Life cycle carbon analysis of packaging products containing purposely grown nonwood fibers: A case study on the use of switchgrass pulp for linerboard and corrugating medium

ANTONIO SUAREZ, ASHOK GHOSH, FRITZ PAULSEN, AND PETER W. HART

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 nonwood fibers requiring lower use of chemicals and energy than wood fibers, along with negative consumer perceptions of tree felling, are helping purposely grown nonwoods to gain market share. The potential nonwood fiber environmental superiority over virgin or recycled wood fibers remains controversial and is often driven more by emotion and public perception rather than facts.

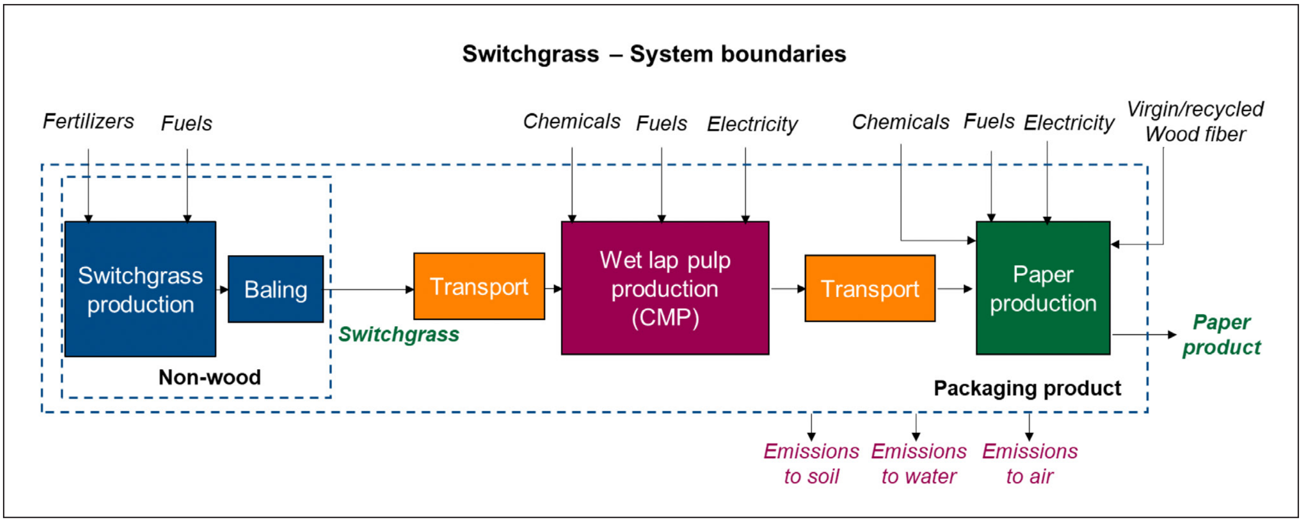
This paper estimates the carbon footprint of corrugating medium and linerboard containing switchgrass pulp compared to analogous wood-based materials. The study includes a life cycle carbon analysis spanning from cradle to gate, which comprises stages for fiber production, pulping, papermaking, and corresponding transportation. Carbon footprints for virgin linerboard, recycled linerboard, virgin medium, and recycled medium were estimated at around 510, 620, 460, and 670 kg carbon dioxide equivalent per metric ton (kg CO_2eq/t), respectively. Replacing 30% of the virgin or recycled material with switchgrass pulp translated into carbon footprint increases of around 60%, 45%, 62%, and 38%, respectively. Thus, 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 nonwood 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 nonwood fibers.

Application: Readers can use these findings to understand the life cycle carbon analysis of corrugating medium and linerboard made from switchgrass pulp and perform informed decision-making pertaining to the sustainability of these nonwood fibers and conventional wood fibers under the studied circumstances.

The use of alternative fibers in paper products is receiving increased attention. Claims of nonwood fibers requiring lower use of chemicals and energy than wood fibers, along with negative consumer perception of tree felling, are helping purposely grown nonwoods to gain market share, which has opened the window to paper products made from these materials [1]. Nevertheless, the preference for nonwoods over wood is often driven by emotion and public perception rather than facts. Thus, nonwood 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]. Nonwoods represent about 1% of the global pulp production, with bamboo as the primary purposely grown nonwood used to make paper [5]. In the United States, nonwood pulp constitutes less than 0.1%, with switchgrass and sorghum as the main purposely grown fibers [5]. Specifically for packaging, nonwoods comprise less than 0.4% of the global furnish. Processes such as soda, kraft, neutral sulfite semichemical, and chemimechanical pulping are used to process these materials [5].

