Environmental Life Cycle Assessment of Premium and Ultra Hygiene Tissue Products in the United States

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Under the controversial concern of using virgin fibers in hygiene tissue products, mostly Bleached Eucalyptus Kraft (BEK) and Northern Bleached Softwood Kraft (NBSK), consumers are responding by purchasing self-labeled sustainable products. As of today, there are no established sustainability reported results to inform consumers about the carbon footprint of hygiene tissue. To fill this gap, this study used Life Cycle Assessment to evaluate the environmental impacts across the supply chain (cradle to gate) to produce Premium and Ultra grades of bath tissue, including the production of feedstock, pulp production, and tissue production stages, with focus on Global Warming Potential (GWP). The results showed that one air-dried metric ton (ADmt) of BEK pulp had an associated GWP of 388 $kgCO_2eq$, whereas one ADmt of NBSK pulp presented values ranging between 448 and 596 $kgCO_2eq$, depending on the emissions allocation methodology used. It was estimated that the GWP of one finished metric ton of tissue weighted average could range from 1,392 to 3,075 $kgCO_2eq$ depending on mill location, electricity source, and machine technology. These results provide an understanding of the factors affecting the environmental impact of hygiene tissue products, which could guide manufacturers and consumers on decisions that impact their carbon footprint.

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INTRODUCTION

The demand for more environmentally friendly consumer goods continues gaining market share (De Assis *et al.* 2018a,b; Euromonitor 2018, 2020). From a social science perspective, this surge in demand can be attributed to the effect of global megatrends, specifically sustainability and changes in social behavior (change in psychographics) (Haller *et al.* 2020; Hensley *et al.* 2020). Additionally, some recent studies suggest that the COVID-19 pandemic might have expedited this trend, as consumers had time to reflect on the consequences of their daily choices (Essity 2020). The 2021 report from The Intergovernmental Panel on Climate Change (IPCC), the major authority on climate change, will likely accelerate the demand for sustainable consumer goods. This report unquestionably describes that humans are driving global warming, and extreme weather will become more frequent during the next decades (IPCC 2021). However, consumers need guidance in decision-making (Haller *et al.* 2020) to ensure that adequate measures are taken. Greenwashing (a term coined to define the process of providing misleading information to persuade the public to purchase products and services which might not be environmentally friendly) is a real and fast-growing threat that is jeopardizing the goodwill of consumers toward the environment (Wicker 2020). As more consumers become sustainable-conscious with the passage of time and are willing to change their habits to reduce Greenhouse Gas (GHG) emissions and impact on the environment, the need for sustainable metrics for goods and services is now more urgent.

After discussing and realizing the need for sustainability metrics, it seems appropriate to understand how people's lifestyle choices can contribute to GHG emissions. Studies show that, on average, U.S citizens contribute to *ca.* 16 tons of carbon dioxide (CO_2) per year (Bank 2020; Conservancy 2021), considering food, housing, services, traveling, and consumer goods, corresponding to 16% of the total figure (Conservancy 2021). Specifically, hygiene tissue paper represents one of the consumer goods products that has been the target of significant controversies, probably due to its single-use nature and the utilization of virgin fibers in its manufacturing process (Euromonitor 2018). Tissue products can be classified into Economy, Premium, and Ultra grades, based on performance, which depends on the combination of fiber properties, pulping chemistry, process conditions, and drying technology (De Assis *et al.* 2018b). In the Premium and Ultra-grade categories, or consumer hygiene tissue products, quality fibers (*i.e.*, virgin fibers) are used, as high performance is expected. Indeed, whereas the US and Canada produce and use almost a quarter of the global hygiene tissue market (Statista 2021), more than half of the raw material (market pulp) used by these two countries to produce hygiene tissue comes from natural and planted forests (Fisher International 2021). Although these types of products are associated with higher use of resources, which is contradictive to the sustainability concept, the premium and ultra tissue market is seeing an increase in consumption because they cater to consumers who are willing to pay premium prices for better quality softness and absorbency. This means that consumers are aware that the higher prices are reflective of the superior product quality. These products offer a better tradeoff between cost and performance (Zambrano *et al.* 2020).

Specifically, Northern Bleached Softwood Kraft (NBSK) and Bleached Eucalyptus Kraft (BEK) represent the most used market pulp types to produce hygiene tissue, accounting for 62% of the total furnish (Fisher International 2021). Most of the NBSK comes from the Canadian boreal forests (Skene and Vinyard 2019), while most of the BEK comes from planted forests in Brazil, Spain, and Portugal (Dias *et al.* 2007; González-García *et al.* 2009; IBÁ 2019).

To the best of the authors' knowledge, there are no comprehensive public reports on sustainability metrics to inform and guide consumers on their selection for sustainable hygiene tissue. Today, the literature on this topic is limited. Some reports and web pages provide rankings without supplying the magnitude of the metrics used (environmental impacts) or are focused on regions different from North America (Skene and Vinyard 2019; Zhang *et al.* 2021). To fill this gap, this study aims to identify previous works on this topic and evaluate the environmental impact of the most used fibers, market pulps, and drying technologies for Premium and Ultra tissue products. The novelty of this work relies on developing quantitative metrics for hygiene tissue products, which could effectively guide society in their environmental choices and reward those manufacturers that are investing in lowering their environmental footprint.

METHODOLOGY

This research evaluates the environmental impacts, mainly climate change, throughout the whole supply chain of Premium and Ultra tissue products manufactured in the United States. The methodology comprised the following steps: search and analysis of previous works dealing with sustainability of consumer goods with a focus on hygiene tissue paper products and raw materials (*i.e*., feedstock and market pulp); identification of the most suitable methodology to assess the environmental impact of consumer hygiene tissue paper; identification of feedstock and materials subject to the life cycle inventory; identification of drying technologies; development of frameworks for goal, scope, and system boundary; methods to analyze and display results.

Literature Review: Search and Analysis of Previous Publications Related with the Sustainability of Tissue Products

An extensive literature review comprising publications and reports assessing the environmental impacts of hygiene tissue products was performed. Scientific databases such as Web of Science, Google Scholar, and Scielo were employed as search engines using combinations of general and specific keywords as listed in Table 1. Life Cycle Assessments of eucalyptus logs produced in Brazil, northern softwood chips produced in the US and Canada, Bleached Eucalyptus Kraft (BEK) market pulp, Northern Bleached Softwood Kraft (NBSK) market pulp, and hygiene tissue products were evaluated. Findings were analyzed in terms of methodology, assumptions, goal and scope, type of LCA, and other aspects that influenced the results. Thus, a clearer picture of the state-of-the-art knowledge on the sustainability of tissue products was obtained.

Table 1. Keywords Employed During the Search

Methodology	Feedstock	Market Pulp	Products
Life cycle assessment	Northern softwood	Bleached eucalyptus kraft	Tissue
Life cycle analysis	Northern softwood chips	Northern bleached softwood kraft	Hygiene tissue
Environmental impact	Eucalyptus		Drying technology
Carbon footprint	Eucalyptus logs		Through-air dry*
Greenhouse gases emissions			
Impact assessment			
Sustainability			
*Denotes all the variations of through-air dry (TAD) technologies: eTAD, CTAD, UCTAD			

Identification of the Methodology to Assess the Environmental Impact of Consumer Goods Products: Focus on Hygiene Tissue Paper

After performing the query, over 40 papers were retrieved. Findings validated that Life Cycle Analysis (LCA) constitutes the most widely used methodology across the literature, since it allows the evaluation of the environmental impact of products and processes (Audsley *et al.* 1997). All studies analyzed followed an attributional approach, meaning that environmental impacts were associated with the different products under study, and no effects outside the system boundaries were evaluated. The majority of the studies followed the ISO 14040 series of standards, while a few did not mention their use. Based on the ISO methodology, the steps to conduct the assessment began with the definition of the goal and scope of the analysis, followed by the construction of the Life

Cycle Inventory (LCI) and the analysis of the environmental impact related to inputs and outputs for each product (LCIA). Different modeling tools, such as Simapro and openLCA, were used across the literature to perform the analysis. Databases, such as Ecoinvent and Gabi, were employed to build the LCI. Various environmental impact categories were assessed, mainly focused on Global Warming Potential (GWP), followed by Acidification, Eutrophication, Ozone Depletion, Photochemical Oxidation, Abiotic depletion, Non-carcinogenic, Carcinogenic, Eco-toxicity, Human-toxicity, Respiratory effects, Smog and Resource depletion.

