Life cycle carbon analysis of packaging products containing nonwood residues: A case study on linerboard and corrugating medium

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ABSTRACT: Circularity is creating momentum toward utilizing waste feedstock in a myriad of applications. The paper industry is not an exception to this trend, and packaging products made from agricultural or agro-industrial residues are receiving more attention now than ever. Additionally, negative consumer perceptions of tree felling are accelerating the acceptance of these fibers. Nevertheless, adopting these residues raises the issue of whether they constitute a better alternative to fight climate change than wood. Answering this question is imperative to ensure that pledges to reduce carbon footprints across the industry are fulfilled.

This paper aims to estimate the carbon footprint of corrugating medium and linerboard containing wheat straw and sugarcane bagasse pulp compared to analogous wood-based materials. The goal was also to understand how methodological decisions to allocate emissions to nonwood residues can affect the results. This study includes a life cycle carbon analysis spanning from cradle to grave, which comprises stages for residue production, pulping, papermaking, waste management, and corresponding transportation.

For the proposed case study, the results suggest that straw- and bagasse-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 chemimechanical pulp. In addition, the lower capacity of nonwood residues to be recycled increases the overall impact. Finally, decisions around emissions allocation highly influence the results. This study helps mitigate part of the uncertainty around the environmental sustainability of corrugating medium and linerboard made from the selected nonwood residues.

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

Sustainability trends are raising attention toward introducing non-conventional fibers into a myriad of products. Consequently, consumer demand for nonwood-based materials has gained momentum, opening the market for pulp, packaging, tissue, and printing and writing paper made from these fibers [1]. Specifically, agricultural residues, such as straw and bagasse, have been perceived to offer sustainability and technical benefits compared to wood sources. Negative perceptions of tree felling are facilitating the adoption of these raw materials. Indeed, many nonwood producers highlight deforestation as a negative aspect promoted by the paper industry, although in North America, the industry plants more trees than it harvests every year [2-4]. Despite this misconception, nonwoods only represent around 1% of the global pulp production, with bagasse and straw as the primary agricultural residues used to make paper products [5]. In the United States, the number is less than 0.1%, with linters and straw as the most prevalently used residues in soda or chemimechanical processes [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 fibers [5].

Although nonwood residues could fill the sustainability strategies of paper companies from a resource utilization point of view, specifically in regions where forests are scarce, or could help reduce particulate matter emissions due to avoiding residue incineration, it is necessary to understand whether these fibers constitute a better alternative to fight climate change than wood. Companies across the industry have pledged reductions in carbon footprints, and raw materials are essential in fulfilling these commitments. In this regard, literature around this topic is abundant, especially focused on life cycle analyses (LCAs) of wheat straw and bagasse used for paper. Nevertheless, results are inconclusive due to biased comparisons against woods by not considering the actual implications of residue utilization or against residues by using data from low-efficiency and outdated processes to handle these materials [6].

Specifically for straw, LCA studies are heavily focused on Chinese practices, with one assessment for Canada [7-12]. Most of this research does not allocate emissions from wheat production to the straw under the assumption that it is a residue, which could favor the results towards straw compared to wood. In addition, yields for straw pulp varied from 35%–90%, with most of the studies within the 35%–50% range for chemical and semichemical processes, which does not reflect the existence of more efficient processes currently available. Different paper grades have been studied, such as market pulp [7,9,11], printing and writing [8,11], packaging [10,11], and tissue [11], with benchmarks mostly made from wood-based kraft and chemithermomechanical pulp. Despite widespread assumptions, carbon footprint results often show lower global warming potential (GWP) impacts from wood utilization than straw [8,9,11,12]. Life cycle analysis studies for paper made from bagasse can also be found in the literature [11,13-15]. These assessments focus on China, Thailand, and Iran for products such as tissue paper [11], wrapping paper [11], market pulp [13], and printing and writing paper [14]. As seen with straw, most of the studies do not allocate environmental burdens to bagasse, with only one study using economic allocation [15]. Overall, results do not show consensus on whether bagasse-based paper constitutes a better alternative than wood, with some studies showing higher impacts for bagasse [11] and others for wood [14,15].

As of today, to the best of the authors' knowledge, studies analyzing the carbon footprint of packaging products containing nonwood residues in the United States have not been published. Overall, the assessments found in the literature focus on comparing wood-based and nonwood products made under processes that do not reflect practices in North America. Considering that nonwoods often need specific processes to enhance the value of the fiber [6], mills in this region very likely would need to supply nonwood pulp instead of producing it on-site to partially substitute for wood fibers. Therefore, evaluating the impact of replacing wood fibers with nonwood residue pulp in existing packaging mills is of utmost importance to understand if this replacement aligns with carbon footprint reductions. In addition, the previously mentioned studies do not address differences in performance or study the environmental impact across the whole life cycle of the product. Thus, this study aims to estimate the carbon footprint of corrugating medium and linerboard partially made from straw and sugarcane in the United States compared to identical products made only from virgin wood and recycled paper. In addition, the goal is to understand how methodological decisions to allocate emissions to nonwood residues can affect the results. Finally, it is also the intent to include changes in performance in the assessment. Thus, this study is expected to mitigate part of the uncertainty around the environmental sustainability of packaging products made from the selected nonwood residues.

