Life cycle carbon analysis of packaging products containing purposely grown non-wood fibers

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Abstract

Sustainability is driving innovation in the pulp and paper industry to produce goods with lower carbon footprints. Although most of the efforts are currently focused on increasing energy efficiency or switching to renewable fuels, the attention toward alternative feedstocks has increased in recent years. Claims of non-wood fibers requiring lower use of chemicals and energy than wood fibers, along with negative consumer perception of tree felling, are helping purposely grown non-woods to gain market share. The potential non-wood fiber environmental superiority over virgin or recycled wood fibers remains controversial and is often driven more by emotion and public perception rather than facts. This paper estimates the carbon footprint of corrugating medium and linerboard containing switchgrass pulp compared to analogous wood-based materials. The study includes a life cycle carbon analysis spanning from cradle to gate, which comprises stages for fiber production, pulping, papermaking, and corresponding transportation. For the proposed case study, the results suggest that switchgrass-based medium and linerboard can present a higher carbon footprint than products made from virgin and recycled wood fibers. The main driver is the production of non-wood mechanical pulp. This study was designed to mitigate part of the uncertainty around the environmental sustainability of medium and linerboard made from the selected purposely grown non-wood fibers.

Keywords: Switchgrass; Packaging; Corrugating medium; Linerboard; Life cycle carbon analysis (LCCA); Carbon footprint

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1. Introduction

The use of alternative fibers in paper products is receiving increased attention. Claims of non-wood fibers requiring lower use of chemicals and energy than wood fibers, along with negative consumer perception of tree felling, are helping purposely grown non-woods to gain market share, which has opened the window to paper products made from these materials [1]. Nevertheless, the preference for non-woods over wood is often driven by emotion and public perception rather than facts. Thus, non-wood producers use deforestation as a marketing strategy to promote the use of purposely grown fibers. However, in North American forestlands managed by the paper industry more trees are planted than harvested every year [2]-[4]. Non-woods represent ca. 1% of the global pulp production, with bamboo as the primary purposely grown non-wood used to make paper [5]. In the United States, non-wood pulp constitutes less than 0.1%, with switchgrass and sorghum as the main purposely grown fibers [5]. Specifically for packaging, non-woods comprise less than 0.4% of the global furnish. Processes such as soda, kraft, neutral sulfite semi-chemical and chemi-mechanical pulping are used to process these materials [5].

Although non-woods currently represent a very small fraction of the feedstock to make paper products, understanding the carbon footprint of paper made from these materials will allow determining if they constitute a better alternative to fight climate change than virgin wood or recycled paper. Thus, companies across the paper industry could have a better understanding of how these fibers fit their carbon footprint reduction pledges. In this regard, literature around this topic is abundant for agricultural residues such as wheat straw or bagasse used for paper. Nevertheless, life cycle assessments (LCA) studies dealing with paper products made from purposely grown non-woods are limited to hemp, flax, and bamboo for market pulp, tissue, and wrapping paper [6][7]. As of today, to the best of the author's knowledge, studies analyzing the carbon footprint of packaging products containing purposely grown non-woods in the United States have not been published. More specifically, LCAs on switchgrass-based packaging products are not available. Considering that non-woods often need a different pulping process than wood to enhance the value of the fiber [8], mills in this region would likely need to supply non-wood pulp instead of producing it on-site to substitute wood fibers partially. Therefore, evaluating the impact of replacing wood fibers with non-wood pulp in existing packaging mills is necessary to understand if this replacement aligns with carbon footprint reductions. Thus, this study aims to estimate the carbon footprint of linerboard and corrugating medium partially made from switchgrass in the United States compared to identical products made only from virgin wood and recycled paper. Thus, this study is expected to mitigate part of the uncertainty around the environmental sustainability of packaging products made from the selected non-wood purposely grown crop.

2. Methodology

Life cycle analysis (LCA) has been widely used to assess the environmental impact of products across their life cycle. The International Organization for Standardization (ISO) outlines the framework of this methodology in the series of 14040 guidelines [9]. The process comprises defining the study's goal and scope, collecting the life cycle inventory (LCI), performing the life cycle impact analysis (LCIA), and interpreting the results. The methodology offers a series of environmental indicators based on the characterization method used. This study is focused on the Global Warming Potential (GWP) of packaging products; therefore, the assessment receives the name of life cycle carbon analysis (LCCA). The following sections describe key assumptions used in this study to perform the assessment.

