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Environmental impact assessment of total chlorine free pulp from *Eucalyptus globulus* in Spain

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ABSTRACT

Pulp industry plays an important role in the structure of European economy and society. Paper pulp manufacture, the industrial utilization of plant biomass, is increasing every year. In Spain, Eucalyptus is the dominant raw material and the Kraft cooking and total chlorine free (TCF) bleaching processes lead the procedures of Eucalyptus paper pulp production. This paper aims to identify and quantify the environmental impacts associated to Eucalyptus TCF pulp manufacture by using Life Cycle Assessment (LCA) as an analytical tool. The system has been defined using a cradle-to-gate perspective, that is to say from forest activities to the exit gate of the pulp mill. The production of chemicals consumed in the cooking and bleaching stages as well as the on-site energy production system is the elements that contribute the most to all impact categories analyzed (more than 50% of total contributions), except for the eutrophication potential where forest activities and waste treatment play an important roles (about 52% of total). Specific actions associated to the recovery boiler, lime kiln and digestion stage could considerably reduce the environmental impact and improve the environmental performance of the Spanish paper pulp industry.

1. Introduction

Manufacture and consumption of paper pulp are continuously growing across the world [1]. Pulp and paper sectors have a large tradition in Spain; in fact, within the EU Spain holds the 5th position as cellulose producer and the 6th as paper producer, with a national production of 2.0 and 6.4 million tons of pulp and paper in 2006, respectively [2].

Nowadays, wood is the main raw material used for paper pulp manufacture in the world [3,4]. European paper industry mainly uses recycled fibers, virgin pulp and non-fibrous materials [5]. Eucalyptus is a key raw material in South-Western European countries (such as Spain and Portugal), Brazil, and other world regions [6], and in particular *Eucalyptus globulus* provides the highest yield and the best pulp quality in Kraft pulping and totally chlorine free (TCF) bleaching [6].

Commonly, pulp and paper industry is divided into different pulping processes: chemical (e.g. Kraft pulping), mechanical (or thermo-mechanical) and a combination of both pulping processes [7]. Mechanical and chemical pulp production accounts for about 25% and 75% respectively, of wood pulp production at the moment [8]. Specifically, Kraft (or sulphate) pulp production is the dominant pulp-making process due to the high quality of pulps obtained with low lignin content and lower energy consumption [8,9]. Regarding the environmentally sound bleaching sequences, they involve substitution of Cl_2 by ClO_2, in the case of elemental chlorine free (ECF) bleaching, and the use of H_2O_2, O_2 and/or O_3 in the case of TCF bleaching. Despite some difficulties in attaining high brightness degrees, TCF sequences have been introduced in the European pulp and paper industry to avoid chlorinated compounds in the mill effluents and final products [10].

Industrial production of pulp and paper is an intensive consumer of energy (fossil fuels, electricity), natural resources (water, wood) and chemicals [7,11]. Several publications are already available on the analysis of the environmental impacts of pulp and paper processes [12–15] as well as processing of waste and wastewater treatment from those industries [16,17]. The environmental performance of ECF pulp production has been studied in detail in Portugal [12,14] and Thailand [13,15], and activities such as chemical recovery, energy generation and wastewater treatment were identified as concerns due to their contributions to waterborne emissions (COD and AOX), airborne emissions (NO_x and SO_2)

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and waste production (dregs, ashes, sludge). However, to the best of our knowledge, no study has dealt with the environmental impact of TCF pulp production (extensively used for eucalyptus wood), and only inventory data have been reported by Dias et al. [18]. The environmental profile of this kind of industry is important to be identified due to the high market demand of TCF paper pulp in Europe [9], the environmental controversy between ECF and TCF bleaching technologies [10] and the increasing concern for the improvement of the environmental impact of all the mill operations.

Life Cycle Assessment (LCA) methodology has proved to be a valuable tool for analysing environmental considerations of product and service systems that need to be part of decision making process towards sustainability [19]. LCA is a technique for assessing the environmental aspects associated with a product over its life cycle [20,21] and it has already been applied to wood-based products [22] such as paper [14], particleboards [23] or floor coverings [24]. The most relevant stages in environmental impact are industrial activities related to high chemicals and energy consumption while a common finding is the minor role that forestry activities play on the whole process.

