



## Life cycle assessment



# 1. Results

In this chapter, the environmental impacts of the three different materials are presented.

## 1.1 ABS

### *ABS midpoint indicators*

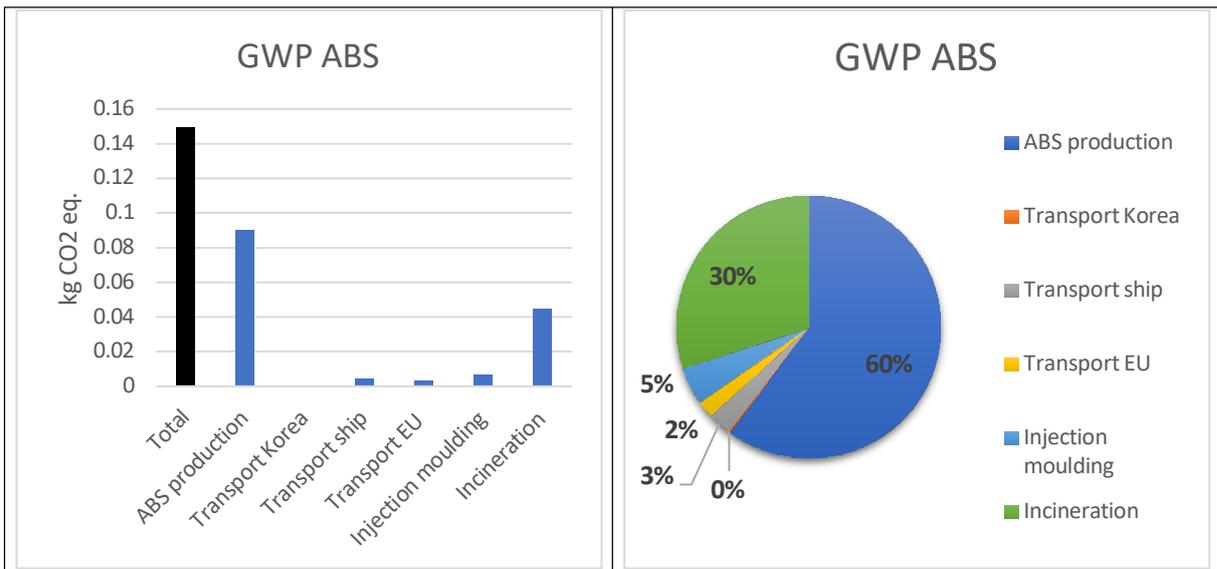
The midpoint results for the ABS are shown below. Table 7 shows the environmental impacts of the different midpoint indicators for each life cycle stage of ABS.

**Table 7: Environmental impacts of the midpoint indicators for ABS**

	GWP	EP	AP	ODP	Water	Human tox
Unit of measurement	kg CO <sub>2</sub> -Eq	mol N-Eq	mol H+-Eq	kg CFC-11-Eq	m <sup>3</sup> water-Eq	CTUh
Total	0.149306771	0.000978092	0.000472146	4.91616E-09	0.089329591	1.89926E-09
ABS production	0.089817348	0.000486197	0.000291403	1.32246E-09	0.047305807	1.14249E-09
Transport Korea	0.000404311	2.56543E-06	1.17009E-06	8.44826E-11	2.82212E-05	9.53385E-12
Transport ship	0.00416478	0.000371293	0.000135743	8.3877E-10	0.000150341	1.23854E-10
Transport EU	0.003179899	2.00732E-05	8.84449E-06	7.22807E-10	0.000219397	6.60773E-11
Injection moulding	0.006917477	4.59578E-05	2.36923E-05	1.64646E-09	0.040723447	2.45935E-10
Incineration	0.044822956	5.20054E-05	1.1293E-05	3.01187E-10	0.000902378	3.11371E-10

It follows a graphical representation of each midpoint indicator. For each midpoint indicator, the impacts of the different life cycle stages and the total impact are shown in a column chart. Through a pie chart, the impact of each phase on the total is shown.

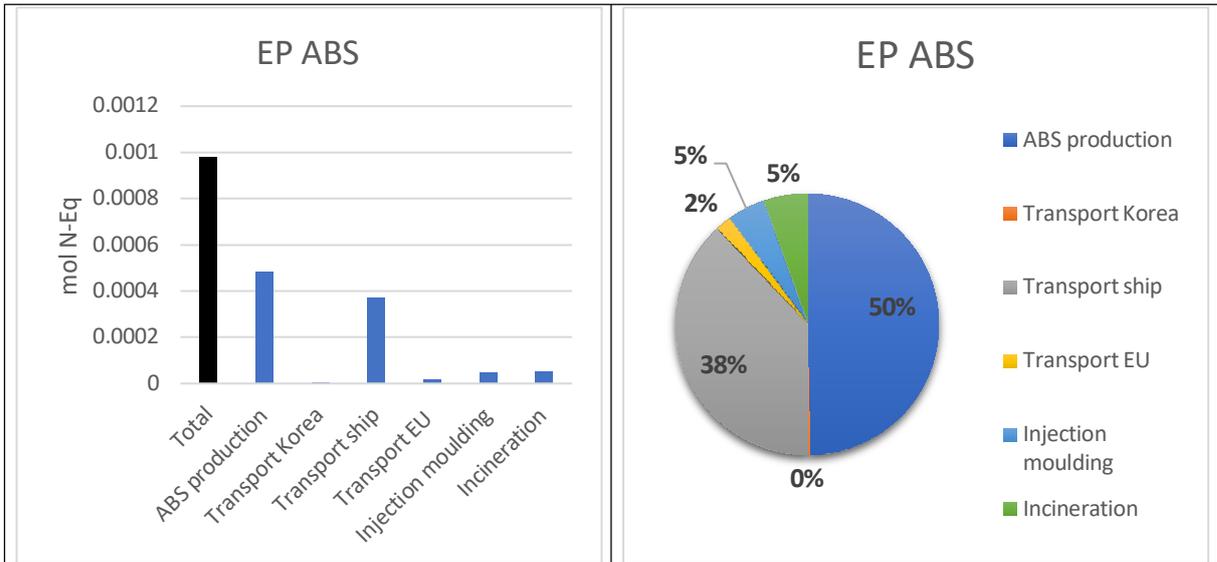
### Global Warming Potential of ABS



As we see in the graphics the production of ABS is the phase with the highest global warming potential impact. This phase alone has an incidence of 60% on the global warming potential. The second phase with the highest impact is the incineration, with an impact of 30%.

The analysis shows that the total global warming potential is equal to 0.14931 kg CO<sub>2</sub> eq.

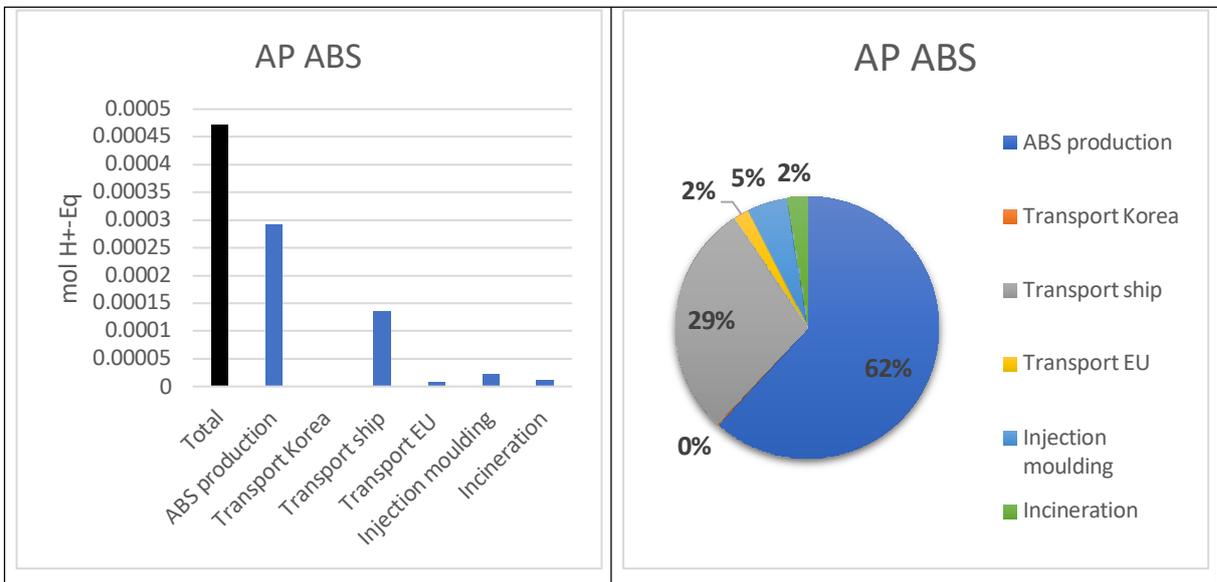
### Eutrophication Potential of ABS



The graphics indicate that the phase which contributes the most to the eutrophication potential is the ABS production which accounts for 50% of the total impact. The second phase with the highest impact on eutrophication is the transport via ship from Korea to Europe.

The analysis shows that the total eutrophication potential is equal to 0.00098 mole of N eq.

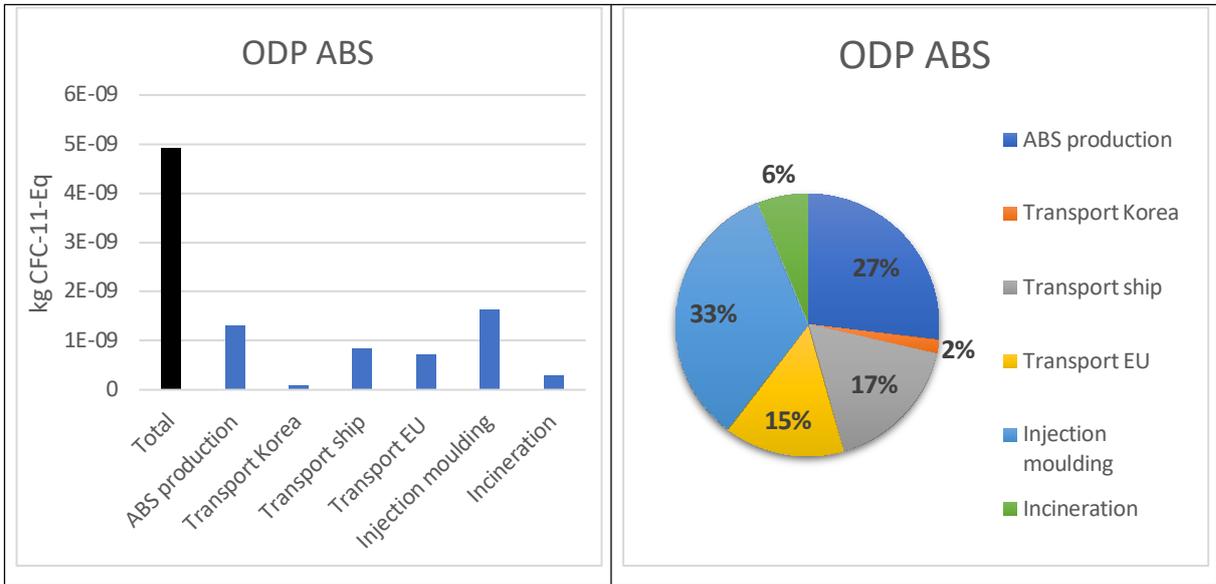
### Acidification Potential of ABS



The proportion of the acidification potential is like that of eutrophication. In this case the production of ABS impact 12% more than for the indicator eutrophication potential. It contributes to 62% of total impact.