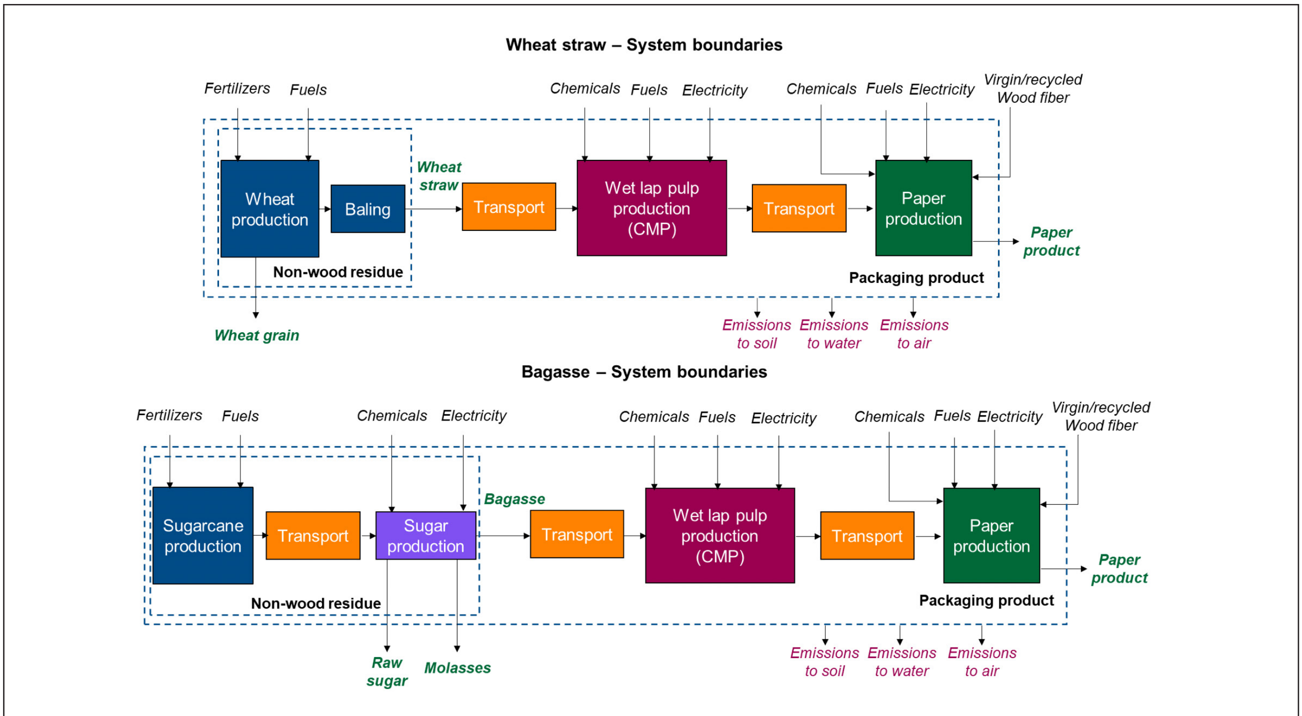
METHODOLOGY

Life cycle analysis has been recognized as a tool to evaluate the environmental impact of products across their life cycle. This methodology is standardized by the International Organization for Standardization (ISO) in the series of guidelines found in ISO Standard 14040:2006 "Environmental management — Life cycle assessment — Principles and framework." Stages to perform an LCA include: i) defining the goal and scope of the study; ii) collecting the life cycle inventory (LCI); iii) assessing the life cycle impact; and iv) interpreting and improving the results. Depending on the characterization method employed, LCA can provide results in numerous impact categories. This study aims to understand the carbon footprint of packaging products, i.e., linerboard and corrugating medium, containing nonwood residues. Thus, the assessment receives the name of life cycle carbon analysis (LCCA), since only GWP is evaluated. Although this framework is clear, there are methodological decisions that require special attention from LCA practitioners and need to be documented to ensure transparency. The following sections describe critical assumptions to perform the LCCA of the desired products.

Life cycle carbon analysis of nonwood residues

Understanding the carbon footprint of nonwood residues first is essential to perform the LCCA analysis of packaging products made from these raw materials. In this part of the study, the goal was to estimate the GWP of wheat straw and sugarcane bagasse produced in the United States. These feedstocks were selected since they represent agricultural and industrial residues, respectively. The analysis followed the framework described by ISO 14040:2006. The functional unit was one dry metric ton of nonwood residues. The assessment spanned from cradle to the pulp mill gate, which included emissions associated with raw materials, residue production, and transportation, as shown in **Fig. 1**. Specifically for wheat straw, the studied stages included the production of wheat and wheat straw, baling, and transportation. For sugarcane bagasse, cultivation and harvesting of sugarcane; production of sugar, molasses, and bagasse; and transportation were considered.

The availability of nonwood residues is geographically dependent. Thus, it was assumed that wheat straw was produced in the northwestern United States (NWUS), while sugarcane bagasse was cultivated in southeastern United States (SEUS). Data used for this study were primarily secondary. Information was retrieved from well-known databases such as the United States Life Cycle Inventory Database (USLCI) [16] and Ecoinvent [17], or the literature. Processes used to build the LCI and respective assumptions can be found in **Table I** and **Table II**. The Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) [24] was used as a characterization method, and SimaPro LCA software (SimaPro; Amersfoot, The Netherlands) was employed to perform the assessment.



1. Cradle-to-gate system boundaries for wheat straw-based (top) and bagasse-based (bottom) packaging paper made with chemimechanical pulp (CMP) process. Note that not all of the inputs and outputs considered for the study were included in this drawing.

Stage	Database Process	Source	Modifications/Assumptions
Wheat and wheat straw production	Wheat, at field	USLCI	• MA and EA approach: Amounts described by the USLCI database [16] were used. Ecoinvent processes [17] 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 [18]. Additional fertilizers for a 30% removal rate of straw were estimated according to [19]. Allocation factors of 28% and 6% were used for straw under MA and EA approaches, respectively. • SE approach: This process was not used. Only extra fertilizers and corresponding direct emissions were considered. • CO approach: This process was not used.
	Baling, processing	Ecoinvent	6.7 units per dry ton of straw. A factor of 0.23 was applied to the number of bales, since baling straw takes less time than silage (0.03 h/bale vs. 0.13 h/bale) [18].
	Bale loading, processing	Ecoinvent	7.44 units per dry ton of straw [18].
	Transport, freight, lorry >32 ton	Ecoinvent	Transport distances of 120 km for straw bales were assumed [20].

MA: mass allocation; EA: economic allocation; SE = system expansion; CO: cut-off.

I. Processes and assumptions used to build the life cycle inventory (LCI) of wheat straw.

Stage	Database process	Source	Modifications/Assumptions
Sugarcane production	Sugarcane production	Ecoinvent	Amounts described by the Ecoinvent database [17] were used. Fertilizers were grouped into urea (N), potassium chloride (K), and triple superphosphate (P_2O_5). Direct and indirect emissions from fertilizers were estimated using the method described by Ecoinvent [18]. Harvesting practices were adapted to 100% mechanical (fodder loading was not considered – manual harvesting). Transport distances of 20 km for sugarcane were assumed [20].
Raw sugar, molasses, and sugarcane bagasse production	–	[21]	• MA and EA approach: LCI described by [21] was used. It was assumed that 15% of bagasse is surplus and can be used to make paper [20]. 12.6% and 1.9% allocation factors were used for bagasse under MA and EA approaches, respectively. • CO approach: This and the previous process were not used.
Bagasse depithing	–	–	Depithing yield was assumed to be about 60% [22]. Electricity consumption was assumed at 0.034 kWh/kg depithed bagasse based on average values [20,23]. 20 km of transportation were assumed [20].