This paper aims to assess and identify the environmental burdens associated to Kraft pulp manufacture in Spain from *E. globulus* by TCF bleaching process, using O_2 and H_2O_2 as bleaching agents. To do so, one representative pulp mill was analyzed in detail by using LCA. To date, there are no environmental studies for the pulp industry in Spain, even though it is one of the most important producing and exporting countries of eucalyptus based pulp [2].

2. Methodology

LCA is a methodology for the comprehensive assessment of the environmental impact associated to a product or process throughout its life cycle (from extraction of raw materials to product disposal at the end of use) and it is sometimes referred to as cradle-to-grave analysis [25]. However, when the system boundaries are restricted to selected life cycle stages, a cradle-to-gate perspective is possible, i.e. from raw materials extraction to product manufacture, which is the option followed in the present study.

According to the ISO standards [26], LCA is compiled of several interrelated components: i) goal and scope definition; ii) inventory analysis; iii) impact assessment and iv) interpretation of results for explanation of conclusions and recommendations, which is the scheme followed in this paper. Regarding the impact assessment stage, CML 2000 baseline impact assessment factors were chosen and modelling was performed using SimaPro 7.0 [27].

2.1. Goal and scope definition

This work aims to analyse and quantify the environmental impacts associated to the production of Eucalyptus Kraft pulp by TCF bleaching process, so as to identify those processes along the process chain that entail the highest environmental impacts. The study covers the whole cycle of pulp production from raw materials production to the pulp mill gate. A Spanish mill with an annual production of 423,535 ton[1] of pulp was selected to carry out the study.

2.2. Functional unit

The functional unit (FU) provides a reference to which the inputs and outputs are normalised [26]. In this study, 1 ton air dried (10% moisture content) of Kraft pulp from *Eucalyptus globulus* was defined as the functional unit.

2.3. System definition and boundaries

The system under study (Fig. 1) was divided into two main subsystems (S1 and S2), which are briefly described below.

2.3.1. Subsystem 1 (S1): forest operations

This subsystem includes all the operations carried out in Eucalyptus stands in Spain: silviculture operations (site preparation, stand establishment and tending), logging operations (harvesting and forwarding) and secondary hauling (transport from forest landing to pulp mill gate). Eucalyptus plantations were considered as they are the only raw material processed in the pulp mill. Although not specifically present in the figure, transports of workers, machinery and materials (fertilizers, pesticides and fuels) to and from forest plantations were also included within the subsystem boundaries. Eucalyptus seedling production was excluded due to the lack of data. A more detailed description of these activities can be found in González-García et al. [28,29].

2.3.2. Subsystem 2 (S2): pulp mill

This subsystem includes all the industrial activities related to pulp production which take place in the mill: Eucalyptus timber debarking, chipping into regular size, cooking with Na_2SO_4 and NaOH, pulp washing, oxygen pre-delignification (two consecutive steps), and bleaching process (O_2, H_2O_2, NaOH and chelating agent). Unlike other processes, there is no final washing step. Hence, the bleached pulp stays in a high density tower until the final optimum bleaching-grade is achieved. Finally, bleached pulp is dried, cut into sheets and it is stored until delivery to paper mills. Black liquor (spent solution) is sent to the chemical recovery unit where energy is generated and cooking chemicals (NaOH and Na_2S) are recovered.

Each pulping process utilizes large amounts of water. The most important sources of wastewaters are cooking, washing and bleaching steps. All wastewater is sent to the wastewater treatment plant (WWTP), which consists on both an aerobic lagoons system and secondary settlers.

Energy consumption is particularly high in pulp mills and it is considered a key environmental issue in this sector [30]. The pulp mill under study is energy self-sufficient, as almost all its energy requirements are satisfied by cogeneration units from biomass waste, black liquor and fossil fuels, and only 1% of total electricity requirements are purchased from the national grid. Background systems for the production of chemicals and fossil fuels were included within the boundaries of this subsystem. Infrastructure and maintenance of capital goods (buildings, materials, etc.) were excluded due to the lack of data for the pulp mill infrastructure. In addition, in accordance with Jungmeier et al. [31] for wood-based products, the differences are negligible compared to the overall environmental impact of the life cycle of the product.