Based on this, Life Cycle Assessment was selected as the methodology to assess the sustainability of consumer hygiene tissue products, the Ecoinvent database to help build the life cycle inventory, as it is the most comprehensive international LCI database (Ecoinvent 2021), and The Tool for Assessment of Chemical and Other Environmental Impacts (TRACI) as a characterization method, as it is the most widely accepted in the United States. An attributional approach following the ISO series of standards (International Standard Organization 2006) was chosen to guide the methodology developed herein. Finally, although Global Warming Potential constitutes the key focus of our assessment, other categories such as eutrophication, acidification, ozone depletion, Non-carcinogenic, Carcinogenic, Eco-toxicity and resource depletion were also considered to establish sustainability metrics for tissue products.

Identification of Feedstock and Materials Subject to the Life Cycle Inventory

To identify which raw materials are mainly used as furnish for the manufacturing of Premium and Ultra grades of tissue products in the United States and Canada, an extensive study was performed. Reports, interviews with industry experts, and business intelligent databases, such as FisherSolve Next, were consulted for this purpose. FisherSolve Next is an intelligence database and analysis tool for the global pulp and paper industry that contains economic, technical, and environmental information for different pulp and paper mills. Specifically for consumer hygiene tissue products, Bleached Eucalyptus Kraft (BEK) and Northern Bleached Softwood Kraft (NBSK) were identified as the most used pulp types. In this sense, in 2020, around 72% of all the softwood used in the industry came from NBSK, and 69% of all the hardwood come from BEK (Fisher International 2021; Zambrano *et al.* 2020). To a lesser extent, other fibers used included Southern Bleached Softwood Kraft and Bleached Northern Hardwood (Fisher International 2021).

Bleached Eucalyptus Kraft (BEK) pulp is produced from eucalyptus logs, mainly in Brazil (IBÁ 2019; Da Silva Magaton *et al.* 2009). Eucalyptus is considered one of the fastest-growing trees and a top-quality pulping species globally due to its high fiber yields. Brazilian plantations have achieved record growth rates of more than 35 cubic meters per hectare per year, and today around 5.7 million hectares are planted (IBÁ 2019). In Brazil, the plantations are mainly located in the states of Minas Gerais (24%), Sao Paulo (17%), and Mato Grosso do Sul (16%) (IBÁ 2019). More than half of the plantations are certified managed and planted areas, considered sustainable and replantable (IBÁ 2019). The most common industrial application of eucalyptus logs is pulp and paper production; around 36% of all planted trees in Brazil go to the pulp and paper industry (IBÁ 2019).

Northern Bleached Softwood Kraft (NBSK) pulp is produced from northern softwood chips. This fiber is mainly produced in Canada, Nordic countries, and the northern United States (Canada 2020). Canada's forest product industry exports are among the major contributors to the economy, and wood pulp accounts for 23% of the total exports

(Natural Resources Canada 2020). The trees are primarily managed and harvested for lumber production. However, softwood chips are a by-product of sawmill operations, and they constitute the primary raw material to produce NBSK market pulp (Canada 2020; Natural Resources Canada 2020).

For tissue production, fiber characteristics play a critical aspect in tissue properties such as softness, tensile strength, bulk, and absorbency. For Premium and Ultra tissue products, it is important to achieve a strong but soft and bulky product. Softwood fibers, like NBSK, are used to impart strength; if the fibers have thin and low coarseness, cell walls can collapse into ribbons to reinforce the fiber web, giving strength. Hardwood fibers such as BEK are mainly used to provide softness and bulk. For example, BEK pulp has lower fiber width and higher coarseness than other hardwoods (de Assis *et al.* 2019), which is used to provide bulk and superior softness. For more information on fiber characteristics the reader can refer to the author mentioned (de Assis *et al.* 2019).

Identification of Drying Technologies subject to Life Cycle Inventory

Premium and Ultra hygiene tissue grades combine virgin fibers and advanced drying technologies to achieve desired characteristics, such as softness, water absorbency, and strength (De Assis *et al.* 2018b). Experts in the field and current statistics were consulted to identify which drying technologies are mainly used to produce Premium and Ultra grades in the United States. It was determined that, in this region, 34% of the total installed drying capacity belongs to Through Air Drying (TAD) technology (Reisinger 2021). Specifically, variations of TAD, such as Creped Through Air Dryer (CTAD), Un-Creped Through Air Drying (UCTAD), and efficient Through Air Drying (eTAD), constitute technologies employed within the consumer hygiene sector (De Assis *et al.* 2018b; Reisinger 2021). One important point to note is that eTAD technology differs from TAD technologies as it does not feature a TAD cylinder in its machine design. Instead, it uses a steam-heated drum for drying. Although this technology could be regarded as a hybrid, it will still be included in the study as it is used for structured tissue that offers superior softness and absorbency. Considering the North American tissue market, around 45% of all the national brands use CTAD as a drying technology, and around 30% use UCTAD (Fisher International 2021). Even though there are other machine technologies in the market such as LDC (Light Dry Creped), with 62% installed capacity in the United States, this technology is used for more conventional and commercial tissue products with less softness, less absorption, and less bulk than that required for premium and ultra-products. LDC will be included in the study, just to compare the environmental impact of hygiene tissue products from virgin fibers using conventional (LDC) and advanced technologies (TAD), not taking into account the difference in product quality and performance. In less extent, there are also ATMOS (Advance Tissue Molding System) and NTT (New Tissue Technology) technologies with 5% installed capacity; however, although they can provide the same bulk as TAD technologies, the absorption and softness are generally lower (Reisinger 2021).

Frameworks for Goal, Scope, and System Boundaries

Based on findings from previous sections, the raw materials selected for the present analysis included Bleached Eucalyptus Kraft, Northern Softwood Kraft market pulp, and the feedstock used to produce them, *i.e.*, eucalyptus logs and northern softwood chips, respectively. The tissue manufacturing processes under analysis were the different Through-Air-Dry (TAD) technologies (*i.e.*, eTAD, cTAD, UCTAD) and LDC just for comparison. For more information on these drying technologies the readers can refer to (De Assis *et al.* 2018b). Therefore, first, all forest plantation management operations were assessed, and their environmental impacts were estimated. Secondly, biomass pulping and all the unit operations to produce market pulp were considered. Finally, machine technology operations were analyzed to determine all the environmental burdens of the final product across the supply chain. As previously discussed, attributional Life Cycle Assessment was selected as the methodology to assess the sustainability of the products stated above, TRACI was used as a characterization method, Ecoinvent database was used to build the LCI, and openLCA software was employed to perform the assessment.

Life cycle assessment of bleached eucalyptus kraft market pulp

This part of the analysis aimed to quantify the environmental burdens of producing BEK in a Brazilian mill from a cradle-to-gate approach, which included the stages shown in Fig. 1. The functional unit was one air-dried metric ton of pulp (ADmt of pulp).

