

1 **Life cycle carbon analysis of packaging products containing non-wood**  
2 **residues**

3 Antonio Suarez<sup>a,\*</sup>, Ashok Ghosh<sup>a</sup>, Fritz Paulsen<sup>a</sup>, Peter W. Hart<sup>a</sup>

4 **Abstract**

5 Circularity is creating momentum toward utilizing waste feedstock in a myriad of applications. The  
6 paper industry is not an exception to this trend, and packaging products made from agricultural  
7 or agro-industrial residues are receiving more attention now than ever. Additionally, negative  
8 consumer perceptions of tree felling are accelerating the acceptance of these fibers.  
9 Nevertheless, adopting these residues raises the issue of whether they constitute a better  
10 alternative to fight climate change than wood. Answering this question is imperative to ensure that  
11 pledges to reduce carbon footprints across the industry are fulfilled. This paper aimed to estimate  
12 the carbon footprint of corrugating medium and linerboard containing wheat straw and sugarcane  
13 bagasse pulp compared to analogous wood-based materials. Also, the goal was to understand  
14 how methodological decisions to allocate emissions to non-wood residues can affect the results.  
15 The study includes a life cycle carbon analysis spanning from cradle to grave, which comprises  
16 stages for residue production, pulping, papermaking, waste management, and corresponding  
17 transportation. For the proposed case study, the results suggest that straw- and bagasse-based  
18 medium and linerboard can present a higher carbon footprint than products made from virgin and  
19 recycled wood fibers. The main driver is the production of non-wood chemi-mechanical pulp. In  
20 addition, the lower capacity of non-wood residues to be recycled increases the overall impact.  
21 Finally, decisions around emissions allocation highly influence the results. This study is expected  
22 to mitigate part of the uncertainty around the environmental sustainability of corrugating medium  
23 and linerboard made from the selected non-wood residues.

24 *Keywords: Wheat straw; Sugarcane bagasse; Packaging; Corrugating medium; Linerboard; Life*  
25 *cycle carbon analysis (LCCA); Carbon footprint*

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## 28 1. Introduction

29 Sustainability trends are raising attention toward introducing non-conventional fibers into a myriad  
30 of products. Consequently, consumers' demand for non-wood-based materials has gained  
31 momentum, opening the market for pulp, packaging, tissue, and printing and writing paper made  
32 from these fibers [1]. Specifically, agricultural residues, such as straw and bagasse, have been  
33 perceived to offer sustainability and technical benefits compared to wood sources. Negative  
34 perceptions of tree felling are facilitating the adoption of these raw materials. Indeed, many non-  
35 wood producers highlight deforestation as a negative aspect promoted by the paper industry,  
36 although in North America, the industry plants more trees than harvests every year [2]-[4]. Despite  
37 this misconception, non-woods only represent ca. 1% of the global pulp production, with bagasse  
38 and straw as the primary agricultural residues used to make paper products [5]. In the United  
39 States, the number is less than 0.1%, with linters and straw as the most important used residues  
40 in soda or chemi-mechanical processes [5]. Specifically for packaging, non-woods comprise less  
41 than 0.4% of the global furnish. Processes such as soda, kraft, neutral sulfite semi-chemical and  
42 chemi-mechanical pulping are used to process these fibers [5].

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

53 Specifically for straw, LCA studies are heavily focused on Chinese practices, with one assessment  
54 for Canada [7]-[12]. Most of this research does not allocate emissions from wheat production to  
55 the straw under the assumption that it is a residue, which could favor the results towards straw  
56 compared to wood. In addition, yields for straw pulp varied from 35-90%, with most of the studies  
57 within the 35-50% range for chemical and semi-chemical processes, which does not reflect the  
58 existence of more efficient processes currently available. Different paper grades have been  
59 studied, such as market pulp [7][9][11], printing and writing [8][11], packaging [10][11], and tissue  
60 [11] with benchmarks mostly made from wood-based kraft and chemi-thermomechanical pulp.

61 Nevertheless, despite widespread assumptions, carbon footprint results often show lower global  
62 warming potential (GWP) impacts from wood utilization than straw [8][9][12][11]. LCA studies for  
63 paper made from bagasse can also be found in the literature [11][13][14][15]. These assessments  
64 focus on China, Thailand, and Iran for products such as tissue paper [11], wrapping paper [11],  
65 market pulp [13], and printing and writing paper [14]. As seen with straw, most of the studies do  
66 not allocate environmental burdens to bagasse, with only one study using economic allocation  
67 [15]. Overall, results do not show consensus on whether bagasse-based paper constitutes a  
68 better alternative than wood, with some studies showing higher impacts for bagasse [11] and  
69 others for wood [14][15].

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

## 87 **2. Methodology**

88 Life cycle analysis (LCA) has been recognized as a tool to evaluate the environmental impact of  
89 products across their life cycle. This methodology is standardized by the International  
90 Organization for Standardization (ISO) in the series of 14040 guidelines [16]. Stages to perform  
91 an LCA include i) defining the goal and scope of the study, ii) collecting the life cycle inventory  
92 (LCI), iii) assessing the life cycle impact, and iv) interpreting and improving the results. Depending  
93 on the characterization method employed, LCA can provide results in numerous impact

94 categories. This study aims to understand the carbon footprint of packaging products, i.e.,  
95 linerboard and corrugating medium, containing non-wood residues. Thus, the assessment  
96 receives the name of life cycle carbon analysis (LCCA) since only global warming potential (GWP)  
97 is evaluated. Although this framework is clear, there are methodological decisions that require  
98 special attention from LCA practitioners and need to be documented to ensure transparency. The  
99 following sections describe critical assumptions to perform the LCCA of the desired products.