2.1. Life cycle carbon analysis of switchgrass

This part of the study aimed to estimate the GWP of switchgrass produced in the south-east United States (SEUS). Switchgrass was selected since it constitutes one of the most used purposely grown non-wood crops used for pulp production in this country. The study followed the framework described by the ISO standards [9]. The functional unit was one dry ton of switchgrass. **Figure 1** depicts the system boundaries of the study, which comprised the production, harvesting, baling, and delivery of switchgrass to the pulp mill. Thus, all raw materials and corresponding direct emissions for these stages were included. Land-use change was not considered. Secondary data from the United States Life Cycle Inventory (USLCI) and Ecoinvent were used. Processes used to build the LCI, and respective assumptions can be found in **Tables 1** and **2**. the The Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) was used as a characterization method, and SimaPro was employed to perform the assessment.

2.2. Life cycle carbon analysis of packaging products containing switchgrass

Different processes can be used to produce packaging products made from purposely grown non-wood fibers. This study assumed that switchgrass was first transformed into wet lap pulp through chemi-mechanical pulping (CMP). Then, this pulp was taken into packaging mills to replace virgin wood or recycled paper partially. Thus, the goal was to estimate the GWP of virgin and recycled linerboard and corrugating medium containing 30% switchgrass pulp. Also, the aim was to compare them with products made 100% from wood fibers to understand the impact of the replacement. The functional unit was 1 ton of paper. The analysis spanned from cradle-to-gate, as depicted in **Figure 1**. Thus, stages included the production of switchgrass, chemi-mechanical pulp, and linerboard or corrugating medium with corresponding transportation between stages.

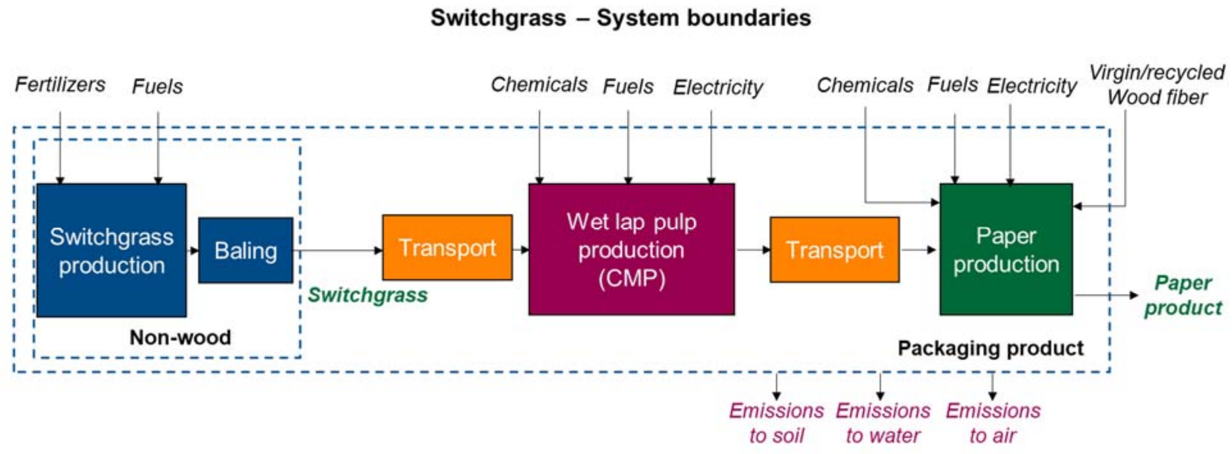

Figure 1. System boundaries for switchgrass-based packaging (Note: not all the inputs and outputs considered for the study were included in this drawing)

As in the previous section, secondary data were used to build the LCI. FisherSolve Next was primarily used to estimate the inputs and outputs of CMP processes. Literature data was used to benchmark this information. The database Ecoinvent was employed to extract the LCIs of linerboard and corrugating medium. Since switchgrass pulp would partially replace wood fibers, the energy and mass balances of these processes were adapted to reflect the replacement. Industrial data were used for this purpose [10]. Processes used to build the LCI, and respective assumptions can be found in **Table 3**. A carbon-neutral approach was followed, TRACI was used as a characterization method, and SimaPro was employed to accomplish the assessment. Sensitivity analyses were performed to understand the impact of variation in LCIs on the results. Specifically, variables related to CMP wet lap pulp production were studied. These can be found in **Table 4** and were chosen due to their contribution to the GWP of non-wood wet lap pulp. Finally, it is important to mention that, due to a lack of data, this study did not address the effect of changes in performance due to the addition of non-wood fibers or the environmental assessment across the entire life cycle of the products, also known as cradle-to-grave analysis. This would require experimental data on product properties and repulping yields that are unavailable.