The analysis shows that the total acidification potential is equal to 0.00057 mole of H+ eq.

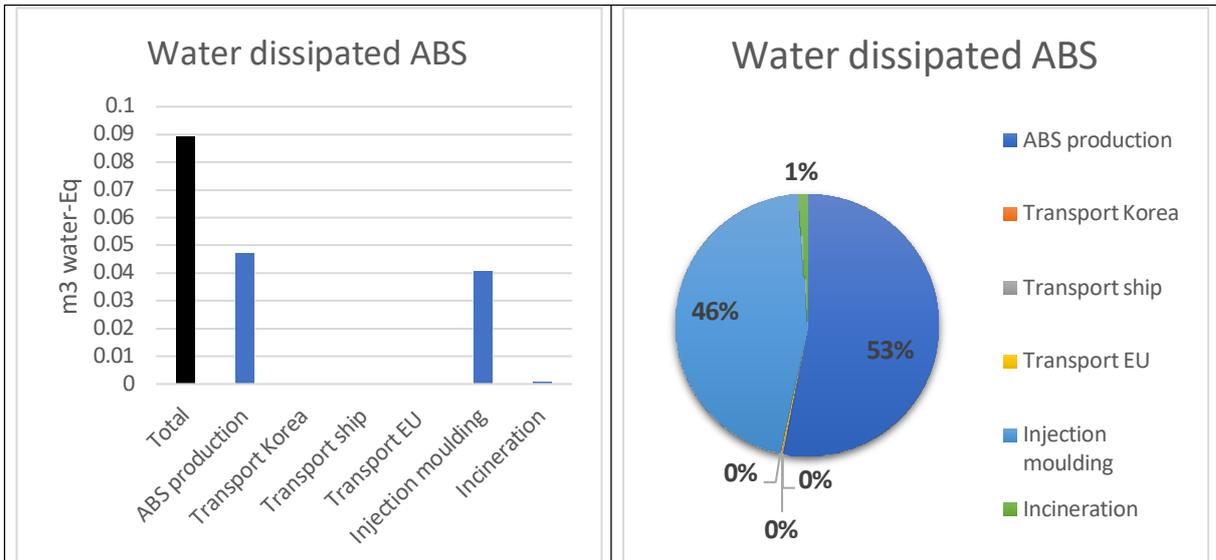
### Ozone Depletion Potential of ABS



The graphic shows that for the ozone depletion potential the life cycle phase with the highest impact is not the ABS production, as for the other indicators seen before, but the injection moulding. The injection moulding phase has an impact of 33%. ABS production has a similar impact as injection moulding, namely 27% of the total.

The analysis shows that the total ozone depletion potential is equal to 4.92E-09 kg of R11 eq.

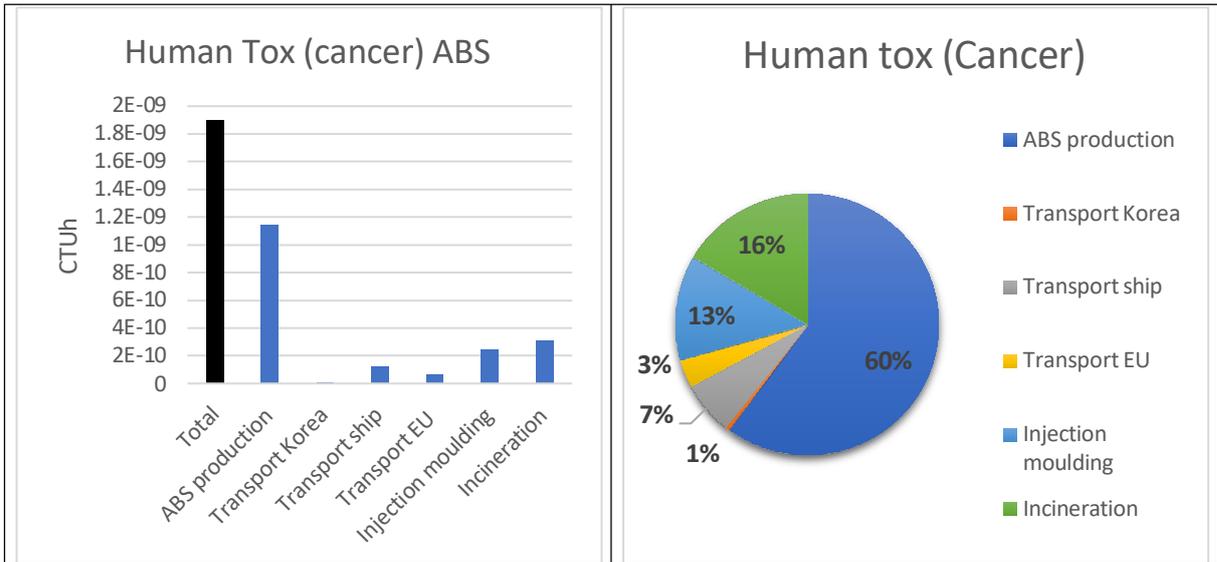
### Dissipated Water of ABS



The phase which requires more water is the production of ABS. The injection moulding process also has a high impact on water consumption. This is due to the type of energy used for this process, hydropower.

The analysis shows that the total dissipated water is equal to 0.08933 m3 of water eq.

## Human toxicity of ABS



The graphics show that the ABS production has the highest contribution (60%) to the carcinogenic effect.

The analysis shows that the total carcinogenic effect is equal to 1.90E-09 CTUh (Comparative Toxic Unit for human).

### ABS endpoint indicators

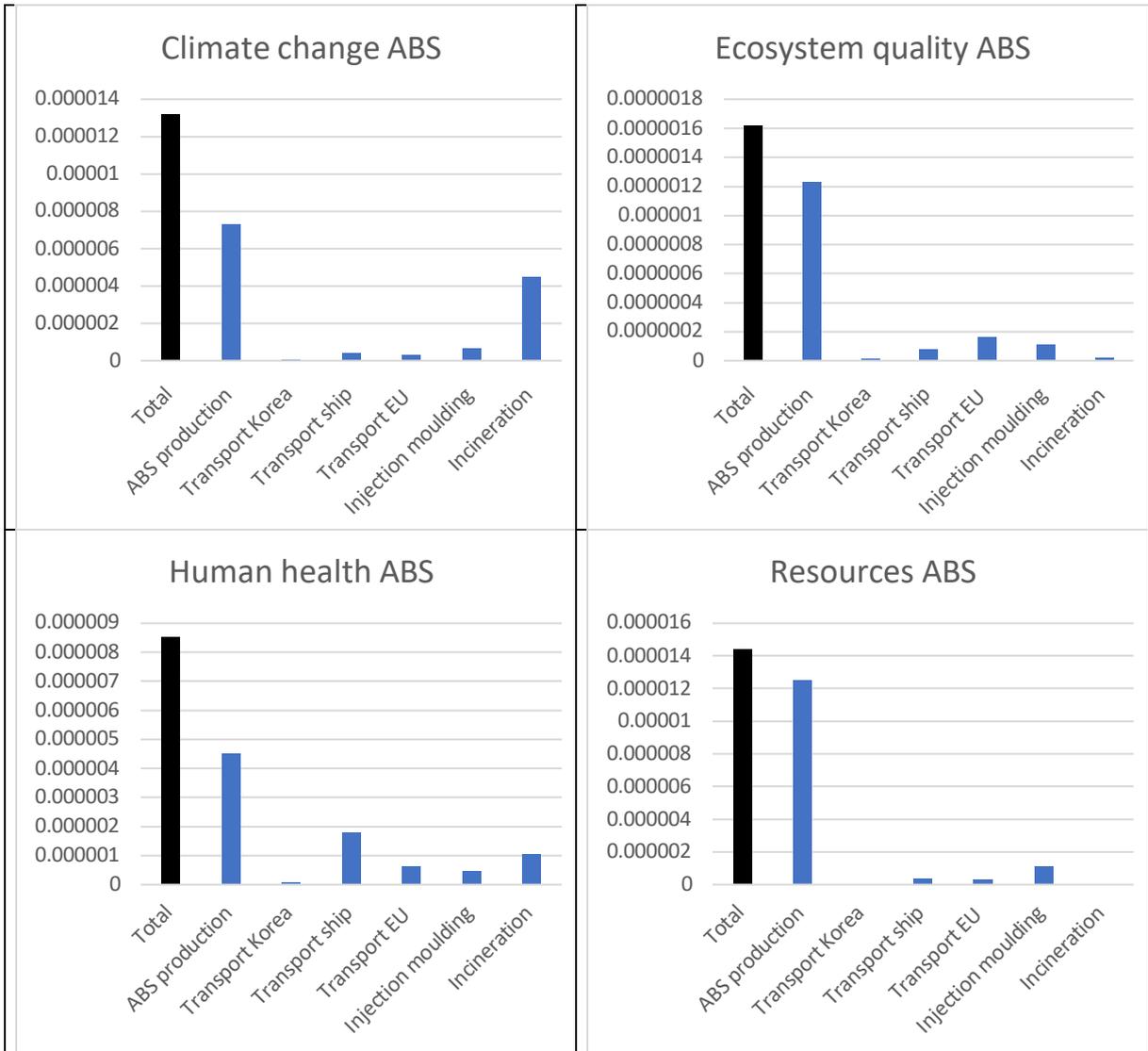
The endpoint results for the ABS are shown below. Table 8 shows the environmental impacts of the different endpoint indicators for each life cycle stage of ABS.

In the endpoint tables and charts the values are shown in points.

**Table 8: Environmental impacts of the endpoint indicators for ABS**

	Climate change	Ecosystem quality	Human health	Resources
Total	1.31967E-05	1.62159E-06	8.53057E-06	1.43991E-05
ABS production	7.30093E-06	1.23283E-06	4.49579E-06	1.24846E-05
Transport Korea	3.94385E-08	1.68994E-08	7.12889E-08	4.10154E-08
Transport ship	4.10023E-07	7.81793E-08	1.80145E-06	3.72341E-07
Transport EU	3.11542E-07	1.62347E-07	6.47126E-07	3.3705E-07
Injection moulding	6.42622E-07	1.09173E-07	4.84115E-07	1.10228E-06
Incineration	4.49212E-06	2.21582E-08	1.0308E-06	6.1807E-08

As for the midpoints, a graphical representation of each endpoint follows. For each endpoint indicator, the impacts of the different life cycle stages and the total impact are shown in a column chart.



From the graphs it can be seen that the phase with the greatest impact for each indicator is ABS production.

## 1.2 PP with calcium carbonate

### *Recycled PP with calcium carbonate midpoint indicators*

Table 9 shows the environmental impacts of the different midpoint indicators for each life cycle stage of the compound with recycled PP and calcium carbonate.

