Sustainable Alternative Fibers Initiative (SAFI): Methodology and Tools for Evaluating Sustainability Dimensions of Non-wood Fibers

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Abstract

Digitalization, changes in social behavior, and sustainability are some of the global megatrends shaping industry evolution. The pulp and paper (P&P) industry, historically based on renewable resources, is facing the same challenges. Even though the environmental life cycle assessment (LCA) methodology has been utilized for more than 30 years now, it is still challenging to apply its concepts to reach a consensus. To address this issue, the Sustainable and Alternative Fibers Initiative (SAFI) has been working to develop a robust methodology to evaluate a range of P&P products from conventional and emergent alternative fibers. The methodology developed included the inclusion of the potential soil organic carbon (SOC) sequestration by each cultivar based on the carbon inputs from below-ground biomass (coarse roots and rhizodeposition) that can increase carbon levels in the soil. Moreover, detailed process simulation based on industrial conditions is used to perform all mass and energy balances, allowing rigorous estimates of the life cycle inventory and total carbon dioxide emissions. As a case study, two types of biomass (eucualyptus and wheat straw) were analyzed for their environmental LCA. Additionally, bleached eucalyptus kraft (BEK) produced in Brazil and wheat straw alkaline-peroxide mechanical pulp (APMP) for possible applications in commercial tissue were also studied. The overall carbon footprint results are dependent on whether or not SOC sequestration is included. Further, the results for carbon emissions are significantly altered when biogenic emissions are considered in addition to anthropogenic emissions. The presentation will discuss the results.

1. Introduction

As society moves toward climate awareness, consumers are demanding more information and better resource management (Ketelsen et al., 2020). Global megatrends, such as digitalization, rapid urbanization, changes in social behavior, rapid urbanization, and sustainability (Retief et al., 2016) are challenging industries in many aspects. Digitalization, as one example, is reducing the amount of Sorted Office Paper (SOP), traditionally used to produce tissue (Fisher International, 2023; Li et al., 2022). This disruption in the supply chain is creating additional pressure to find new substitutes for recycled fibers.

Disruption in the supply chain is even more exacerbated by the growth of sustainability interests within society. As recycled fibers have traditionally been perceived as more sustainable, a replacement for them must comply with this perception. However, the sustainability lens is contentious since the definition of sustainability can be different among people, priorities, and socio-demographic characteristics (Peano et al., 2019).

A definition of sustainability is “meeting the needs of the present without compromising the ability of future generations to meet their own needs” (United Nations, 1987). Sustainability is often based on three pillars, environmental, social, and economic (Van Schoubroeck et al., 2019). Additionally, a product needs to fulfill certain technical characteristic requirements to make it useful for an established application.

The evaluation of each one of the sustainability pillars has its challenges. The environmental sustainability pillar along with the economic pillar are somehow the more long-lived. However, there is still a lack of good and firm implementation of consistent data among all industries. One of the reasons for this is the complexity and subjectivity associated with these analyses. As an example, agricultural practices in biomass production systems can vary drastically between countries, states, and even counties due to changes in fertilization rates, soil management practices, soil conditions, technology availability, etc, and so the choice of the process details used to represent a product can involve subjective choices.

The construction of a robust methodology that allows for the environmental characterization of fibers is crucial for the P&P industry. With the same base for comparison, industry decision-makers can consider the reduction in environmental emissions as one key performance indicator of their process and product for optimization. Using this information, for example, the disruption in the recycled fibers supply chain can be overcome with a solid comparison among possible replacement fibers. Moreover, company marketing can start branding their reductions in environmental impacts such as carbon dioxide reduction with quantifiable indicators, providing more confident sustainability claims.

This article describes the development of a robust methodology to assess the environmental impact of fibers produced by the pulp and paper industry. As a study case, we will explore the the global warming impact analysis for biomass production of eucalyptus and wheat straw and market pulp production of resulting Bleached Eucalyptus Kraft (BEK) and wheat straw alkaline-peroxide-mechanical pulp (APMP).