## 100 2.1. Life cycle carbon analysis of non-wood residues

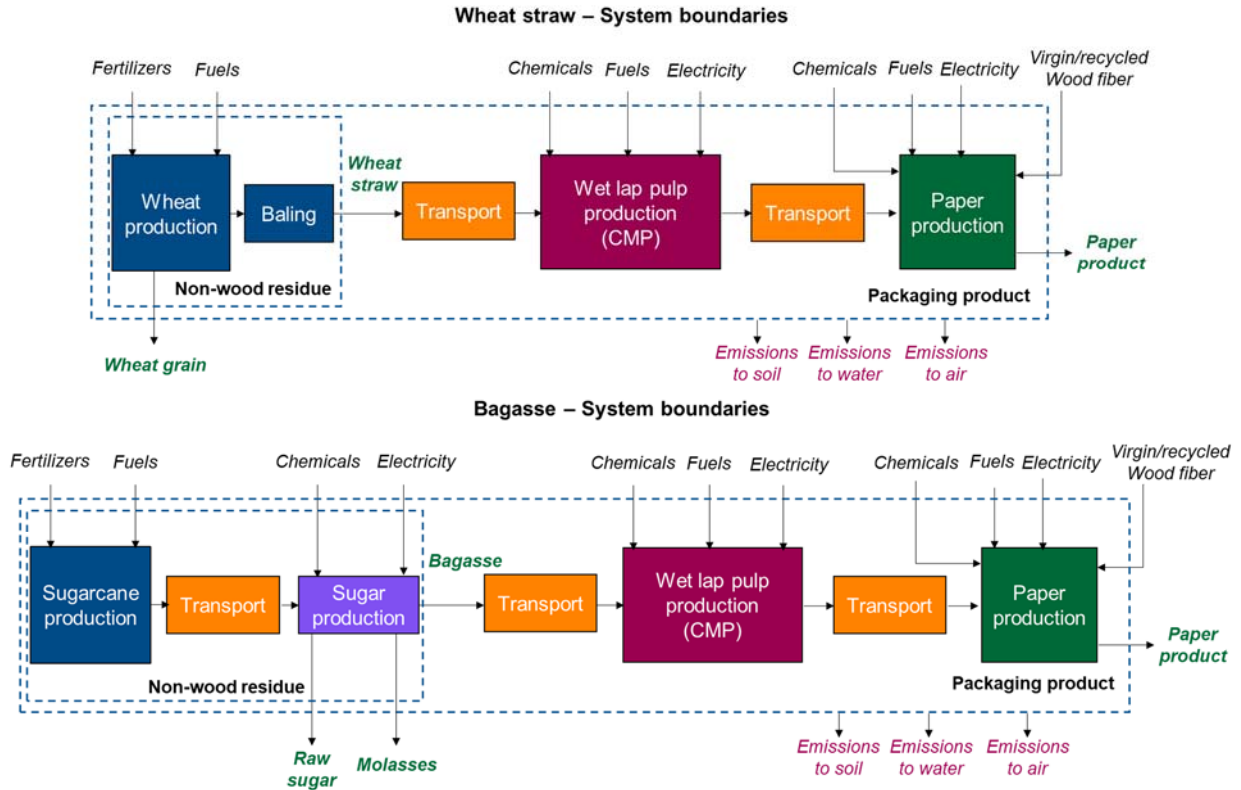
101 Understanding the carbon footprint of non-wood residues first is essential to perform the life cycle  
102 carbon of packaging products made from these raw materials. In this part of the study, the goal  
103 was to estimate the GWP of wheat straw and sugarcane bagasse produced in the United States.  
104 These feedstocks were selected since they represent agricultural and industrial residues,  
105 respectively. The analysis followed the framework described by the ISO standards [16]. The  
106 functional unit was one dry ton of non-wood residues. The assessment spanned from cradle to  
107 the pulp mill gate, which included emissions associated with raw materials, residue production,  
108 and transportation, as shown in **Figure 1**. Specifically for wheat straw, the studied stages included  
109 the production of wheat and wheat straw, baling, and transportation. For sugarcane bagasse,  
110 cultivation and harvesting of sugarcane, production of sugar, molasses, and bagasse, and  
111 transportation were considered.

112 Non-wood residues availability is geographically dependent. Thus, it was assumed that wheat  
113 straw was produced in north-west United States (NWUS), while sugarcane bagasse was  
114 cultivated in south-east United States (SEUS). Data used for this study were primarily secondary.  
115 Information was retrieved from well-known databases such as the United States Life Cycle  
116 Inventory Database (USLCI) and Ecoinvent, or the literature. Processes used to build the LCI,  
117 and respective assumptions can be found in **Tables 1** and **2**. The Tool for Reduction and  
118 Assessment of Chemicals and Other Environmental Impacts (TRACI) was used as a  
119 characterization method, and SimaPro was employed to perform the assessment.

120 Another essential aspect when dealing with residues is how to allocate emissions to them. Wheat  
121 straw and sugarcane bagasse are produced in systems where the primary activity is to produce  
122 wheat and raw sugar, respectively. It has been a common practice to assume that they are free  
123 of shared burdens from the primary system since they are residues. Thus, only emissions  
124 associated with handling and transportation are considered. This approach receives the name of  
125 cut-off (CO). Nevertheless, producing non-wood residues could introduce changes into the  
126 primary system that the CO method would overlook. For instance, it has been reported that

127 removing straw from the field increases the need for fertilizers to produce wheat since it provides  
128 the soil with nutrients when left uncollected [17]. The system expansion (SE) approach captures  
129 this impact and represents the preferred method by the ISO standards to deal with  
130 multifunctionality or systems producing more than one product. In this case, any differences in  
131 inputs and outputs introduced by removing non-wood residues from the primary system are  
132 allocated to the residues. Emissions associated with handling and transportation are also  
133 considered. Finally, the environmental burdens from the primary systems can be shared between  
134 products and by-products based on a mass or economic basis, known as the mass allocation  
135 (MA) and economic allocation (EA) approach. This study assessed the effect of all these allocation  
136 methods on the GWP of wheat straw and sugarcane bagasse to understand the influence of this  
137 assumption and provide a more robust assessment.

138       2.2.       Life cycle carbon analysis of packaging products containing non-wood residues  
139 Once non-wood residues are produced, they are transformed into paper products. Although  
140 different production pathways could be followed, this study assumed that chemi-mechanical wet  
141 lap non-wood pulp (CMP) was produced as an intermediate. Then it was used as raw material in  
142 packaging mills to replace virgin wood or recycled paper. This part of the study aimed to evaluate  
143 the GWP of virgin and recycled linerboard and corrugating medium containing 30% of non-wood  
144 pulp. Also, the aim was to compare them with products made 100% from wood fibers to  
145 understand the impact of the replacement. The functional unit was 1 ton of paper. The analysis  
146 spanned from cradle-to-gate as depicted in **Figure 1**. Thus, stages included the production of  
147 non-wood residues, chemi-mechanical pulp, and linerboard or corrugating medium with  
148 corresponding transportation between stages.