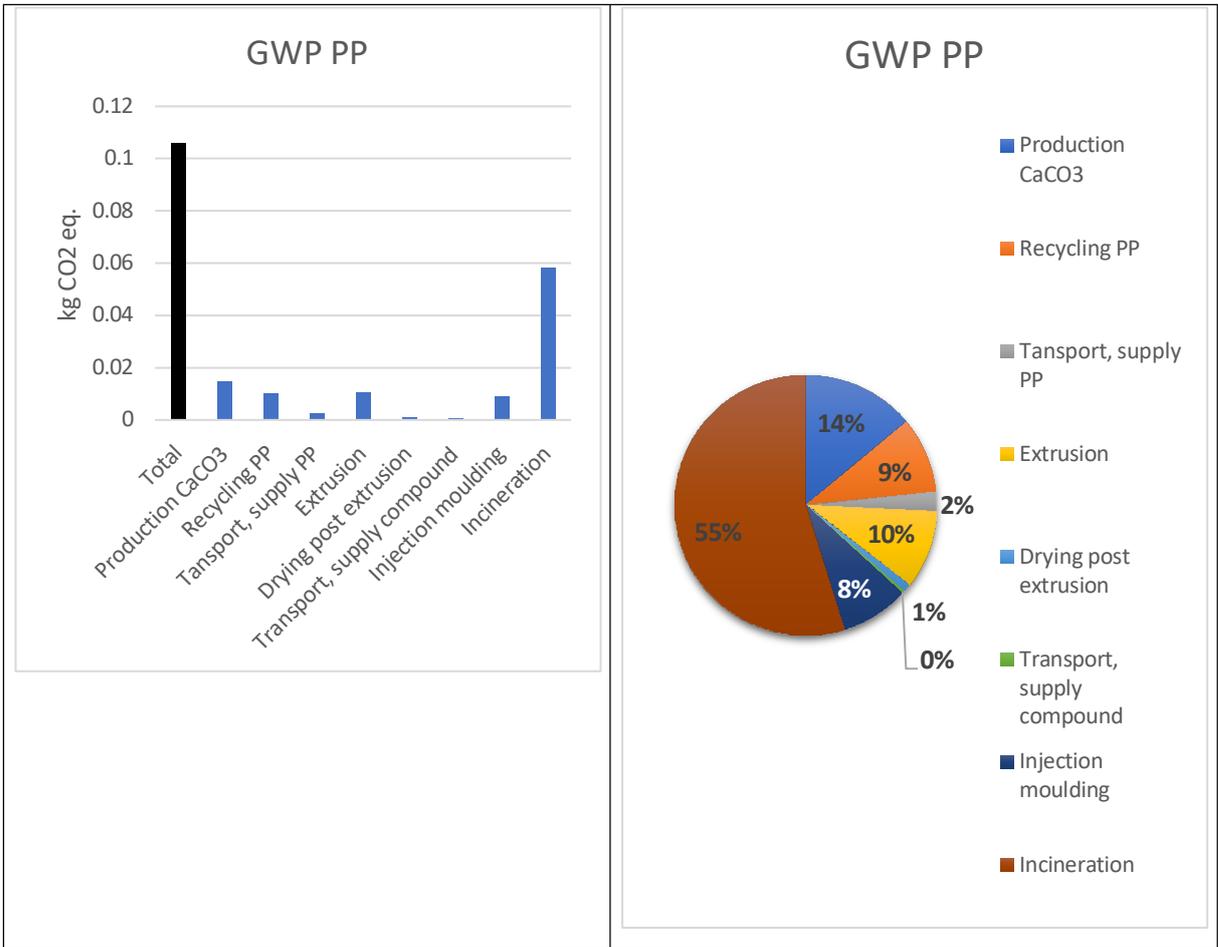
**Table 9 : Environmental impacts of the midpoint indicators for the compound with recycled PP and calcium carbonate**

	GWP	EP	AP	ODP	Water	Human tox
Unit of measurement	kg CO <sub>2</sub> -Eq	mol N-Eq	mol H <sup>+</sup> -Eq	kg CFC-11-Eq	m <sup>3</sup> water-Eq	CTUh
Total	0.105850504	0.000396415	0.000182429	5.15756E-09	0.07217026	2.21717E-09
Production CaCO <sub>3</sub>	0.014798122	0.000069235	3.37612E-05	1.02694E-09	0.003104665	2.81542E-10
Recycling PP	0.009944613	4.71211E-05	2.73416E-05	1.25514E-12	0.001331506	7.67705E-10
Transport, supply PP	0.002527612	1.59557E-05	7.03023E-06	5.74539E-10	0.000174392	5.2523E-11
Extrusion	0.010303544	9.49517E-05	5.90335E-05	7.63451E-10	0.012877497	3.31366E-10
Drying post extrusion	0.001034709	4.04664E-05	9.11222E-06	1.99527E-10	0.00088809	5.53558E-11
Transport, supply compound	0.000342065	2.07012E-06	9.43928E-07	7.56775E-11	2.6042E-05	8.34874E-12
Injection moulding	0.008935075	5.93621E-05	3.06025E-05	2.12668E-09	0.05260112	3.17666E-10
Incineration	0.057964765	6.72531E-05	1.46041E-05	3.89493E-10	0.00116695	4.02663E-10

A graphical representation of each midpoint indicator follows. For each indicator, the impacts of the different life cycle stages and the total impact are shown in a column chart.

Through a pie chart, the impact of each phase on the total is shown.

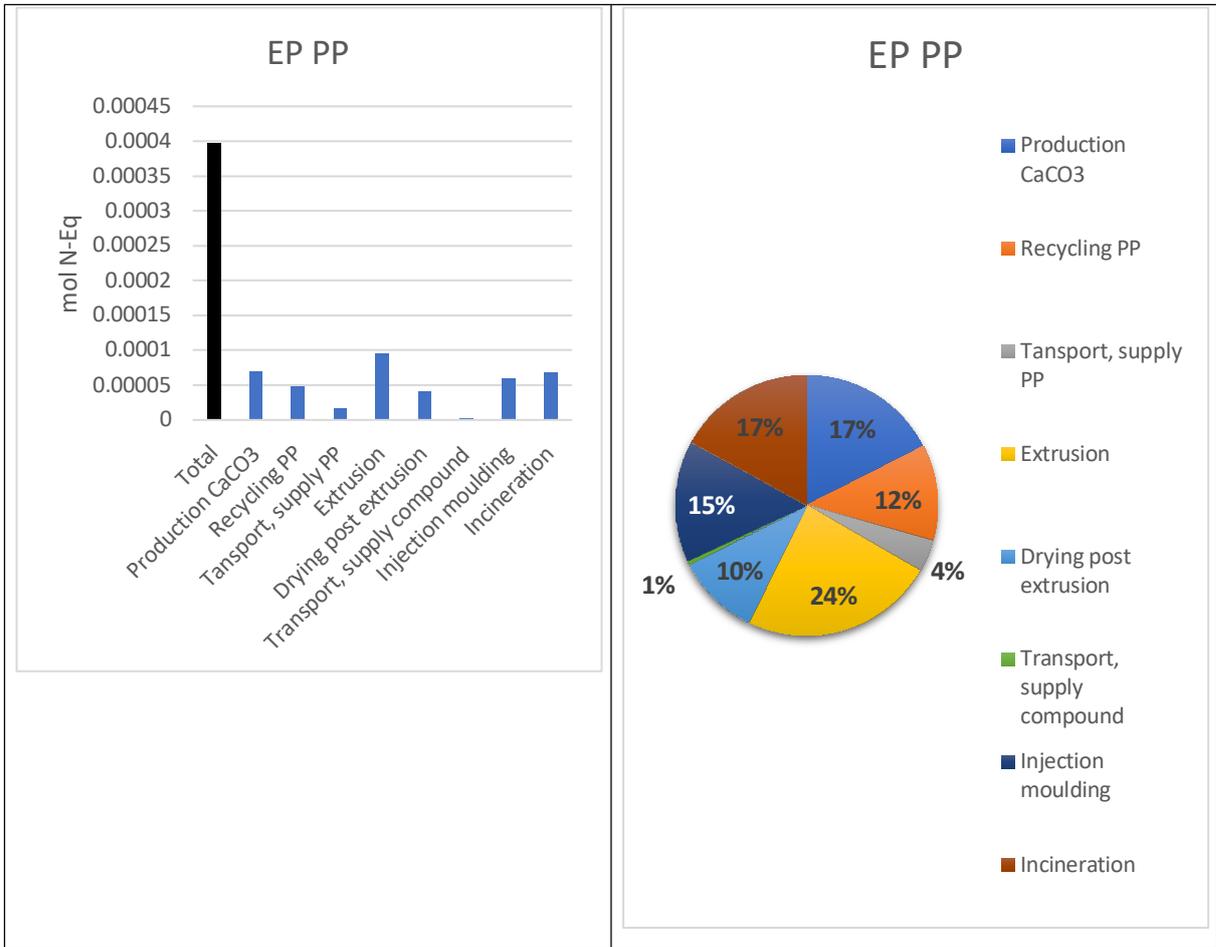
Global Warming Potential of the compound with recycled PP and calcium carbonate



The graphics show that the phase with the highest global warming potential impact is the incineration phase. This phase impacts 55%. The second phase with the highest impact is the injection moulding, which counts for 14% of the total global warming potential impact.

The analysis shows that the total global warming potential is equal to 0.10581 kg CO<sub>2</sub> eq.