Table 1. Processes and assumptions used to build the life cycle inventory of switchgrass

Stage	Database process	Source	Modifications/assumptions
Switchgrass production	Switchgrass, production, US, 2022	USLCI	Amounts described by the USLCI database were used. Ecoinvent processes replaced USLCI processes to avoid the possible use of “dummy” processes. Direct and indirect emissions from fertilizers were estimated using the method described by Ecoinvent [11].
	Mowing, by rotary mower	Ecoinvent	-
	Baling, processing	Ecoinvent	4.4 units per dry ton of switchgrass. A Factor of 0.33 was applied to the number of bales since baling switchgrass takes less time than silage (0.04 h/bale vs. 0.13 h/bale) [11][12].
	Bale loading, processing	Ecoinvent	7.7 units per dry ton of straw [11].
	Transport, freight, lorry >32 ton	Ecoinvent	Transport distances of 75 km for straw bales were assumed [13].

Table 3. Processes and assumptions used to build life cycle inventory of packaging products

Stage	Database process	Source	Modifications/assumptions
Virgin linerboard production	Containerboard production, linerboard, kraftliner	Ecoinvent	Raw materials, electricity, and thermal energy were adjusted to reflect a 30% substitution of wood fiber with non-wood residue pulp.
Recycled linerboard production	Containerboard production, linerboard, testliner		
Virgin corrugating medium	Containerboard production, fluting medium, semi-chemical		
Recycled corrugating medium	Containerboard production, fluting medium, recycled		
Landfill	Treatment of waste paperboard, sanitary landfill		-
Incineration	Treatment of waste paper, municipal incineration		-
Sorting	Treatment of waste paper, unsorted, sorting		-
Collecting	Municipal waste collection service by 21 metric ton lorry		-

Table 4. Parameters for sensitivity analysis of switchgrass chemi-mechanical pulp

Variable	**Negative variation from the average scenario**	**Positive variation from the average scenario**
Chemical charge	-35% [8]	+35% [8]
Power purchased	-10%	+50% [5]
External fuel usage	-20% [5]	+20% [5]
Yield	-15% [6]	+25% [5]
Pulping chemical	Potassium hydroxide [8] and Sodium hydroxide [5]	
Transportation	Bales 5x6 [8] and 4x6	
Allocation for liquor residue/by-product	Cut-off and mass allocation	

3. Results and discussions

3.1. Life cycle carbon analysis of switchgrass

Figure 2 depicts the Global Warming Potential (GWP) of switchgrass grown in the United States. It was found that producing one dry ton of this crop has associated ca. 195 kgCO_2eq. Fertilizers and corresponding soil emissions are the main contributors to this impact (ca. 80%). **Figure 2** also compares the GWP of switchgrass to values for non-wood residues estimated in a previous study [14]. Although the GWP of non-wood residues highly depends on methods used to allocate emissions from primary systems, switchgrass presented overall higher GWP than straw and bagasse, except under mass allocation (MA) scenarios. The cut-off method (CO) assumes that no emissions from primary systems should be allocated to residues. Therefore, values are low compared to switchgrass since only handling and transport are included. System expansion (SE) considers that removing residues can alter the primary system, allocating any difference to residues. This is the preferred method by ISO standards [9]. Results for straw under this approach are slightly lower than switchgrass since removing straw requires less fertilizer per ton of biomass than the needed to produce switchgrass. Finally, mass allocation (MA) and economic allocation (EA) distribute the environmental burdens of the primary system between all the products based on a mass or economic basis, respectively. MA sets a heavy burden on residues, which causes a higher GWP compared to switchgrass. This could bias results towards benefiting the use of purposely grown non-wood fibers compared to residues. Finally, EA presents lower GWPs since the economic value of residues is lower than primary products, which yields a lower shared burden. It is important to note that this method is influenced by the prices of residues. Therefore, as demand for these materials increases, prices could increase, and a higher share of the burden would be attributed to residues. This raises the need to evaluate the impact based on market dynamics constantly.