149

150 Figure 1. Cradle-to-gate system boundaries for wheat straw-based (top) and bagasse-based  
 151 (bottom) packaging paper (Note: not all the inputs and outputs considered for the study were  
 152 included in this drawing)

153 The data used were secondary. FisherSolve Next was primarily used to estimate the life cycle  
 154 inventory of CMP processes, and it was benchmarked against literature data. In addition,  
 155 Ecoinvent was used for LCIs of linerboard and corrugating medium. These were adapted to reflect  
 156 scenarios with the substitution of wood fibers with non-wood wet lap pulp based on energy  
 157 consumption per area depicted in industry benchmarks [18]. Processes used to build the LCI, and  
 158 respective assumptions can be found in **Table 3**. A carbon-neutral approach was followed, TRACI  
 159 was used as a characterization method, and SimaPro was employed to perform the assessment.

160

161 Table 1. Processes and assumptions used to build the life cycle inventory of wheat straw

| Stage                          | Database process                  | Source    | Modifications/assumptions  |
|--------------------------------|-----------------------------------|-----------|--|
| Wheat & wheat straw production | Wheat, at field                   | USLCI     | <ul style="list-style-type: none"> <li>• MA and EA approach: 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 [19]. Additional fertilizers for a 30% removal rate of straw were estimated according to [17]. 28% and 6% allocation factors were used for straw under MA and EA approaches, respectively.</li> <li>• SE approach: This process was not used. Only extra fertilizers and corresponding direct emissions were considered.</li> <li>• CO approach: This process was not used</li> </ul> |
|                                | 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) [19].   |
|                                | Bale loading, processing          | Ecoinvent | 7.44 units per dry ton of straw [19].  |
|                                | Transport, freight, lorry >32 ton | Ecoinvent | Transport distances of 120 km for straw bales were assumed [20].   |

162

163 Table 2. Processes and assumptions used to build life cycle inventory of sugarcane bagasse

| Stage   | Database process      | Source    | Modifications/assumptions  |
|---|-----------------------|-----------|--|
| Sugarcane production                                  | Sugarcane, production | Ecoinvent | Amounts described by the Ecoinvent database were used. Fertilizers were grouped into Urea (N), Potassium chloride (K), and Triple Superphosphate (P <sub>2</sub> O <sub>5</sub> ). Direct and indirect emissions from fertilizers were estimated using the method described by Ecoinvent [19]. 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]      | <ul style="list-style-type: none"> <li>• 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.</li> <li>• CO approach: This and the previous process were not used.</li> </ul>   |
| Bagasse depithing                                     | -                     | -         | Depithing yield is assumed to be ca. 60% [22]. Electricity consumption ca. 0.034 kWh/kg depithed bagasse based on average values [20][23]. 20 km of transportation were assumed [20].  |

164

165 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 |           | -  |

166

167

168 LCA is highly dependent on assumptions and LCIs. Therefore, a sensitivity analysis around the  
 169 production of CMP wet lap pulp was performed to mitigate uncertainty and understand the impact  
 170 of data variation on the results. Also, since data variability exists, the analysis can provide  
 171 robustness to this research. The variables selected can be found in **Table 4**. These were chosen  
 172 due to their contribution to the GWP of CMP wet lap pulp.

173 Table 4. Parameters for sensitivity analysis of CMP pulp

| 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 5x6 [6] and 4x6                            |  |
| Allocation for liquor residue/by-product | Cut-off and mass allocation                      |  |

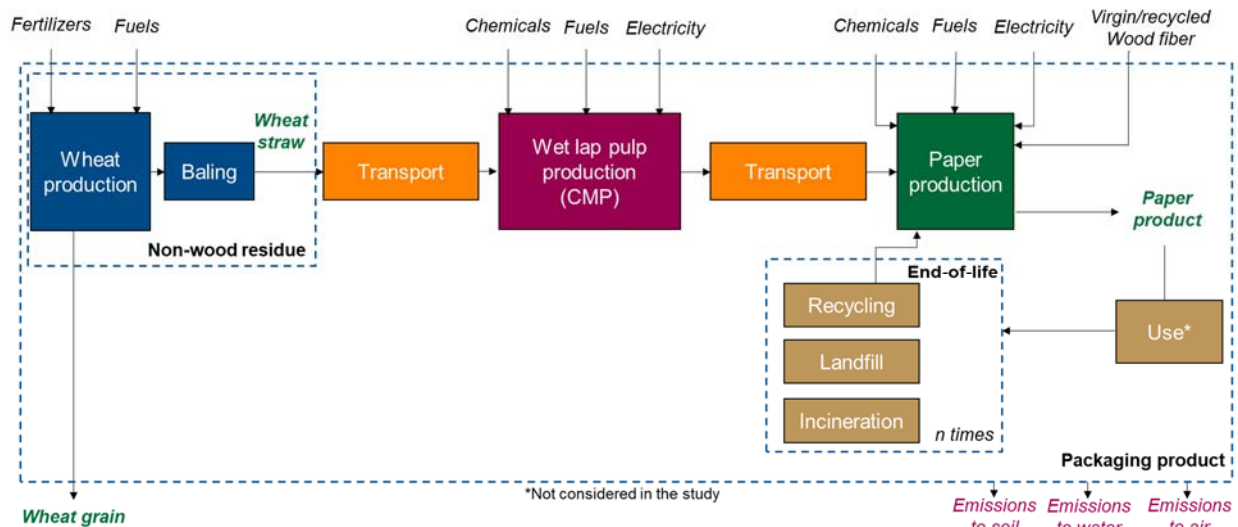
174 \*Only for wheat straw pulp

175 Finally, it has been reported that replacing wood fibers with non-wood residues can impact product  
 176 performance. The effect of properties changes was included in the LCA by using 1 m<sup>2</sup> as the  
 177 functional unit instead of a mass basis. It was assumed that the basis weight of the paper was  
 178 120 gsm as per experimental data [6]. Then, the basis weight of paper containing non-wood  
 179 residues was changed based on performance variations. Due to data availability, this was only  
 180 applied to virgin linerboard containing wheat straw.