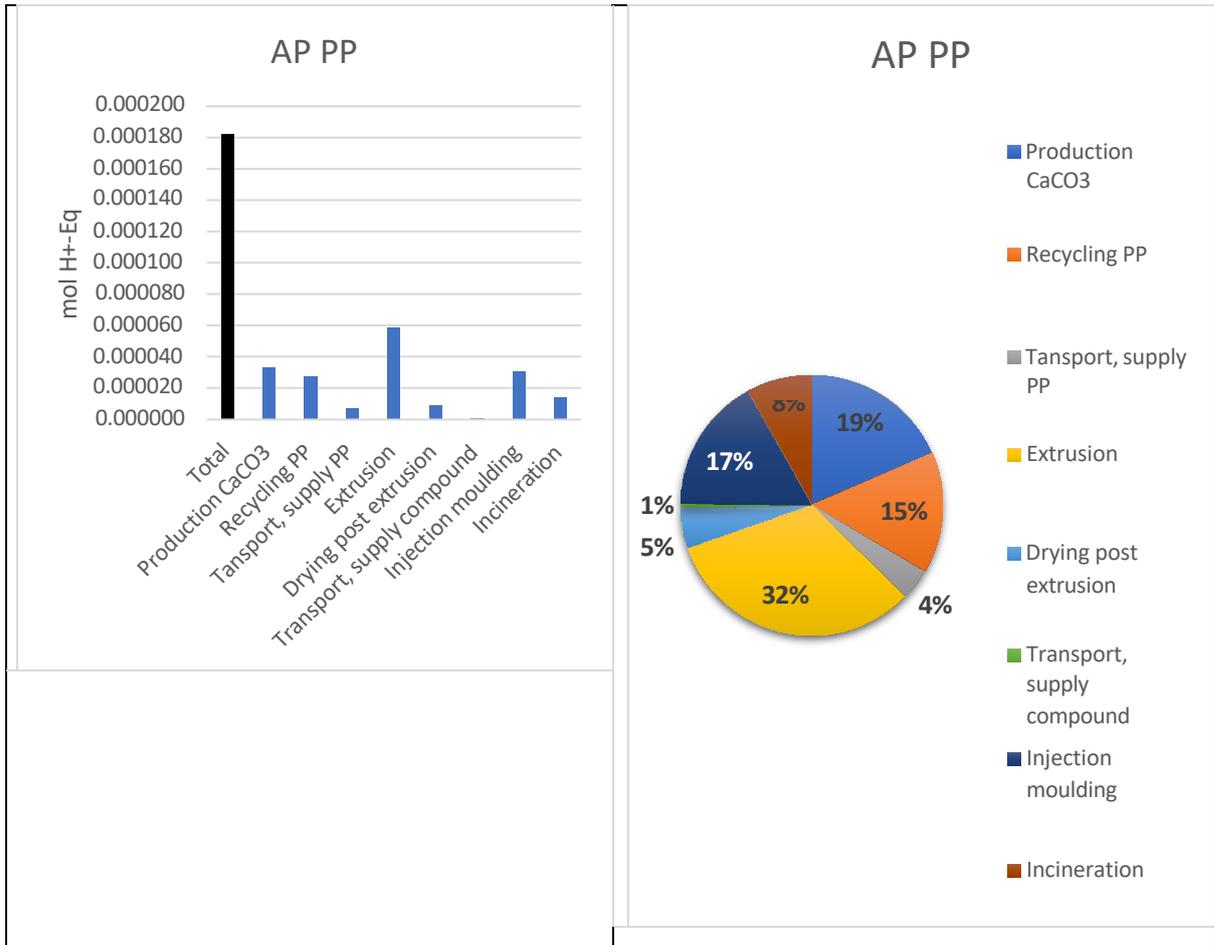
Eutrophication Potential of the compound with recycled PP and calcium carbonate



The phase which contributes the most for the eutrophication potential is the extrusion with 24% of the total impact. At the second place there are the production of CaCO<sub>3</sub> and incineration, they impact 17%.

The analysis shows that the total eutrophication potential is equal to 0.00040 mole of N eq.

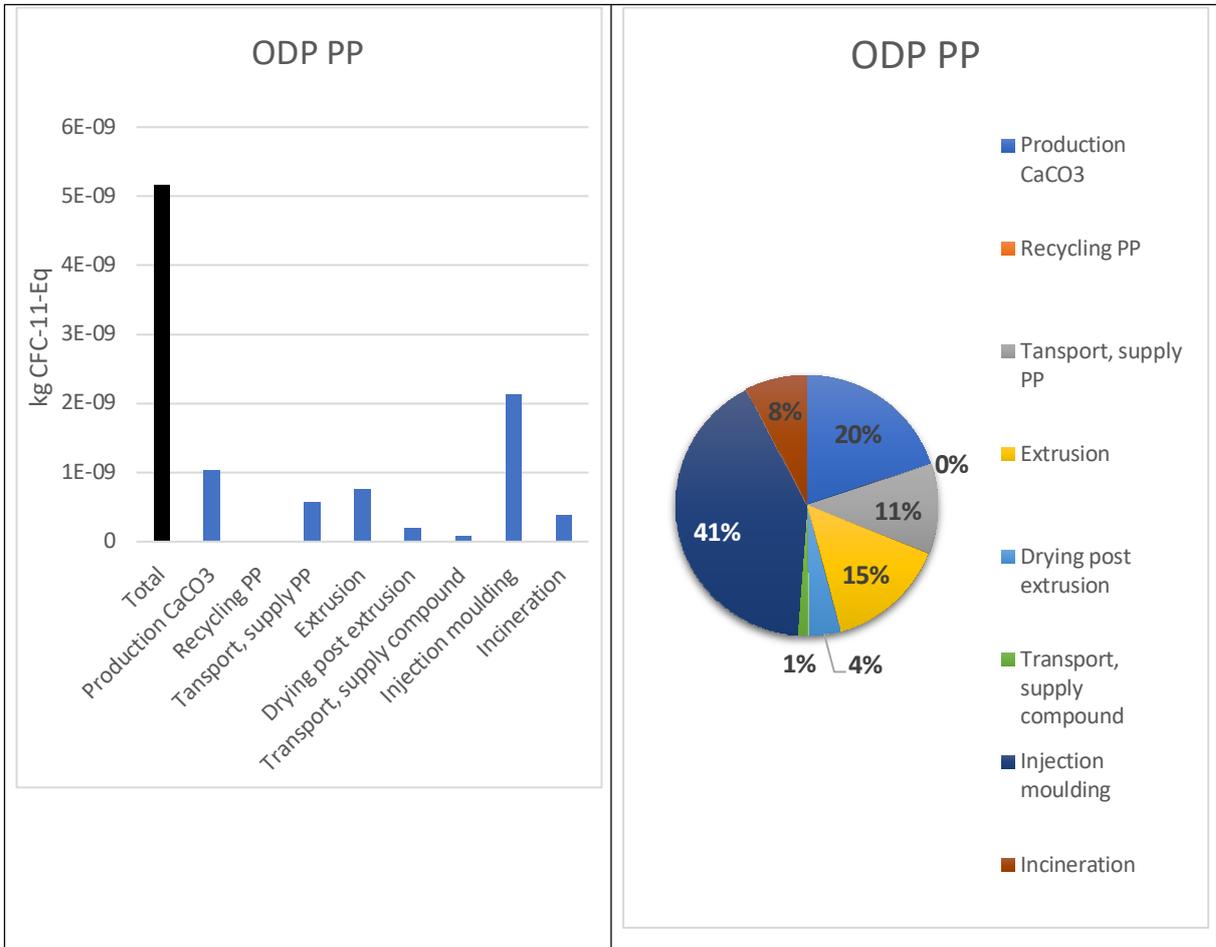
Acidification Potential of the compound with recycled PP and calcium carbonate



The pie chart shows that the phase which impacts the most on the acidification potential is the extrusion with its 32% of the total impact.

The analysis shows that the total acidification potential is equal to 0.00018 mole of H<sup>+</sup> eq.

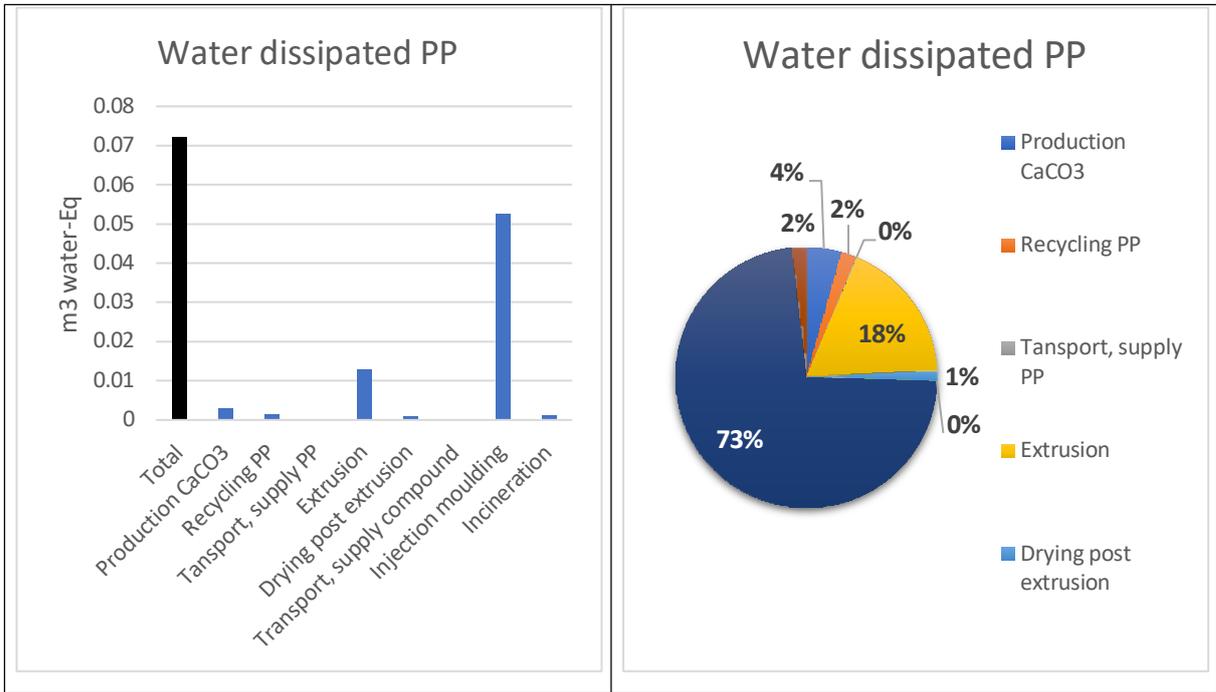
Ozone Depletion Potential of the compound with recycled PP and calcium carbonate



In the graphs it can be seen that for the ozone depletion potential the life cycle phase with the highest impact is also the injection moulding. The ozone depletion of the injection moulding phase for PP with calcium carbonate is higher (2.13E-09) than the one of the ABS (1.65E-09) and it has an impact of 41%.

The analysis shows that the total ozone depletion potential is equal to 5.16E-09 kg of R11 eq.

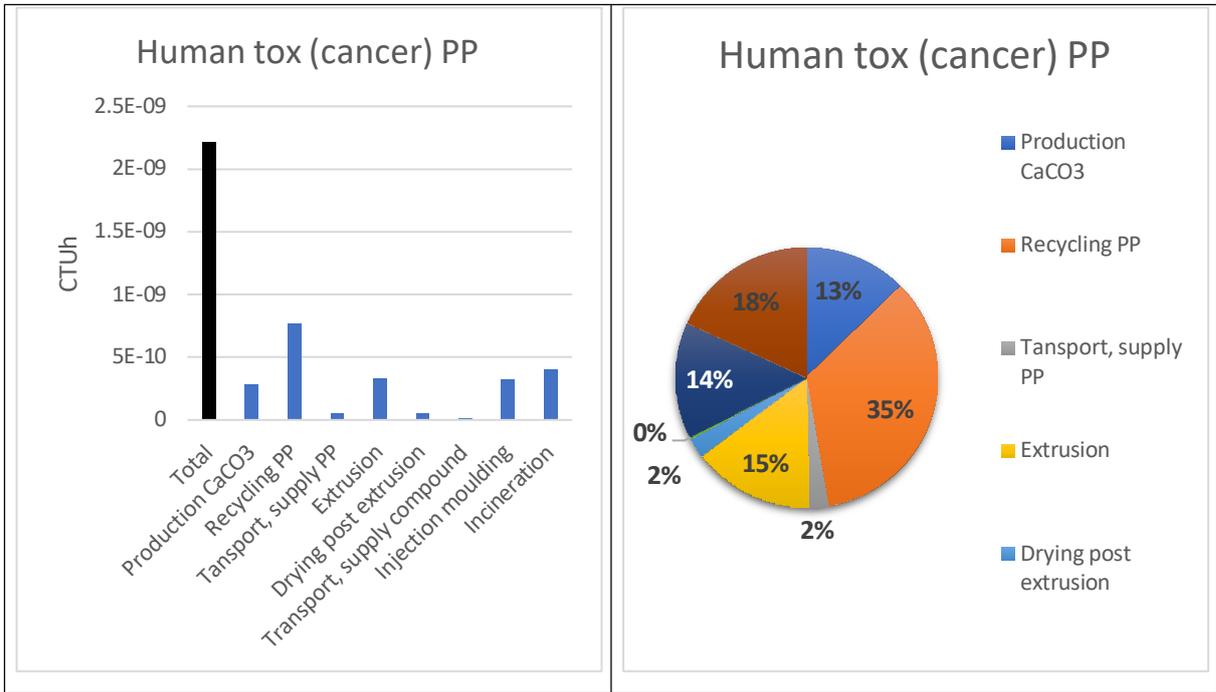
Dissipated Water of the compound with recycled PP and calcium carbonate



The graphs show that the process which requires more water is the injection moulding. It uses alone 73% of the total dissipated water.