Although nonwoods 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 analysis (LCA) studies dealing with paper products made from purposely grown nonwoods are



1. System boundaries for switchgrass-based packaging based on a chemimechanical pulp (CMP) process. Note that not all the inputs and outputs considered for the study were included in this drawing.

limited to bamboo for market pulp, tissue, and wrapping paper [6]. As of today, to the best of the authors' knowledge, studies analyzing the carbon footprint of packaging products containing purposely grown nonwoods in the United States have not been published. More specifically, LCAs on switchgrass-based packaging products are not available. Considering that nonwoods often need a different pulping process than wood to enhance the value of the fiber [7], mills in this region would likely need to supply nonwood pulp instead of producing it on-site to substitute wood fibers partially. Therefore, evaluating the impact of replacing wood fibers with nonwood 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. Consequently, this study is expected to mitigate part of the uncertainty around the environmental sustainability of packaging products made from the selected nonwood purposely grown crop.

METHODOLOGY

Life cycle analysis has widely been 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 guidelines found in ISO Standard 14040:2006 "Environmental management — Life cycle assessment — Principles and framework." 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.

Life cycle carbon analysis of switchgrass

This part of the study aimed to estimate the GWP of switchgrass produced in the southeastern United States (SEUS). Switchgrass was selected since it constitutes one of the most used purposely grown nonwood crops used for pulp production in this country. The study followed the framework described by ISO Standard 14040:2006. The functional unit was one dry metric 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 concerning GWP for these stages were included. Land-use change was not considered. Processes used to build the LCI and respective assumptions can be found in **Table I**. Secondary data from the United States Life Cycle Inventory (USLCI) [8] and Ecoinvent [12] databases were used. The characterization factors for global warming from the Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) [13] were used as a characterization method, and SimaPro LCA software (SimaPro; Amersfoot, The Netherlands) was employed to perform the assessment.

Life cycle carbon analysis of packaging products containing switchgrass

Different processes can be used to produce packaging products made from purposely grown nonwood fibers. This study assumed that switchgrass was first transformed into wet lap pulp through chemimechanical pulping. Then, this pulp was taken into packaging mills to partially replace virgin wood or recycled paper. Thus, the goal was to estimate the GWP of virgin and recycled linerboard and cor-

Stage	Database Process	Source	Modifications/Assumptions
Switchgrass production	Switchgrass production, United States, 2022	USLCI	Amounts described by the USLCI database [8] 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 [9].
	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) [9,10].
	Bale loading, processing	Ecoinvent	7.7 units per dry ton of straw [9].
	Transport, freight, lorry >32 ton	Ecoinvent	Transport distances of 75 km for switchgrass bales were assumed [11].

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

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 nonwood residue pulp.
Recycled linerboard production	Containerboard production, linerboard, testliner		
Virgin corrugating medium	Containerboard production, fluting medium, semichemical		
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		–

II. Processes and assumptions used to build life cycle inventory (LCI) of packaging products.

rugating 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 metric ton of paper. It is important to note that it was assumed that the performance of linerboard and medium would be equivalent before and after replacing wood fibers with switchgrass. In reality, this is not necessarily true. Paper properties and paper machine runnability could vary significantly due to the replacement, which could lead to changes in life cycle inventories between scenarios or the need to use different amounts of paper to satisfy the function of the system. Nevertheless, due to lack of experimental data, changes in paper performance or machine operability were not considered. The analysis spanned from cradle-to-gate, as depicted in Fig. 1. Thus, stages included the production of switchgrass, chemi-mechanical pulp (CMP), and linerboard or corrugating medium with corresponding transportation between stages.

As in the previous section, secondary data were used to build the LCI. FisherSolve Next [5] was primarily used to estimate the inputs and outputs of CMP processes. Literature data was used to benchmark and adjust this information. The Ecoinvent database [12] 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 [14]. Processes used to build the LCI and respective assumptions can be found in **Table II**. These include inputs and outputs affecting global warming. A carbon-neutral approach for biogenic carbon was followed. This method assumes that atmospheric carbon removed during biomass

Variable	Negative Variation from the Average Scenario	Positive Variation from the Average Scenario
Chemical charge	-35% [7]	+35% [7]
Power purchased	-10%	+50% [5]
External fuel usage	-20% [5]	+20% [5]
Yield	-15% [7]	+25% [5]
Pulping chemical	Potassium hydroxide [7] and sodium hydroxide [5]	
Transportation*	Bales 5 ft x 6 ft [7] and 4 ft x 6 ft	
Allocation for liquor residue/byproduct	Cut-off (100% emissions allocated to pulp) and mass allocation (61.7% emissions allocated to pulp and 38.3% allocated to liquor residue/byproduct)	

* Different bale sizes have been reported. Since the transportation of switchgrass is volume limited, bale size will define the number of bales, and therefore the weight, that can be transported. A greater number of bales transported translates into more efficient transportation and less emissions per metric ton of biomass.