2.4. Inventory analysis

High quality data are crucial in an LCA to make a reliable evaluation. Forest operations and field process data (season 2006–2007) were supplied by a leading Spanish company with sustainable forest management certification. Interviews and company visits were carried out to gather inventory data, which were completed with environmental declarations, internal company reports and bibliographic sources. The most relevant data for S1 are shown in Table 1. Inventory data for the pulp mill activities, S2

[1] All tons in this paper are metric tons, hereafter referred as ton(s).

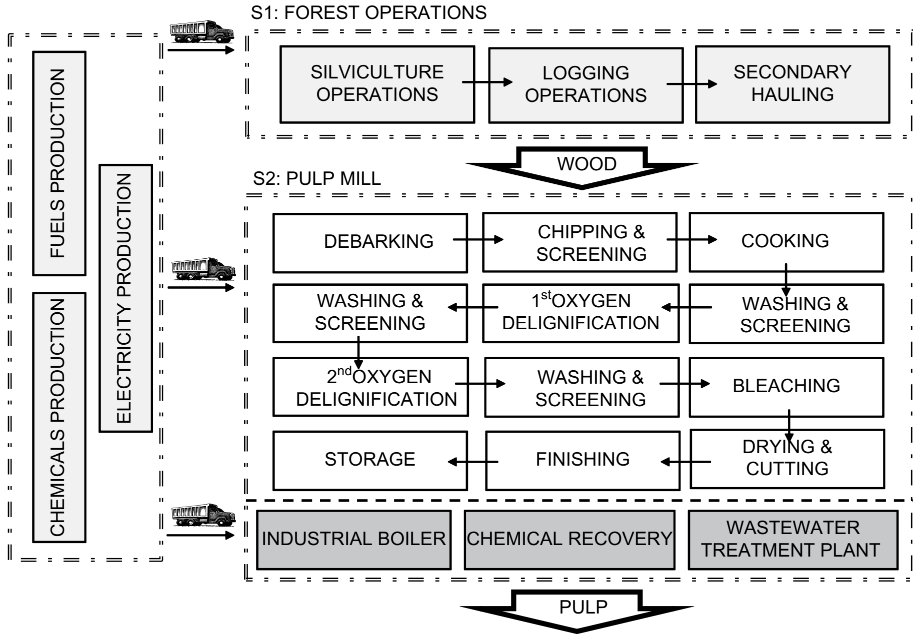

Fig. 1. System boundaries and process chain under study.

(Table 2) were obtained from average annual data (years 2004–2007) of on-site measurements:

- As mentioned, steam and electricity come from the cogeneration units where renewable fuels: wood waste (dust and bark), sludge from wastewater treatment (in the solid biomass boiler) and black liquor (in the liquid biomass boiler), are burnt. However, propane is used in the start-up of the boilers and fuel oil is also used in the lime kiln for lime combustion. Both air emissions associated to this unit and the consumption of raw materials (CaO, fuel oil and propane) were included in the global inventory table (Table 2). Background data for the production of fossil fuels were taken from the Ecoinvent database [32] and renewable fuels (biomass waste generated) were considered with no environmental burden allocation.
- Data for the production of chemicals (such as cooking and bleaching agents) were also from the Ecoinvent database [33]. Distances of transportation routes were supplied by plant workers and background data for transport systems came also from Ecoinvent [34].
- Waste treatment was included within the system boundaries: glass, paper and cardboard are sent to recycling. Green liquor dregs and ashes (from boilers and recovery unit), debris, scrap and municipal solid waste are sent to landfill. The amounts of each waste were identified as well as the average distance of transport (20 km in trucks). Inventory data for these treatments were taken from Ecoinvent database [35].

Table 1
Summary of energy and chemicals consumption in forest operations (S1) per 1 ton air dried (10% moisture content) of Kraft pulp.