Another critical aspect is emissions related to transport. Transportation distances for straw are higher than switchgrass, partly explaining the more significant impact on the residue. Nevertheless, the bulk density of switchgrass is larger, which translates into a higher capacity truck utilization (volume-limited transportation) and lower emissions, i.e., fewer trucks. On the other hand, bagasse shows lower transport emissions since distances are lower and transport mode is more efficient (weight-limited transport).

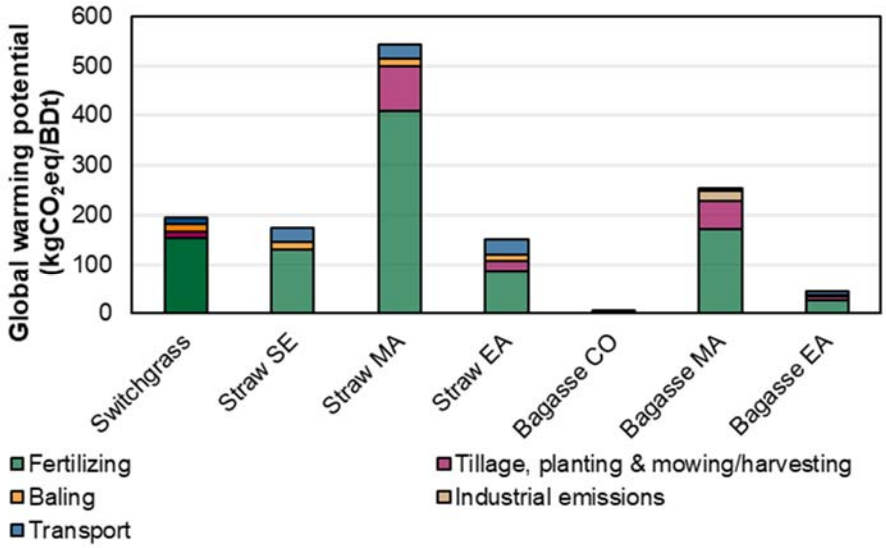

Figure 2. Global warming potential for non-wood biomass under different allocation methods. Note: Values for wheat straw and bagasse were obtained from [14]

3.2. Life cycle carbon of packaging products containing switchgrass

The carbon footprint of packaging products made from switchgrass pulp was assessed. In this study, it was assumed that the non-wood would be transformed into wet lap pulp and later into paper products. Wood benchmarks were also evaluated. Virgin wood and recycled paper were assumed to be processed in integrated mills through chemical, semi-chemical, or recycling processes. Thus, no intermediate wet lap pulp was needed. It is essential to mention that the goal was to understand the effect of replacing wood fibers with switchgrass pulp and not to compare recycled and virgin packaging products. Datasets used come from different sources, and using them for comparison could lead to wrong conclusions.

Figures 3 and **4** depict the GWP of virgin linerboard and corrugating medium containing switchgrass pulp and wood benchmarks produced in south-east United States (SEUS). GWPs for wood-based linerboard and corrugating medium were ca. 510 kgCO_2eq/ton and 460 kgCO_2eq/ton, respectively. In both cases, the main contributors to the impact were electricity purchased and direct emissions from burning fossil fuels. Partially replacing wood fibers with switchgrass pulp translated into larger GWPs for linerboard and corrugating medium (ca. 60% higher). The main driver for these results was the GWP associated with non-wood pulp. Overall, the chemi-mechanical process used to pulp switchgrass presents a lower chemical and energy use than kraft or semi-chemical processes for wood. Nevertheless, it lacks chemical recovery areas or power co-generation and uses a larger share of fossil fuels, which translates into a larger impact. Thus, the high efficiency in recovering chemicals and the ability to produce on-site combined heat and power from a high share of renewable fuels are critical for the lower environmental impact of virgin wood-based paper.