III. Parameters for sensitivity analysis of switchgrass chemimechanical pulp.

growth will eventually be released during the life cycle of the product. Thus, removals or releases of biogenic CO_2 are not included in this LCA, and only anthropogenic carbon emissions are tracked. The characterization factors for global warming from TRACI [13] were used as a characterization method, and SimaPro LCA software 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 III** and were chosen due to their contribution to the GWP of nonwood wet lap pulp. Finally, it is important to mention that, due to a lack of data, this study did not address 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.

RESULTS AND DISCUSSION

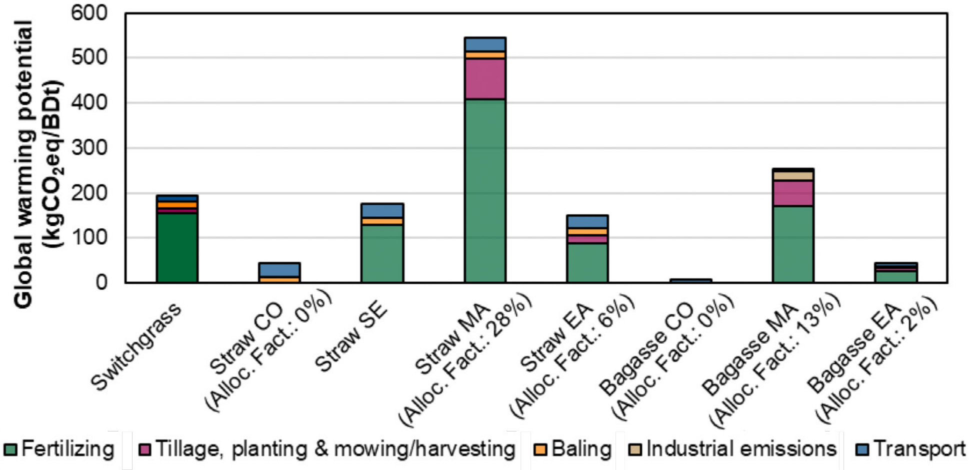
Life cycle carbon analysis of switchgrass

Figure 2 depicts the GWP of switchgrass grown in the United States. It was found that producing one dry metric ton of this crop is associated with about 195 kg carbon dioxide equivalent (CO_2eq). Fertilizers and corresponding soil emissions are the main contributors to this impact (about 80%). Figure 2 also compares the GWP of switchgrass to values for nonwood residues estimated in a previous study [15]. Although the GWP of nonwood 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 Standard 14040:2006. Results for straw under this approach are slightly lower than switchgrass, since removing straw requires less fertilizer per metric 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. The 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 nonwood 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 constantly evaluate the impact based on market dynamics.

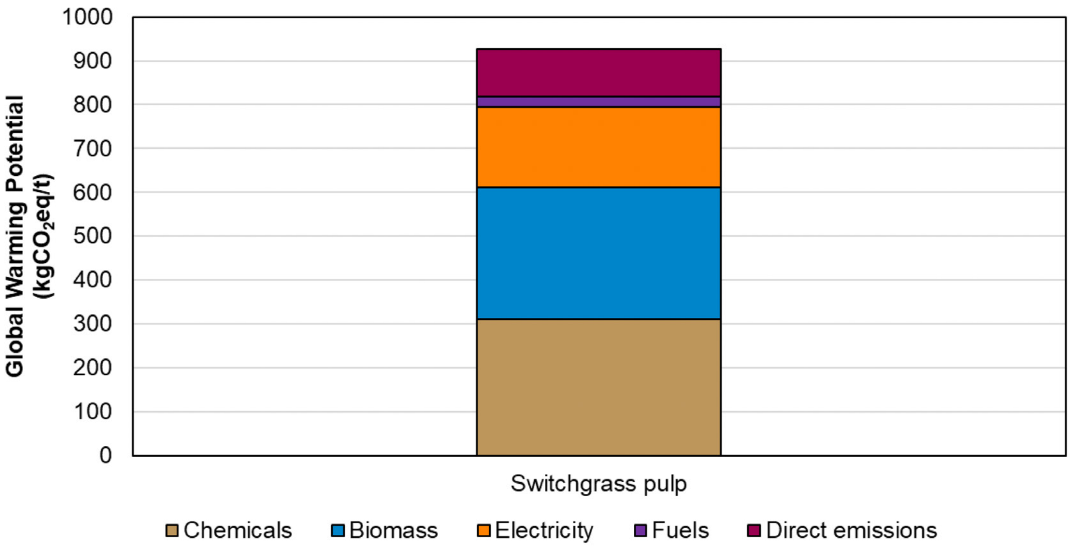
Another critical aspect is emissions related to transport. Transportation distances for straw (120 km [11]) are higher than switchgrass (75 km [11]), partly explaining the more significant impact on the residue. Nevertheless, the bulk density of switchgrass (168 kg/m³ [11]) is higher than the density of straw (123 kg/m³ [11]), 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 (20 km [11]), and transport mode is more efficient (weight-limited transport). More information on the results for straw and bagasse can be found in [15].