II. Processes and assumptions used to build LCI of sugarcane bagasse.

Another essential aspect when dealing with residues is how to allocate emissions to them. Wheat straw and sugarcane bagasse are produced in systems where the primary activity is to produce wheat and raw sugar, respectively. It has been a common practice to assume that they are free of shared burdens from the primary system since they are residues. Thus, only emissions associated with handling and transportation are considered. This approach receives the name of cut-off (CO). Nevertheless, producing nonwood residues could introduce changes into the primary system that the CO method would overlook. For instance, it has been reported that removing straw from the field increases the need for fertilizers to produce wheat since it provides the soil with nutrients when left uncollected [19]. The system expansion (SE) approach captures this impact and represents the preferred method by ISO 14040:2006 to deal with multifunctionality or systems producing more than one product. In this case, any differences in inputs and outputs introduced by removing nonwood residues from the primary system are allocated to the residues. Emissions associated with handling and transportation are also considered. Finally, the environmental burdens from the primary systems can be shared between products and byproducts based on a mass or economic basis, known as the mass allocation (MA) and economic allocation (EA) approach. This study assessed the effect of all these allocation methods on the GWP of wheat straw and sugarcane bagasse to understand the influence of this assumption and provide a more robust assessment.

Life cycle carbon analysis of packaging products containing nonwood residues

Once nonwood residues are produced, they are transformed into paper products. Although different production pathways could be followed, this study assumed that chemimechanical wet lap nonwood pulp (CMP) was produced as an intermediate. Then, it was used as raw material in packaging mills to replace virgin wood or recycled paper. This part of the study aimed to evaluate the GWP of virgin and recycled linerboard and corrugating medium containing 30% nonwood 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. The analysis spanned from cradle-to-gate, as depicted in Fig. 1. Thus, stages included the production of nonwood residues, CMP, and linerboard or corrugating medium, with corresponding transportation between stages.

The data used were secondary. FisherSolve Next [5] was primarily used to estimate the LCI of CMP processes, and it was benchmarked against literature data. In addition, the Ecoinvent database [17] was used for LCIs of linerboard and corrugating medium. These were adapted to reflect scenarios with the substitution of wood fibers for nonwood wet lap pulp based on energy consumption per area depicted in industry benchmarks [25]. Processes used to build the LCI and respective assumptions can be found in **Table III**. A carbon-neutral approach was followed, TRACI [24] was used as a characterization method, and SimaPro software was employed to perform the assessment.

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		-

III. Processes and assumptions used to build LCI of packaging products.

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

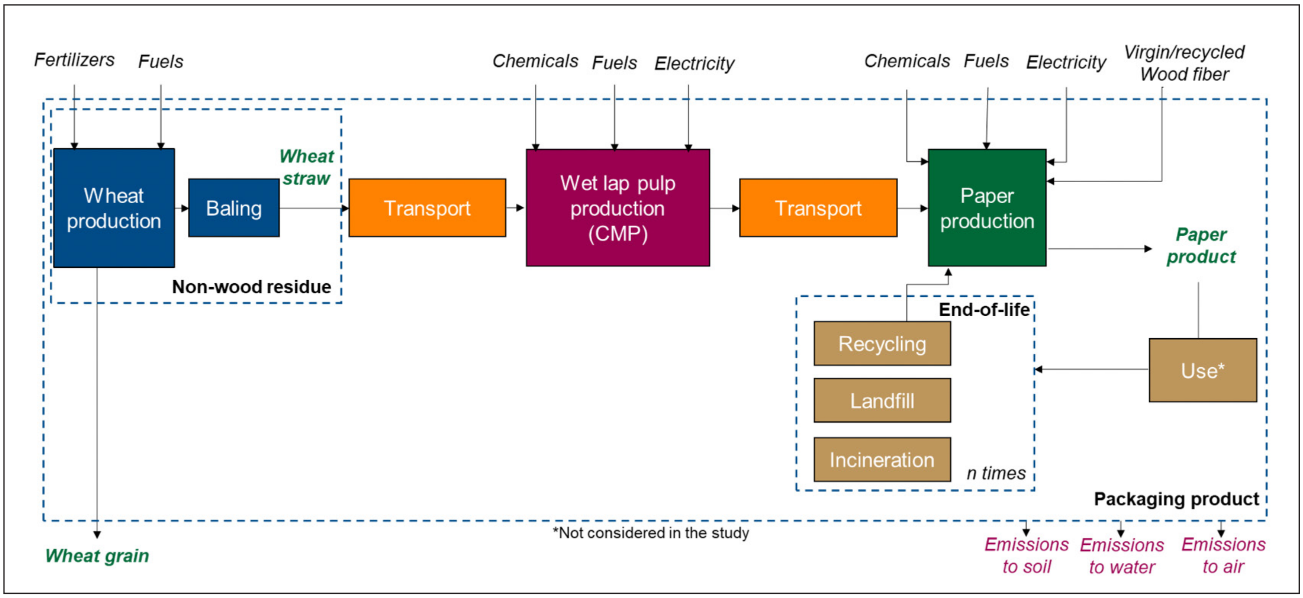
IV. Parameters for sensitivity analysis of chemimechanical pulp (CMP).

An LCA is highly dependent on assumptions and LCIs. Therefore, a sensitivity analysis around the production of CMP wet lap pulp was performed to mitigate uncertainty and understand the impact of data variation on the results. Also, since data variability exists, the analysis can provide robustness to this research. The variables selected can be found in **Table IV**. These were chosen due to their contribution to the GWP of CMP wet lap pulp.

Finally, it has been reported that replacing wood fibers with nonwood residues can impact product performance. The effect of changes in properties was included in the LCA by using 1 m^2 as the functional unit instead of a mass basis. It was assumed that the basis weight of the paper was 120 g/m^2 as per experimental data [6]. Then, the basis weight of paper containing nonwood residues was changed based on performance variations. Due to data availability, this was only applied to virgin linerboard containing wheat straw.

