	-
	Selection of coppice stems (chainsaw)	2	2	2	-
Logging	Felling (chainsaw or processor)	3	3	3	3
	Extraction (tractor or forwarder)	3	3	3	3
	Loading onto truck (crane)	3	3	3	3
Infrastructure establishment	Road building	1	1	-	-
	Road maintenance	36	36	-	-
	Firebreak building	1	1	-	-
	Firebreak maintenance	36	36	-	-

In forests under intensive management, logging includes (i) cutting and processing with a chainsaw or processor, (ii) extraction with an agricultural tractor or forwarder and (iii) log loading onto a truck with the crane of the truck. In forests extensively managed, logging is conducted in the same way, but it uses neither a processor nor a forwarder.

Infrastructure establishment includes road and firebreak construction (once per revolution) and maintenance (once every year for each rotation) in forests under intensive management. These operations are not implemented in forests extensively managed.

The weighted average distance associated with the road transport of eucalyptus wood produced in Portugal to the pulp mill is 51 km. This transport is performed by trucks with a gross volumetric weight of over 32 metric tons. The weighted average distances associated with the transport of imported eucalyptus wood are 9150 and 270 km for sea and road transport, respectively. Sea transport is performed by ships with a tank size of approximately 50,000 deadweight tonnage, and road transport is performed by trucks with a gross volumetric weight of over 32 metric tons.

Inventory data for forest operations were provided by forest managers based on real operational data, representative of the different management models. Data on wood transport were based on real data from the pulp mill. Additionally, some data were obtained from the scientific literature. In particular, the volumetric weights of diesel (850 kg/m^3) and gasoline (725 kg/m^3) used in the mechanised operations were taken from the study by Dias et al. [17]. The emission factors adopted to estimate emissions from fuel combustion were retrieved from the Intergovernmental Panel on Climate Change (IPCC) [18] in the case of GHGs (carbon dioxide [CO_2], methane [CH_4] and nitrous oxide [N_2O]), and the Environmental Protection Agency (EEA) [19] for emissions of carbon monoxide (CO), nitrogen oxides (NO_x), ammonia (NH_3) and sulphur dioxide (SO_2). The emission factors to calculate the emissions of N_2O and NH_3 to air and nitrates (NO_3^-) to water derived from the application of nitrogen-containing fertilisers were recommended by the IPCC [18], more specifically, 0.01 kg N_2O-N, 0.1 kg NH_3-N and 0.3 kg NO_3^--N per kg of N in the fertiliser. To estimate emissions resulting from the application of phosphorous (P)-containing fertilisers, an emission factor of 0.024 kg P per kg of P in the fertiliser was applied [20]. Furthermore, data on the production of fuels, fertilisers, electricity, herbicides, lubricants and trucking and shipping operations were obtained from the ecoinvent 3.7.1 database [21].

Softwood Forest

Softwood forest management was taken from the ecoinvent 3.7.1 database [21], including pine and spruce production in Germany and Sweden. Regarding the system boundaries, the inventory data include site preparation, stand establishment, stand tending, logging and infrastructure establishment. The data on the transport of softwood to the pulp mill include a mix of road transport by trucks of different size categories.

2.3.2. Manufacturing

Manufacturing includes the pulp production, jumbo roll production and finished product production stages. The tissue paper assessed requires approximately 70% eucalyptus pulp and 30% softwood pulp. The eucalyptus pulp is produced in Portugal and the softwood pulp is produced in Central and Northern Europe, and both are produced by the kraft method.

The inventory data on eucalyptus pulp and tissue paper production used in this study are based on real data provided by the P&P industry representative for the period of 2017–2019. All the thermal energy required in the eucalyptus pulp production process is generated on site by a biomass boiler using bark and residual forest biomass (logging residues), and by a recovery boiler using black liquor (wood-cooking liquor). Both boilers use ancillary fuels, including natural gas and heavy fuel oil in the biomass boiler, as well as heavy fuel oil in the recovery boiler.

The inventory data for jumbo roll production differ according to the two scenarios analysed, in particular regarding the consumption of electricity from the grid and fuels and, consequently, in the emissions and waste originating from the fuels. In S1, all the electricity consumed in the tissue mill is supplied by the national grid, and steam is produced in a natural gas boiler. In S2, the eucalyptus pulp mill biomass boiler produces excess steam (from the additional consumption of residual forest biomass) that is transferred to the tissue mill, which no longer requires steam produced from natural gas. In addition, the eucalyptus pulp mill biomass boiler produces excess electricity, which is also transferred to the tissue mill, resulting in a decrease in electricity consumption from the grid.