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 nonwood would be transformed into wet lap pulp and later into paper products. Wood benchmarks



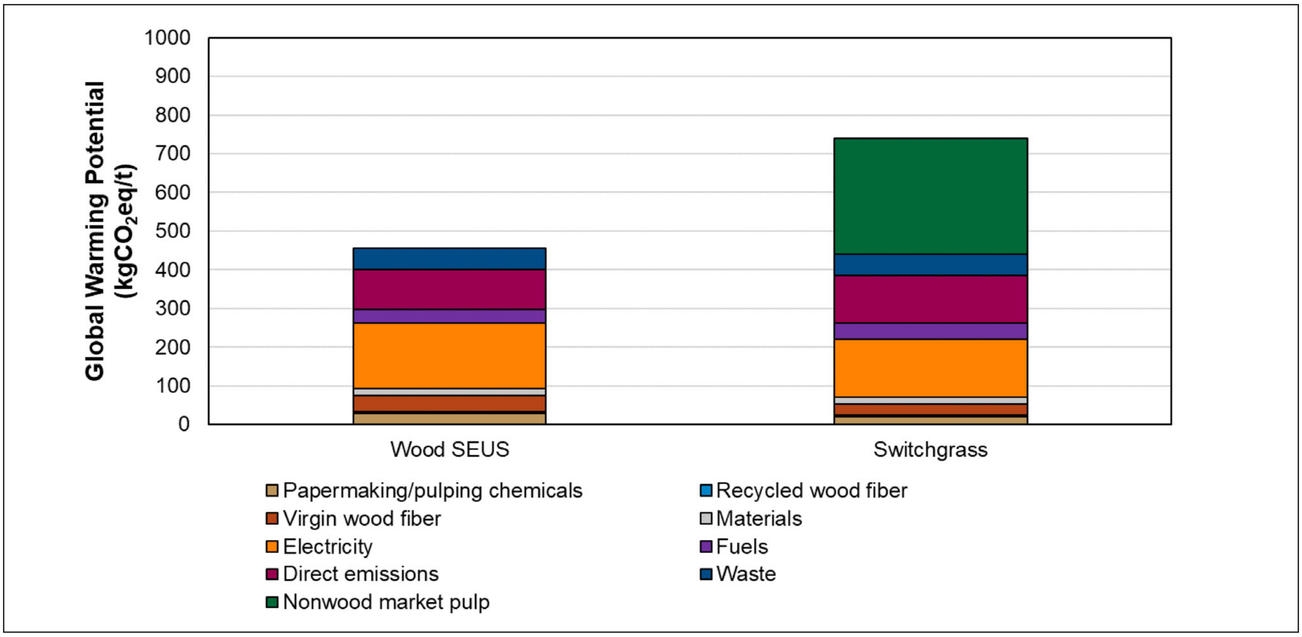
2. The global warming potential (GWP) in kilograms of carbon dioxide equivalent per bone-dry metric ton (kgCO$_2$eq/BDt) for nonwood biomass under different allocation methods (CO: cut-off; SE: system expansion; MA: mass allocation; EA: economic allocation). Note that global warming potential values and allocation factors (Alloc. Fact.) for wheat straw and bagasse were obtained from [15].