The analysis shows that the total dissipated water is equal to 0.07217 m<sup>3</sup> of water eq.

Human toxicity of the compound with recycled PP and calcium carbonate



The total carcinogenic effect is higher than the one of ABS (1.90E-09) and the process that contributes the most to it is the recycling of PP with 35%.

The analysis shows that the total carcinogenic effect is equal to 2.22E-09 CTUh (Comparative Toxic Unit for human).

*Recycled PP with calcium carbonate endpoint indicators*

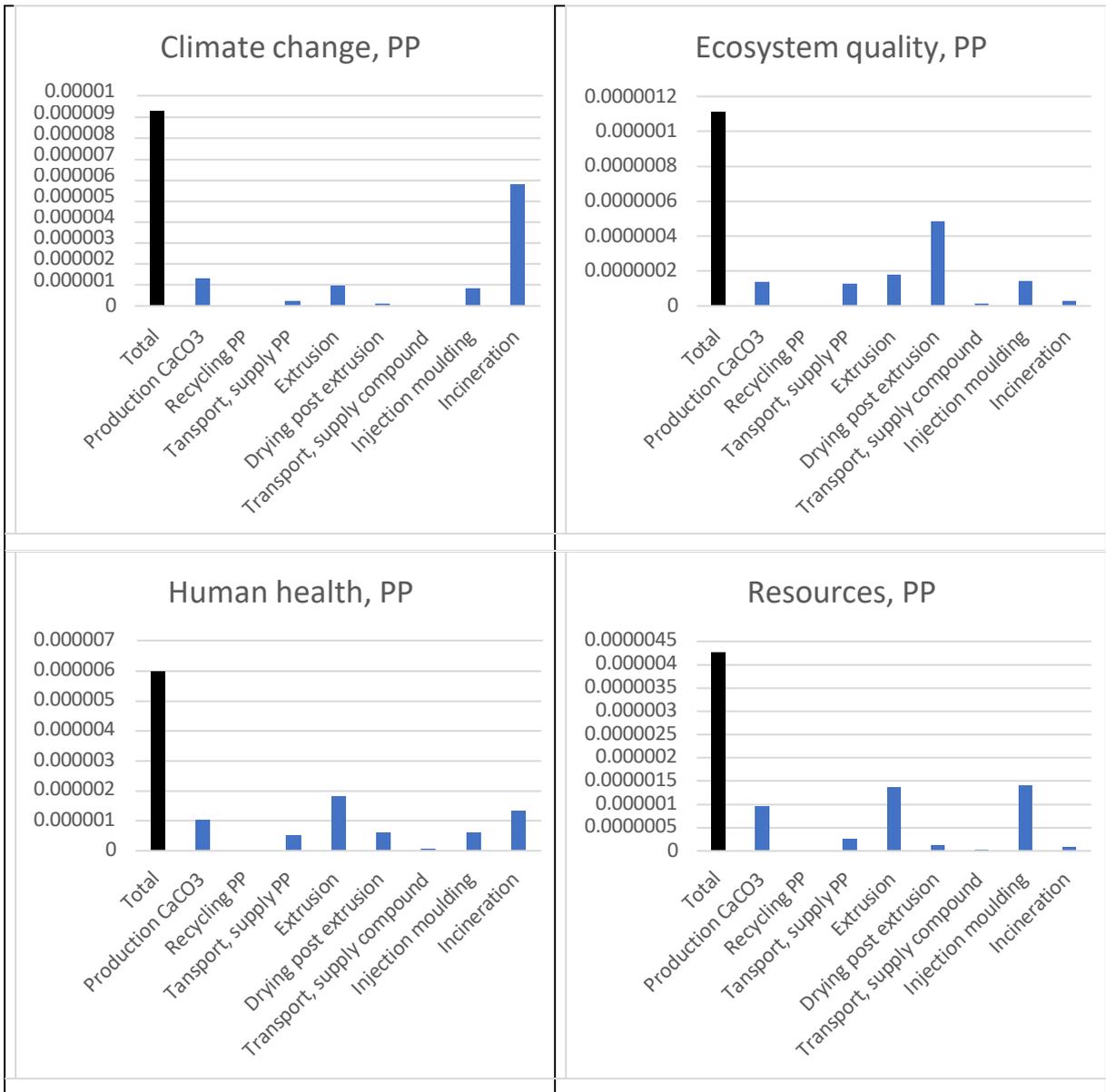
The endpoint results for the compound with PP and calcium carbonate are shown below. Table 10 shows the environmental impacts of the different endpoint indicators for each life cycle stage of the compound with recycled PP and calcium carbonate.

**Table 10: Environmental impacts of the endpoint indicators for the compound with recycled PP and calcium carbonate**

	Climate change	Ecosystem quality	Human health	Resources
Total	9.30962E-06	1.1102E-06	5.99443E-06	4.27826E-06
Production CaCO3	1.31201E-06	1.36069E-07	1.03984E-06	9.6134E-07
Recycling PP	0	0	0	0
Transport, supply PP	2.47636E-07	1.29045E-07	5.14382E-07	2.67912E-07
Extrusion	9.79064E-07	1.78929E-07	1.82094E-06	1.38545E-06
Drying post extrusion	9.81841E-08	4.81903E-07	6.0163E-07	1.24019E-07

Transport, supply compound	3.34884E-08	1.45832E-08	5.9296E-08	3.58284E-08
Injection moulding	8.30053E-07	1.41015E-07	6.25315E-07	1.42378E-06
Incineration	5.80918E-06	2.86549E-08	1.33303E-06	7.99284E-08

A graphical representation of each endpoint follows.



In this case, the phase of the life cycle with the greatest impact is no longer related to the production of the material. For the indicator climate change the incineration phase has the highest impact whereas for the indicators human health and resources the injection moulding process has the highest impact. For the ecosystem quality indicator, on the other hand, the phase with the greatest impact is the post-extrusion drying process.

### 1.3 Compound XI

#### *Compound XI midpoint indicators*

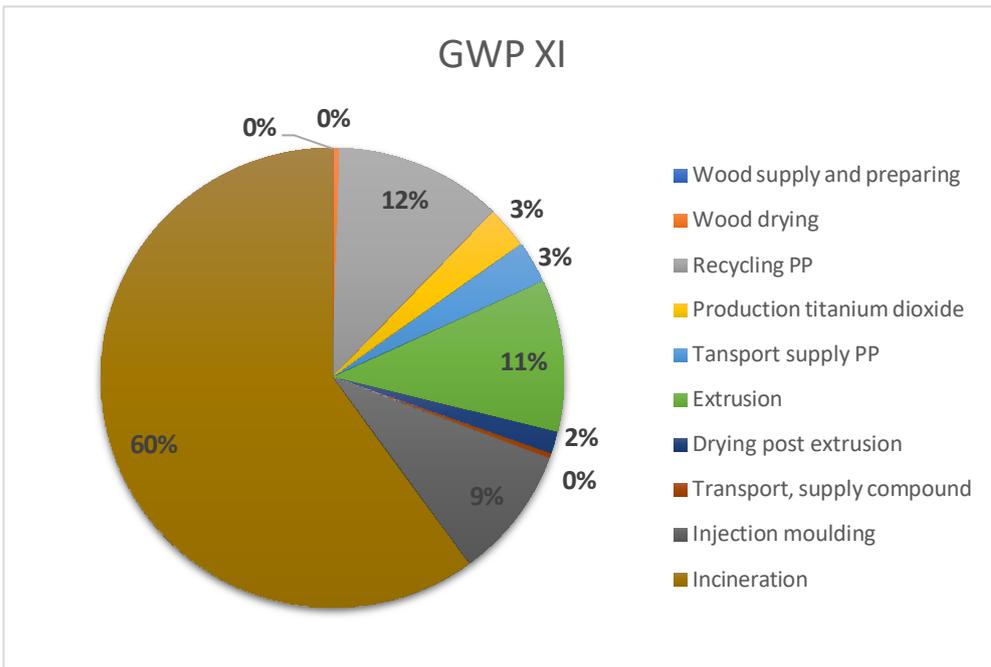
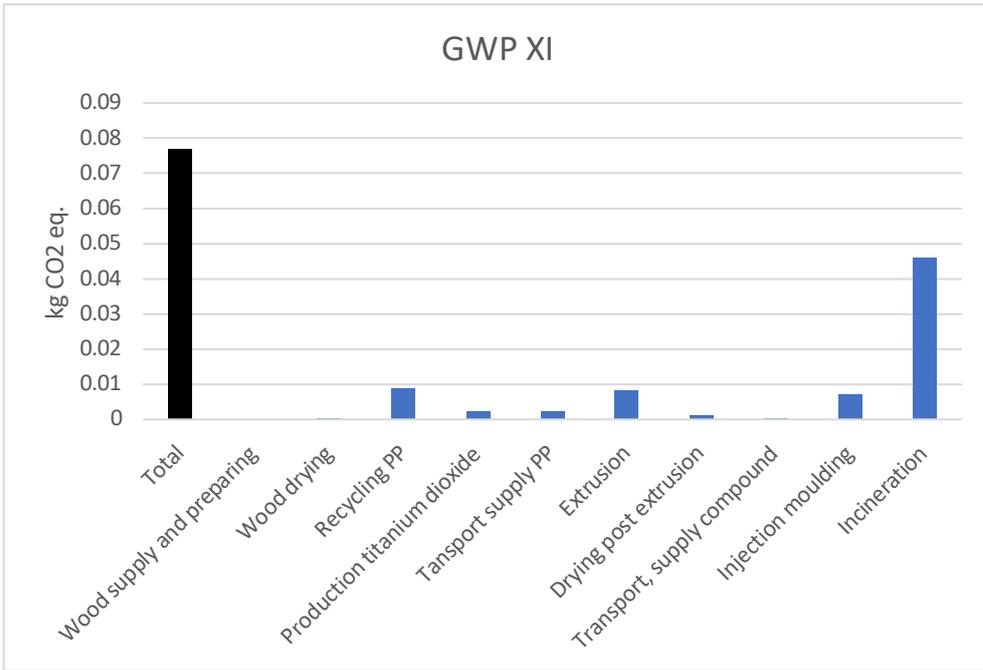
Table 11 shows the environmental impacts of the different midpoint indicators for each life cycle stage of the compound XI.