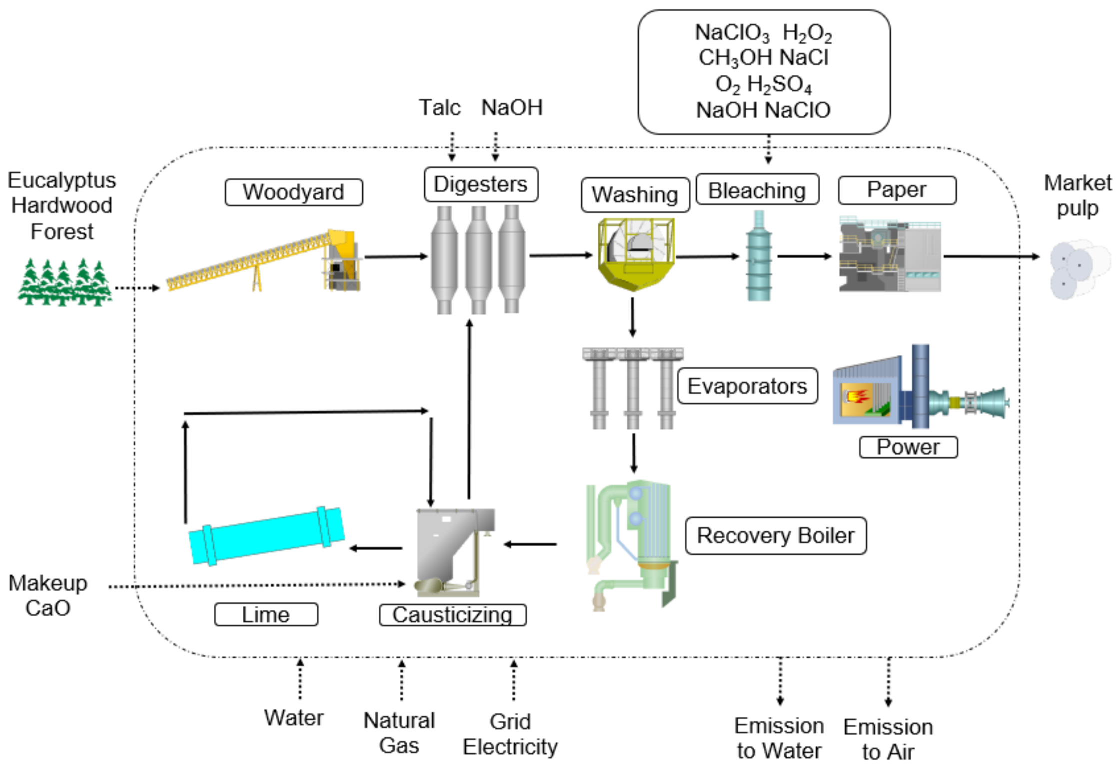

Fig. 1. Cradle-to-gate system boundary for BEK market pulp production

To build the LCI, a WinGEMS model was developed. WinGEMS is a process-based simulation software designed specifically for the pulp and paper industry (Culbertson *et al.* 2016). The simulation inputs were validated through literature values, experts from the industry, and business intelligence databases. An overall yield of 49% w/w, white liquor charge (AA) of 15.8 %, and sulfidity of 30% (Colodette 2020; Dence and Reeve 1996; Dias *et al.* 2007; Fisher International 2021; Judl *et al.* 2011) were assumed. The fuel used in the power boiler fuel was simulated using data reported by FisherSolve Next (Fisher International 2021). Mills producing only BEK in Brazil were analyzed, and average fuel distribution was estimated. Thus, it was determined that 97.5% of the steam produced in the power boiler in BEK mills is sourced from wastewood and 2.5% from natural gas (Fisher International 2021). Also, these mills presented overall power self-sufficiency of *ca.* 80%.

Life cycle assessment of northern bleached softwood kraft market pulp

For the environmental assessment of NBSK, the aim was to quantify the environmental burdens of producing NBSK from northern softwood chips (Lodgepole pine, Spruce, and Fir) from the United States and Canada. The analysis spanned from cradle to gate, including the stages shown in Fig. 2. The Functional unit was one air-dried metric ton of pulp (ADmt of pulp).

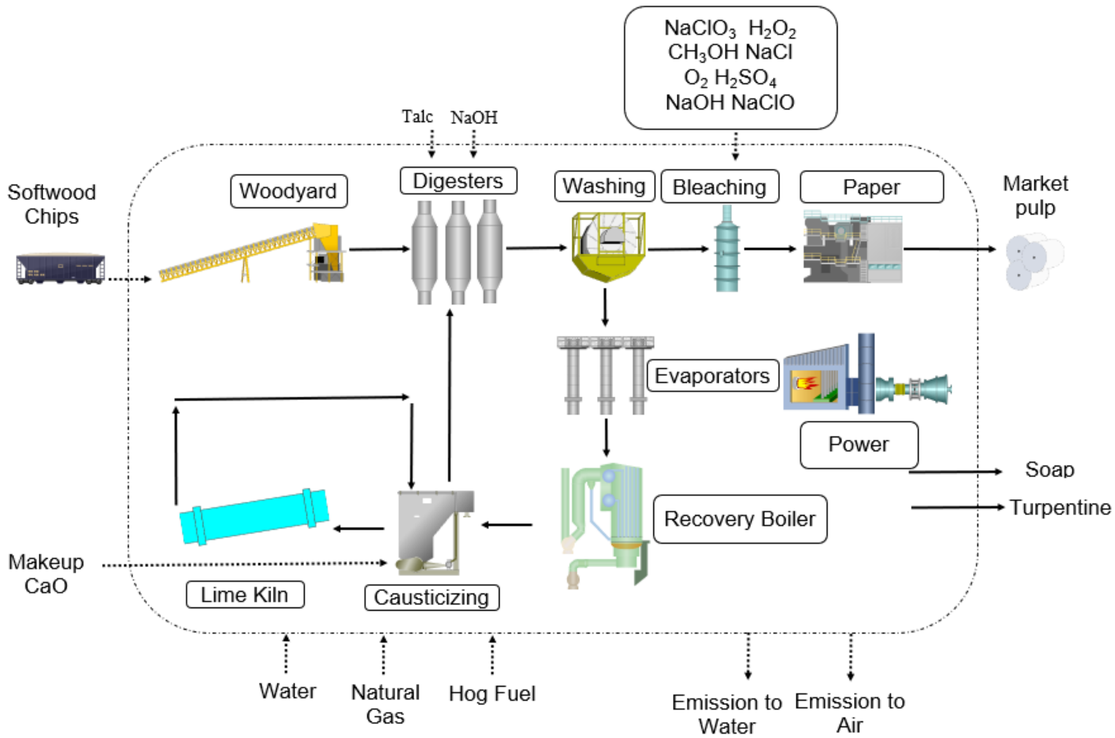

Fig. 2. Cradle-to-gate system boundary for NBSK market pulp production

For the LCI, a winGEMS model was also developed. The main inputs for the simulation were validated against literature values (Echeverria *et al.* 2021; Favero *et al.* 2017; Fisher International 2021). An overall yield of 45% w/w, white liquor charge (AA) of 19%, and sulfidity of 30% was assumed. The fuels used in power boilers were estimated using data reported by FisherSolve Next (Fisher International 2021) for mills producing NBSK market pulp in the United States and Canada. It was determined that 83% of the steam produced in these power boilers is sourced from wastewood and 17% from natural gas. Also, these mills were power self-sufficient.

In addition, turpentine and tall oil production in NBSK mills were considered. Therefore, the need to allocate emissions among the different products was raised for this LCA, and three different methods were followed. First, system expansion was used to take environmental credits from producing tall oil and turpentine. For this scenario, it was assumed that these products displace fatty acids for soap production and organic solvent in the market. Second, the mass allocation method was employed to distribute the emissions on a physical basis. Finally, economic allocation allowed assigning the environmental burdens to each product based on economic value.