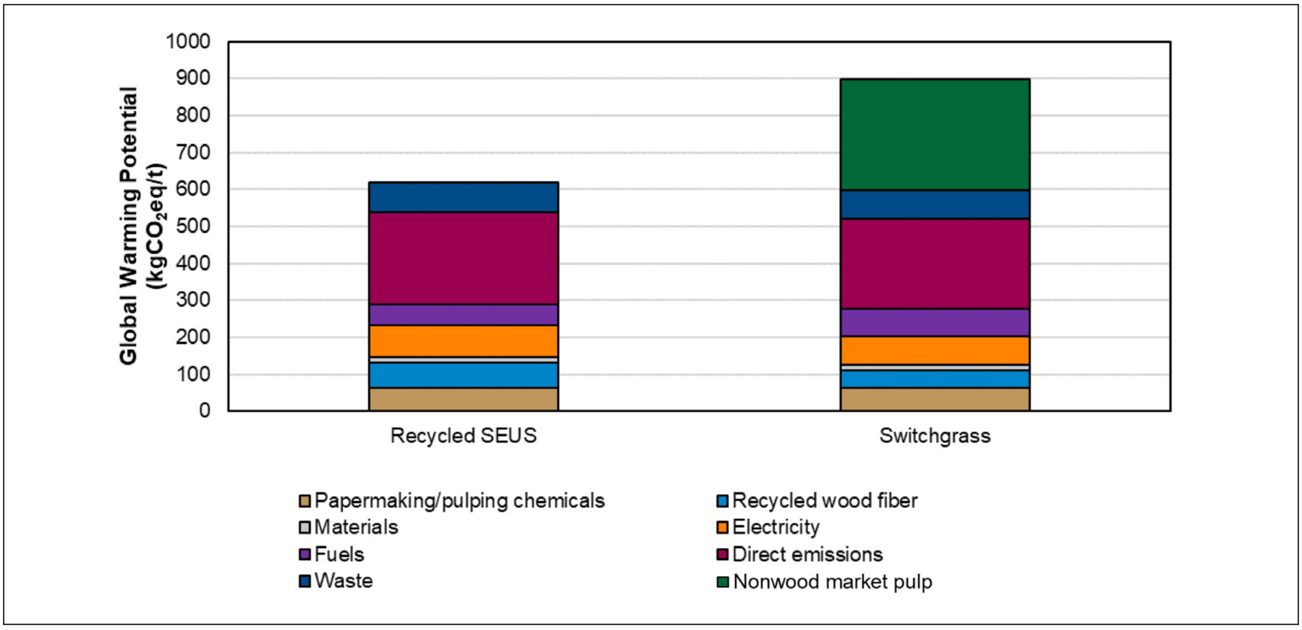
3. The GWP of switchgrass CMP in kilograms of carbon dioxide equivalent per metric ton (kgCO$_2$eq/t), with baseline scenario using potassium hydroxide as pulping chemical and cut-off method for the residual/byproduct liquor.

were also evaluated. Virgin wood and recycled paper were assumed to be processed in integrated mills through chemical, semichemical, 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 the wrong conclusions.

Figure 3 presents the GWP results and contributors associated with switchgrass chemimechanical pulp. The predominant factors influencing this environmental impact encompass biomass, chemicals, and sourced electricity. Despite the superior yields observed in chemimechanical pulping in comparison to kraft pulping, the elevated GWP of switchgrass, arising predominantly from fertilizer usage and its associated emissions, imposes a substantial burden on the overall GWP of the pulp. Notably, the absence of a chemical recovery system results in a significant contribution from chemicals. This implies a heightened requirement for chemical inputs, amplifying the overall environmental impact. Furthermore, the studied process lacks a combined heat and power unit, leading to sourcing the required electricity from the grid to fulfill the mechanical requirements. Consequently, the confluence of a heightened GWP for biomass, the necessity to import all



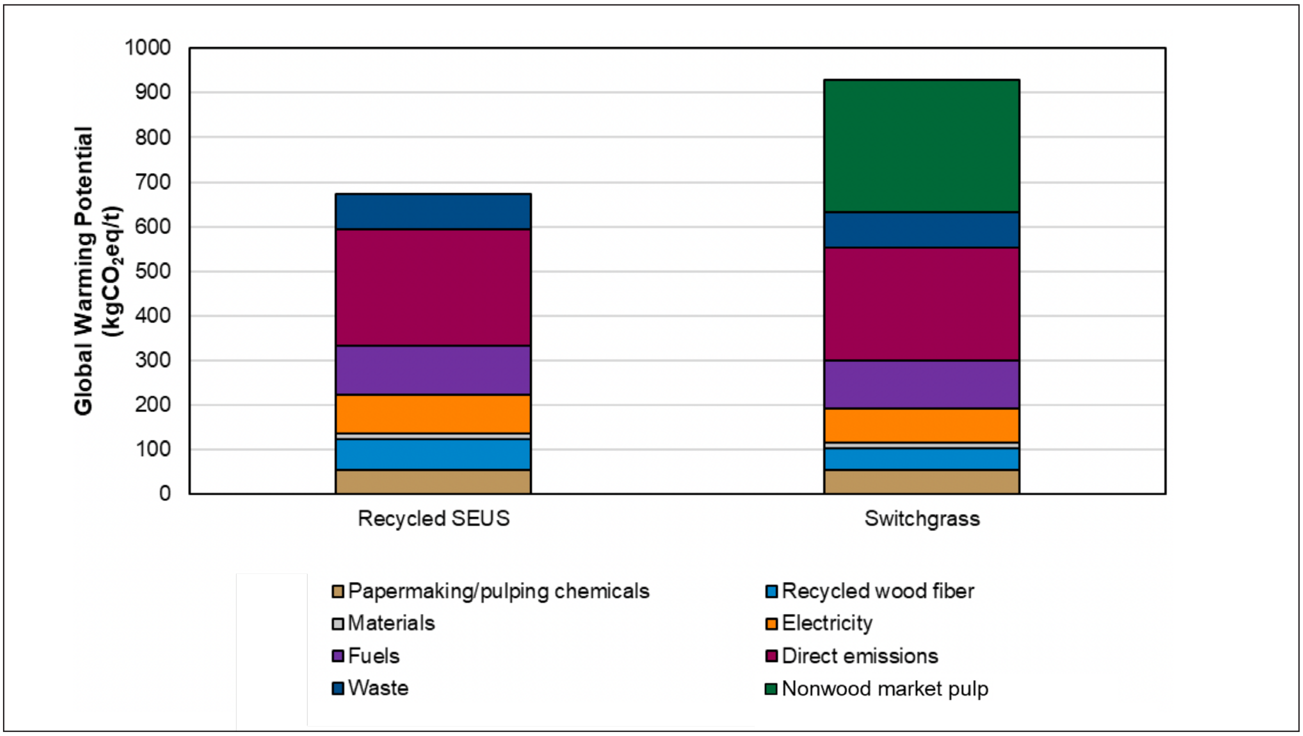
4. The GWP in kilograms of carbon dioxide equivalent per metric ton (kg CO_2/t) of virgin wood-based linerboard and similar product containing 30% switchgrass pulp (SEUS: southeastern United States).