Table 2 presents the parameters considered in eucalyptus pulp, jumbo roll and finished product production, and how they change in S2 compared with S1 for these processes as a whole. Data on the impacts from the production of the inputs and end of life of solid wastes were taken from the ecoinvent 3.7.1 database [21]. For softwood pulp production, the original ecoinvent process of the production of bleached kraft pulp from softwood in Europe was adapted to reflect the electricity mix and fuel origins in Germany, Sweden and Finland—that is, the countries from where softwood pulp is imported. The transport of market pulp from the pulp mill to the tissue mill consists of 1 km by truck for the eucalyptus pulp, and 390 km by truck and 3375 km by ship for the softwood pulp.

Table 2. Inventory parameters associated with eucalyptus pulp, jumbo roll and finished product production, and how they change in S2 compared with S1 for these processes as a whole.

Inventory Parameters	Changes in S2 Compared to S1
Input	
Materials	
Eucalyptus wood	Equal
Softwood pulp	Equal
Coreboard	Equal
Pallets (EURO-pallet)	Equal
Packaging film (polyethylene)	Equal
CaO	Equal
H_2O_2 50%	Equal
H_2SO_4 98%	Equal
$NaClO_3$	Equal
NaOH 50%	Equal
Energy	
Electricity from the grid	33% Decrease
Natural gas	27% Decrease
Fuel oil	Equal
Bark and residual forest biomass	448% Increase
Water	Equal
Output	
Product	
Tissue paper	Equal
Emissions to air	
Carbon dioxide, fossil	25% Decrease
Nitrogen oxides	22% Increase
Carbon monoxide	101% Increase
Particles	69% Increase
Sulphur dioxide	30% Increase
Emissions to water	
Nitrogen	Equal
Phosphorus	Equal
Solid waste	
Sludge (for valorisation)	Equal
Ash (for valorisation)	448% Increase
Dregs	Equal
Grits	Equal

2.4. Impact Assessment

The impact assessment translates the inventory indicators (resource extraction and emissions) into environmental impact scores. In this study, ReCiPe 2016 Midpoint v1.01 from the hierarchist perspective [22] was selected as the default method to estimate the impacts of the tissue paper systems. Seven impact categories were selected considering the availability of inventory data and the relevance of the impacts: global warming (GW), ozone formation, human health (OFHH), terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME), mineral resource scarcity (MRS) and fossil resource scarcity (FRS).

To evaluate the robustness of the results, a sensitivity analysis was performed by applying the European Commission's Environmental Footprint method [23]. The equivalent Environmental Footprint categories to those of the ReCiPe were used, namely, climate change—fossil (CC); photochemical ozone formation (POF); acidification (A); eutrophication, freshwater (EF); eutrophication, marine (EM); resource use, minerals and metals (RUMM); and resource use, energy carriers (RUEC). For GW and CC, the biogenic CO_2 balance is considered neutral, that is, all CO_2 sequestered during forest biomass growth is released back into the atmosphere along the paper life cycle.

3. Results

3.1. Hotspot Analysis and Comparison Between Scenarios

Table 3 presents the total impact assessment results for S1 and S2, using the ReCiPe method, and Figure 3 highlights the contribution of each life cycle stage. In the hotspot analysis, the jumbo roll production stage has the highest impact in four out of seven categories (GW, OFHH, TA and FRS) in both scenarios, with contributions ranging from 39% to 61%. The exceptions are FE, ME and MRS. For FE, the jumbo roll production stage has the largest share in S1 (41%), followed by pulp production (38%), whereas in S2, the main contribution comes from pulp production (41%), followed by jumbo roll production (34%). The forest stage is the most significant for ME (contributions of 60% and 49%, respectively, for S1 and S2), mainly due to nitrate emissions in water, resulting from the application of nitrogen-based fertilisers during forest management operations. The pulp production stage is the most significant for MRS (contributions of 45% and 44%, respectively, for S1 and S2), mainly due to the extraction and consumption of mineral resources during the production of chemicals used in the pulp production process (e.g., sodium chlorate used in eucalyptus pulp production and sulphuric acid used in softwood pulp production). The finished product production stage also presents an important contribution to MRS (28–29%), mainly derived from the use of packaging film and pallets.

Table 3. Total impacts obtained with the ReCiPe method for the two scenarios (S1 and S2) per functional unit (FU).

Impact Categories	S1	S2
Global warming (kg $CO_{2eq.}$)	1849	1485
Ozone formation, human health (kg $NO_{xeq.}$)	6.17	5.83
Terrestrial acidification (kg $SO_{2eq.}$)	6.69	5.81
Freshwater eutrophication (kg $P_{eq.}$)	0.0803	0.0729
Marine eutrophication (kg $N_{eq.}$)	0.114	0.138
Mineral resource scarcity (kg $Cu_{eq.}$)	0.522	0.528
Fossil resource scarcity (kg $oil_{eq.}$)	585	478