Life cycle assessment of machine drying technology for premium and ultra hygiene tissue

The goal and scope were to quantify the environmental burdens associated with the production of tissue products in the United States from a cradle-to-gate perspective. The functional unit was one metric ton of finished tissue product, moisture content at 5%, ready to be distributed. For this assessment, market pulp transportation to the US was considered, including land and ocean transport for BEK and land transport for NBSK market pulp.

To build the LCI, a chemical and energy profile for the different TAD machine drying technologies was created (Tables 2 and 3) employing databases (*e.g*., FisherSolve Next) and further consolidated with industry experts (Cambell 2020; Fisher International 2021; Reisinger 2020). For non-integrated mills, it was determined that the energy requirements were sourced from natural gas for steam production and the required electricity bought from the grid. The furnish composition for the different TAD technologies was also considered in the analysis. Mills producing consumer tissue in North America through TAD processes were analyzed, and the average furnish was estimated. Thus, the eTAD furnish used was 65% BEK and 35% NBSK, for UCTAD, the average furnish used was 78% BEK, and 22% NBSK, and finally, for CTAD, and for LDC the average furnish used was 65% BEK and 35% NBSK (Fisher International 2021). Even though the furnish composition between the different machine technologies is similar, this was included for totaling environmental emissions. Importantly, certain materials used and generated during the tissue drying process were omitted from the investigation, namely the machine clothing. These were excluded as they fell under the cut-off criteria of the analysis.

Table 2. Furnish and Energy Consumption Profiles for the Different TAD Technologies (Fisher International 2021; Reisinger 2020)

Technology	Furnish	Gas (mmBTU/Ton)	Electricity (MWh/Ton)	Creping Aid (kg/Ton)
eTAD	65% BEK, 35% NBSK	7.68	1.06	1.43
CTAD	70% BEK, 30% NBSK	10.65	1.72	2.85
UCTAD	78% BEK, 22% NBSK	15.54	2.06	-
LDC	65% BEK, 35% NBSK	7.1	1.07	1.29

Table 3. Chemicals Consumption Profiles for the Different TAD Technologies (Fisher International 2021; Reisinger 2020)

Technology	Release Agent (kg/Ton)	Retention Aid (kg/Ton)	Dyes (kg/Ton)	Dry Strength (kg/Ton)
eTAD	1.00	0.03	0.05	10.00
CTAD	1.36	0.03	0.05	10.00
UCTAD	0.47	0.04	0.05	8.00
LDC	0.43	0.04	0.05	0.9

The cut-off criteria were implemented to ensure that the Life Cycle Assessment (LCA) was focused on the significant environmental impacts of the hygiene tissue product, while also making the analysis practical in terms of resources and data availability. It is important to note that although these technologies can provide differences in properties, we have not included such differences in this analysis, which could be addressed in future studies.

Finally, carbon footprint from the fisher solve data base were assessed. FisherSolve is the intelligence database for the pulp and paper industry that contains economic, technical, and environmental information. For this part of the study, carbon benchmarking was used including cradle to gate results for specific technologies.

Methods to Analyze and Display Results

Once the different environmental impacts were determined using TRACI and OpenLCA, a hotspot analysis was performed, and the main impact contributors were identified. Since little data on the environmental impact of machine technology was found, the use of different drying technologies was considered relative to the global warming potential contribution of Premium and Ultra tissue products. Also, a sensitivity analysis was performed, assessing how the electricity sourced by region and mill location can influence the environmental impact category mentioned above. This study focused mainly on the Global Warming Potential (GWP) category, measured in kgCO_2eq. As part of the validation process, the average GWP results of this study were compared with the carbon benchmarking tool from the intelligence database FisherSolve next.

RESULTS AND DISCUSSION

This work focused on the life cycle inventory analysis (LCIA) results for BEK market pulp, NBSK market pulp, and the different machine technologies for Premium and Ultra grades tissue production. The LCIA and the environmental burdens for eucalyptus logs, and northern softwood chips, can be found in the supplementary information (see Appendix) as well as the LCIA of BEK and NBSK market pulp.

Life Cycle Inventory Analysis for Market Pulp Production

Bleached eucalyptus kraft market pulp

The TRACI environmental impact results for BEK market pulp production are shown in Table 4. For GWP, it was determined that one ADmt of bleached eucalyptus kraft pulp had associated 388.2 kgCO_2eq. In addition, as shown in Fig. 3, it was found that the main contributors to this category are the production of eucalyptus logs with 109.2 kg of CO_2eq (including transport), followed by the direct emissions from the process (fossil fuels emissions from the lime kiln and power boiler) with 78.3 kgCO_2eq, and the upstream emissions from natural gas production. Although most of the literature LCA studies on eucalyptus-based paper products do not focus on market pulp, one could estimate emissions associated with the pulp to benchmark. Judl *et al.* (2011), Silva *et al.* (2015), and Jour *et al.* (2015) reported *ca.* 421 kgCO_2eq, *ca.* 483 kgCO_2eq, and *ca.* 320 kgCO_2eq respectively. Therefore, the present values are aligned with these studies. Different assumptions, such as credits for selling electricity to the grid, could explain the observed differences.

Table 4. Cradle-to-gate Environmental Impact Results for BEK and NBSK* Pulp Production

Environmental Impact Categories	Unit	BEK Market Pulp (Emissions/ADmt)	NBSK Market Pulp (Emissions/ADmt)
Acidification	kg SO_{2eq}	2.28	2.26
Global Warming	kg CO_{2eq}	388.2	447.9
Respiratory effects	kg $PM2.5_{eq}$	0.26	0.18
Smog	kg O_{3eq}	19.40	19.65
Eutrophication	kg N_{eq}	2.28	1.2
Ozone Depletion	kg $CFC\text{-}11_{eq}$	8.97E-05	7.97E-04
Non-carcinogenic	CTUh	4.68E-05	4.84E-05
Carcinogenic	CTUh	2.30E-05	2.53E-05
Eco-toxicity	CTUe	1,286	1,091
Resource depletion	MJ surplus	446.1	1,030.7