Cradle-to-grave life cycle carbon analysis of packaging products containing nonwood residues

Evaluating the GWP of packaging products throughout their life cycle is of utmost importance to understand their global impact on the environment. This section aimed to evaluate the GWP of linerboard containing 30% wheat straw pulp from a cradle-to-grave perspective and compare it to wood-based linerboard. The functional unit was 1 metric ton of linerboard. System boundaries for this section are depicted in **Fig. 2**. Results from previous sections for extraction of raw materials, production of CMP from nonwood residues, and manufacturing of virgin and recycled linerboard were used. Based on statistics on the end-of-life of paper products, about 82% was assumed to be recycled, about 14.5% was landfilled, and about 3.5% was incinerated [26]. An essential parameter in the study is the yield of making recycled linerboard. Thus, around 83% [27] was assumed for wood fibers, while a correlation was used for the wheat straw fraction based on experimental data at different recycling cycles [28]. It is important to note that a cascade recycling approach was followed until no fiber was available to make new products [29] (approximately ten cycles). A mass balance was performed to estimate the amount of wood or nonwood fibers after each product cycle, i.e., virgin and consequent recycled products. Emissions for each stage were accounted for and allocated to the total amount of paper produced. Finally, due to data avail-



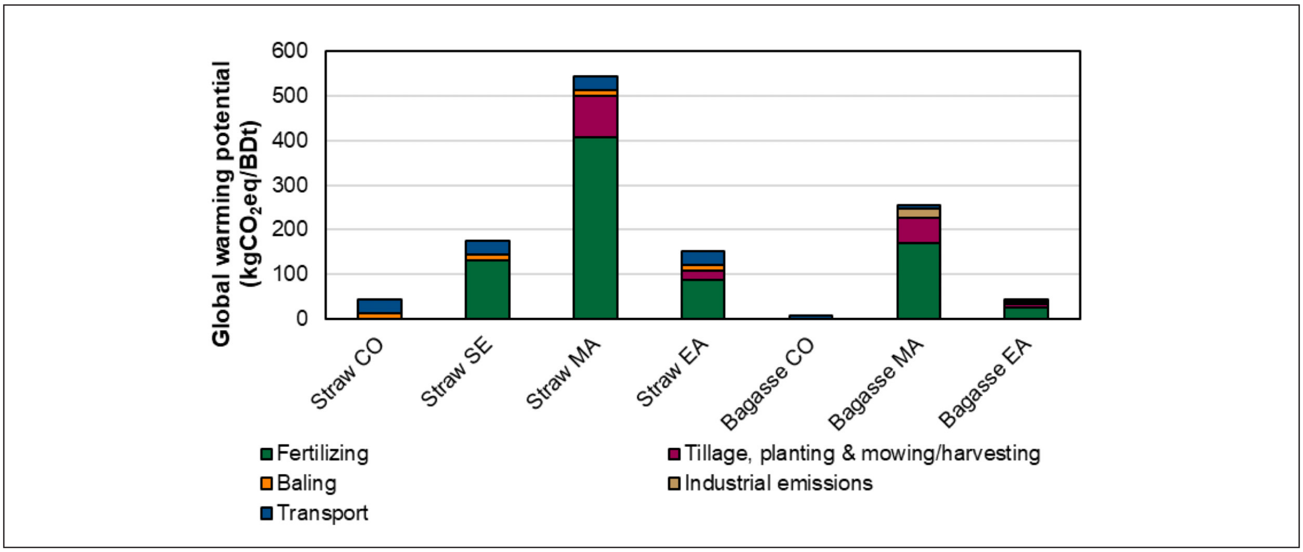
2. Cradle-to-grave system boundaries for wheat straw-based linerboard packaging paper made with CMP process. Note that not all of the inputs and outputs considered for the study were included in this drawing.

ability, the stage of using the products was not considered. It is important to mention that for this part of the study, changes in the performance of the paper across the different recycling loops was not considered due to a lack of data. Nevertheless, the authors recognize that this is an important aspect that needs to be addressed in future research.

RESULTS AND DISCUSSION

Life cycle carbon analysis of nonwood residues

Figure 3 depicts the GWP of selected nonwood residues under different allocation scenarios. Results are highly dependent on the method used to allocate emissions between primary products of the system (i.e., wheat grain or sugar) and residues. Overall, values obtained from the CO method present lower impacts due to the assumption that residues are waste; therefore, environmental burdens from the primary system are not allocated to them. Only additional emissions related to handling and transportation are accounted for. On the other hand, results under the MA method set a heavy toll on biomass and represent the highest values among different allocation methods. In this case, residues are treated as a byproduct, and environmental burdens from the primary system are shared based on a mass basis. Specifically for wheat straw, GWP could range between around 45 to 545 kg carbon dioxide equivalent per bone-dry metric ton (kg CO_2eq/BDt) of biomass deliv-



3. The global warming potential (GWP) in kilograms of carbon dioxide equivalent per bone-dry metric ton (kgCO_2eq/BDt) for nonwood residues under different allocation methods (CO: cut-off; SE: system expansion; MA: mass allocation; EA: economic allocation).

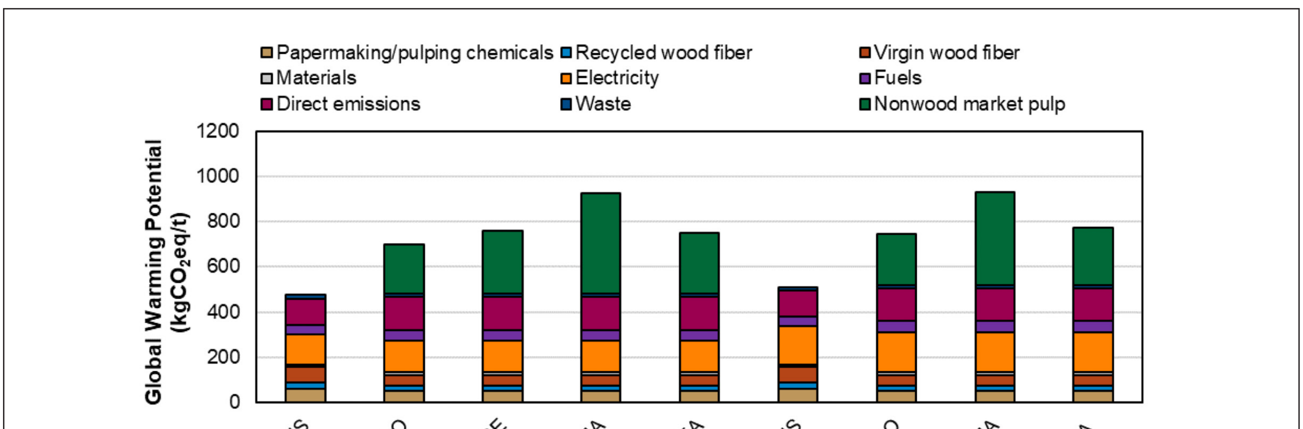
ered to the pulp mill. On the other hand, sugarcane bagasse could vary from about 7 to 255 kg CO_2eq/BDt of biomass. This large difference illustrates the influence of allocation methods on the results. Therefore, arbitrarily choosing one method over others could provide a wrong answer to better understanding the environmental impact of these residues. Assessing this variability is of utmost importance to ensure a better understanding of the effect of methodological decisions on LCA results.