INPUTS from TECHNOSPHERE			
Materials	**Silviculture operations**	**Logging operations**	**Secondary hauling**
Chemicals			
Fertilizer (NPK)	10.69 kg	–	–
Pesticide (glyphosate)	0.426 L	–	–
Fossil fuels			
Diesel	6.10 kg	8.14 kg	6.50 kg

3. Environmental impact assessment

Among the phases defined by the impact assessment phase in the LCA methodology [26], only classification and characterization stages were considered. Normalization and evaluation were excluded since they are optional elements and according to the goal and scope defined here, they would not provide extra useful information.

Characterization factors reported by the Centre of Environmental Science of Leiden University (CML 2 baseline 2000 V2.1 method) were considered [25], and the impact categories analyzed are: abiotic resources depletion (AD), global warming (GW), ozone layer depletion (OLD), human toxicity (HT), freshwater aquatic ecotoxicity (FE), marine aquatic ecotoxicity (ME), terrestrial ecotoxicity (TE), photochemical oxidants formation (POF), acidification (A) and eutrophication (E).

Table 3 presents the total results from the characterization stage for each impact category, while Fig. 2 shows the relative contributions of the two subsystems defined, where the dominance of the industrial activities related to pulp mill (S2) is clear in all the impact categories under study.

This small contribution of the forest activities to almost all impact categories is in agreement with other related papers available in the literature [12–14]. A detailed analysis of forest activities as well as the definition of improvement actions have been separately studied and further information can be found [28,29]. Notably, eucalyptus wood production (main raw material) figures 49% of photochemical oxidants formation mainly due to fossil CO emissions (energy related emission) associated to the combustion of fossil fuels in forest operations associated to the high mechanization degree. In addition, these activities showed an important contribution in A related to diesel, gasoline and N-based fertilizer use as well as to E, mainly due to the application of fertilizers into the soil (phosphorous and nitrogen based fertilizers).

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Table 2
Global inventory data for Pulp mill (S2) per 1 ton air dried (10% moisture content) of Kraft pulp.

INPUTS from TECHNOSPHERE			
Materials	**Value**	**Materials**	**Value**
Biomass		Wire[a]	2.60 kg
Green Eucalyptus logs	2.70 m^3	Fossil fuels	
Wood waste	0.50 kg	Fuel oil	53.00 kg
Chemicals (100% purity)		Propane	0.40 kg
O_2	27.00 kg	**Energy**	**Value**
H_2O_2	23.00 kg	Electricity	575 kWh[b]
NaOH	14.60 kg	Steam	5.50 ton[c]
H_2SO_4	10.70 kg	**Transport**	
Na_2SO_4	7.30 kg	20–28 ton trucks	57.44 t km
CaO	4.40 kg	Trans. freight ship	20.68 t km
EDTA	3.00 kg		
H_2	1.90 kg		
$MgSO_4$	0.30 kg		
Anthraquinone	0.22 kg		
INPUTS from ENVIRONMENT			
Water	32.70 m^3		
OUTPUTS			
To TECHNOSPHERE		**To ENVIRONMENT**	
Materials	**Value**	**Emissions to air**[d]	**Value**
Bleached pulp (10% moisture)	1 ton AD	CO_2	212.70 kg
Energy		NO_x	1.02 kg
Electricity to grid	32.32 kWh[f]	SO_2	0.58 kg
Waste to treatment		Particulates	0.43 kg
Ashes (to landfill)	14.68 kg	TRS	0.013 kg
Dregs (to landfill)	12.85 kg	**Emissions to water**[e]	
Debris (to landfill)	1.18 kg	AOX	0.004 kg
Scrap (to landfill)	1.34 kg	COD	5.84 kg
Municipal solid waste (to landfill)	0.85 kg	BOD_5	1.44 kg
Paper and cardboard (to recycling)	39.87 g	N	0.28 kg
Glass (to recycling)	3.74 g	P	0.070 kg
		TSS	1.14 kg
		Water effluent	32.70 m^3

[a] Wire is used in the packaging step, for making the bleached pulp bales (250 kg/bale).
[b] From those only 5.82 kWh are taken from the grid and the remaining comes from cogeneration units.
[c] From biomass boilers.
[d] Direct emissions from the biomass and black liquor boilers as well as lime kiln.
[e] Direct emissions from the WWTP.
[f] Electricity surplus is sold to the national grid.