Figure 4 shows the impacts of the processes involved in the jumbo roll production stage using the ReCiPe method. The consumption of electricity produced from the national grid is the most pronounced hotspot for all categories in S1 (contribution ranging from 49% to 89%), except for ME, which is dominated by direct emissions of nitrogen into the water. Of note, the shares of electricity produced from coal and natural gas are 26% and 25%, respectively [21]. In S2, the consumption of electricity produced from the national grid is also the main cause of impacts for OFHH, TA, FE and MRS, with contributions ranging from 41% to 77%. For GW and FRS in S2, the combustion of natural gas in dryers used in the tissue paper mill to produce hot air for tissue paper drying has the largest contributions (49% and 51%, respectively), mainly due to the emissions of CO_2 and the depletion of natural gas, respectively. Electricity from the national grid is also relevant in these impact categories, with shares of 48% and 46%, respectively, for GW and FRS. Moreover, the combustion of natural gas in dryers is relevant for OFHH in both scenarios (28% in S1 and 32% in S2), mainly as a result of NOx emissions. For ME in S2, the production of energy in the biomass boiler has the largest contribution to the total impacts (69%), mainly due to upstream emissions of nitrogen during the fertilisation of the forest biomass consumed in the boiler.

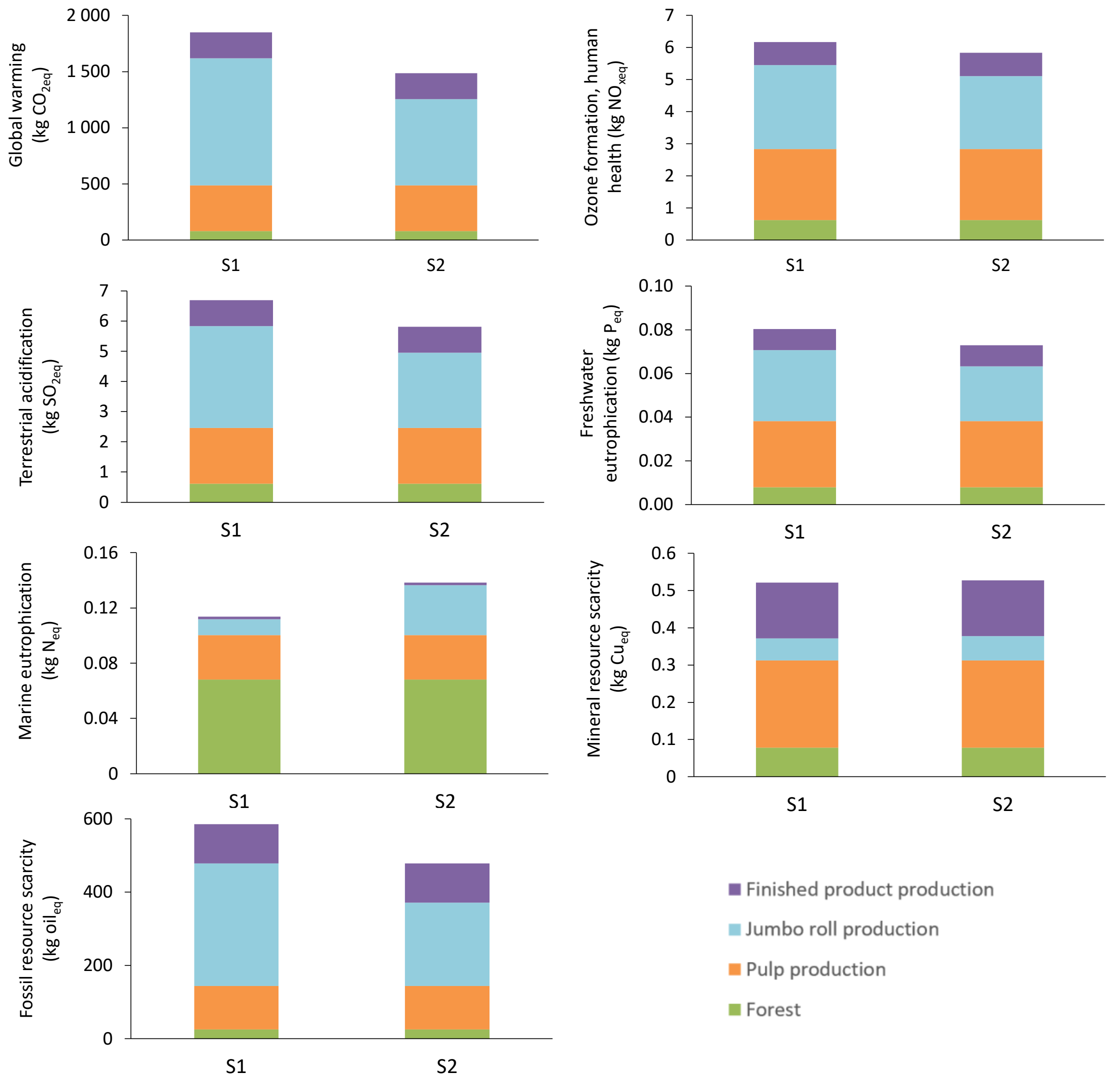

Figure 3. Impact assessment results with the ReCiPe method for the two scenarios (S1 and S2) per functional unit (FU).