Figure 3 also shows the contribution tree for GWP depicted by stage. Production of nonwood residues presents the highest contribution under SE, MA, and EA scenarios. This includes handling impacts plus shared burdens of fertilizers, fuels, and agricultural emissions for wheat straw. For sugarcane bagasse, it comprises shared impact of sugarcane production, chemicals, energy, and direct emissions. Transportation to the paper mill is the most significant contributor to the CO scenario. Specifically, distances for straw are larger than sugarcane bagasse based on reported values for the United States [20], which explains the more considerable impact of this parameter for straw. It is essential to mention that if other geographies were to be studied, transportation distances would need to be modified to reflect local practices. In addition, straw transportation is volume-limited, increasing the number of trucks needed per metric ton of residue [6]. Thus, optimizing bales sizes could help decrease the overall transportation impact.

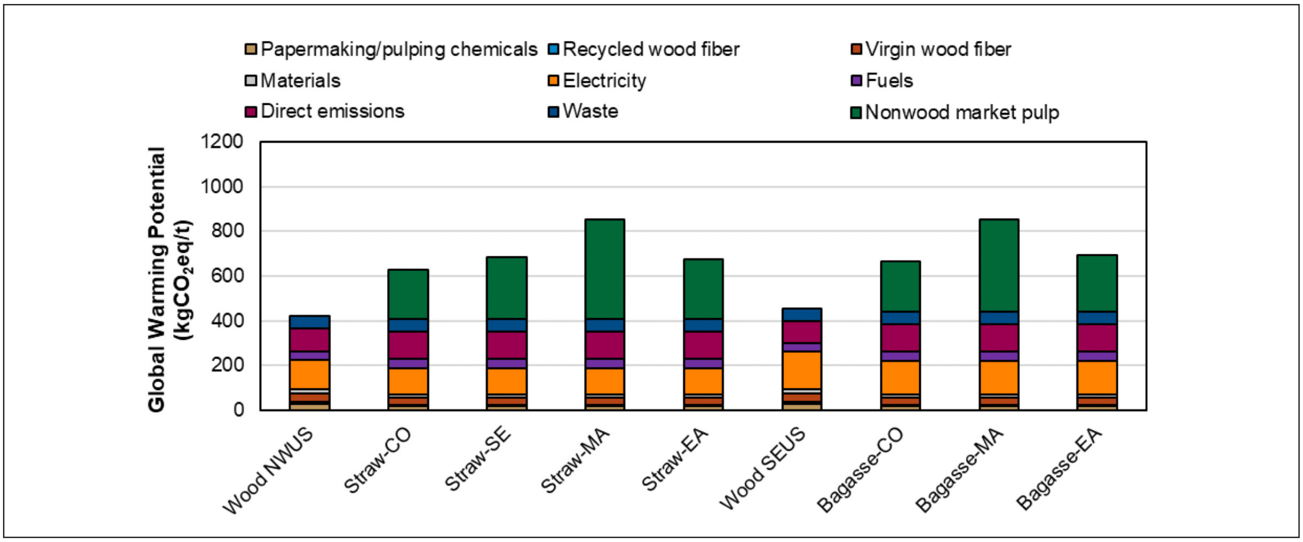
Life cycle carbon of packaging products containing nonwood residues

Studying the environmental impact of nonwood biomass is a critical part of the study, but it does not show the whole picture. Virgin wood, recycled paper, and nonwood residues follow different paths to be transformed into paper. In this study, nonwood residues are transformed into wet lap pulp and later into packaging products. On the other hand, virgin wood and recycled paper are converted into paper in integrated facilities through chemical, semichemical, or recycling processes, depending on the final product, without the need for wet lap pulp intermediate. It is essential to mention that this study does not aim to compare these processes, but the intent is to understand the effect of adding nonwood pulp into virgin or recycled wood products. The data used come from a variety of sources, and using them for comparison could provide the wrong conclusions.