*For NBSK the results correspond to the system expansion scenario

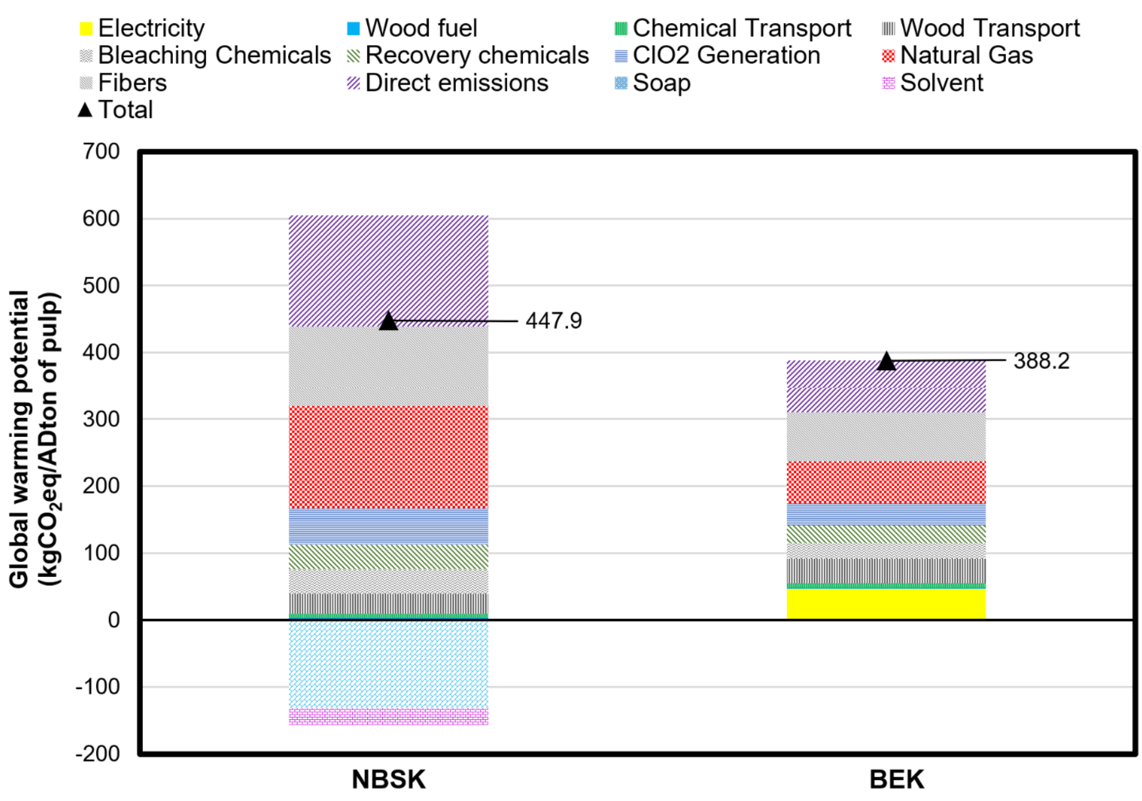

Fig. 3. Cradle-to-gate global warming potential hotspot analysis of one ADmt of BEK and NBSK market pulp production

For acidification, it was determined that the production of one ADmt of BEK pulp emitted 2.28 kgSO_2eq. The main contributors (Table 6) to this category are the direct (on site) emissions, followed by chemicals used during pulp production forestry stage, and the chemicals used during pulp production. When comparing our value with the literature search, it is on the lower end. Dias *et al.* (2007) reported 5.0 kgSO_2eq; however, the author did not specify the main contributor to the acidification category for the pulp-making process, which complicates the comparison. Nevertheless, it is discussed that the main contributor to acidification in the end product (printing and writing paper) is associated with the energy production stages, which will depend on the type of fuel being used; the authors also explained how acidification differs from Portuguese and German markets due to the final product distribution factor and final disposal. Silva *et al.* (2015) reported a value for printing and writing paper (8.7 kgSO_2eq), but not for just pulp production. However, they indicated that the main contributors are due to inorganic air emissions of hydrogen sulfide, bleaching, and chemical recovery. Finally, it was difficult to find benchmarking values for eutrophication. Dias *et al.* (2007) reported values for pulp making but were not expressed in comparable units.

Northern bleached softwood kraft market pulp

TRACI environmental impacts were determined for NBSK market pulp production (Table 5). As previously mentioned, NBSK mills constitute multi-functional systems, producing paper, tall oil, and turpentine. Thus, the environmental burdens associated with the primary product, *i.e.*, NBSK pulp, will depend on the method selected to allocate the emissions. Table 5 contains the GWP results for the three methods followed in this study to deal with the multi-product issue. First, it was determined that producing one ADmt of NBSK pulp emitted 447.7 kgCO_2eq using system expansion. Under this approach, credits were taken due to tall oil production (-131.1 kgCO_2eq), which can displace fatty acids used to manufacture soap, and turpentine (-25.4 kgCO_2eq), which can replace organic solvent production in the market. Second, using mass allocation, the GWP of one ADmt of NBSK pulp had associated 579.5 kgCO_2eq. Finally, economic allocation provided a GWP of 595.7 kgCO_2eq for the studied functional unit.

Table 5. Allocation Factors for NBSK Pulp Production under Different Allocation Methods

Product	System Expansion Factor (%)	Mass (mt/ADmt of pulp)	Mass Allocation Factor (%)	Price ($/mt)	Economic Allocation Factor (%)
Tall Oil	-	0.03	3.20%	493	1.02
Turpentine	-	0.01	0.94%	716	0.43
NBSK	74.10%	1.00	95.87%	1590	98.55

Tall oil and turpentine prices were obtained from FisherSolve (Fisher International 2021) and NBSK price was retrieved from RISI (Fastmarkets 2022).

It is important to note that the values shown in Table 5 present a marked difference, mainly attributable to the nature of the methods. Mass and economic allocation are intrinsically proportional to the amount of each product. Therefore, for the studied case, NBSK was assigned most of the system's emissions since *ca.* 96% of the total mass corresponds to it. On the other hand, system expansion reduces the environmental burden due to displacing other raw materials or products in the market. In this specific system, a significant reduction comes from tall oil replacing fatty acids. Thus, system expansion provides an overall lower impact. In this regard, questioning which method is more appropriate could be reasonable. However, the ISO series of guidelines establish that system expansion is preferred over any allocation, which should be avoided. Thus, further analysis in this study is made using this method.

The hotspot analysis showed that the main contributors to the GWP of NBSK (Fig. 3) are the direct emissions from the process, namely lime kiln, and power boiler, with *ca.* 166 kgCO_2eq, followed by upstream natural gas production (amount). When comparing GWP results to the literature, it was observed that previous authors had reported a range of values. For instance, Madsen (2007) obtained 543.8 kgCO_2eq following an economic approach, which agrees with the value herein estimated using the same method. On the other hand, Favero *et al.* (2017) reported an interval of 500-600 kgCO_2eq but did not specify how they dealt with multi-functionality. In either case, the values obtained in the present study are similar to those reported in the literature.

Table 6. Hotspot Analysis (%) of GWP, Eutrophication and Acidification Impact Categories

	Global Warming (kg CO_2 eq/ADmt)		Eutrophication (kg N eq/ADmt)		Acidification (kg SO_2 eq/ADmt)	
	NBSK*	BEK	NBSK*	BEK	NBSK*	BEK
Electricity	0.0%	12.1%	0.0%	3.5%	0.0%	5.7%
Wood fuel	0.7%	0.5%	0.6%	0.2%	0.8%	0.4%
Transportation	8.2%	11.0%	4.4%	10.3%	11.6%	13.0%
Chemicals	28.5%	21.3%	33.8%	13.5%	30.3%	24.0%
Natural Gas	34.1%	16.2%	3.1%	1.2%	19.0%	4.0%
Fibers	26.5%	18.7%	9.3%	19.2%	20.3%	23.0%
Direct emissions	37.0%	20.2%	53.3%	52.5%	23.8%	31.0%
Soap	-29.3%	0.0%	-47.5%	0.0%	-10.5%	0.0%
Solvent	-5.7%	0.0%	-4.4%	0.0%	-4.4%	0.0%
Total	100%	100%	100%	100%	100%	100%

*Values for NBSK correspond to system expansion

For acidification and eutrophication, the main contributors (Table 6) were the upstream production of chemicals and natural gas used for the market pulp production, the direct (onsite) emissions, and forestry operations. When comparing these values with the literature, they were in the same order of magnitude. However, the difference in acidification was challenging to explain relative to the findings of Favero *et al.* (2017), since those authors report values from literature reviews ranging from 3.2 to 6.8 kgSO_2eq and do not detail the main contributor for each category. Once more, the authors did not indicate which allocation approach was followed, which could also explain any differences. For eutrophication the author reports values from 1.02 to 1.36 kgNeq, which agrees with the present work.

Finally, Fig. 3 also presents the GWP comparison between both types of market pulp analyzed. The main difference corresponds to the direct emissions from the lime kiln and power boilers and is therefore associated with using natural gas. As previously discussed, for the BEK market pulp production, only 3% of the steam produced in power boilers is generated from natural gas, whereas for NBSK, this number increases to 17%. This leads to higher direct emissions, as they originate from fossil fuel combustion and production; the contributions are 78.3 kg CO_2eq for BEK and 166 kgCO_2eq for NBSK. Overall, BEK shows lower environmental impacts due to wood waste being the mill's primary source of steam production. Finally, it is essential to clarify that these two types of market pulp are not interchangeable, and both are used to produce tissue products. Therefore, herein the comparison is made to understand the main contributors for each type of pulp instead of suggesting replacing one with another.