181 2.3. Cradle-to-grave life cycle carbon analysis of packaging products containing non-  
 182 wood residues

183 Evaluating the GWP of packaging products throughout their life cycle is of utmost importance to  
 184 understand their global impact on the environment. This section aimed to evaluate the GWP of  
 185 linerboard containing 30% wheat straw pulp from a cradle-to-grave perspective and compare it to  
 186 wood-based linerboard. The functional unit was 1 ton of linerboard. System boundaries for this  
 187 section are depicted in **Figure 2**. Results from previous sections for extraction of raw materials,  
 188 production of chemi-mechanical non-wood pulp, and manufacturing of virgin and recycled  
 189 linerboard were used. Based on statistics on the end-of-life of paper products, ca. 82% was  
 190 assumed to be recycled, ca. 14.5% was landfilled, and ca. 3.5% was incinerated [24]. An essential

191 parameter in the study is the yield of making recycled linerboard. Thus, ca. 83% [25] was assumed  
 192 for wood fibers, while a correlation was used for the wheat straw fraction based on experimental  
 193 data at different recycling cycles [26]. It is important to note that a cascade recycling approach  
 194 was followed until no fiber was available to make new products [27] (ca. ten cycles). A mass  
 195 balance was performed to estimate the amount of wood or non-wood fibers after each product  
 196 cycle, i.e., virgin and consequent recycled products. Emissions for each stage were accounted  
 197 for and allocated to the total amount of paper produced. Finally, due to data availability, the stage  
 198 of using the products was not considered. It is important to mention that for this part of the study,  
 199 changes in the performance of the paper across the different recycling loops was not considered  
 200 due to a lack of data. Nevertheless, the authors recognize that this is an important aspect that  
 201 needs to be addressed in future research.



202  
 203 Figure 2. Cradle-to-grave system boundaries for wheat straw-based linerboard packaging paper  
 204 (Note: not all the inputs and outputs considered for the study were included in this drawing)

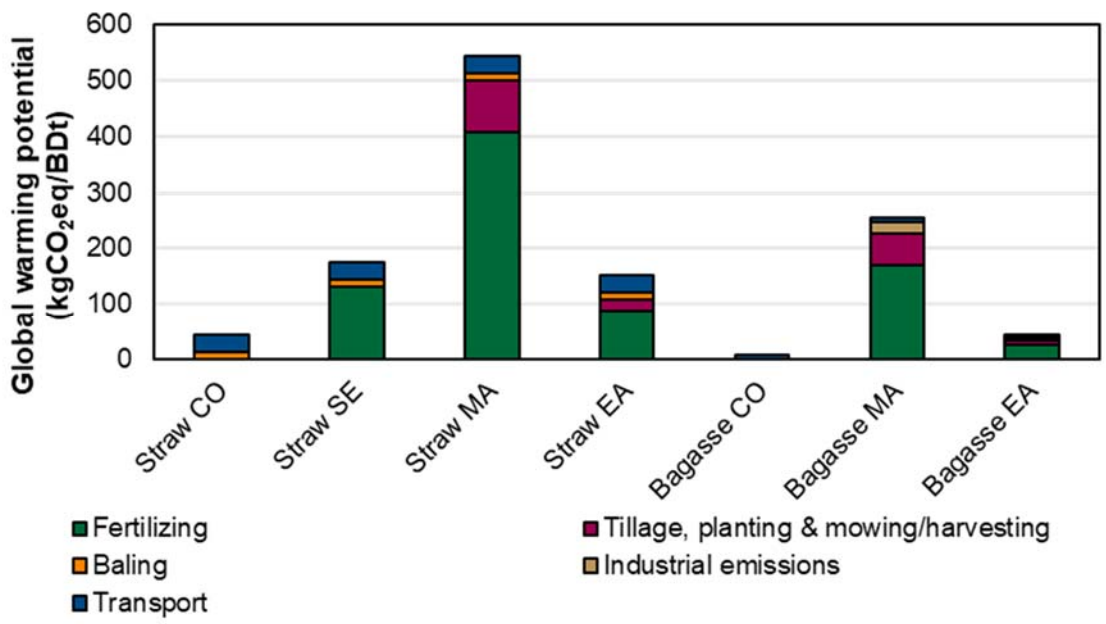
205 **3. Results and discussions**

206 3.1. Life cycle carbon analysis of non-wood residues

207 **Figure 3** depicts the global warming potential (GWP) of selected non-wood residues under  
 208 different allocation scenarios. Results are highly dependent on the method used to allocate  
 209 emissions between primary products of the system (i.e., wheat grain or sugar) and residues.  
 210 Overall, values obtained from the cut-off method present lower impacts due to the assumption  
 211 that residues are waste; therefore, environmental burdens from the primary system are not  
 212 allocated to them. Only additional emissions related to handling and transportation are accounted

213 for. On the other hand, results under mass allocation set a heavy toll on biomass and represent  
 214 the highest values among different allocation methods. In this case, residues are treated as a by-  
 215 product, and environmental burdens from the primary system are shared based on a mass basis.  
 216 Specifically for wheat straw, GWP could range between ca. 45 to 545 kgCO<sub>2</sub>eq per BDT of biomass  
 217 delivered to the pulp mill. On the other hand, sugarcane bagasse could vary from ca. 7 to 255  
 218 kgCO<sub>2</sub>eq per BDT of biomass. This large difference illustrates the influence of allocation methods  
 219 on the results. Therefore, arbitrarily choosing one method over others could provide a wrong  
 220 answer to understanding the environmental impact of these residues better. Assessing this  
 221 variability is of utmost importance to ensure a better understanding of the effect of methodological  
 222 decisions on LCA results.

223 **Figure 3** also shows the contribution tree for GWP depicted by stage. Production of non-wood  
 224 residues presents the highest contribution under SE, MA, and EA scenarios. This includes  
 225 handling impacts plus shared burdens of fertilizers, fuels, and agricultural emissions for wheat  
 226 straw. For sugarcane bagasse it comprises shared impact of sugarcane production, chemicals,  
 227 energy, and direct emissions. Transportation to the paper mill is the most significant contributor  
 228 to the CO scenario. It is essential to mention that distances for straw are larger than sugarcane  
 229 bagasse, which explains the more considerable impact of transportation for straw. In addition,  
 230 straw transportation is volume-limited, increasing the number of trucks needed per ton of residue  
 231 [6]. Thus, optimizing bales sizes could help decrease the overall transportation impact.