In the comparative analysis between the two scenarios, S2 has a better environmental performance in five out of seven categories. The impact reduction in these categories ranges from 5% for OFHH to 20% for GW; it results mainly from the decrease in impacts associated with the electricity consumed, which in S1 is produced from the national grid and in S2 is produced both from the national grid and on site in the biomass boiler (Figure 4). Thus, the increase in some on-site air emissions in S2 associated with the biomass boiler is offset by the decrease in emissions derived from the grid electricity consumption. In the case of GW and FRS, the impact reduction also results from a decrease in impacts associated with steam production, which in S1 is based on natural gas and in S2 is based on forest biomass (Figure 4).

However, S2 is the worst scenario for ME, with an increase of 22% due to higher nitrate emissions into the water from fertilisations associated with the production of forest biomass used in the biomass boiler. For MRS, there are no significant differences between S1 and S2 (there is an increase of 1%), as the integration of bioenergy in P&P mills does not significantly influence the consumption of mineral resources.

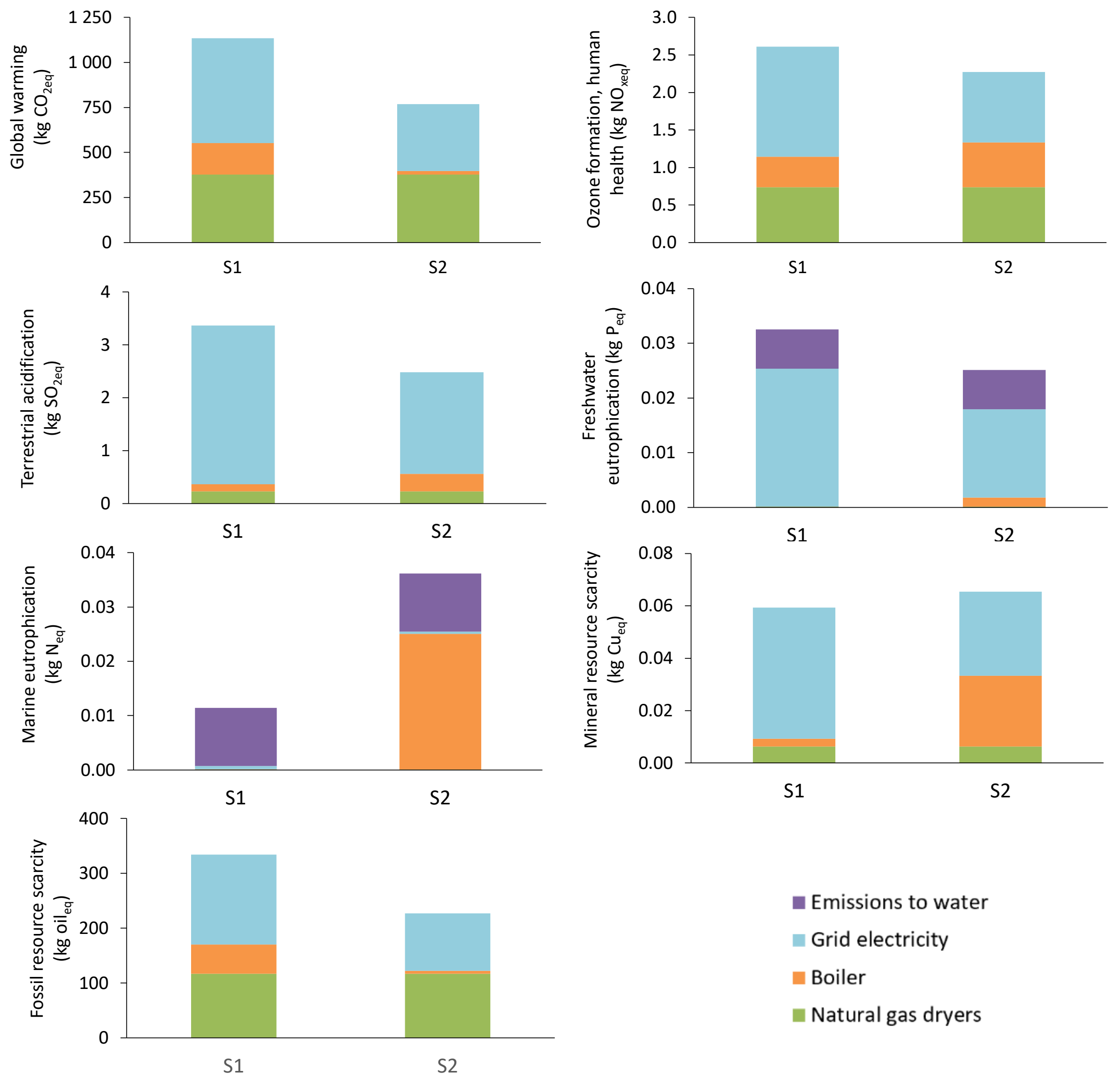

Figure 4. Impact assessment results for the jumbo roll production stage with the ReCiPe method for the two scenarios (S1 and S2) per functional unit (FU). S1 uses a natural gas boiler and S2 uses a biomass boiler.