Regarding the pulp mill subsystem (S2), a more detailed study for each impact category was performed (Fig. 3) in order to see the relative contribution of the processes included in S2: production and transport of chemicals consumed in the pulp mill (excluding CaO since it was included in the energy production process), production of energy (both the internal production and the national grid) and transport and treatment of the waste produced.

Table 3
Results from characterization. Data are presented per 1 ton air dried (10% moisture content) of Kraft pulp.

Category	Unit	Value
Abiotic depletion (AD)	kg $Sb_{eq} \times 10^6$	7.65
Global warming (GW)	kg CO_{2eq}	431.30
Ozone layer depletion (OLD)	kg CFC-$11_{eq} \times 10^5$	3.46
Human toxicity (HT)	kg 1,4-DB_{eq}	39.19
Freshwater aquatic ecotoxicity (FE)	kg 1,4-DB_{eq}	32.47
Marine aquatic ecotoxicity (ME)	kg 1,4-$DB_{eq} \times 10^{-4}$	7.73
Terrestrial ecotoxicity (TE)	kg 1,4-DB_{eq}	0.943
Photochemical oxidation (POF)	kg C_2H_{2eq}	0.139
Acidification (A)	kg SO_{2eq}	2.83
Eutrophication (E)	kg $PO_4{}^{-3}{}_{eq}$	0.698

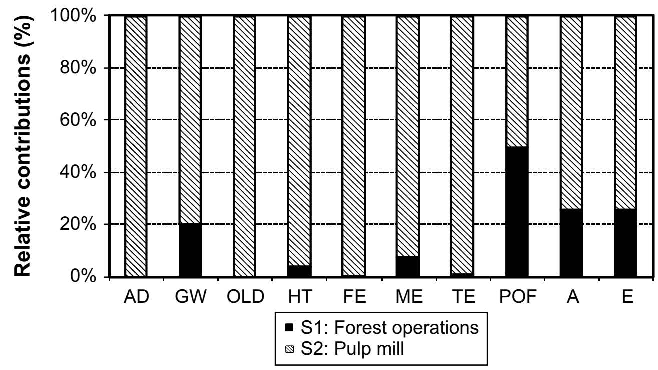

Fig. 2. Relative contribution per subsystem to each impact category.

3.1. Abiotic resources depletion (AD)

AD is totally dominated by the production of chemicals (~100%), and in particular the chelating agent used in the bleaching stage for removal of metals was identified as the mainly responsible with a contribution of ~98%.

3.2. Global warming (GW)

Only the CO_2 originated during non-renewable fuel combustion was taken into account since the CO_2 released from renewable sources is assumed to be balanced with CO_2 absorption during eucalyptus tree growing. The combustion of fuel oil in lime kiln stands for 65% of the impact followed by chemicals production (31%). GW could be reduced by displacing the consumption of fossil fuels by renewable fuels in the chemical recovery system. In fact nowadays, renewable fuels are commonly used as unique source for energy production in other pulp mills [12]. Fuel combustion was also identified as the most important source of fossil CO_2 emissions in Kraft pulp mills by other authors [15]. Regarding substances, fossil CO_2 dominates the impact with a contribution around 100%.

3.3. Ozone layer depletion (OLD)

The production of energy stands for two thirds of this impact category, mainly due to the production of fossil fuels used to strike the boilers and lime kiln. Behind, the production of chemicals used in cooking and bleaching stages (specifically H_2O_2) is the other important element (~29%). Regarding emissions, Halon 1301 and 1211 from the production of the fuel oil used in the lime kiln represented 76% and 13%, respectively of the total contributing emissions (CFC-11 equivalent).