2. Methodology

2.1 Scenario development and system boundary

Bleached eucalyptus kraft (BEK) and wheat straw alkaline-peroxide mechanical pulp (APMP) were selected as representative chemical and mechanical pulping processes. Additionally, to show the application of alternative fibers, wheat straw was selected as a potential raw material within the US. Due to the restrictions that non-wood biomasses pose for chemical pulping (Jahan et al., 2021), mechanical pulping of wheat straw represents a good opportunity to use a more easily refined biomass without the derived problems in chemical recovery. BEK has traditionally been used for tissue production. However, wheat straw pulps have been identified as a good replacement for recycled fibers in economy bath tissue (De Assis et al., 2019).

For the analysis, the system boundary was divided into two main stages, biomass production, and conversion to market pulp. Biomass production includes the quantification of all the chemical and energy requirements for soil preparation, fertilization, management, harvesting, and biomass handling and transportation to the pulp mill. Market pulp production involves all the processes in the mill as well as processes involved in the production of inputs such as simulation for mass and energy balances within the mill, gathering fossil fuel, electricity, chemical, and water consumption.

For BEK production, eight mills were selected to produce a weighted average of process conditions based on production level. On the other hand, as there are no industrial wheat straw mechanical pulp production readily available, average conditions were generated based on published reports and laboratory results.

2.2 Database for simulation

Three main sources of information were used to develop the average conditions for the BEK and wheat straw APMP. Firstly, FisherSolve data was used to find information about the process conditions of existing mills. This database includes production, digester type, yield, bleaching sequences, etc (Fisher International, 2023). Secondly, laboratory data was used to simulate the production of wheat straw mechanical pulp, including yield, chemical charges, brightness, etc. Finally, whenever information was missing in these sources, industry experts were consulted for data. Table 1 presents the summary of the process conditions for simulation purposes. These estimates will be refined as new information becomes available.

Table 1: Process condition for simulation

Parameter	Unit	BEK production	Wheat straw - APMP
Digester yield	%	51	75
Pulping temperature	°C	170	90
EA; Sulfidity	% as Na_2O	10.4; 30	-
Chemical charge	%	-	NaOH: 6 H_2O_2: 6 DTPA: 0.5
Fuel lime kiln	%	Number 6 oil: 69 Gas: 31	-
Fuel power boilers	%	Woodwaste: 55 Natural gas: 15 Waste heat: 2	Natural gas: 100
Power self-sufficiency	%	100	0
Power consumption	kWh/ADt	870	841
Bleaching sequence	-	O/O-A-D-Eop-D-P	None

Detailed process simulations for mass and energy balances were performed using WinGEMS software. This tool is specialized for the pulp and paper industry, effectively modeling complex operations such as chemical recovery within kraft mills.

2.3 Life cycle assessment

The environmental analysis was constructed considering all carbon dioxide flows within the system in a cradle-to-gate fashion following the ISO 14040 standard. According to the ISO standard, an LCA study is divided into four stages: goal and scope, life cycle inventory, life cycle impact assessment, and interpretation of results, and these are discussed below.

2.3.1 Goal and scope

This study seeks to conduct a comprehensive cradle-to-gate environmental assessment encompassing the cultivation and conversion of eucalyptus and wheat straw to market pulp for tissue applications. The chosen functional units for this assessment are one oven-dry metric ton (ODt) of biomass and one air-dry metric ton (ADt) of market pulp as the final product. One of the challenges presented in any LCA (and in this study) involves the allocation of burdens in multi-output systems. Wheat straw is a by-product of wheat grain production. However, several options exist on how to distribute total emissions between the co-products. The ISO standard recommends avoiding allocation by means of system expansion. Nevertheless, it is not possible to subtract emissions from overall emissions to obtain wheat straw emissions alone, as wheat grain can only be produced attached to wheat grain (system expansion by substitution). Therefore, in this study, an economic allocation approach was applied to distribute burdens among products. In the case of wheat straw production, an allocation factor of 12% was used based on expected revenue.