**Table 11 : Environmental impacts of the midpoint indicators for the compound XI**

	GWP	EP	AP	ODP	Water	Human tox
Unit of measurement	kg CO <sub>2</sub> -Eq	mol N-Eq	mol H <sup>+</sup> -Eq	kg CFC-11-Eq	m <sup>3</sup> water-Eq	CTUh
Total	0.076816596	0.000321635	0.000172918	3.73344E-09	0.058395048	2.25648E-09
Wood supply and preparing	5.18261E-05	4.56E-07	2.80214E-07	3.28081E-12	2.82781E-05	4.96415E-12
Wood drying	0.000375014	1.46664E-05	3.30258E-06	7.23152E-11	0.000321874	2.00628E-11
Recycling PP	0.008968489	4.24959E-05	2.46578E-05	1.13194E-12	0.001200811	6.9235E-10
Production titanium dioxide	0.002277906	2.50516E-05	4.41217E-05	2.39761E-10	0.002570274	5.84562E-10
Transport, supply PP	0.002283004	1.44116E-05	6.34989E-06	5.18938E-10	0.000157516	4.74401E-11
Extrusion	0.008205593	7.56182E-05	4.70134E-05	6.08002E-10	0.010255452	2.63895E-10
Drying post extrusion	0.001192379	4.66327E-05	1.05008E-05	2.29931E-10	0.001023418	6.3791E-11
Transport, supply compound	0.000256549	1.55259E-06	7.07946E-07	5.67581E-11	1.95315E-05	6.26156E-12
Injection moulding	0.007115634	4.72743E-05	2.43709E-05	1.69362E-09	0.041890005	2.5298E-10
Incineration	0.046090201	5.34757E-05	1.16123E-05	3.09702E-10	0.00092789	3.20174E-10

A graphical representation of each midpoint indicator follows. For each indicator, the impacts of the different life cycle stages and the total impact are shown in a column chart. Through a pie chart, the impact of each phase on the total is shown.

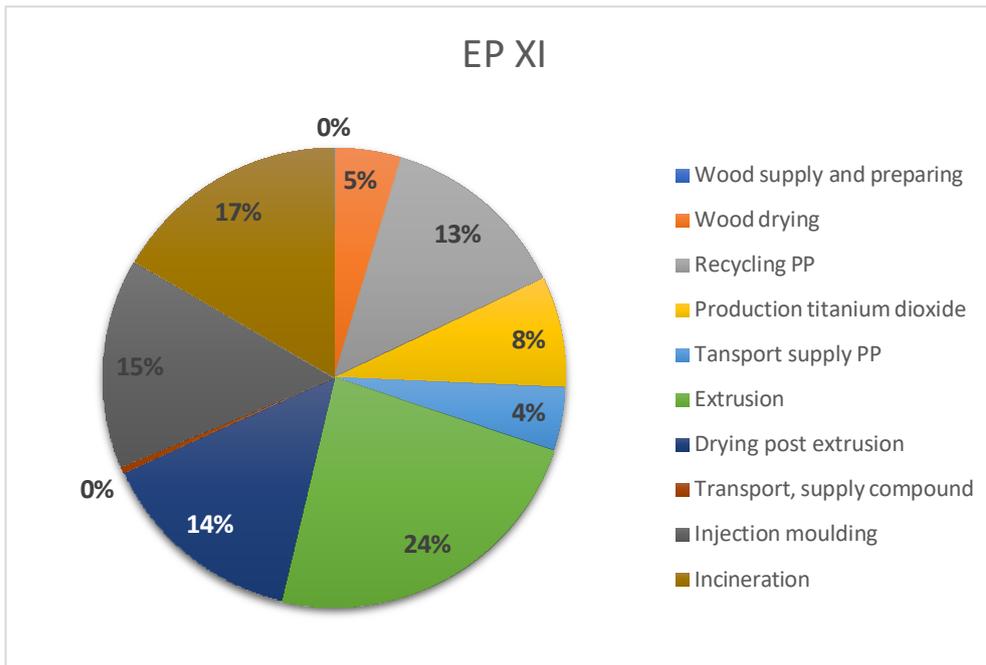
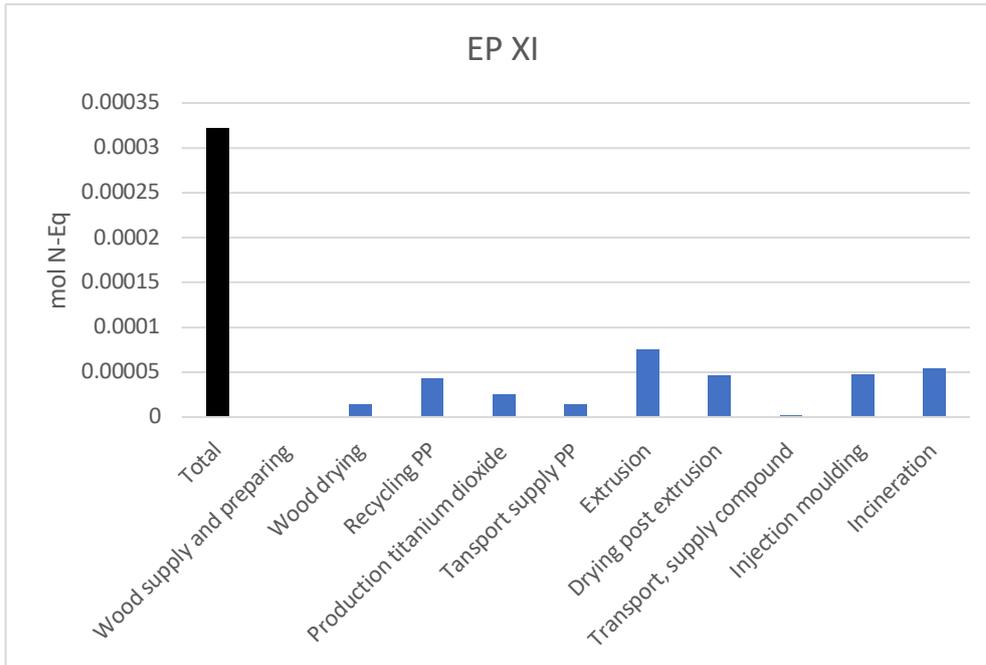
Global Warming Potential of the compound XI



In the graphs it can be observed that the phase with the highest global warming potential impact is the same as for the life cycle of PP with calcium carbonate, it is the incineration phase. This phase accounts for 60% of the total global warming potential impact. The second phase with the highest impact is the injection moulding, 12%. The extrusion process has a similar impact to the injection moulding process and account for 11% of the total GWP impact.

The analysis shows that the total global warming potential is equal to 0.07682 kg CO<sub>2</sub> eq.

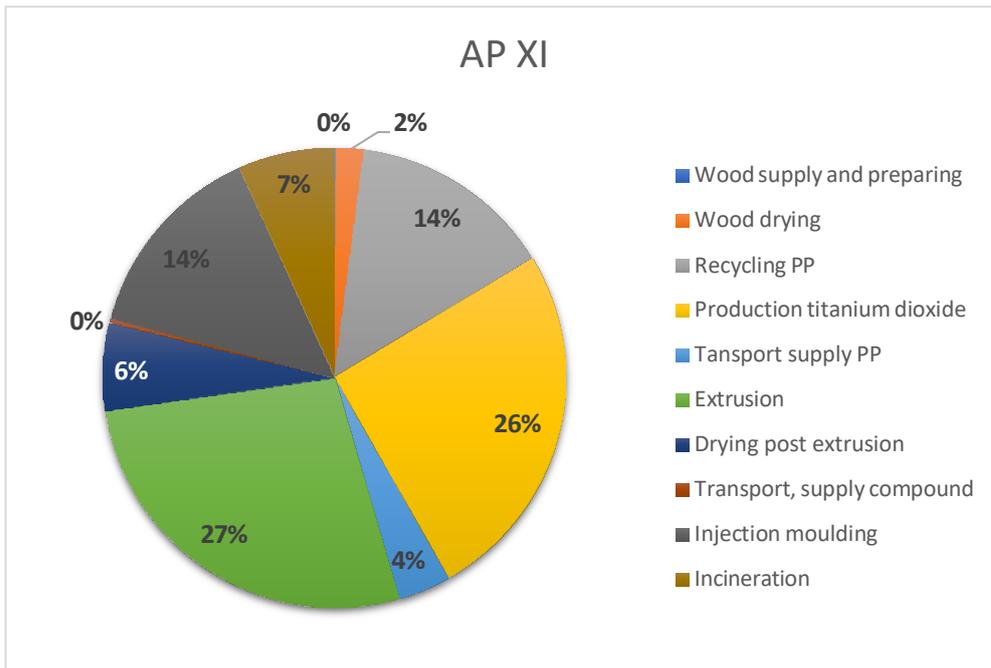
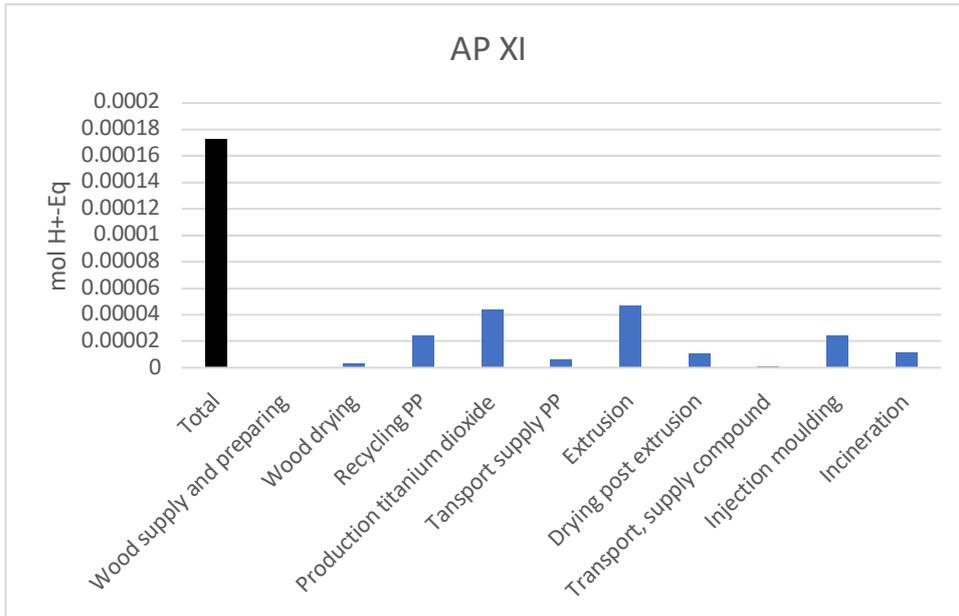
## Eutrophication Potential of the compound XI



The phase which contributes the most for the eutrophication potential is the extrusion with 24% of the total impact. The second phase with the highest impact is the incineration and its impact is similar to the injection moulding and the drying post extrusion. They all have an impact of around 15%

The analysis shows that the total eutrophication potential is equal to 0.00032 mole of N eq.