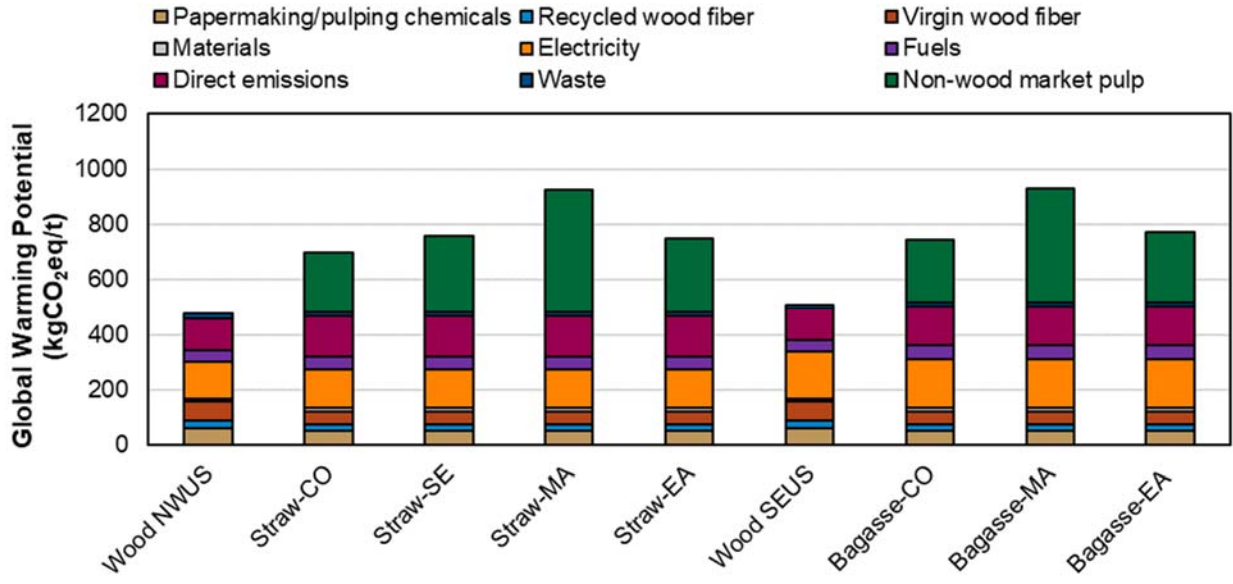


232

233 Figure 3. Global warming potential for non-wood residues under different allocation methods

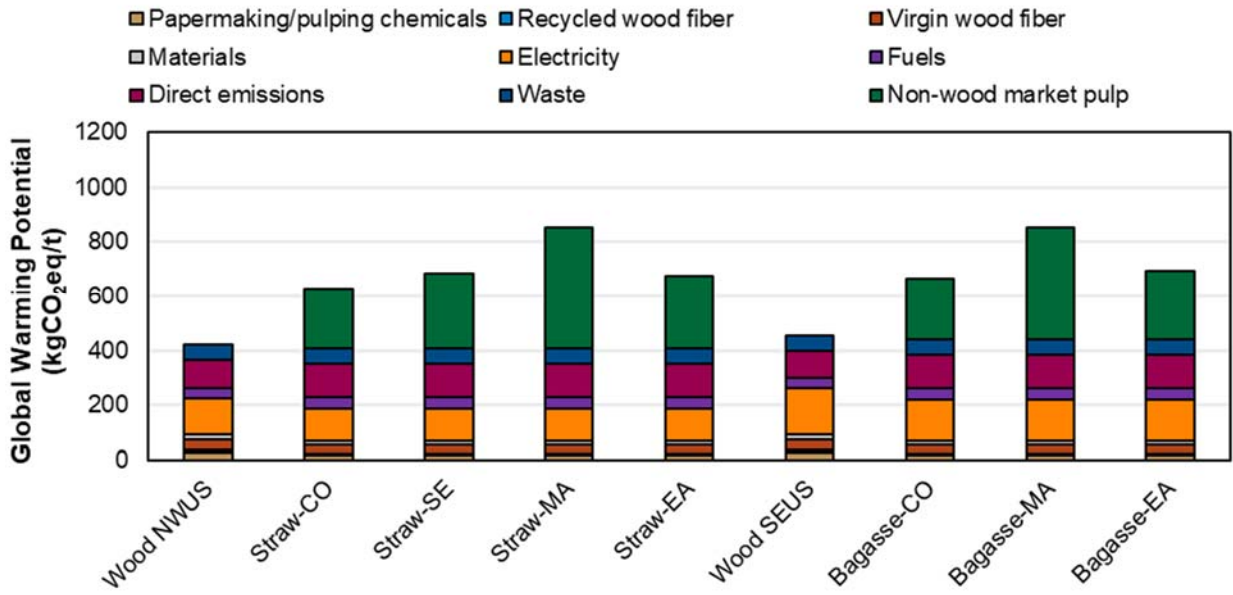
234 3.2. Life cycle carbon of packaging products containing non-wood residues  
235 Studying the environmental impact of non-wood biomass is a critical part of the study, but it does  
236 not show the whole picture. Virgin wood, recycled paper, and non-wood residues follow different  
237 paths to be transformed into paper. In this study, non-wood residues are transformed into wet lap  
238 pulp and later in packaging products. On the other hand, virgin wood and recycled paper are  
239 converted into paper in integrated facilities through chemical, semi-chemical, or recycling  
240 processes depending on the final product, without the need for wet lap pulp intermediate. It is  
241 essential to mention that this study does not aim to compare these processes, but the intent is to  
242 understand the effect of adding non-wood pulp into virgin or recycled wood products. Data used  
243 come from a variety of sources and using them for comparison could provide wrong conclusions.

244 **Figures 4** and **5** depict the GWP of virgin linerboard and corrugating medium under different  
245 allocation methods, containing or not non-wood residues. Since the supply of non-wood fibers is  
246 geographically dependent, two scenarios for wood were assessed. Thus, wood NWUS is the  
247 benchmark for straw, and wood SEUS is the comparison for bagasse. Results show that GWP  
248 values depend on allocation methods used to assess the environmental impact of residues.  
249 Nevertheless, replacing virgin wood fibers with wet lap non-wood pulp increased the GWP of  
250 products in all cases. The driver of the higher impact compared to benchmarks is non-wood pulp.  
251 Although the studied CMP process presents an overall lower chemical and energy consumption  
252 than conventional chemical processes, the overall impact was higher. The CMP method lacks a  
253 chemical recovery and power co-generation system, and uses a higher share of fossil fuels, which  
254 explains the more considerable burden compared to chemical and semi-chemical pulp. Thus, the  
255 high efficiency in recovering chemicals and the ability to produce on-site combined heat and  
256 power from a high share of renewable fuels are critical for the lower environmental impact of the  
257 virgin wood-based paper. **Figures 6** and **7** show the GWP of recycled linerboard corrugating  
258 medium, respectively. Although results depend on the allocation methods, replacing recycled pulp  
259 with non-wood wet lap pulp also translates into increased GWPs. Direct and electricity-related  
260 emissions decrease due to less handled recycled paper. Nevertheless, the high GWP of non-  
261 wood pulp drives the higher impact compared to benchmarks.