2.3.2 Life cycle inventory (LCI)

A literature review was conducted for biomass cultivation, whereas process simulation was used as a resource to calculate the LCI of the conversion processes. Air emissions caused by fossil fuel combustion in the cultivation stage (CH_4, CO_2, N_2O) were calculated based on the tier 1 factors developed by the European Environment Agency (EEA) for agriculture and forestry activities (EEA, 2009). Additionally, EPA factors were used for estimating the air emissions related to fossil fuel burning within mills (United States Environmental Protection Agency, 2019). Field emissions due to nitrogen fertilization were calculated using emission factors of 0.01 kg N2O-kg N, 0.1 kg NH3-kg N, and 0.3 kg NO3-kg N based on the IPCC and literature review (Cowan et al., 2020; Goebes et al., 2003; Intergovernmental Panel on Climate Change, 2019). One kilogram of phosphorous-containing fertilizers was assumed to release 0.024 kg P to water-based in (Clift et al., 1997). Additionally, emission factors of 0.2 and 0.12 kg CO_2 were used to estimate the emissions from one kilogram of urea and limestone, respectively, because of degradation (H. Eggleston et al., 2019). The Ecoinvent 3.8 data set also accounted for upstream processes such as fertilizers, fossil fuels, and chemical production emissions.

One key factor of this analysis involves the inclusion of the potential soil organic carbon (SOC) sequestration during the cultivation stage. This methodology is based on the estimation of the annual carbon inputs to the soil by coarse roots and rhizodeposition. Carbon in coarse roots for the studied product (C_{R_PP}) is estimated using each crop's productivity, root-to-shoot ratio (RSR), defined as the dry mass of coarse roots divided by the dry mass of standing biomass, carbon mass fraction (X_C), and the economic/mass allocation factor (X_{PP}) as described in equation 1.

$$C_{R\_PP} = AGB * RSR * X_C * X_{PP} \tag{1}$$

The carbon associated with rhizodeposition of extra roots (C_{E_PP}) was calculated as $0.65 x C_{R\_PP}$ as suggested in the literature (Bolinder et al., 2007; Kuzyakov and Domanski, 2000). Rhizodeposition is the flow of organic and inorganic compounds from the living roots that are a significant source of carbon input to soil (Kuzyakov et al., 2018; Virk et al., 2022).

Once the annual carbon inputs are calculated, a fixed factor is used to estimate the formation of the stable carbon fraction in soil (C_{stable}, in ton C/ha/yr), defined as potential SOC sequestration. The stabilization factor is defined as the fraction of organic residues converted to stable carbon fractions (Berti et al., 2016) with turnover rates that can span from decades to hundreds of years. Turnover rates are the average time a carbon atom stays in the soil (Luo et al., 2019). Stabilization factors for roots (coarse + rhizodeposition) carbon inputs have been reported to be between 0.10-0.35 and 1.5 to 3.7 times higher than the stabilization factor of shoot-derived inputs (residues) (Berti et al., 2016; Rasse et al., 2005). Therefore, a rate of stabilization of C input was assumed as 0.15-ton C per ton of C input on a conservative basis. Additionally, the soil is assumed to be initially degraded with the capacity to store carbon. Thus, it is assumed that the increase in the SOC concentration can be achieved every year within this study, meaning that it has not reached a steady state concentration.