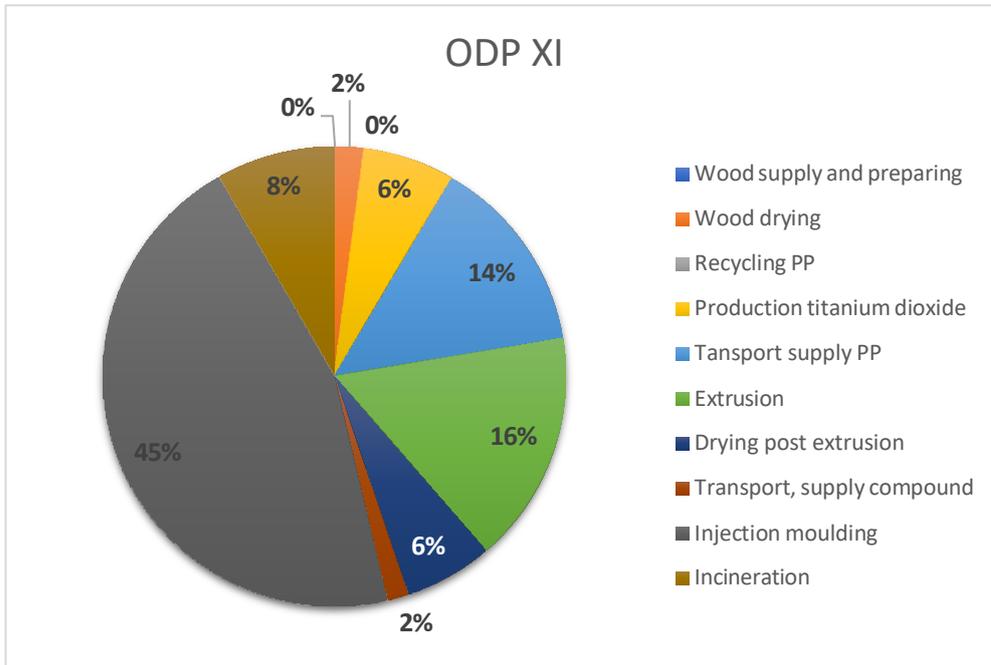
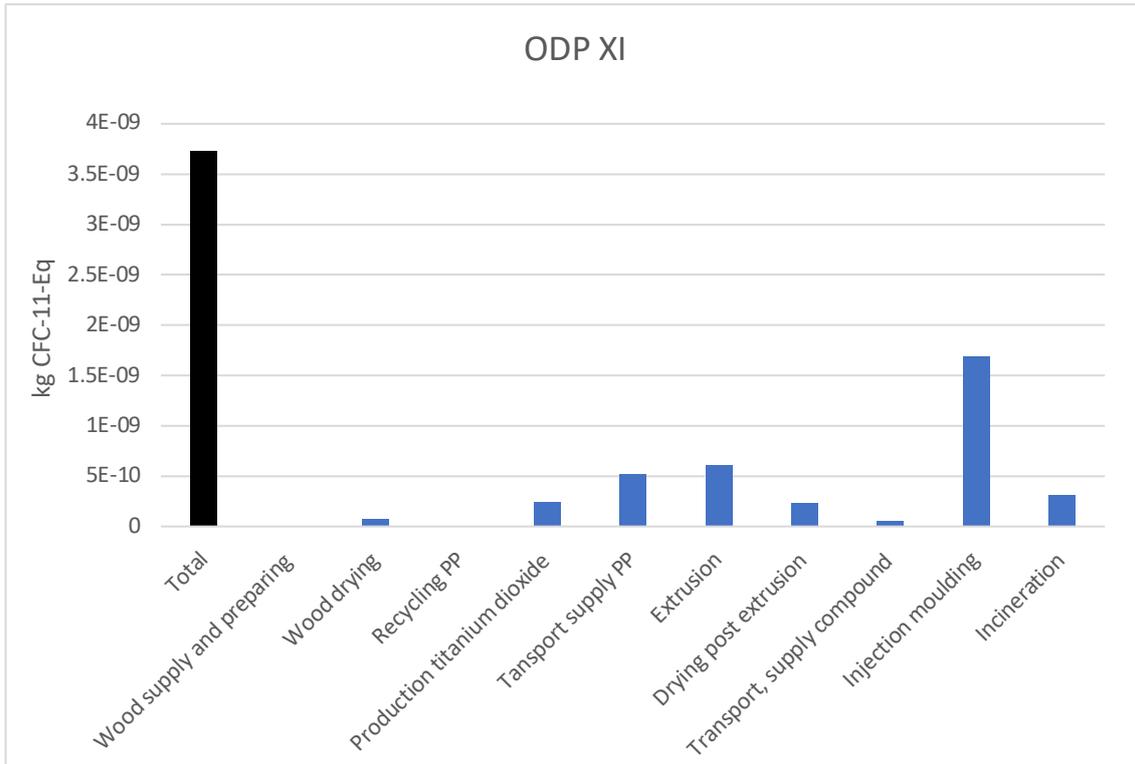
Acidification Potential of the compound XI



The pie chart indicates that extrusion accounts for 27% of the total impact and the production of titanium dioxide has a similar impact, 26% of the total acidification potential.

The analysis shows that the total acidification potential is equal to 0.00017 mole of H<sup>+</sup> eq.

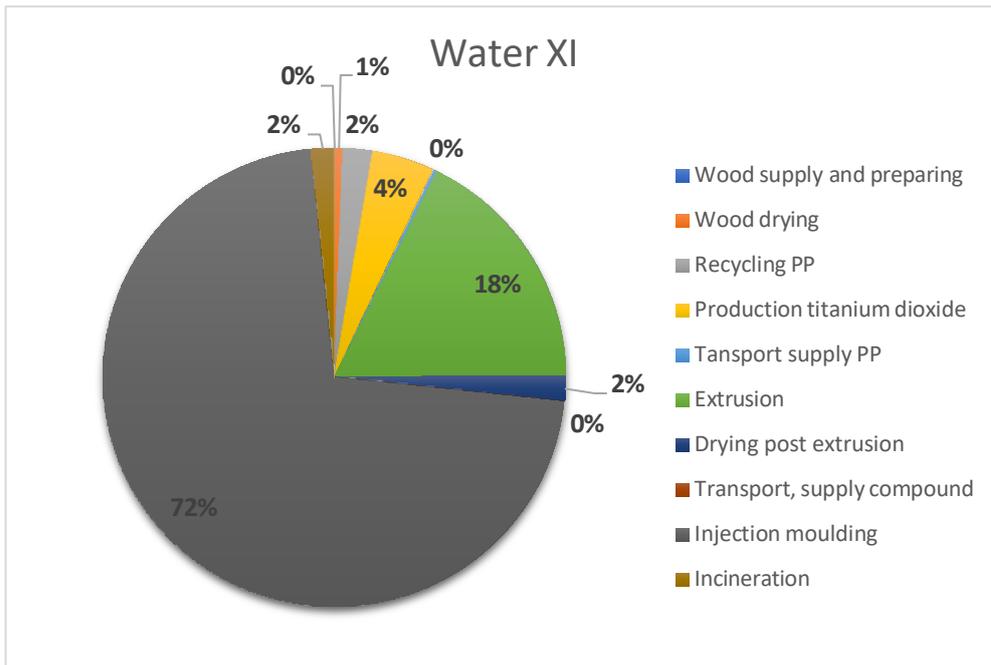
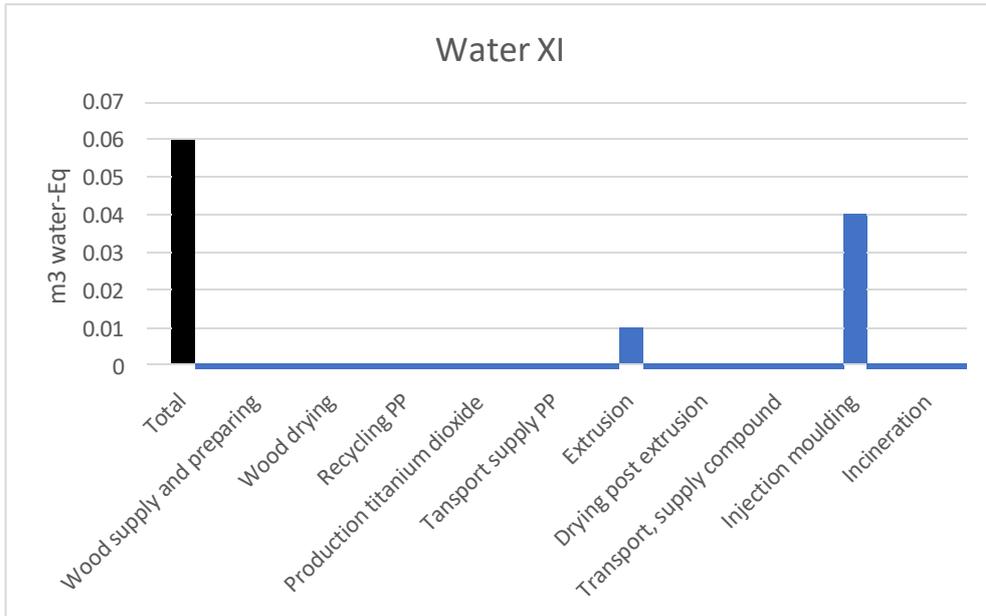
Ozone Depletion Potential of the compound XI



For the ozone depletion, the graphs display that the life cycle phase with the highest impact is also the injection moulding, which accounts for 45% of the total impact.

The analysis shows that the total ozone depletion potential is equal to 3.73E-09 kg of R11 eq.