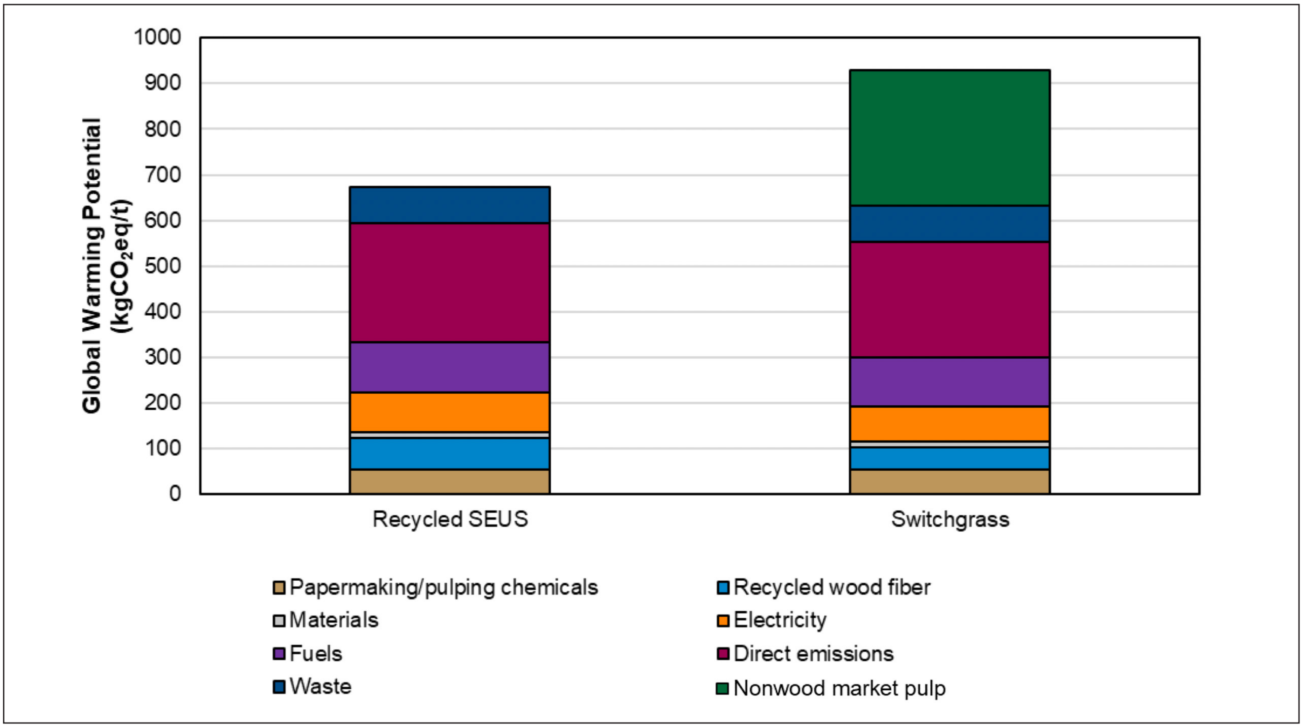
5. The GWP of virgin wood-based corrugating medium and similar product containing 30% switchgrass pulp (SEUS: southeastern United States).

requisite chemicals, and the reliance on externally sourced electricity translates into an approximate GWP of 930 kg carbon dioxide equivalent per bone-dry metric ton (CO_2eq/BDt) for this particular pulp.