2.3.3 Life cycle assessment (LCA)

To assess the biomass cultivation process, the open-source software openLCA was utilized, which allowed access to the Ecoinvent 3.8 database. The impact assessment methodology was TRACI 2.1, developed by the Environmental Protection Agency (EPA). TRACI methodology classifies LCI inputs and outputs into ten categories, including ozone depletion potential, respiratory effects potential, and global warming potential (GWP). Other categories include carcinogenic potential, fossil fuel depletion potential, acidification potential, eutrophication potential, smog potential, ecotoxicity potential, and noncarcinogenic potential. A GWP analysis was conducted with a time horizon of 100 years, if carbon sequestered in the soil would remain there while growing each cultivar for at least 100 years (Paul, 2016).

3. Results and discussion

3.1 Biomass environmental assessment

Biomass production is highly dependent on cultivation practices, crop type, and soil condition. Two very different biomasses, wheat straw and eucalyptus, were analyzed from an environmental perspective and the carbon footprint results are shown in Fig. 1.

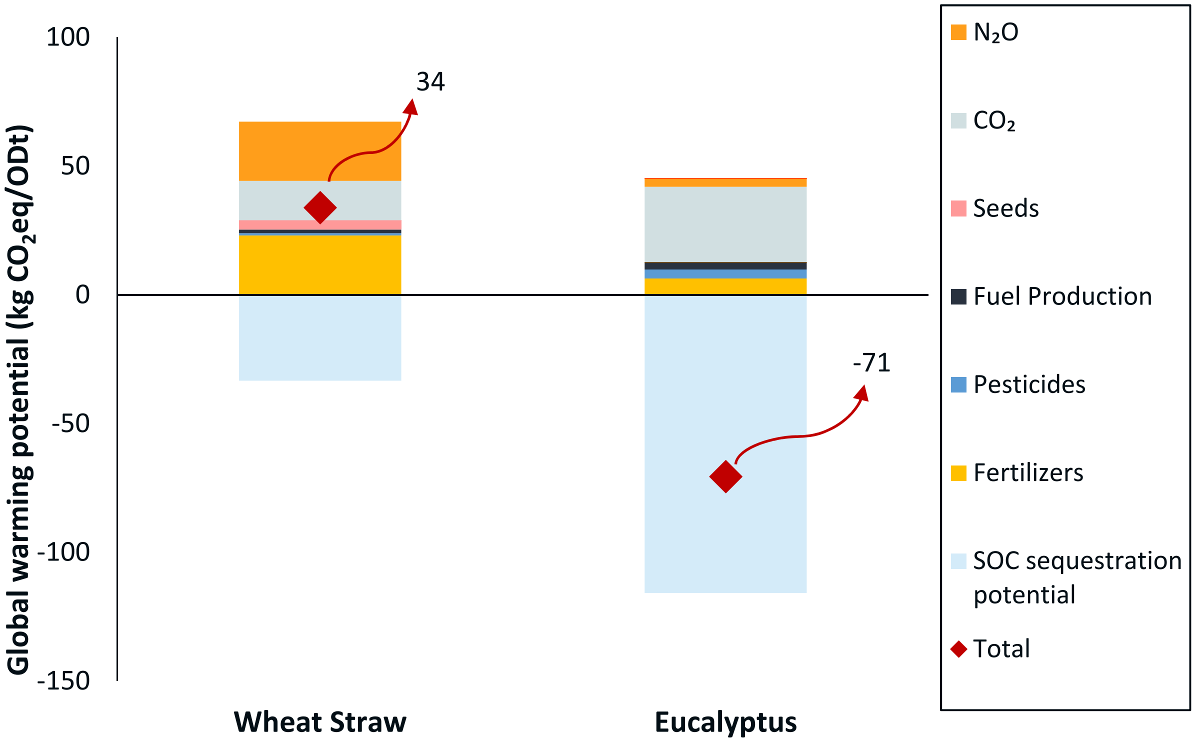

Fig.1. Cradle-to-farm gate carbon footprint of biomass production including the potential SOC sequestration.