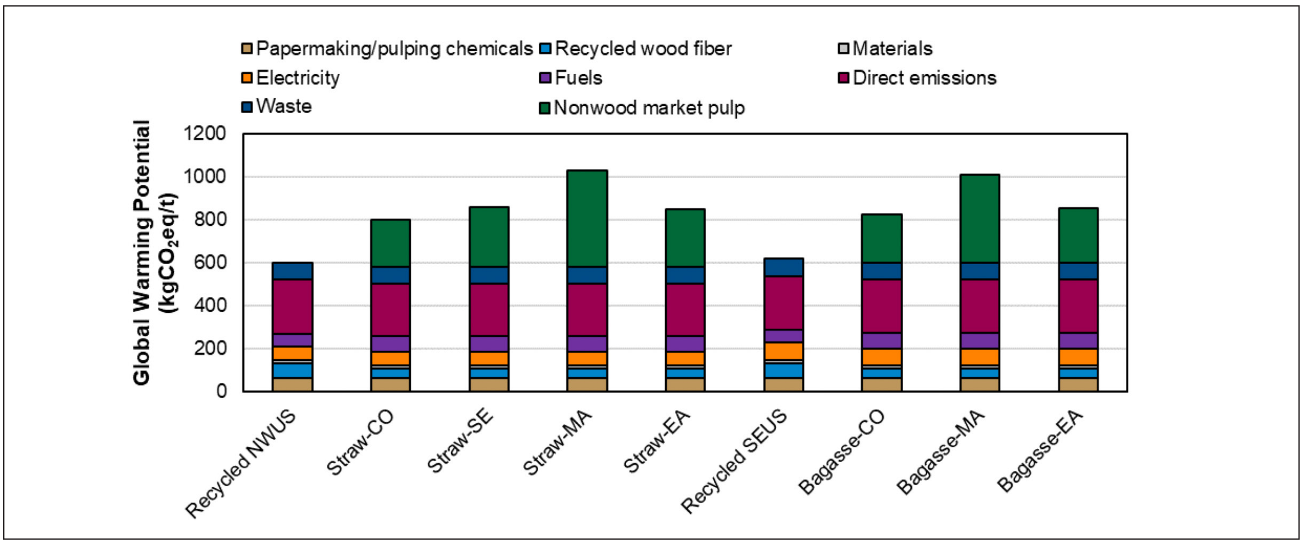
Figure 4 and **Fig. 5** depict the GWP of virgin linerboard and corrugating medium under different allocation methods, containing or not containing nonwood residues. Since the supply of nonwood fibers is geographically dependent, two scenarios for wood were assessed. Thus, wood NWUS is the benchmark for straw, and wood SEUS is the comparison for bagasse. Results show that GWP values depend on allocation methods used to assess the environmental impact of residues. Nevertheless, replacing virgin wood fibers with wet lap nonwood pulp increased the GWP of products in all cases. The driver of the higher impact compared to benchmarks is nonwood pulp. Although the studied CMP process presents an overall lower chemical and energy consumption than conventional chemical processes, the overall impact was higher. The CMP method lacks a chemical recovery and power co-generation system, and uses a higher share of fossil fuels, which explains the more considerable burden compared to chemical and semichemical pulp. 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 the virgin wood-based paper.



4. The GWP in kilograms of carbon dioxide equivalent per metric ton (kgCO_2eq/t) for virgin linerboard containing nonwood residue pulp under different allocation methods (NWUS: northwestern United States; CO: cut-off; SE: system expansion; MA: mass allocation; EA: economic allocation; SEUS: southeastern United States).



5. The GWP for virgin corrugating medium containing nonwood residue pulp.

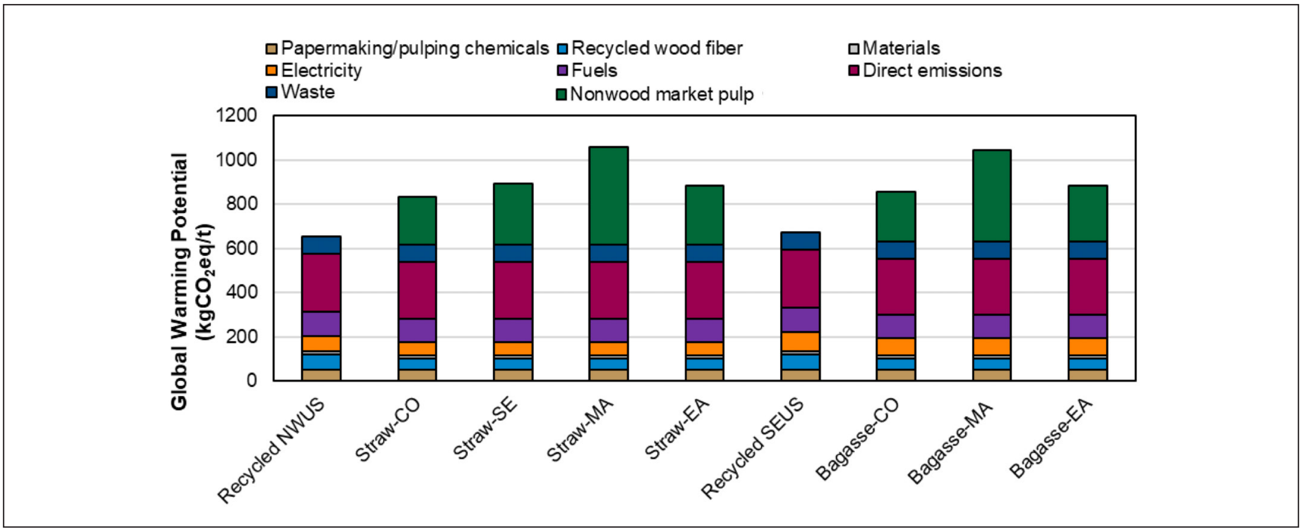


6. The GWP for recycled linerboard containing nonwood residue pulp.

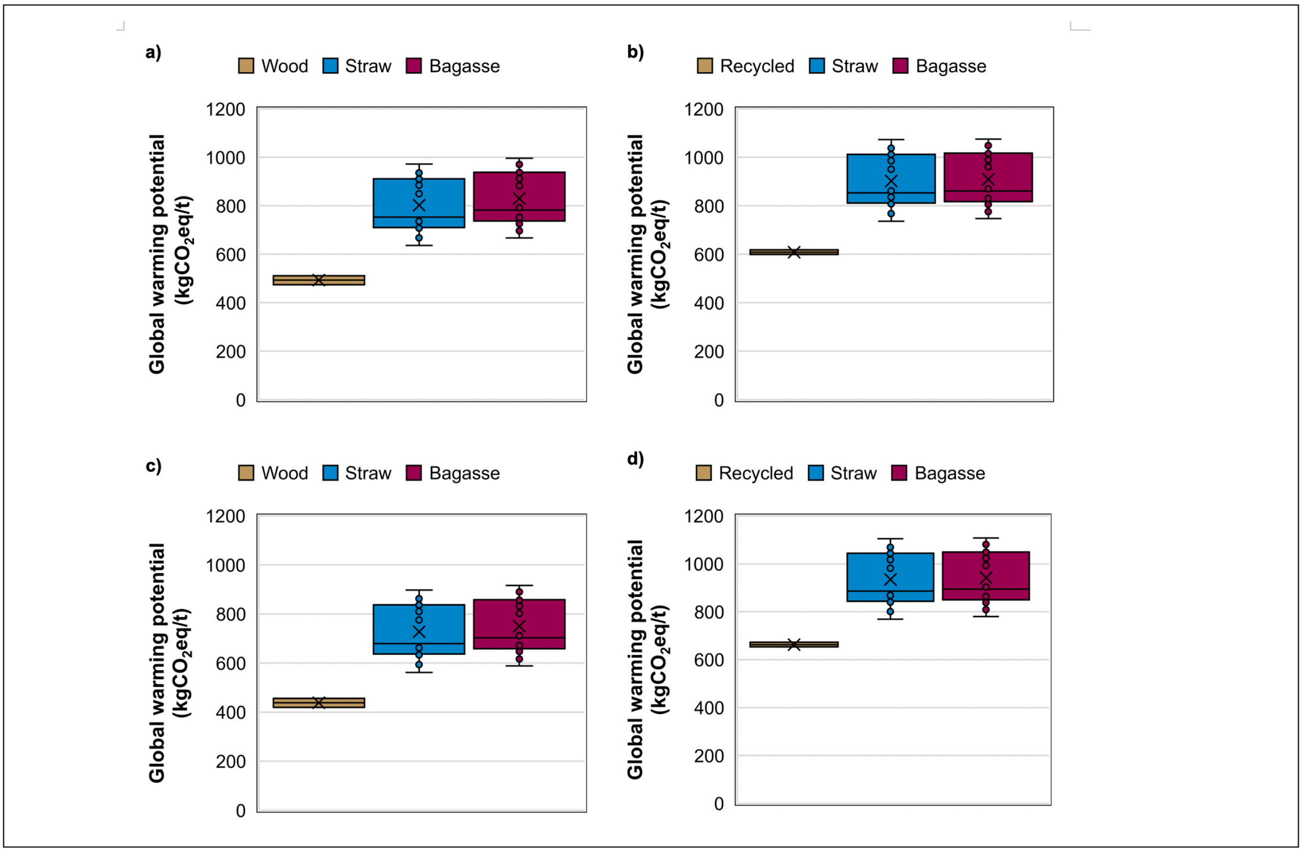
Figure 6 and **Fig. 7** show the GWP of recycled linerboard and corrugating medium, respectively. Although results depend on the allocation methods, replacing recycled pulp with nonwood wet lap pulp also translates into increased GWPs. Direct and electricity-related emissions decrease due to less handled recycled paper. Nevertheless, the high GWP of nonwood pulp drives the higher impact compared to benchmarks.