Figures 5 and **6** show the GWP of recycled linerboard and corrugating medium containing switchgrass pulp and benchmarks produced from recycled paper. GWPs for recycled linerboard and corrugating medium were ca. 620 kgCO_2eq/ton and 670 kgCO_2eq/ton, respectively. The largest contributor to the impact was direct emissions from fossil fuel incineration. Partially replacing recycled pulp with switchgrass pulp increased the GWP of packaging products (ca. 40%). Direct and electricity-related emissions slightly decreased due to less recycled paper handled, but the overall higher GWP of switchgrass pulp produced larger carbon footprints. Thus, replacing the equivalent amount of recycled pulp with non-wood pulp did not translate into environmental benefits.

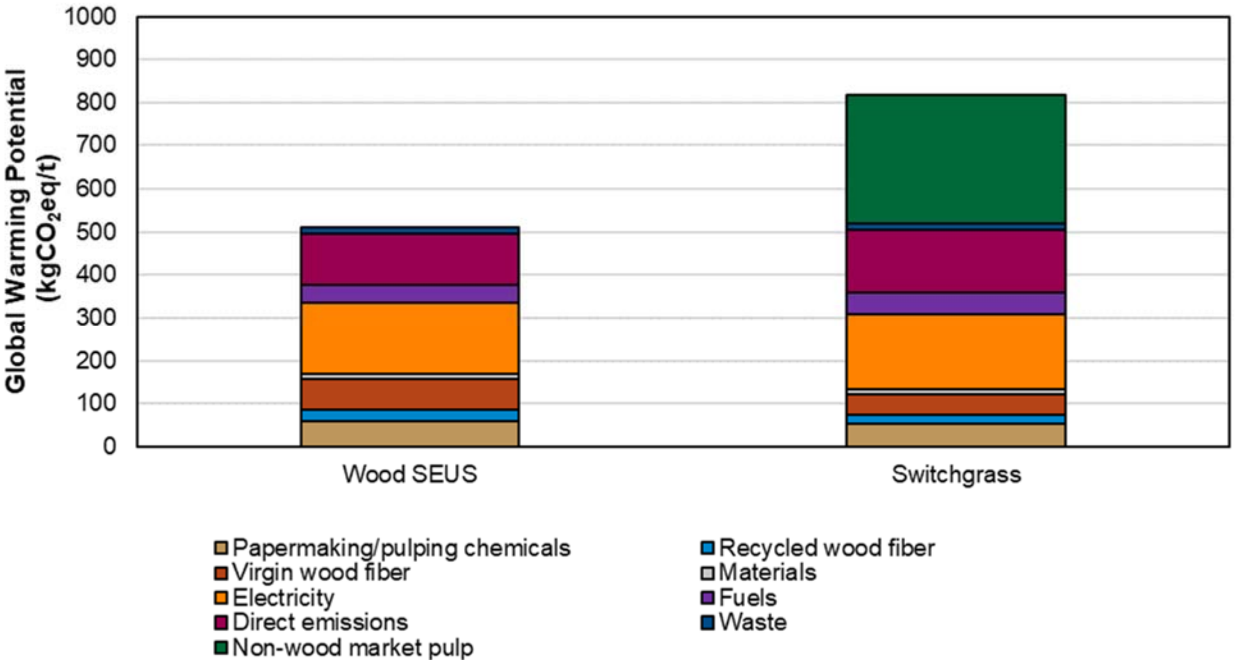

Figure 3. Global warming potential virgin wood-based linerboard and similar product containing 30% switchgrass pulp