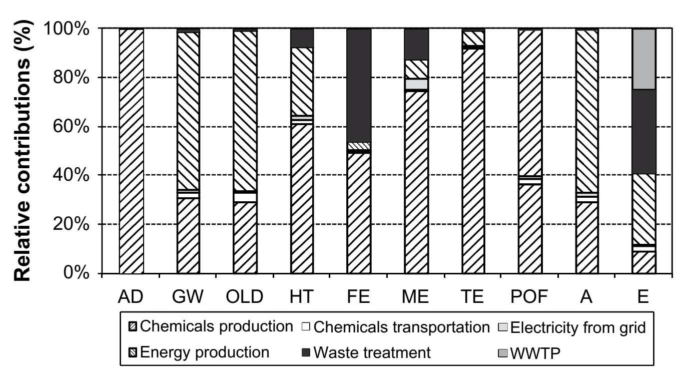

Fig. 3. Relative contributions of the different processes involved in the pulp production system.

3.4. Human toxicity (HT)

The pulp production process under study is totally chlorine free so chlorinated compounds are not used as bleaching agents. In this process, AOX emissions are really low due to the absence of chlorinated compounds and are associated to the wastewater treatment plant. Just like other impact categories, the production of chemicals seems to be the main responsible (~61%), mainly due to H_2O_2 and NaOH, followed by energy production (Fig. 3). Human toxicity in our process is mainly caused by water and airborne emissions such as PAH (15%) and nickel (10%) to air and, PAH (10%) and barium (10%) to water, mainly from the chemicals and fuels production.

3.5. Freshwater aquatic ecotoxicity (FE)

FE potential is mainly divided between two processes: chemicals production (specifically H_2O_2) and the treatment of waste generated in the process (mainly due to the disposal in a landfill of the green liquor dregs and ashes derived from chemical recovery unit). Three substances are the main contributors: copper (31%), vanadium (25%) and nickel (18%) from both processes.

3.6. Marine aquatic ecotoxicity (ME)

Chemicals production was mainly responsible for the contributions to this category (~75%), followed by waste treatment (13%) and energy production (8%). The emission of hydrogen fluoride to air represented 56% of total, followed by vanadium (11%) and beryllium (8%) to water, mostly from O_2, NaOH and H_2O_2.

3.7. Terrestrial ecotoxicity (TE)

With a contribution of more than 92%, chemicals production dominates this impact, specifically NaOH (roughly 60% of total) and H_2O_2 (18%) consumed in the cooking and bleaching processes. The main emissions were mercury to air (73%) from NaOH production and vanadium to air (22%) related to H_2O_2 production.

3.8. Photochemical oxidants formation (POF)

The main contributor to this impact category was the production of energy in the mill which accounted more than 60% due to the chemical recovery unit (Fig. 3). SO_2 emissions represented more than 83% of total emissions, principally derived from recovery boiler (black liquor as fuel) and lime kiln. Both sources were also identified as problematic by other authors [12,15].

3.9. Acidification (A)

Energy production related processes represented roughly 67% of total emissions. Specifically, the chemical recovery unit was found to be the major contributor to SO_2 emissions due to the use of Na_2SO_4 and the use of fuel oil in the lime kiln. SO_2 emissions contribute to ~69% of total emissions, followed by NO_x emissions (31% of total), which comes mainly from combustion in the boilers (biomass and recovery boiler) and from fuel oil in the lime kiln.

3.10. Eutrophication (E)

Waste treatment, energy production and WWTP represented 35%, 29% and 25% respectively, of total eutrophicating emissions (Fig. 3). Specifically, emissions to water represented more than 62% due to COD emissions (from WWTP and disposal in landfill of green liquor dregs). NO_x emissions to air contributed to ~33% of the total eutrophicating emissions derived from energy production.

4. Discussion

Within the cradle-to-gate perspective defined, the pulp mill subsystem is the largest contributor to all impact categories under study (Fig. 2). Based on the results of this study (Table 4), the less environmental friendly processes over the life cycle of pulp production (up to pulp mill gate) were identified according to the environmental impact assessment results. The on-site production of energy to fulfil the electrical and thermal requirements of the pulp process plays an important role in GW, OLD, POF and A, with more than half of the total contribution.