The LCA highly depends on the LCI used for the study. Thus, sensitivity analyses provide an understanding of the effects of data variability on LCA results. As explained in the methodology section, parameters related to the production of nonwood pulp were changed, and their effect on the GWP of linerboard and corrugating medium was assessed. **Figure 8** shows these sensitivity analyses. It was found that packaging products containing nonwood residues present GWPs approximately 15%–100% higher compared to benchmarks. This constitutes a high variability and shows how sensitive results are to baseline assumptions. Nevertheless, under the studied scenarios, nonwood-containing packaging products presented an overall higher impact. Besides allocation methods for nonwood residues, allocation around byproducts of nonwood pulp, type of pulping chemical, and chemical charges during nonwood pulping presented the greatest influence in the results.

It has been reported that replacing wood fibers with nonwood residues can impact product performance. Studies for linerboard [6] show that replacing softwood with up to 30% wheat straw pulp does not significantly affect tensile or short-span compression indexes. Nevertheless, as shown in **Fig. 9a and 9c**, increasing wheat straw content in linerboard translates into decreasing tear index (approximately 9.5%) and burst index (approximately 11.5%). The effect of this decrease in performance was considered for the

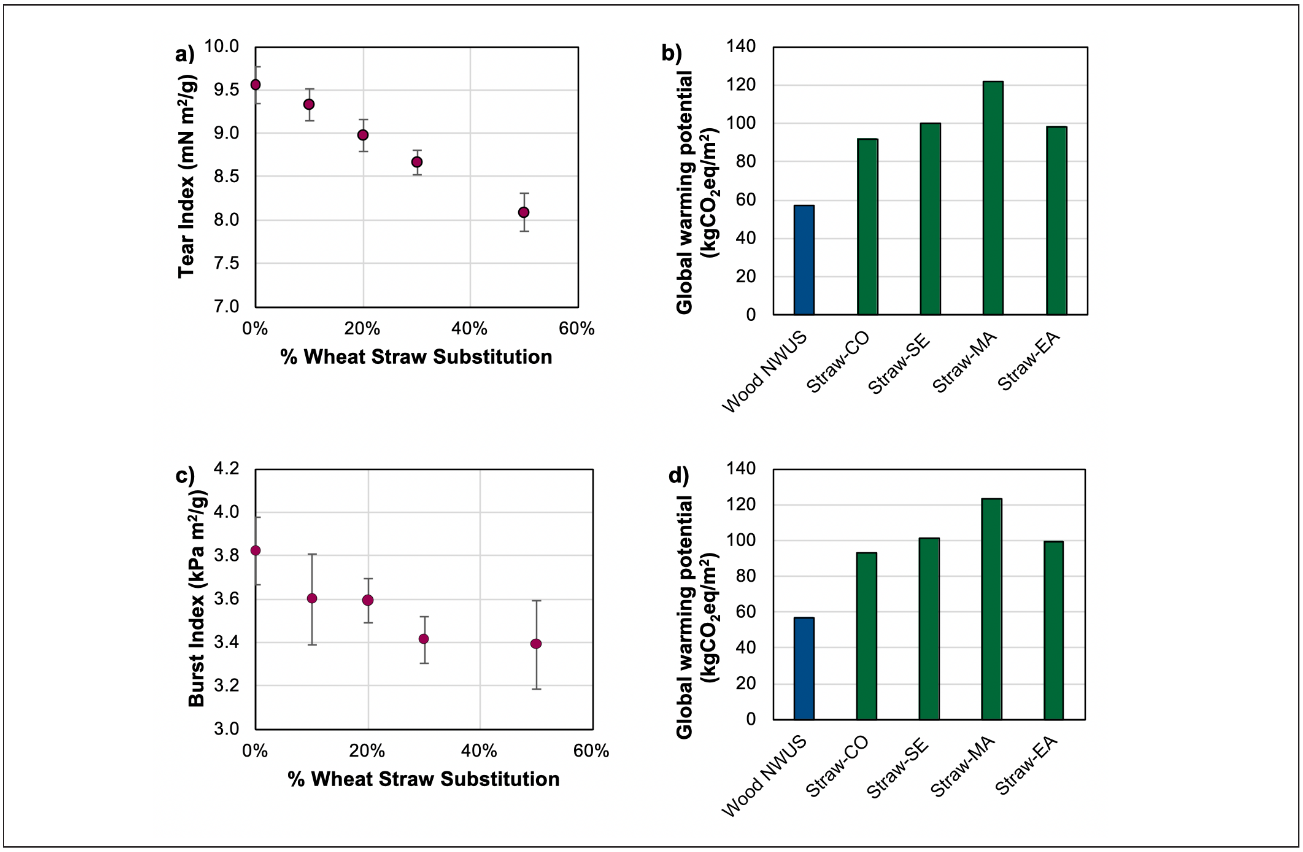


7. The GWP for recycled corrugating medium containing nonwood residue pulp.

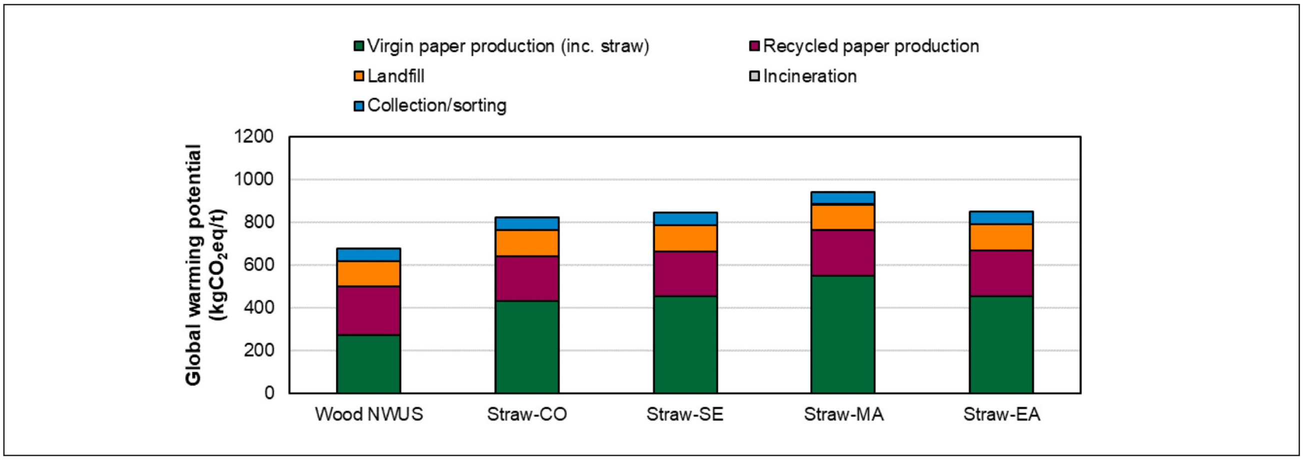


8. Sensitivity analysis for packaging products containing nonwood residue pulp: a) virgin linerboard, b) recycled linerboard, c) virgin medium, and d) recycled medium.

LCA, as is depicted in Fig. 9b and 9d. It was found that linerboard containing 30% of the straw pulp can present GWPs that are about 60%–115% higher than the wood benchmark. As seen before, results depend on allocation methods, but considering performance magnifies results depicted in Fig. 4. Since performance is decreasing, more fiber is required per product area, which translates into an overall increase in basis weight to achieve product specifications. Thus, GWP per area can be around 19%–29% and around 22%–33% higher than GWP per mass if tear or burst indexes are considered, respectively. It is important to note that if performance was improved, LCA results could be more favorable, since less fiber would be needed. Thus, searching for applications where nonwood residues can



9. a) Effect of wheat straw substitution on linerboard tear index [6]; b) effect of changes in tear index on GWP of linerboard containing wheat straw pulp; c) effect of wheat straw substitution on linerboard burst index [6]; and d) effect of changes in burst index on GWP of linerboard containing wheat straw pulp.



10. Cradle-to-grave GWP of linerboard containing wheat straw pulp.

bring improved performance could help reduce the carbon footprint of nonwood-based packaging products. It is important to mention that in this case, the studied properties were selected as examples for the linerboard. For future studies, the effect of performance on other products, such as corrugating medium, could be assessed.