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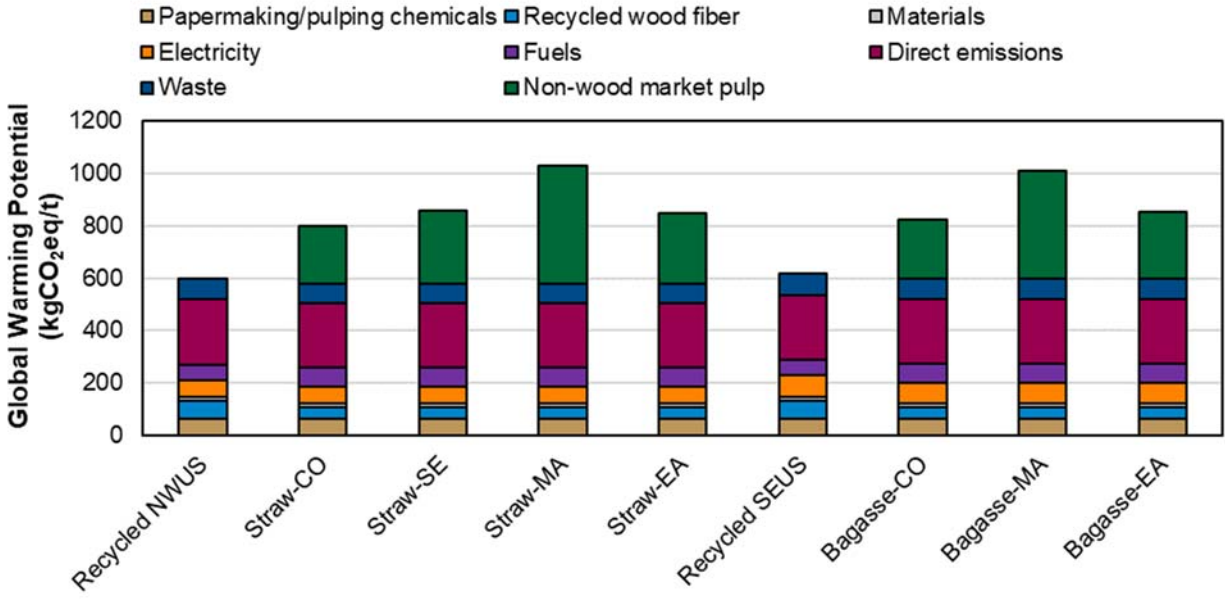
263 Figure 4. Global warming potential for virgin linerboard containing non-wood residue pulp



264

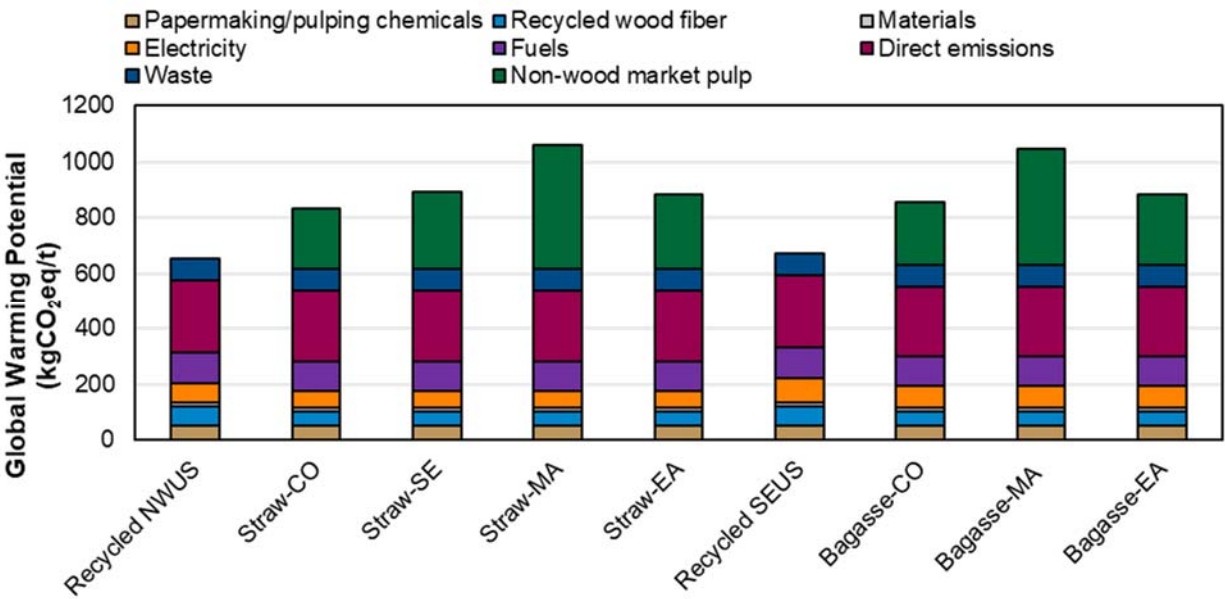
265 Figure 5. Global warming potential for virgin medium containing non-wood residue pulp