Figures 4–5 depict the GWP of virgin linerboard and corrugating medium containing switchgrass pulp and wood benchmarks produced in the southeastern United States (SEUS). The GWPs for wood-based linerboard and corrugating medium were approximately 510 kg CO_2eq/t and 460 kg CO_2eq/t, 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 (approximately 60% higher). The main driver for these results was the GWP associated with nonwood pulp. Overall, the chemimechanical process used to pulp switchgrass presents a lower chemical and energy use than kraft or semichemical processes for wood. Nevertheless, as mentioned before, 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



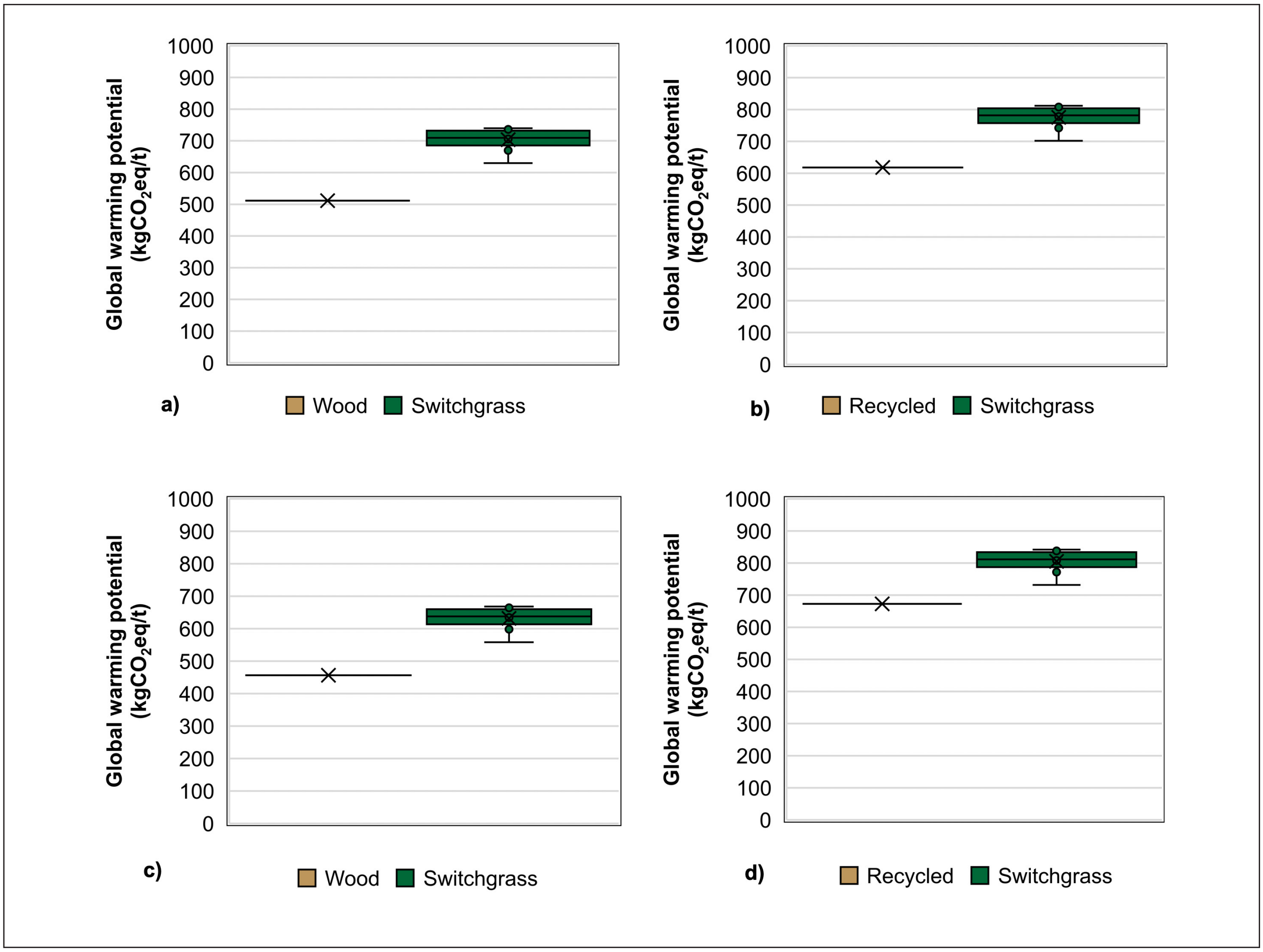
6. The GWP of recycled linerboard and similar product containing 30% switchgrass pulp (SEUS: southeastern United States).



7. The GWP of recycled medium and similar product containing 30% switchgrass pulp (SEUS: southeastern United States).

combined heat and power from a high share of renewable fuels are critical for the lower environmental impact of virgin wood-based paper.