COD emissions to water from the WWTP and from the leakages from landfill of green liquor dregs are important contributions to E, which is in agreement with other related studies after excluding paper production, distribution and disposal (cradle-to-grave perspective) [12,14]. In both studies, energy production from biomass combustion (wood waste and black liquor) was also identified as the main contributor for A due to NO_x and SO_2 emissions, in agreement with our results as well as with the results from Jawjit et al. [13], where options to reduce the environmental impact in Kraft pulp industry were proposed.

Commonly, AOX (Adsorbable Organic Halides) emissions appear in the pulp production systems caused by the chlorine/chlorine compounds consumption in the bleaching process (e.g. ECF bleaching). These compounds are formed as a result of reaction between residual lignin from wood fibers and bleaching chemicals [36]. However, AOX discharged depends on more factors such as wood source and less AOX is produced when hardwood (such as eucalyptus) is bleached due to the higher lignin content in comparison with softwood [37]. Moreover, COD in effluents is also related to lignin residuals [38] and the COD reduction in the effluent treatment is higher for hardwood-based pulp, since lignin is very little affected of the biological effluent treatment. Both parameters reflect lignin wastes and could be related [38]. Incorporating TCF sequence in bleaching stage allows the reduction in total AOX emissions as well as COD in up to 75% and 60% respectively [15,18] since liquid emissions are largely affected by the use of different bleaching technologies.

Apart from the pulp mill, the background production of chemicals has been identified as a critical activity due to its high contribution to AD, HT, FE, ME and TE. These processes, specifically H_2O_2, NaOH and DTPA production, were important contributors of PAH (HT), HF (ME) and Hg (TE) emissions to air and Cu (FE) and PAH (HT) to water. Note that this is not the first time that the production of H_2O_2 is identified as an energy-intensive process and very important from an environmental point of view [39].

The disposal of the green liquor dregs and ashes to landfill entails and significant emission of pollutants such as Cu and Va with an important contribution to FE.

The wood production subsystem (S1) plays a minor role in the environmental impacts, although the contribution to POF, A and E of this subsystem due to the high use of fossil fuels (associated to the high mechanization degree and unfavourable land conditions) as well as fertilizers application is not negligible.

Having seen the dominance of S2, the definition of improvement options should be focused on that subsystem. Future alternatives in pulp digestion, such as ozone and enzyme delignification, could considerably reduce the consumption of bleaching agents [15,40]; but many of these applications are still at the research and development stage [10]. Nevertheless, a recent paper by Skals et al. [41] has concluded that small amounts of enzyme provide the same function as large amounts of chemicals, requiring less fossil fuels consumption than conventional processes and getting environmental improvements (in categories such as GW, A and E).

Improvement options regarding energy production could also be introduced. So, the substitution of fuel oil in the lime kiln for

Table 4
Contribution of processes to environmental flows.

Parameter	Forest operations(1)	Chemicals production(2)									Chemicals transport(3)	Electricity production(4)	Energy production(5)	WWTP(6)	Waste treatment(7)			
	Eucalyptus stand	H_2O_2	H_2	DPTA	O_2	NaOH	H_2SO_4	$MgSO_4$	Na_2SO_4	AQ					Recycling	Sanitary landfill	Inert Landfill	Others
AD		1 - 9.99%		> 50%														
GW	20 - 29.99%	10 - 19.99%		1 - 9.99%	1 - 9.99%	1 - 9.99%					1 - 9.99%		> 50%					1 - 9.99%
OLD											1 - 9.99%		> 50%					
HT	1 - 9.99%	20 - 29.99%		1 - 9.99%	1 - 9.99%	10 - 19.99%			1 - 9.99%	1 - 9.99%	1 - 9.99%	1 - 9.99%	20 - 29.99%			1 - 9.99%		1 - 9.99%
FE		30 - 49.99%		1 - 9.99%	1 - 9.99%	1 - 9.99%				1 - 9.99%			1 - 9.99%			30 - 49.99%		10 - 19.99%
ME	1 - 9.99%	20 - 29.99%		1 - 9.99%	1 - 9.99%	20 - 29.99%			1 - 9.99%	1 - 9.99%		1 - 9.99%	1 - 9.99%			1 - 9.99%		1 - 9.99%
TE		10 - 19.99%		1 - 9.99%	1 - 9.99%	> 50%				1 - 9.99%			1 - 9.99%					
POF	30 - 49.99%	1 - 9.99%		1 - 9.99%	1 - 9.99%	1 - 9.99%	1 - 9.99%			1 - 9.99%	1 - 9.99%		30 - 49.99%					
A	20 - 29.99%	1 - 9.99%		1 - 9.99%	1 - 9.99%	1 - 9.99%	1 - 9.99%			1 - 9.99%	1 - 9.99%	1 - 9.99%	30 - 49.99%					
E	20 - 29.99%	1 - 9.99%		1 - 9.99%		1 - 9.99%					1 - 9.99%		20 - 29.99%	10 - 19.99%		1 - 9.99%		20 - 29.99%