266



267

268 Figure 6. Global warming potential for recycled linerboard containing non-wood residue pulp



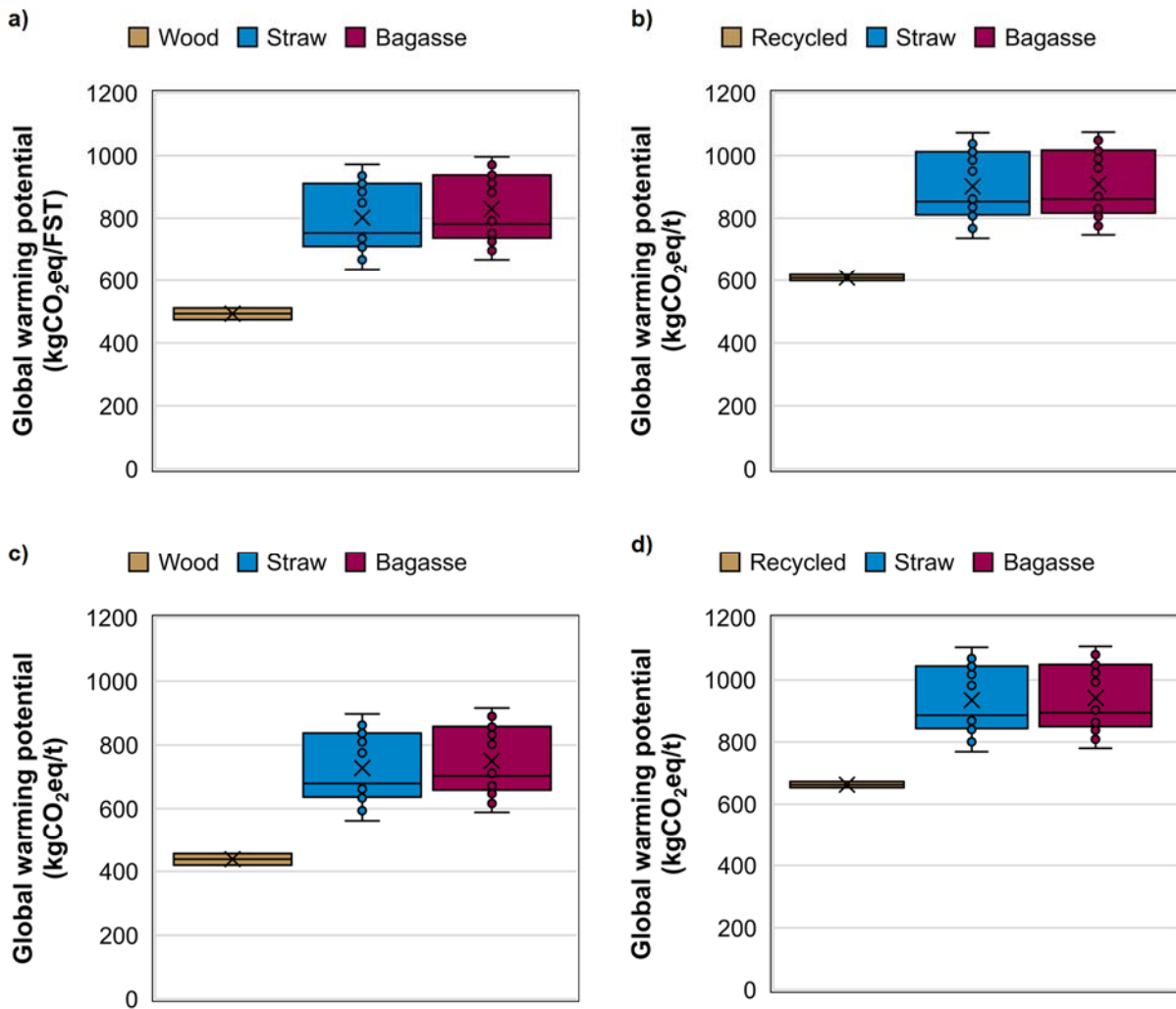
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270 Figure 7. Global warming potential for recycled medium containing non-wood residue pulp

271 LCA highly depends on the life cycle inventory used for the study. Thus, sensitivity analyses allow  
 272 to understand the effects of data variability on LCA results. As explained in the methodology  
 273 section, parameters related to the production of non-wood pulp were changed, and their effect on  
 274 the GWP of linerboard and corrugating medium was assessed. **Figure 8** shows these sensitivity  
 275 analyses. It was found that packaging products containing non-wood residues present GWPs

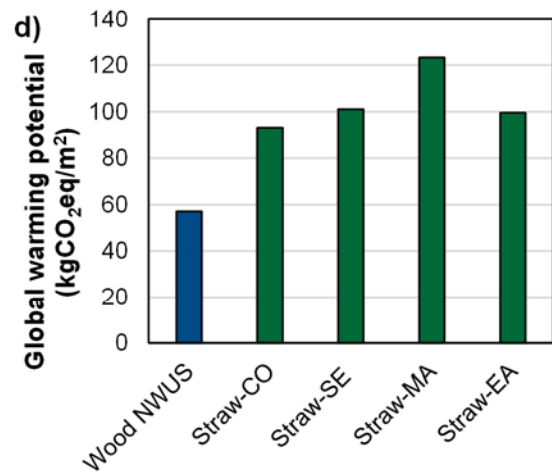
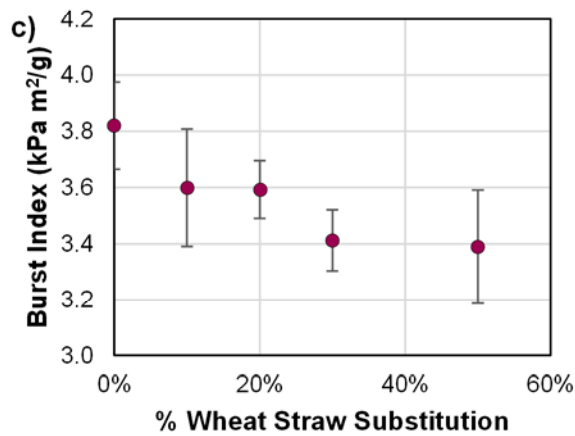
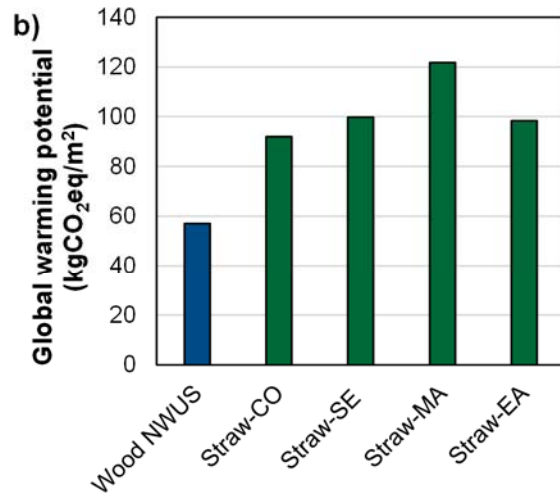
276 between ca. 15-100% higher compared to benchmarks. This constitutes a high variability and  
 277 shows how sensitive results are to baseline assumptions. Nevertheless, under the studied  
 278 scenarios, non-wood-containing packaging products presented an overall higher impact. Besides  
 279 allocation methods for non-wood residues, allocation around by-products of non-wood pulp, type  
 280 of pulping chemical, and chemical charges during non-wood pulping presented the greatest  
 281 influence in the results.