3.2. Sensitivity Analysis

Table 4 shows the total impact assessment results obtained for S1 and S2, using the Environmental Footprint method, and Figure 5 illustrates the contribution of each life cycle stage. Except for EM and RUMM, the impacts follow the same trends in terms of the hotpots and the comparative analysis between the two scenarios as those observed for the ReCiPe method.

Table 4. Total impacts obtained with the Environmental Footprint method for the two scenarios (S1 and S2) per functional unit (FU).

Impact Categories	S1	S2
Climate change, fossil (kg $CO_{2eq.}$)	1847	1485
Photochemical ozone formation (kg $NMVOC_{eq.}$)	9.10	8.15
Acidification, terrestrial and freshwater (mol $H^+{}_{eq.}$)	10.3	9.14
Eutrophication, freshwater (kg $P_{eq.}$)	0.0802	0.0728
Eutrophication, marine (kg $N_{eq.}$)	2.59	2.59
Resource use, minerals and metals (kg $Sb_{eq.}$)	5.47×10^{-4}	5.32×10^{-4}
Resource use, energy carriers (MJ)	2.73×10^{4}	2.66×10^{4}

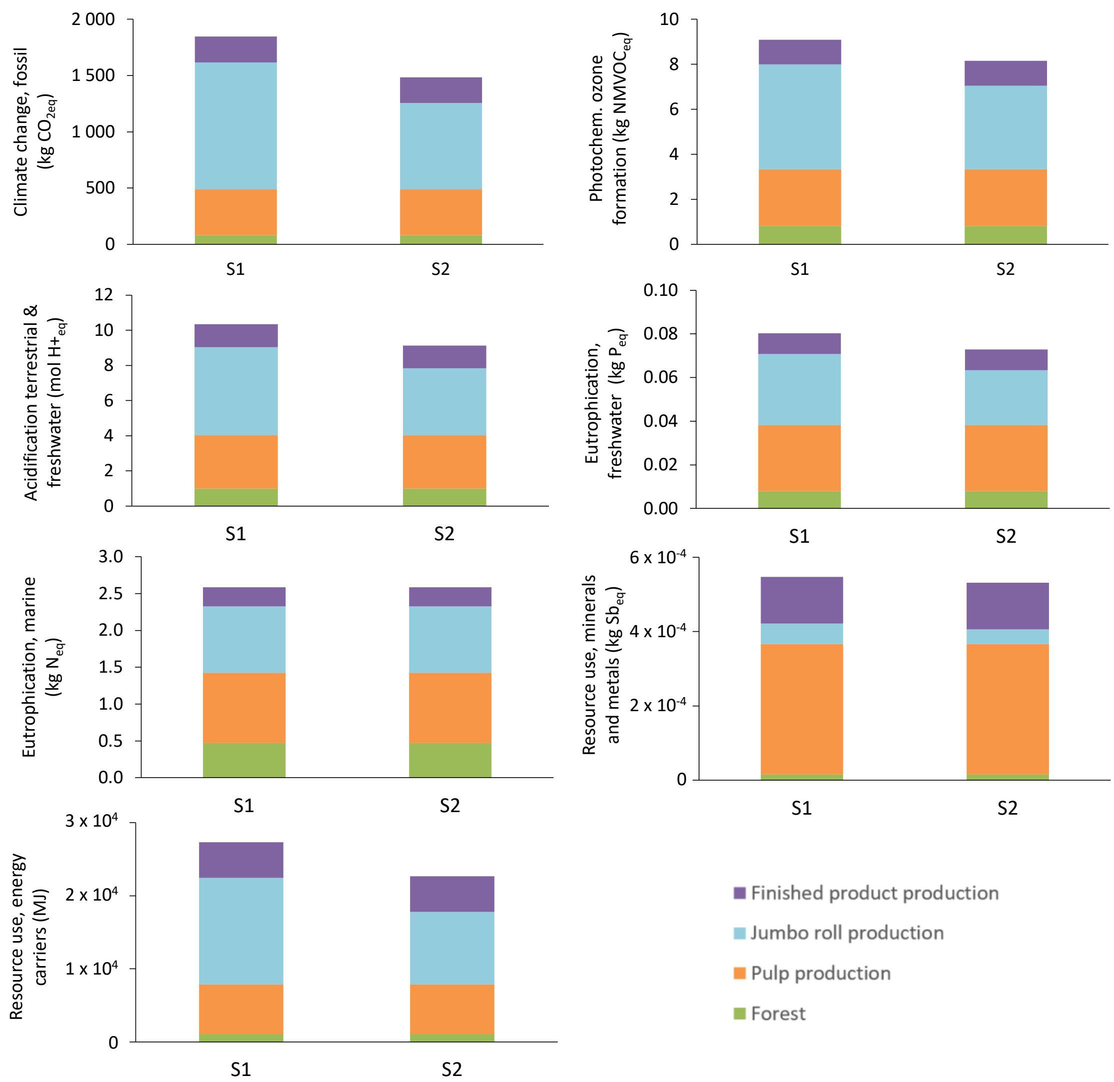

Figure 5. Impact assessment results with the Environmental Footprint method for the two scenarios (S1 and S2) per functional unit (FU).