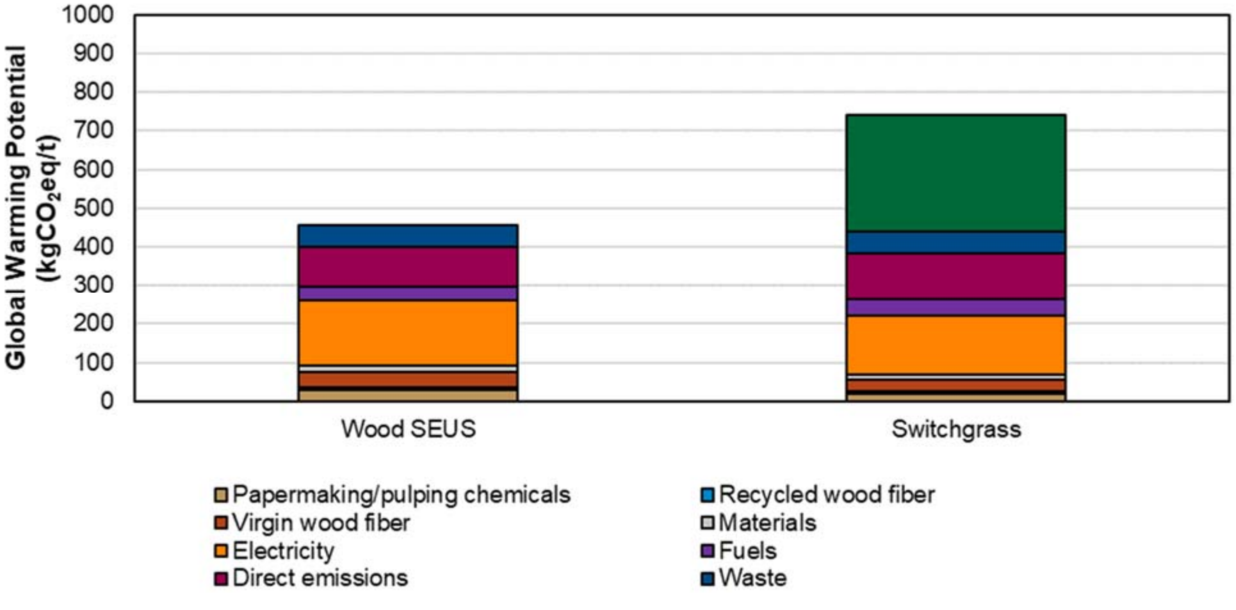

Figure 4. Global warming potential virgin wood-based corrugating medium and similar product containing 30% switchgrass pulp

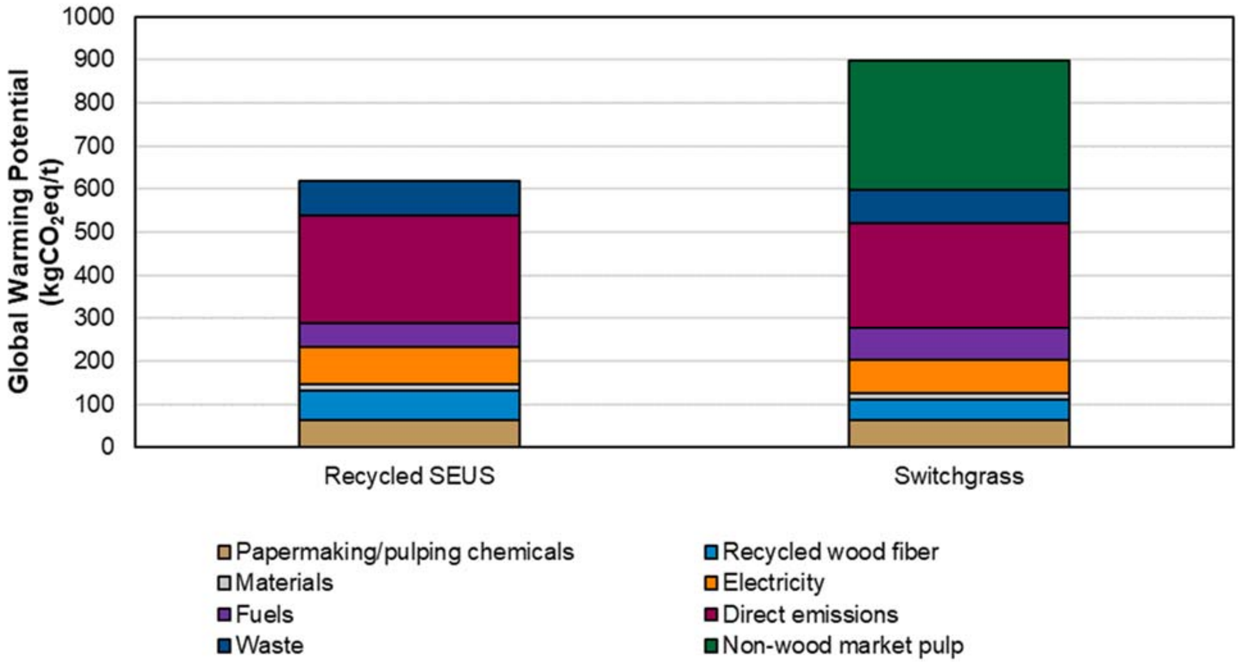

Figure 5. Global warming potential recycled linerboard and similar product containing 30% switchgrass pulp