Life Cycle Inventory Analysis for Machine Drying Technology for Premium and Ultra Hygiene Tissue

The environmental impact analysis to produce consumer hygiene tissue focused on greenhouse gas emissions. The environmental burdens across the supply chain to produce consumer bath tissue for Premium and Ultra grades were linked together to obtain a holistic result. In this part of the study, the effect of TAD machine technologies was evaluated. Specific thermal energy requirements, electricity usage, and chemicals profile were considered. Average furnish compositions were varied among technologies as follows: for eTAD, the furnish used was 65% BEK and 35% NBSK; for UCTAD, 78% BEK and 22% NBSK; and CTAD and LDC was 65% BEK and 35% NBSK based on intelligence data (Fisher International 2021). Mills using TAD and LDC technologies were analyzed, and the average furnish compositions shown were estimated. In addition, the effect of geography/location was assessed. Thus, it was assumed that tissue products could be produced in four different regions in the United States (Northeast, West, Southeast, and Midwest). This sensitivity analysis was done because the electricity source highly depends on geography (Popovich and Plumer 2020), which affects the environmental impact of the final product.

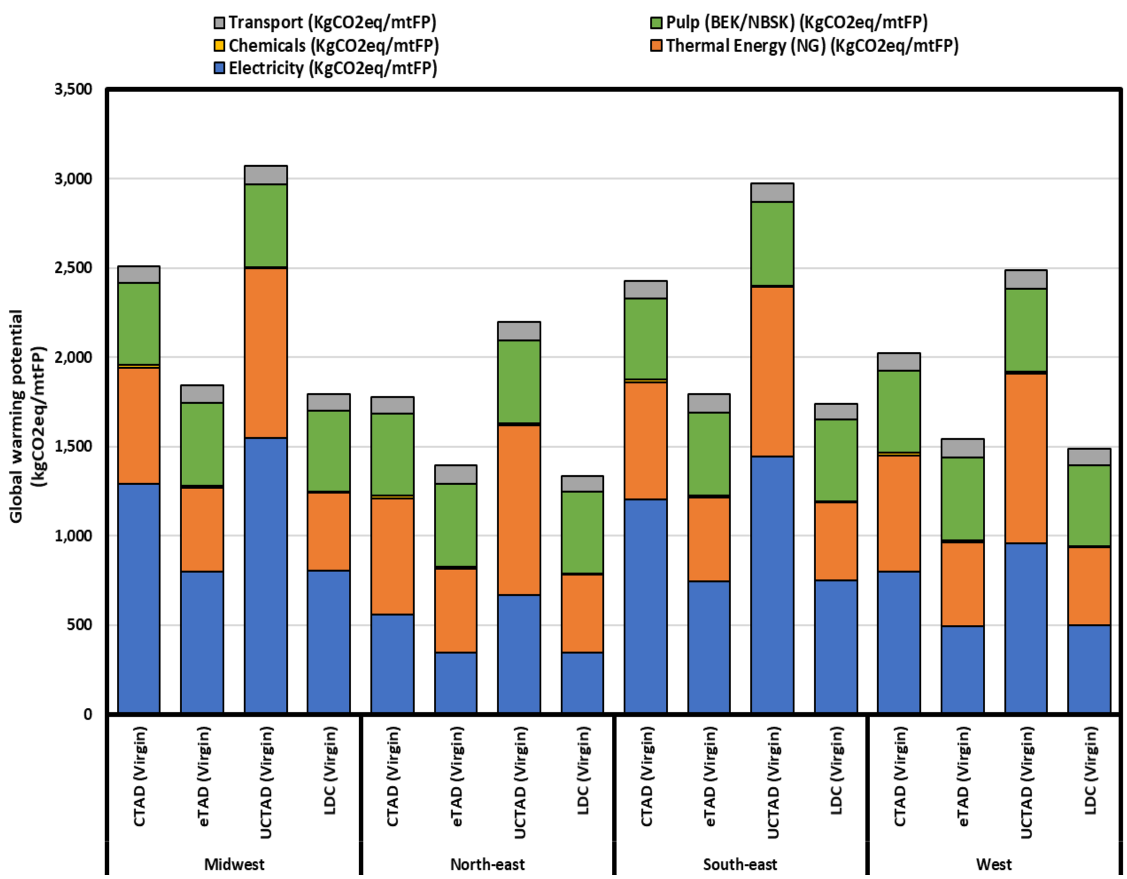

Fig. 4. Cradle-to-gate global warming potential per metric ton of finished tissue products (mtFP) in different regions of the United States

Results show that the GWP associated with producing one tonne of Premium and Ultra tissue can range from 1,392 to 3,075 kgCO_2eq depending on mill location and machine technology used (Fig. 4). The main contributors to this impact are thermal energy, *i.e.*, natural gas, and electricity. Also, it was determined that grids in the Midwest and Southeast regions have, on average, the highest amount of kgCO_2eq emissions per MWh, primarily because of a higher share of fossil fuels, *e.g.*, coal, lignite, or natural gas, to produce electricity. Thus, tissue products manufactured in these regions presented an overall higher carbon footprint. It is important to note that, since cradle-to-gate constitutes the scope of this study, no transportation to the market was considered.

Specifically for emissions from electricity usage in each technology, Fig. 4 shows that UCTAD presented the highest value, since it is the most energy-intensive technology, ranging from 670 to 1,550 kgCO_2eq per tonne of pulp depending on mill location. It was followed by CTAD, with values ranging from 560 to 1,300 kgCO_2eq, eTAD with electricity emissions from 350 to 805 kgCO_2eq, and LDC with values from 350 to 805 KgCO_2eq. The difference in electricity usage could be justified because UCTAD technology was developed to increase machine runnability, tackling limitations caused by the creping process at high speeds. In addition, the main differentiator factor between UCTAD and the other TAD technologies is that UCTAD does not have a wet-pressing process. Wet-pressing augments the solids content (dryness) up to 40% previous to the trough-air dryers. As UCTAD technology does not include a wet pressing process, the thermal energy usage is significantly higher than their counterparts. Thus, it was found that mills using UCTAD as machine technology located in the Midwest and Southeast regions had the overall highest environmental CO_2eq emissions per ton of tissue products.