In the hotspot analysis, the jumbo roll production stage continues to be the largest hotspot for most categories in the two scenarios (contributions ranging from 41% to 61%). For EM, the forest stage is no longer the main hotspot; instead, pulp production and jumbo roll production have the greatest impacts in both scenarios (contributions of 37% and 35%, respectively, with the same contributions in the two scenarios). NOx emissions into the air are the main cause; they derive mainly from the recovery boiler in the eucalyptus pulp mill and the production of electricity consumed in the tissue mill. Of note, the Environmental Footprint method provides characterisation factors for NOx emissions, whereas the ReCiPe method excludes these emissions, which explains the differences between the two methods. Finally, for RUMM, the pulp production stage continues to be the main hotspot, but it has higher contributions (64% and 66%, respectively, for S1 and S2) than in the equivalent category in ReCiPe, MRS (45% and 44%, respectively, for S1 and S2), due to differences between the two methods in terms of the substances and characterisation factors. The substances that most contribute to impacts are silver, zinc, tin and copper for RUMM, and aluminium, pumice, titanium and copper for MRS.

In the comparative analysis between the two scenarios, S2 has lower impacts than S1 in all categories other than EM. The impact reduction in these categories ranges from 3% for RUMM to 20% for CC; it results mainly from the decrease in impacts associated with the electricity consumed in jumbo roll production. For EM, the results are similar in both scenarios, whereas there is an increase of approximately 22% for S2 compared with S1 when using ReCiPe. In the latter method, NOx emissions are not accounted for in ME and, thus, the increase in S2 is dominated by the increase in nitrate emissions into the water from the production of forest biomass combusted to produce energy. With the Environmental Footprint method, in S2, the higher nitrate emissions from forest biomass production are compensated for by the lower NOx emissions associated with the reduced use of electricity from the national grid. Regarding RUMM, S2 represents a decrease of 3% compared with S1, whereas there is a slight 1% increase for MRS when using ReCiPe. This discrepancy is due to small differences between the two methods regarding the substances and characterisation factors.

4. Discussion

The environmental assessment performed with the ReCiPe impact assessment method shows that, for both scenarios analysed, the jumbo roll production stage plays the major role for most impact categories, except for ME and MRS, where the forest and the pulp production stages have the greatest impacts, respectively. The pulp production stage is also the hotspot for FE in S2. In the categories for which the jumbo roll production stage is the greatest hotspot, grid electricity consumption is the dominant cause. Given that changing the electricity mix in the national grid is not under the control of the P&P industry, possible improvement measures that can be implemented on site to decrease these impacts may include the optimisation of electricity consumption and the integration of a higher amount of electricity from alternative sources such as, for example, photovoltaics. Natural gas consumption used to produce hot air for tissue paper drying is also relevant in some impact categories, mainly in S2. Improvement measures may include the optimisation of natural gas consumption. In ME, the forest stage is the greatest hotspot, mainly due to emissions from the application of nitrogen-based fertilisers during forest management operations. This impact may be reduced by optimising fertiliser application. For MRS, the pulp production stage is the greatest hotspot, mostly from the consumption of chemicals in the production of both eucalyptus and softwood pulps. Possible measures to decrease this impact may include the optimisation of the consumption of these chemicals and the selection of the appropriate suppliers to ensure the best environmental practices.

The sensitivity analysis with the Environmental Footprint method confirms the same trends observed for the ReCiPe method in terms of hotspots, except for EM and RUMM. For EM, the forest stage is no longer the main hotspot; instead, pulp production and jumbo roll production are the hotspots in both scenarios. For RUMM, the pulp production stage remains the main hotspot but has a higher contribution than in the equivalent category in ReCiPe. These findings demonstrate the need to use more than one impact assessment method to ensure there is robust support for decisions.