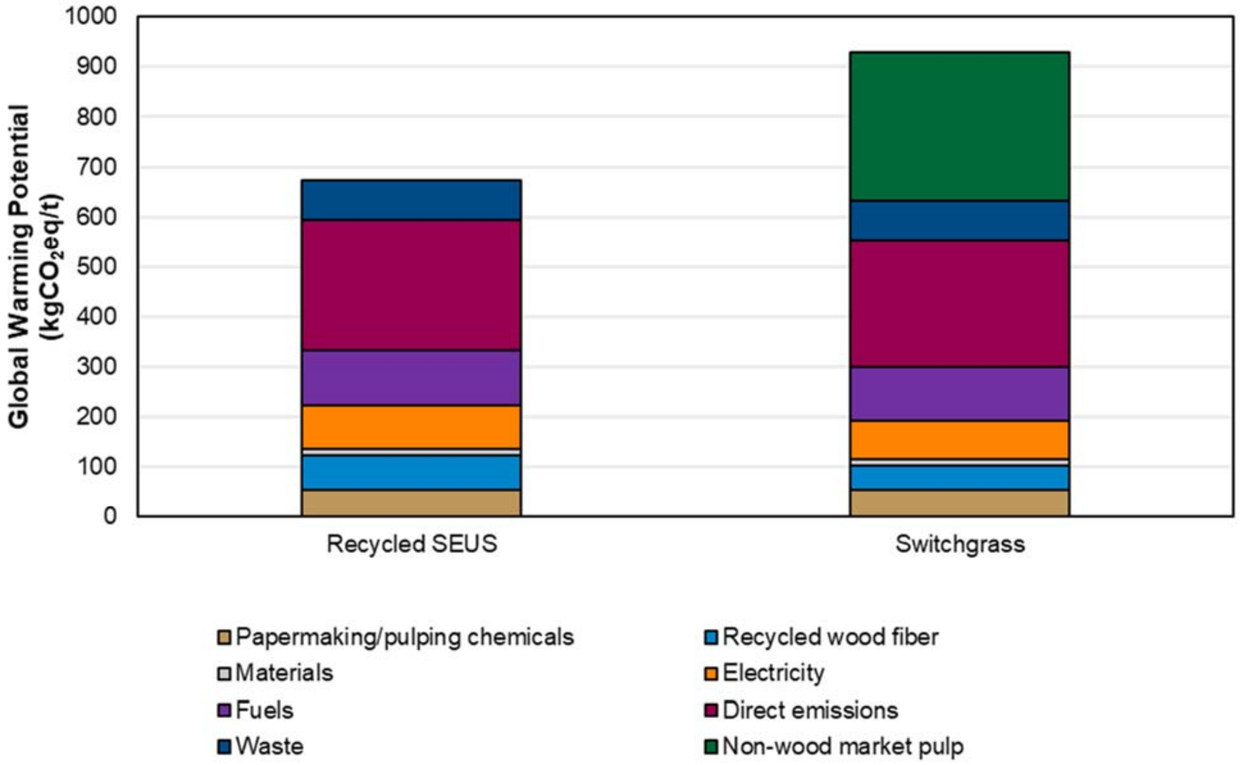

Figure 6. Global warming potential recycled medium and similar product containing 30% switchgrass pulp

Sensitivity analyses depicted in **Figure 7** were performed to understand how LCI variability affects GWP results. Specifically, variables related to the chemi-mechanical process used to make switchgrass pulp were varied. It was found that packaging products containing non-wood residues presented GWPs between ca. 25-60% higher compared to benchmarks. Thus, GWP results were susceptible to changes in switchgrass pulping. Specifically, allocation methods for by-products of non-wood pulping, type of pulping chemical, and chemical charges during non-wood pulping presented the most significant influence on the results. Nevertheless, results for packaging products containing switchgrass pulp presented larger GWPs under all evaluated scenarios. Similar findings were observed in previous studies for non-wood residues [14]. Therefore, considering these results, replacing virgin wood or recycled pulp with chemi-mechanical pulp might be unfavorable to reduce the carbon footprint of corrugating medium and linerboard.