Anthropogenic CO_2 emissions are positive contributions to the carbon footprint on the Y-axis. Wheat straw shares the environmental burdens with wheat grain, allocated based on revenue. The main hotspots are fertilizers production, and direct N_2O emissions from the soil due to N-based fertilizer application. In contrast, eucalyptus plantations are less intensively managed, requiring lower fertilization rates. CO_2 emissions experienced due to fossil fuel burning during management and harvesting are the hot spot for the eucalyptus. Additionally, Fig.1 shows the potential of each biomass to sequester carbon in the soil under the assumption of unsaturated degraded lands. Due to the annual nature of wheat plantations, the root system developed by this type of crop is shallow. Therefore, the below-ground biomass carbon inputs developed by wheat straw are relatively lower when compared to longer-lived plantations such as eucalyptus. The contribution of the SOC sequestration to the total biomass carbon footprint allows for a reduction of around 50% of the emissions for the wheat straw. For eucalyptus, the SOC sequestration is approximately double all the positive carbon emissions and causes the net carbon footprint of the eucalyptus to be negative. This type of analysis allows us to elucidate which biomass might act better for land remediation and potential carbon sink regarding goals for net zero biomass sources.

Biomass production is a key factor in the production of renewable-based energy and products, greatly impacting both economic and environmental sustainability. However, the conversion of these biomasses to finished products can be chemically and energy intensive and contribute greatly to the overall carbon footprint of the products (Tomberlin et al., 2020; Sagues et al., 2020). Therefore, the contributions of the conversion of the biomass into fiber has been studied and is the focus of ongoing research.

3.2 Environmental characterization of market pulp production

The production of mechanical pulps is characterized by the absence of a chemical recovery system within the mill. This brings consequently the lack of steam/electricity generation from biomass on-site and the discarding of chemicals together with the spent liquor. It is crucial to consider the electricity source for power supply. Nevertheless, the steam requirement still present in the mill for operations such as drying is fulfilled often by burning fossil fuels. In the pulping of BEK, CO_2 emissions from fossil fuels burning in the lime kiln and power boilers for steam generation are prevalent. Kraft mills can partially fulfill their steam and power requirements using the recovery boiler within the chemical recovery system. Particularly for current Brazilian BEK mills, the average electrical power self-sufficiency is 100%. Therefore, on average, mills burn additional fuels to generate excess steam that is used in turbine systems for electricity generation. This solution is advantageous, especially for those mills that use biomass boilers, where CO_2 emissions are considered biogenic. The second hotspot related to BEK production is the synthesis of bleaching chemicals. Chlorine dioxide generation within the mill is simulated herein using R-8 technology, where sodium chlorate, methanol, and sulfuric acid react to form this compound.

Based on detailed process simulations the overall carbon footprint and the total carbon emissions for the two different pulps has been estimated. The results are dependent on whether or not SOC sequestration is included in the analysis of the biomass. Further, the results for overall carbon emissions from cradle to pulp manufacturing gate are significantly altered when biogenic emissions are considered in addition to anthropogenic emissions. The presentation will discuss these results.

4. Conclusions

Environmental characterization of pulp and paper industry products is challenging. Numerous variables play against or in favor of their sustainability, such as biomass sources, agricultural practices, types of cooking processes, etc. In this study, a robust methodology for the carbon footprint estimation of two market pulps, BEK, and wheat straw APMP, was described and explained.

The SAFI initiative has been focused on incorporating soil organic carbon (SOC) sequestration potential, and detailed process modeling to traditional data collection for LCA analyses. Once done, both items show a significant impact on the final carbon footprint. It has also been shown that the inclusion of biogenic carbon to the overall carbon discussion affects the results considerably between different pulps.

Finally, the analysis herein shows that there is room for optimization in mechanical pulp production, with it being crucial to consider the electricity source for power supply. In the case of BEK production, the main contributor to total CO_2 emissions is related to the burning of the spent liquor in the recovery boiler (biogenic emissions), a technically challenging aspect of the overall CO_2 emissions reduction.

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