The comparison between the two scenarios demonstrates that the integration of bioenergy into the P&P mills leads to a reduction of 5–20% in impacts and in all categories analysed with the ReCiPe method, except for ME and MRS. For ME, the production of a higher amount of bioenergy generated from forest biomass production contributes to a 14% increase, whereas for MRS, there is a slight 1% increase. With the Environmental Footprint method, the trends in the variation in the impacts between the two scenarios are similar to those observed with the ReCiPe method, except for EM and RUMM. For EM, S1 and S2 present similar results, and for RUMM, S2 represents a 3% decrease relative to S1. Therefore, this study demonstrates that the integration of bioenergy into tissue paper production not only enhances industrial decarbonisation but also contributes to reducing the environmental footprint of tissue products. However, to achieve additional improvements concerning marine eutrophication and the use of mineral resources, it is essential to implement measures to decrease nitrogen emissions along the value chain and the impacts derived from certain chemicals used in pulp production.

The results of this study provide valuable insights into how to improve the environmental performance of tissue paper mills. The findings should support strategies and policies towards more sustainable practices. The results also underscore that the energy configuration considered in S2 can be a strategy under the European Green Deal, which defines ambitious climate targets aiming to achieve net-zero GHG emissions by 2050 in the European Union [24]. Renewable energy sources are recognised to play an essential role for this purpose. However, the sustainable use of forest biomass for bioenergy is paramount because biomass is a finite resource [25]. Residual forest biomass, used to produce the surplus steam in the biomass boiler in S2, presents several advantages as feedstock for bioenergy, including the fact that its use does not cause deforestation. Moreover, in countries such as Portugal that are prone to frequent forest fires, the collection of residual forest biomass is a strategy to reduce the risk of these fires. However, part of the residual forest biomass should be left on the forest floor to replenish nutrients depleted from the soil as the trees grow, ensuring soil fertility [26]. Therefore, estimating the available residual forest biomass and planning its use are pivotal to ensure the sustainable use of this resource.

It should be noted that the results of this study are affected by uncertainty associated with the parameters (data), models and methodological choices [27]. Although most of the data adopted in this study for the foreground processes (eucalyptus forest, pulp and tissue paper production) are primary and based on real operations and measurements, some secondary data were also used in the absence of primary data sources. For example, emission factors for estimating emissions from fuel combustion and fertiliser application were used for the eucalyptus forests. However, the effect of the uncertainty associated with these parameters is expected to have a small effect on the conclusions of this study as the forest stage has a relatively low contribution to the total impacts. Secondary data were also obtained from the ecoinvent database, which also contributes to the parameter uncertainty, despite the efforts to select the most representative datasets. The assumption that the environmental burdens of eucalyptus wood production abroad are similar to those of domestically produced eucalyptus wood also introduces uncertainty, albeit a very small uncertainty given the low percentage of imported wood (2.5%).

Model uncertainty arises mainly from the adoption of eucalyptus forest management models that are considered to be the most representative. They are not actually applied over the entire eucalyptus forests that supply the pulp mill, as not all forest owners adopt the same models. However, given the small contribution of the forest stage, the effects of this uncertainty in the results are not expected to be relevant. Uncertainty due to the methodological choices also affects the results, as demonstrated by the sensitivity analysis on the use of different impact assessment methods.

The results are also affected by data variability, which, unlike data uncertainty, cannot be decreased with more knowledge because it represents natural variations in the real world [28]. Data variability occurs mainly in the forest processes. For example, the amount of fertiliser needed may differ depending on factors such as the soil and climate conditions.

Table 5 presents previous studies that have used LCA methodology to evaluate the environmental performance of tissue paper. This study differs from these in several normative choices (e.g., system boundaries, databases, impact categories and impact assessment methods) that prevent a fair comparison of the results. Despite this limitation, the GW impact (equivalent to the carbon footprint) has been compared, given that all studies use global warming potentials (as characterisation factors for the different GHGs) recommended by the IPCC, although they may differ among the studies for non-CO_2 gases. Therefore, the values for the GW impacts of previous studies are also shown in Table 5, expressed in kg CO_2 equivalents per ton of tissue paper when they are reported in this unit or when the conversion to this unit was possible.

For the present study, the GW impacts from cradle to gate are 1485 and 1849 kg CO_{2eq} per ton of tissue paper for S2 and S1, respectively. These values are within the wide range of variation (from 1061 to 3075 kg CO_{2eq} per ton of tissue paper) reported in the studies presented in Table 5 for tissue paper produced from virgin fibre based on a cradle-to-gate approach (similarly to the present study). As mentioned above, the different normative choices of these studies may partially explain the differences. Additionally, the fact that these studies analysed distinct products with different production processes, raw materials and technologies and in distinct years in different countries also explains the variation in the results. For example, the present study represents a mix of both non-wet- and wet-strength products, whereas some of the studies addressed the production of specific non-wet-strength (e.g., toilet paper) or wet-strength (e.g., napkins) tissue products. Some of the differences associated with the results obtained in the studies can also be explained by the different energy requirements, such as electricity, which is produced from distinct sources in each country or region. For example, Brito et al. [10] reported great variation in the GW impact of premium and ultra grades of tissue paper produced in the United States depending on the mill location due to different electricity production mixes. They concluded that tissue paper produced in mills located in regions where the electricity mix has a higher share of fossil fuels presents a higher GW impact.