Finally, a cradle-to-grave assessment was conducted for linerboard containing wheat straw pulp and is depicted in **Fig. 10**. This part of the study considers experimental data on the repulpability of products containing this nonwood residue. In this scenario, it was assumed that virgin wood was replaced with wheat straw pulp during the production of linerboard, and this product then followed recycling with corresponding losses to landfill or incineration. All emissions throughout the product life cycle were accounted for and allocated to the total amount of paper produced. It was found that products containing wheat straw pulp presented GWPs that were about 21%–25% higher than wood benchmarks. Interestingly, these differences are lower than those observed in cradle-to-gate studies. This is due to the allocation of wheat straw pulp emissions to the total amount of paper produced instead of only to the virgin linerboard. As shown in Fig. 10, emissions associated with the production of virgin product are the main contributor to the GWP. This value is higher for linerboard containing wheat straw pulp. In addition, it was observed that products with nonwood residues presented an overall lower repulping yield, translating into higher emissions per metric ton of product. The GWPs per metric ton were then constant after wheat straw was no longer in the system.

CONCLUSIONS

This study evaluated the impact of replacing wood fibers with straw and sugarcane pulp on the carbon footprint of linerboard and corrugating medium produced in the United States. Results highly depended on the allocation methods chosen to assign emissions to these residues. Therefore, indiscriminately selecting an allocation approach can bias the impact towards residues if emissions are not allocated or against them if a mass allocation is used. Nevertheless, despite this variability, replacing virgin wood or recycled paper with nonwood residues translated into increased GWPs. Intermediate nonwood wet-lap pulp was the driver for this impact. The lack of chemical recovery and on-site power generation explains the more considerable impact. Sensitivity analyses showed that assumptions around the production of pulp greatly influenced results. Thus, the GWPs of packaging products containing residues can be 15%–100% higher than the comparable wood-based products. Including the effect of changes in performance magnified these results for the selected case study. Decreased tear and burst indexes caused larger GWPs of linerboard, since higher basis weights were needed to match product specifications. Finally, from a cradle-to-grave perspective, agricultural residue-containing linerboard presented higher GWPs than wood-based paper. It was seen that lower repulping yields associated with straw caused higher GWPs per metric ton of paper. Overall, from these findings, straw and sugarcane 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 journal

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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 nonwood residues. Thus, this topic was relevant for research.

The most difficult aspect of this study was to develop a life cycle analysis (LCA) framework that captured environmental and technical data on nonwood residues. 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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