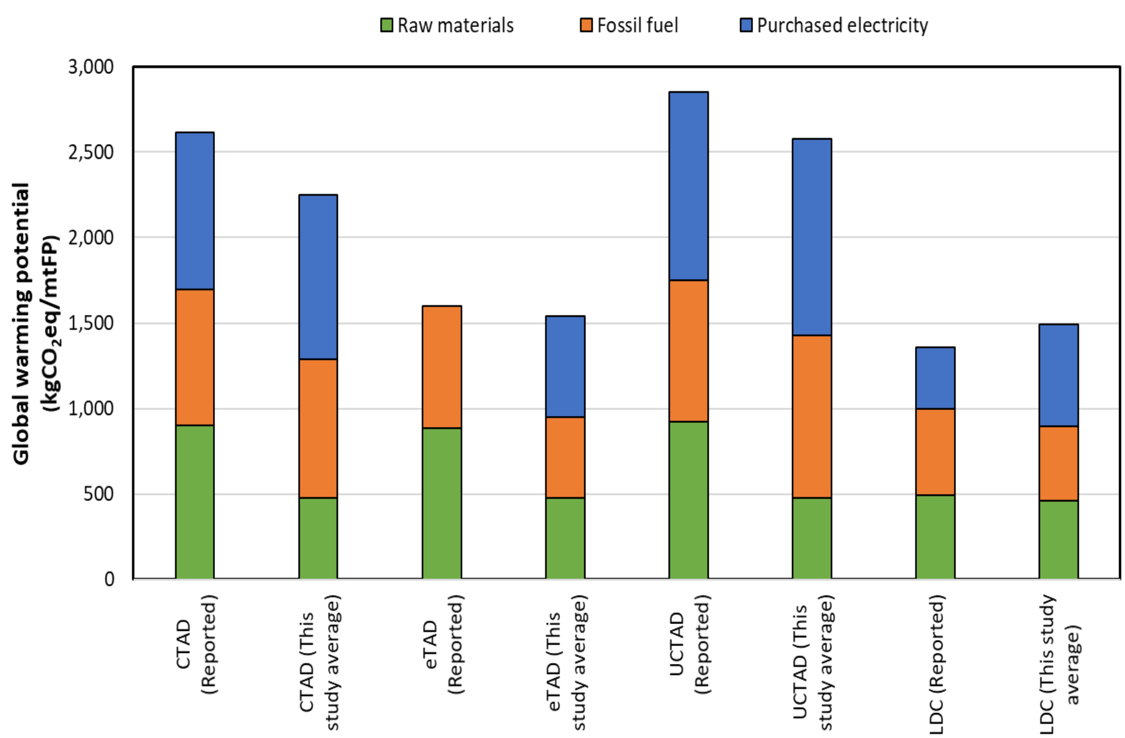

Fig. 5. Cradle-to-gate global warming potential per metric ton of finished tissue products (mtFP) reported by FisherSolve for specific mills

It is important to note that the scenarios herein evaluated are non-integrated mills. This manufacturing scheme uses market pulp as an intermediate to produce high-end tissue. Energy is required to produce the market pulp (drying) which is later shipped to tissue manufacturing facilities. This causes a higher environmental impact in the final product compared to an integrated mill. Nevertheless, since BEK is one of the most use fibers in tissue products, which is produced in Brazil. This study was focused on North America, and the approach was to study non-integrated mills.

Finally, Fig. 5 depicts the average GWP of different drying technologies reported by FisherSolve for specific mills. It can be seen that overall, these values are aligned with results herein presented. The only difference is related to the eTAD process. In this case, FisherSolve only reports one mill using this technology, which is power self-sufficient. Therefore, no electricity is purchased. However, it can be discussed that this is the reason this mill is shown with having more emissions associated with fossil fuels. Nevertheless, the similarity between the values reported here in and those of the database serve as validation for the present study.

CONCLUSIONS

1. Virgin Premium and Ultra Tissue products manufactured in North America can present carbon footprints ranging from 1,392 to 3,075 kgCO_2eq per metric ton, depending on machine technologies and mill locations.
2. In terms of machine technologies, UCTAD presents the most associated CO_2eq emissions, followed by CTAD. Overall, electricity, thermal energy and fibers are the main contributors to the carbon footprint of these products.
3. LDC conventional technology showed the least environmental emissions, but the quality of this product is less soft and absorbent than those made with TAD technologies.
4. Mill location highly influences the carbon footprint of virgin Premium and Ultra Tissue. Regions relying on a higher share of fossil fuels to produce electricity present an overall higher carbon footprint associated with tissue products.
5. Bleached Eucalyptus Kraft (BEK) pulp used to produce virgin Premium and Ultra tissue products can present a carbon footprint of *ca.* 388 kgCO_2eq and per air-dried metric ton. The main contributors to this impact are direct emissions from the process (lime kiln and power boiler), the production of eucalyptus logs, and the natural gas used in the lime kiln.
6. Northern Bleached Softwood Kraft (NBSK) pulp used to produce virgin Premium and Ultra tissue products can present carbon footprints ranging from *ca.* 448 to 596 kgCO_2eq per air-dried metric ton depending on the method selected to deal with multifunctionality. Thus, system expansion allows for taking credits of *ca.* 155 kgCO_2eq due to the displacement of fatty acids and organic solvents by tall oil and turpentine respectively, while economic and mass allocation reduce the carbon footprint of NBSK by *ca.* 9 and 25 kgCO_2eq respectively due to the distribution of the emissions among the mill products.

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APPENDIX

Electronic Supplementary Information

Table S1. Life Cycle Inventory Inputs for Eucalyptus Logs Production

Inputs-Description	Unit	Amount
Limestone	Kg/ dry ton	18.65
Sulfuramid/ Insecticide	Kg/ dry ton	0.12
Triple superphosphate, as P_2O_5	Kg/ dry ton	0.97
Potassium chloride, as K_2O	Kg/ dry ton	1.35
Urea, as N	Kg/ dry ton	0.65
Glyphosate	Kg/ dry ton	0.13
Goal®	Kg/ dry ton	0.03
Fodor®	Kg/ dry ton	1.48
Logs Transportation	Km	75
Chemical Transportation	Km	150
Diesel	Kg/ dry ton	4.15

Table S2. Life Cycle Inventory Outputs for Eucalyptus Logs Production

Outputs- Description	Unit	Amount	Emission to:
Eucalyptus logs	OD ton	1.0	Product
Glyphosate	kg/dry ton	1.3E-01	Emission to water
Nitrate	kg/dry ton	1.4E-01	Emission to water
Methane	g/ton fuel	0.0016	Emission to air
Carbon monoxide	g/ton fuel	45.35	Emission to air
Carbon dioxide	kg/ton fuel	23.0	Emission to air
N_2O	g/ton fuel	0.57	Emission to air
NH_3	g/ton fuel	0.03	Emission to air
NMVOC	g/ton fuel	13.96	Emission to air
NOx	g/ton fuel	145.3	Emission to air
PM10	g/ton fuel	7.21	Emission to air
PM2.5	g/ton fuel	7.21	Emission to air
TSP	g/ton fuel	7.21	Emission to air
N2O	Kg/kg N	0.01	Emission to air
NH_3	Kg/kg N	0.1	Emission to air
NO_3-	Kg/kg N	0.3	Emission to air
P	Kg/kg P	0.024	Emission to air
Cadmium	mg/dry ton	0.022	Emission to soil
Chromium	mg/dry ton	0.9	Emission to soil
Copper	mg/dry ton	2.6	Emission to soil
Glyphosate	kg/dry ton	0.083	Emission to soil
Glyphosate	kg/dry ton	0.1128	Emission to soil
Lead	mg/dry ton	83.3	Emission to soil
Nickel	mg/dry ton	28.9	Emission to soil
Nitrogen	kg/dry ton	0.127	Emission to soil
Zinc	mg/dry ton	183.3	Emission to soil
Pesticides, unspecified	kg/dry ton	5.6E-02	Emission to soil

Table S3. Life Cycle Inventory Inputs for Northern Rough Green Lumber Production

Inputs- Description	Unit	Amount
Diesel	L/m^3	10.4
Transportation distance for logs	Km/m^3	110.3
Lubricants	L/m^3	0.3
Water	L/m^3	104.2
Electricity	KWh/m^3	42.9
Gasoline	L/m^3	0.15
Propane	L/m^3	0.032
Antifreeze	L/m^3	0.0004

Table S4. Life Cycle Inventory Outputs for Northern Rough Green Lumber Production. Products Expressed as Dry Equivalents

Outputs-Products (dry equivalent)	Unit/m^3	Value
Rough green lumber	m3	1.0
Pulp chips	kg	221.8
Sawdust	kg	44.7
Bark	kg	90.7
Wood fuel	kg	31.6
Solid emissions	**Unit/m^3**	**Value**
Solid emissions, Organic (kg)	kg	0.046
Solid emissions, inorganic (kg)	kg	0.49
Emissions to air	**Unit/m^3**	**Value**
Wood dust (kg)	kg	0.065
Particulates, >10 lm	kg	0.0086
Particulates, <2.5 lm	kg	0.0030
VOCs	kg	0.0016
Carbon dioxide	kg	27.23
Methane	kg	0.0017
Dinitrogen monoxide	kg	0.0013
Carbon monoxide	kg	0.117