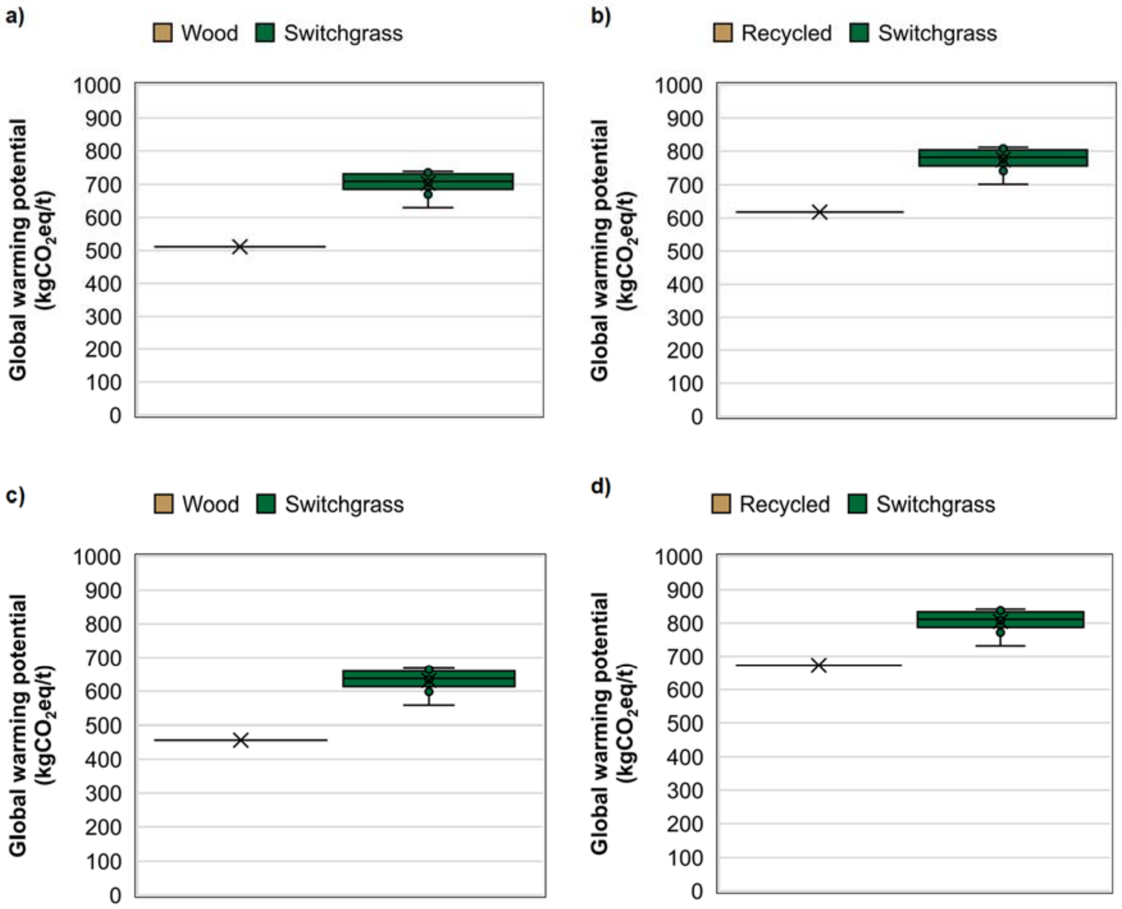

Figure 7. Sensitivity analysis for packaging products containing switchgrass pulp and wood-based benchmarks: a) virgin linerboard, b) recycled linerboard, c) virgin medium, d) recycled medium

4. Conclusions

This research examined the impact of substituting wood fibers with switchgrass pulp on the carbon footprint of linerboard and corrugating medium produced in the United States. Results show that this replacement translates into increased GWPs. Switchgrass wet lap pulp was the main driver for the larger impact. Although the chemi-mechanical process used to make the pulp has a lower chemical and energy demand than conventional kraft processes, it lacks chemical recovery and power generation areas, and uses a larger share of fossil fuels, which explains the largest environmental burdens. Also, results were susceptible to variables around the production of wet lap pulp. Thus, the GWPs of packaging products containing switchgrass could be 25-60% higher than products made from virgin wood or recycled paper. Overall, from these findings, using chemi-mechanical pulp made from switchgrass might not be a solution to reduce the carbon footprints of linerboard and corrugating medium under the studied scenarios in the United States.

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