The environmental hotspots also vary depending on the study. Four studies [29–32] identified P&P production (as a whole) as the greatest hotspot for the GW impact. Additionally, Brito et al. [10] and Gemechu et al. [33] showed that tissue paper production is the greatest hotspot because it is an energy-intensive process with high fuel requirements and high use of electricity from the national grid. Wellenreuther et al. [34] also concluded that the main hotspot is paper production, although the main causes have not been identified. Furthermore, Masternak-Janus and Rybaczewska-Błażejowska [35] showed that electricity from the national grid is a major hotspot in the production of tissue paper from virgin pulp. Ingwersen et al. [9] reported that pulp production is the largest hotspot. According to Madsen [36], who evaluated several tissue paper grades, the main hotspots are pulp production and electricity.

It is noteworthy that none of the studies analysed and compared different pulp and energy integration scenarios. Nevertheless, the study conducted by Madsen [36] highlights that the implementation of measures to improve energy efficiency and the shift to alternative non-fossil-based sources of energy in tissue manufacturing are important opportunities to minimise the environmental impacts.

Table 5. Literature review of the studies reporting the global warming impact of tissue paper.

Study	Product	Country	System Boundary	Type of Industrial Site	Hotspot	GW Impact (kg $CO_{2eq}t_{tissue}^{-1}$)
Madsen [36]	Several grades	North America and Europe	Cradle to grave	Several types	P&P	-
Ekstrom [29]	Facial tissue	USA	Cradle to gate	-	P&P	2379 from virgin fibre
Gemechu et al. [33]	Tissue paper not specified	Spain	Cradle to gate	Integrated	Paper	1900 from virgin fibre; 1300 from recycled fibre
Macri et al. [37]	Tissue paper not specified	USA	Cradle to gate	Non-integrated	-	2362 from virgin fibre; 2112 from recycled fibre
Jewell and Wentsel [30]	Napkins	USA	Cradle to grave	-	P&P	-
Joseph et al. [3]	Paper towel	USA	Cradle to gate	Integrated	-	-
Masternak-Janus and Rybaczewska-Błażejowska [35]	Tissue paper not specified	Poland	Cradle to grave	-	Electricity	-
Ingwersen et al. [9]	Paper towel	USA	Cradle to grave	-	Pulp	-

Table 5. *Cont.*

Study	Product	Country	System Boundary	Type of Industrial Site	Hotspot	GW Impact (kg $CO_{2eq}t_{tissue}^{-1}$)
Thi and Anh [31]	Tissue paper not specified	Vietnam	Cradle to gate	Non-integrated	P&P	1061 from virgin fibre; 751 from recycled fibre
Tomberlin et al. [32]	Tissue paper not specified	USA	Cradle to gate	Several types	P&P	1720 from virgin fibre
Wellenreuther et al. [34]	Tissue paper with 16 g/m^2	Germany	Cradle to gate	Non-integrated for virgin; integrated for recycled	Paper	~1280–1360 from virgin fibre; ~1190 from recycled fibre
Brito et al. [10]	Premium- and ultra-grade tissue paper	USA	Cradle to gate	Non-integrated	Paper	1392–3075 from virgin fibre

5. Conclusions

This LCA study evaluated, for the first time, the environmental performance of tissue paper produced at a typical industrial site in Portugal to fill the current knowledge gaps in the identification of the major hotspots and in the quantification of the effects of integrating bioenergy produced in the pulp mill into the tissue mill. Two alternative scenarios differing in the sources of steam and electricity consumed in the tissue mill were studied. In S1, steam is produced on site from natural gas and electricity that comes from the national grid. In S2, steam and 33% of the electricity are produced on site in the biomass boiler of the eucalyptus pulp mill, and the remaining electricity comes from the national grid.

The results support decision making at different levels. First, the results are paramount for the industrial site evaluated, highlighting the main hotspots and identifying possible mitigation measures, and demonstrating that the replacement of natural gas with bioenergy contributes to decarbonisation and can reduce other impacts. However, some other impacts, such as marine eutrophication and the use of mineral resources, may increase, requiring the implementation of additional measures. The results are also relevant for the P&P industry in general, regardless of the location and paper grades produced, as they provide quantitative insights into the potential environmental trade-offs derived from bioenergy integration into paper mills. Other industries where the replacement of natural gas with bioenergy is feasible may also take advantage of these results. Thus, this type of study can be replicated at other industrial sites to predict the environmental performance before implementing similar strategies. The results are also relevant for the authorities in charge of industrial licensing and those responsible for the definition of environmental policies, incentives and tax regulations—for example, for achieving decarbonisation goals. In particular, this study underlines the importance of conducting an LCA study before implementing strategies based on the replacement of fossil fuels with bioenergy towards more informed and strategic decisions that lead to more sustainable processes in a holistic way.

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