Figures 6–7 show the GWP of recycled linerboard and corrugating medium containing switchgrass pulp and benchmarks produced from recycled paper. The GWPs for recycled linerboard and corrugating medium were approximately 620 kg CO_2eq/t and 670 kgCO_2eq/t, 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 by about 40%. Direct and electricity-related



8. Sensitivity analysis for packaging products containing switchgrass pulp and wood-based benchmarks: a) virgin linerboard; b) recycled linerboard; c) virgin medium; and d) recycled medium. Each marker represents the GWP resulting from changing one variable during switchgrass pulp production at the time (manipulated variables can be found in Table III).

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 nonwood pulp did not translate into environmental benefits.

Sensitivity analyses depicted in **Fig. 8** were performed to understand how LCI variability affects GWP results. Specifically, variables related to the CMP process used to make switchgrass pulp were varied. It was found that packaging products containing switchgrass presented GWPs between around 25%–60% higher compared to virgin and recycled wood benchmarks when varying the LCI of switchgrass pulp production. Therefore, due to the high variation, the pulping stage presents an important influence in the GWP of papers containing this fiber. Specifically, allocation methods for byproducts of nonwood pulping, type of pulping chemical, and chemical charges during nonwood pulping presented the most significant influence on the results, as seen in **Table IV**. Nevertheless, results for packaging products containing switchgrass pulp presented larger GWPs under all evaluated scenarios. Similar findings were observed in previous studies for nonwood residues [15]. Therefore, considering these results, replacing virgin wood or recycled pulp with chemimechanical pulp from switchgrass might be unfavorable to reduce the carbon footprint of corrugating medium and linerboard. Additional research to understand the effect on other environmental impact categories could provide valuable information to complement findings from our study.

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 CMP 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 it uses a larger share of fossil fuels, which explains the largest environmental burdens. Also, results were susceptible to vari-

Sensitivity Analysis Variable	Variable Change from Baseline	Change in GWP of Virgin Linerboard	Change in GWP of Recycled Linerboard	Change in GWP of Virgin Medium	Change in GWP of Recycled Medium
Chemical charge	-35%	-3.9%	-3.6%	-4.4%	-3.4%
	+35%	+3.9%	+3.6%	+4.4%	+3.4%
Power purchased	-10%	-0.7%	-0.6%	-0.8%	-0.6%
	+50%	+3.5%	+3.0%	+4.0%	+3.0%
External fuel usage	-20%	-1.0%	-0.9%	-1.1%	-0.9%
	+20%	+1.0%	+0.9%	+1.1%	+0.9%
Yield	-15%	+3.2%	+2.9%	+3.6%	+2.8%
	+15%	-3.8%	-3.4%	-4.2%	-3.3%
Pulping chemical	Potassium hydroxide	0% (baseline chemical)	0% (baseline chemical)	0% (baseline chemical)	0% (baseline chemical)
	Sodium hydroxide	-6.0%	-5.5%	-6.7%	-5.3%
Transportation	Bales 5 ft x 6 ft	0% (baseline size)	0% (baseline size)	0% (baseline size)	0% (baseline size)
	Bales 4 ft x 6 ft	-0.3%	-0.3%	-0.3%	-0.2%
Allocation for liquor residue/byproduct	Cut-off	0% (baseline method)	0% (baseline method)	0% (baseline method)	0% (baseline method)
	Mass allocation	-11.6%	-10.6	-12.9%	-10.2%

IV. Effect of different variables during the production of switchgrass pulp on the GWP of switchgrass-based virgin linerboard, recycled linerboard, virgin medium, and recycled medium.

ables 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 chemimechanical 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. **TJ**

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ABOUT THIS PAPER

Cite this article as:
Suarez, A., Ghosh, A., Paulsen, F., et al., *TAPPI J.* 23(3): 143(2024). https://doi.org/10.32964/TJ23.3.143

DOI: https://doi.org/10.32964/TJ23.3.143

ISSN: 0734-1415

Publisher: TAPPI Press

About this journal

ABOUT THE AUTHORS

Because the pulp and paper industry aims to decarbonize, there is a need to understand the environmental sustainability (specifically, carbon footprint) of linerboard and corrugating medium made from switchgrass. Thus, this topic was relevant for research. As no previous research was found on life cycle analysis (LCA) of packaging products made from switchgrass pulp, the findings from this study are novel.

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The most difficult aspect of this study was to develop an LCA framework that captured environmental and technical data on nonwoods. This was addressed by including validated environmental data, properties/performance data, and recyclability information. Therefore, a robust study was performed.

We found that the comparison of wood vs. nonwood (in terms of sustainability) needs to include a holistic approach addressing the different life cycle stages. It is not enough to compare raw materials only.

Mills can use the information presented here for decision-making around which fibers to use to ensure lower carbon footprints.

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