282



283  
 284 Figure 8. Sensitivity analysis for packaging products containing non-wood residue pulp: a) virgin  
 285 linerboard, b) recycled linerboard, c) virgin medium, d) recycled medium

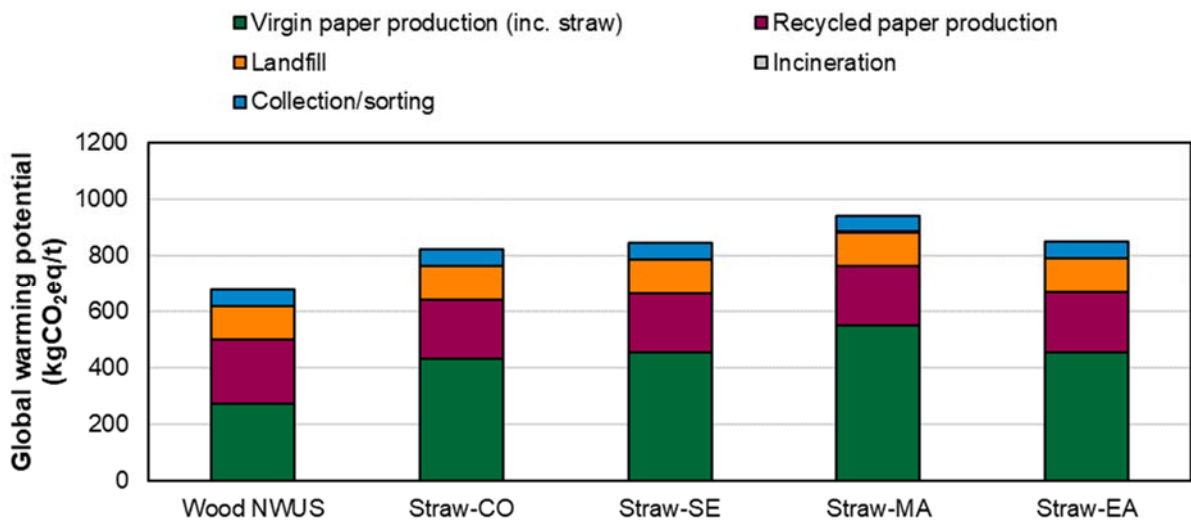
286 It has been reported that replacing wood fibers with non-wood residues can impact product  
287 performance. Studies for linerboard [6] show that replacing softwood with up to 30% wheat straw  
288 pulp does not significantly affect tensile or short-span compression indexes. Nevertheless, as  
289 shown in **Figure 9a and 9c**, increasing wheat straw content in linerboard translates into  
290 decreasing tear index (ca. 9.5 %) and burst index (ca. 11.5%). The effect of this decrease in  
291 performance was considered for the LCA, as is depicted in **Figure 9b and 9d**. It was found that  
292 linerboard containing 30% of the straw pulp can present GWPs ca. 60-115% higher than the wood  
293 benchmark. As seen before, results depend on allocation methods, but considering performance  
294 magnifies results depicted in **Figure 4**. Since performance decreases, more fiber is required per  
295 product area, which translates into an overall increase in basis weight to achieve product  
296 specifications. Thus, GWP per area can be ca. 19-29% and ca. 22-33% higher than GWP per  
297 mass if tear or burst indexes are considered, respectively. It is important to note that if  
298 performance was improved, LCA results could be more favorable since less fiber would be  
299 needed. Thus, searching for applications where non-wood residues can bring improved  
300 performance could help reduce the carbon footprint of non-wood-based packaging products. It is  
301 important to mention that in this case, the studied properties were selected as examples for the  
302 linerboard. For future studies, the effect of performance on other products, such as corrugating  
303 medium, could be assessed.



304  
 305 Figure 9. a) Effect of wheat straw substitution on linerboard tear index [6] b) Effect of changes in  
 306 tear index on Global Warming Potential of linerboard containing wheat straw pulp c) Effect of  
 307 wheat straw substitution on linerboard burst index [6] d) Effect of changes in burst index on Global  
 308 Warming Potential of linerboard containing wheat straw pulp

309 Finally, a cradle-to-grave assessment was conducted for linerboard containing wheat straw pulp  
 310 and is depicted in **Figure 10**. This part of the study considers experimental data on the  
 311 repulpability of products containing this non-wood residue. In this scenario, it was assumed that  
 312 virgin wood was replaced with wheat straw pulp during the production of linerboard, and this  
 313 product then followed recycling with corresponding losses to landfill or incineration. All emissions  
 314 throughout the product life cycle were accounted for and allocated to the total amount of paper  
 315 produced. It was found that products containing wheat straw pulp presented GWPs ca. 21-25%

316 higher than wood benchmarks. Interestingly, these differences are lower than those observed in  
 317 cradle-to-gate studies. This is due to the allocation of wheat straw pulp emissions to the total  
 318 amount of paper produced instead of only to the virgin linerboard. As shown in **Figure 10**,  
 319 emissions associated with the production of virgin product is the main contributor to the GWP.  
 320 This value is higher for linerboard containing wheat straw pulp. In addition, it was observed that  
 321 products with non-wood residues presented an overall lower repulping yield, translating into  
 322 higher emissions per ton of product. GWPs per ton were then constant after wheat straw was no  
 323 longer in the system.



324  
 325 Figure 10. Cradle-to-grave global warming potential of linerboard containing wheat straw pulp

326 **4. Conclusions**

327 This study evaluated the impact of replacing wood fibers with straw and sugarcane pulp on the  
 328 carbon footprint of linerboard and corrugating medium produced in the United States. Results  
 329 highly depended on the allocation methods chosen to assign emissions to these residues.  
 330 Therefore, indiscriminately selecting an allocation approach can bias the impact towards residues  
 331 if emissions are not allocated or against them if a mass allocation is used. Nevertheless, despite  
 332 this variability, replacing virgin wood or recycled paper with non-wood residues translated into  
 333 increased GWPs. Intermediate non-wood wet-lap pulp was the driver for this impact. The lack of  
 334 chemical recovery and on-site power generation explains the more considerable impact.  
 335 Sensitivity analyses showed that assumptions around the production of pulp greatly influenced  
 336 results. Thus, the GWPs of packaging products containing residues can be 15%-100% higher

337 than the comparable wood-based products. Including the effect of changes in performance  
338 magnified these results for the selected case study. Decreased tear and burst indexes caused  
339 larger GWPs of linerboard since higher basis weights were needed to match product  
340 specifications. Finally, from a cradle-to-grave perspective, agricultural residue-containing  
341 linerboard presented higher GWPs than wood-based paper. It was seen that lower repulping  
342 yields associated with straw caused higher GWPs per ton of paper. Overall, from these findings,  
343 straw and sugarcane might not be a solution to reduce the carbon footprints of linerboard and  
344 corrugating medium under the studied scenarios in the United States.

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