Process contribution key:

< 0.99%	1 - 9.99%	10 - 19.99%	20 - 29.99%	30 - 49.99%	> 50%

(1) Including fuels (diesel and gasoline) production; machinery operation; fertilizers and pesticide production, transportation to forest and application; hauling of pulpwood from forest landing to mill gate was considered as well as workers to and from forest; fuel dependent emissions (to air, water and soil) derived from engines were also included. Infrastructure production and maintenance were excluded from subsystem boundary.
(2) All chemicals manufacture includes the process with consumption of raw materials and energy as well as the generation of solid wastes (and management) and emissions to air and water. It also includes transportation of raw materials and wastes. Infrastructure production and maintenance were excluded from subsystem boundary.
(3) Including fuel production and distribution as well as fuel dependent emissions (to air, water and soil) derived from engines.
(4) Spanish electricity generation profile, including fuels production and distribution in the national grid. Infrastructure production and maintenance were excluded from subsystem boundary.
(5) Including fuels (propane and fuel oil) and CaO production and distribution. Emissions derived from industrial boilers and chemical recovery process (with wood waste, sludge from WWTP and black liquor as main fuel) were also considered. Infrastructure production and maintenance were not taken into account.
(6) Wastewater treatment plant consisting on both aerobic lagoons system and secondary settlers.
(7) Standardised treatment and disposal processes of solids and dregs-like wastes generated in the mill excluding infrastructures from the study.

lime combustion by natural gas has been identified as an interesting alternative for reducing SO_2, NO_x and CO_2 emissions [12,15] that consequently reduce the impact of GW, A and E. Another interesting option for the lime kiln is enhancing the washing step of lime sludge (between the causticizer and the lime kiln) [15,40]. By taking out the sodium salts (specifically Na_2S) from the sludge ($CaCO_3$) before its combustion in the kiln, H_2S emissions are reduced up to 60% [15]. In addition, the introduction of an improved evaporation step of the black liquor before its combustion in the recovery boiler would also reduce the SO_2 and TRS emissions associated to this unit [15].

5. Summary and conclusions

The production of pulp and paper has been traditionally considered an important source of pollution due to its intensive energy consumption and its use of large amounts of chemicals, fuels and water. In this paper, the production of eucalyptus pulp by Kraft cooking and TCF bleaching processes was studied using LCA methodology with a cradle-to-gate perspective. Based on the inventory analysis and impact assessment results, the environmental profile of the process was quantified and those processes with higher burdens identified.

This study demonstrated that activities related to wood paper pulp manufacture that take place inside the mill, such as cooking, bleaching and wastewater treatment, are not always the main contributors to the environmental impact of the process. In fact, a background process such as the upstream production of chemicals and fuels has been identified as the main contributor to impact categories related to toxicity (more than 50% of total contributions) and abiotic resources depletion (~100% of total). In addition, on-site energy production system seems to be an important concern in terms of acidification, global warming and ozone layer depletion mainly due to the use of fossil fuel in the lime kiln. Several improvement options have been identified and the next step would be their implementation in the pulp mill in order to check the expected environmental benefits associated.

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