Table S5. Cradle to Gate Environmental Impacts of Eucalyptus Logs and Northern Softwood Chips

Environmental Impact Categories	Unit	Unit per ODmt of eucalyptus logs	Emissions/ ODmt of Wood chips
Acidification	kg $SO_{2\ eq}$	0.35	0.2
Global Warming	kg $CO_{2\ eq}$	58.2	55.2
Respiratory effects	kg $PM2.5_{eq}$	0.03	0.02
Smog	kg $O3_{eq}$	2.81	3.4
Eutrophication	kg N_{eq}	0.11	0.1
Ozone Depletion	kg $CFC\text{-}11_{eq}$	1.19E-05	1.36E-05
Non-carcinogenic	CTUh	3.73E-06	1.78E-06
Carcinogenic	CTUh	8.33E-07	7.93E-07
Eco-toxicity	CTUe	97.61	48.2
Resource depletion	MJ surplus	91.74	274.1

Table S6. Life Cycle Inventory Inputs for BEK Market Pulp Production

Inputs	**BEK Market Pulp**
Raw materials	**mt/ADmtpulp**
Biomass feed Total	**2.27**
Hardwood chips	2.1
Woodwaste	0.17
Bleaching chemicals	**mt/ADmtpulp**
Sodium hydroxide (NaOH) @50%	0.026
Sulfuric acid (H_2SO_4)	0.0050
Hydrogen peroxide (H_2O_2) @50%	0.01
Oxygen (O_2)	0.0286
ClO_2 generation	**mt/ADmtpulp**
Sodium chlorate ($NaClO_3$) @100%	0.033
Methanol (CH_3OH) @10%	0.002
Sulfuric acid (H_2SO_4) @98%	0.023
Recovery chemicals	**mt/ADmtpulp**
Lime (CaO) @ 100%	0.022
Sodium hydroxide (NaOH) 50%	0.029
Sodium sulfate makeup (Na_2SO_4) @ 100%	0.033
Energy	**MWh/ADmtpulp**
Power required	0.87
Power generated from steam	0.69
Power surplus (+)/needed (-) from process	-0.18
Fuel	
Natural gas to kiln (MJ/ADmtpulp)	993.0
Natural gas to the gas boiler (MJ/ADmtpulp)	139.0
Transport Assumptions	Km*t
Transport for Wood*	177.9
Transport for Chemicals*	31.8

Table S7. Life Cycle Inventory Outputs for BEK Market Pulp Production

Outputs	**BEK Market Pulp**
Bleached Pulp AD(mt)	1
Emissions to air	mt/ADmtpulp
Fossil Carbon dioxide (CO_2)	mt/ADmtpulp
Carbon dioxide (CO_2) - Lime Kiln	0.068
Carbon dioxide (CO_2) - Power Boiler	0.01
Biogenic Carbon dioxide (CO_2)	mt/ADmtpulp
Carbon dioxide (CO_2) - Biogenic -Hog Fuel	0.60
Carbon dioxide (CO_2) - Biogenic Recovery Boiler	1.10
Nitrous Oxide (N_2O) - Recovery Boiler (mg/mt)	4.14
Nitrous Oxide (N_2O) -Power Boiler (mg/mt)	0.0156
Methane (CH_4) - Recovery Boiler (mg/mt)	18.70
Methane (CH_4) - Power Boiler (mg/mt)	0.16
Sulfur dioxide (SO_2) - Hog Fuel	0.0007
Emissions to water	mt/ADmtpulp
*AOX (Kg/mt of pulp)	0.15
Effluents	36.43
COD (Kg/ADmt of pulp)	28
Waste to treatment	mt/ADmtpulp
Ashes	0.00231
Dregs and grits	0.023
Mud inert	0.006
Dust Loses	0.001

Table S8. Life Cycle Inventory Inputs for NBSK Market Pulp Production

Inputs	**NBSK Market Pulp**
Raw materials	**mt/ADmtpulp**
Biomass feed Total	**2.45**
Chip to process	2.00
Woodwaste purchased	0.45
Bleaching chemicals	**mt/ADmtpulp**
Sodium hydroxide (NaOH) @50%	0.0395
Oxygen (O_2)	0.026
Hydrogen peroxide (H_2O_2) @50%	0.017
ClO_2 generation	**mt/ADmtpulp**
Sodium chlorate ($NaClO_3$ 100%)	0.042
Methanol (CH_3OH) @100%	0.005
Sulfuric acid (H_2SO_4) @98%	0.02
Recovery chemicals	**mt/ADmtpulp**
Sodium sulfate Na2SO4	0.02
Lime (CaO) @ 100%	0.0023
Sodium hydroxide (NaOH) 50%	0.02
Fresh water (m^3/Admt)	40.02
Energy	**MWh/ADmtpulp**
Power required	1.01
Power generated from steam	1.01
Power surplus (+)/needed (-) from process	-
Fuel	**MJ/ADmtpulp**
Natural gas to kiln (MJ/ADmtpulp)	944
Natural gas to the gas boiler (MJ/ADmtpulp)	1657
Transport Assumptions	Km*t
Transport for Wood*	275.1
Transport for Chemicals*	30.64

Table S9. Life Cycle Inventory Outputs for NBSK Market Pulp Production

Outputs	**NBSK Market Pulp**
Bleached Pulp AD(mt)	1
Tall Oil (kg/mt)	33.25
Turpentine	9.78
Fossil Carbon dioxide (CO_2)	**mt/ADmtpulp**
Carbon dioxide (CO_2) - Lime Kiln	0.064
Carbon dioxide (CO_2) - Recovery Boiler	0.101
Biogenic Carbon dioxide (CO_2)	**mt/ADmtpulp**
Carbon dioxide (CO_2) - Biogenic -Hog Fuel	1.2
Carbon dioxide (CO_2) - Biogenic Recovery Boiler	1.3
Methane (CH_4) fossil - Power Boiler (mg/mt)	3.7
Methane (CH_4) fossil - Recovery Boiler (g/mt)	22.4
Nitrous Oxide (N_2O) -Power Boiler (mg/mt)	0.6
Nitrous Oxide (N_2O) -Recovery Boiler (mg/mt)	5.0
Sulfur dioxide (SO_2) - Hog Fuel	0.00125
Emissions to water	**mt/ADmtpulp**
*AOX (Kg/mt of pulp)	0.63
water to effluents	35.9
COD (Kg/ADmt of pulp)	24
Waste to effluent	**kg/ADmtpulp**
Ashes	0.870
Dregs and grits	14.2
Mud inert	5.93
Dust Losses	0.37

Table S10. Life Cycle Inventory Inputs for Hygiene tissue in The United States for different drying technologies (Energy profile)

Technology	Furnish	Gas (mmBTU/Ton)	Electricity (MWh/Ton)	Creping Aid (kg/Ton)
eTAD	65% BEK, 35% NBSK	7.68	1.06	1.43
CTAD	70% BEK, 30% NBSK	10.65	1.72	2.85
UCTAD	78% BEK, 22% NBSK	15.54	2.06	-
LDC	65% BEK, 35% NBSK	7.1	1.07	1.29

Table S11. Life Cycle Inventory Inputs for Hygiene tissue in The United States for Different Drying Technologies (Chemical profile)

Technology	Release Agent (kg/Ton)	Retention Aid (kg/Ton)	Dyes (kg/Ton)	Dry Strength (kg/Ton)
eTAD	1.00	0.03	0.05	10.00
CTAD	1.36	0.03	0.05	10.00
UCTAD	0.47	0.04	0.05	8.00
LDC	0.43	0.04	0.05	0.9

Table S12. Transportation distances for virgin fiber used in for Hygiene tissue in The United States

Transport	Land (Km)	Ocean (Km)
BEK	320	8500
NBSK	240	