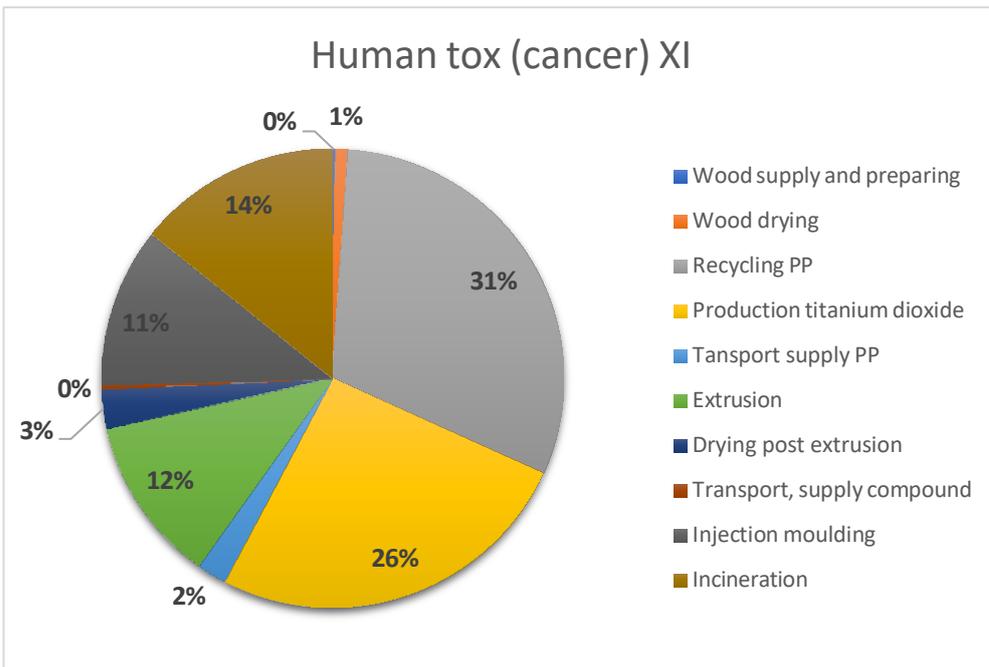
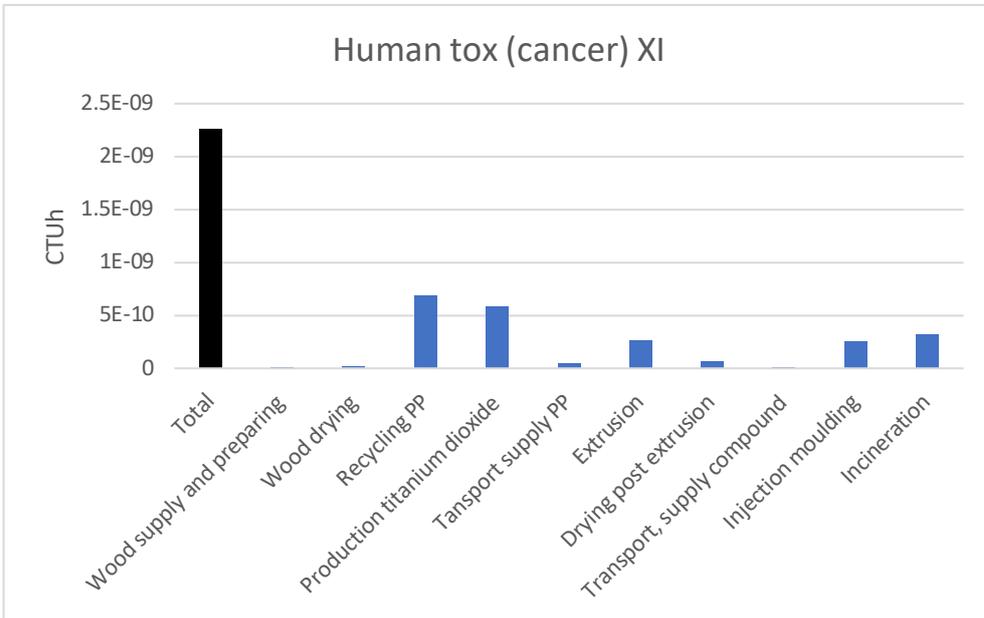
Dissipated Water of the compound XI



The graphs indicate that the two processes which require more water are the same as for the compound with PP and calcium carbonate, they are injection moulding and extrusion. Together they need 90% of the total dissipated water. The high impact in the injection moulding phase is due to the type of energy utilized, hydropower energy.

The analysis shows that the total dissipated water is equal to 0.05840 m3 of water eq.

Human toxicity of the compound XI



The graphs show that the recycling of PP contributes for 31% of the total carcinogenic effect and the production of titanium dioxide for 26%.

The analysis shows that the total carcinogenic effect is equal to 2.26E-09 CTUh (Comparative Toxic Unit for human).

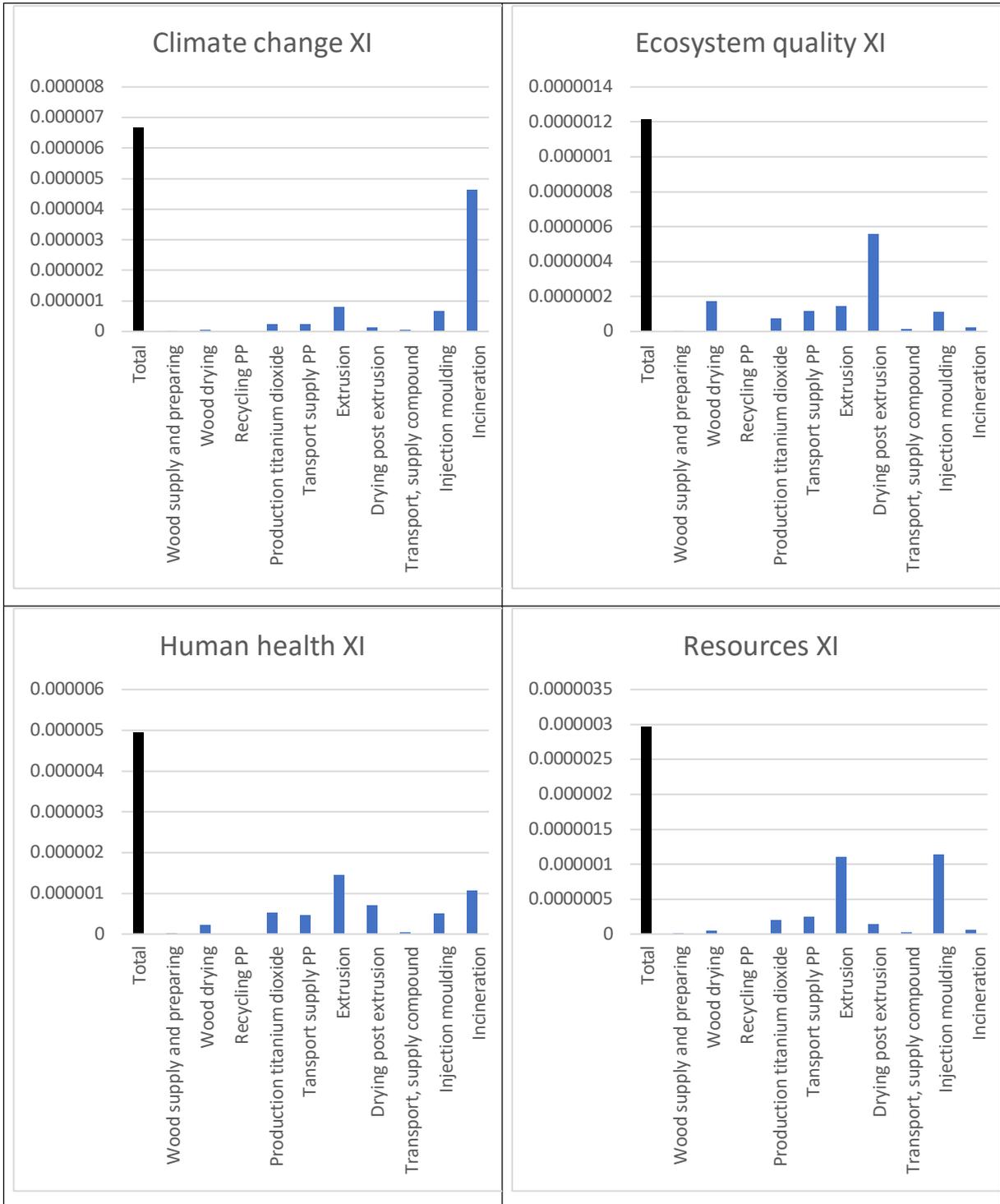
*Compound XI endpoint indicators*

Table 12 shows the environmental impacts of the different endpoint indicators for each life cycle stage of the compound XI.

**Table 12: Environmental impacts of the endpoint indicators for the compound XI**

	Climate change	Ecosystem quality	Human health	Resources
Total	6.67884E-06	1.21158E-06	4.95462E-06	2.97249E-06
Wood supply and preparing	4.93793E-09	7.47015E-10	9.73195E-09	7.37303E-09
Wood drying	3.55853E-08	1.74658E-07	2.18051E-07	4.49488E-08
Recycling PP	0	0	0	0
Production titanium dioxide	2.1652E-07	7.57661E-08	5.1635E-07	2.07625E-07
Transport, supply PP	2.23671E-07	1.16557E-07	4.64603E-07	2.41985E-07
Extrusion	7.79712E-07	1.42496E-07	1.45017E-06	1.10336E-06
Drying post extrusion	1.13146E-07	5.55336E-07	6.93307E-07	1.42917E-07
Transport, supply compound	2.51163E-08	1.09374E-08	4.4472E-08	2.68713E-08
Injection moulding	6.6103E-07	1.123E-07	4.97983E-07	1.13386E-06
Incineration	4.61912E-06	2.27847E-08	1.05995E-06	6.35544E-08

It follows a graphical representation of each endpoint indicator.



The endpoint indicators of the XI life cycle have a similar trend to those of the life cycle of polypropylene with calcium carbonate. The incineration process has also the greatest impact on the CO<sub>2</sub> emissions and the drying post extrusion process on the ecosystem quality indicator. For the indicator resources, the injection moulding process has the highest impact whereas for the indicator human health the extrusion process contributes the most to it.

## 2. Comparison and discussion

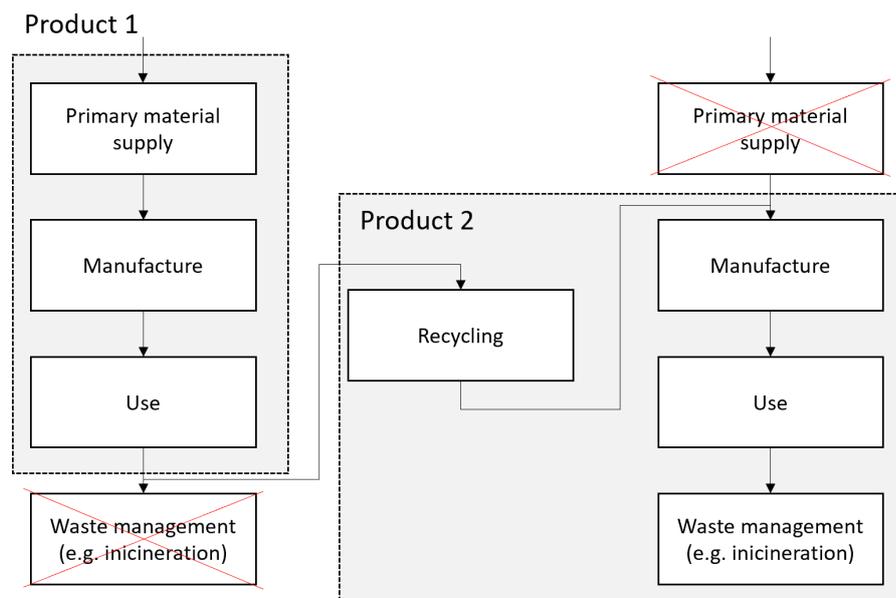
This chapter is meant to present the comparison of the environmental impacts of the three materials analyzed.

Specifically, two separated EoL scenarios are here discussed. In one case the incineration process is the final step for all three model and therefore included. In the other case it is assumed that the materials of the compounds are recycled. In the recycled content approach recycling is the first step of the new life cycle and therefore not included in the current life cycle which stops at the use phase.

**It is important to note that the different impacts for the processes *extrusion, injection molding* and *incineration* for the three different models are only due to the different weights of the three pieces.**

### 2.1 Case 1: incineration process included in all three models

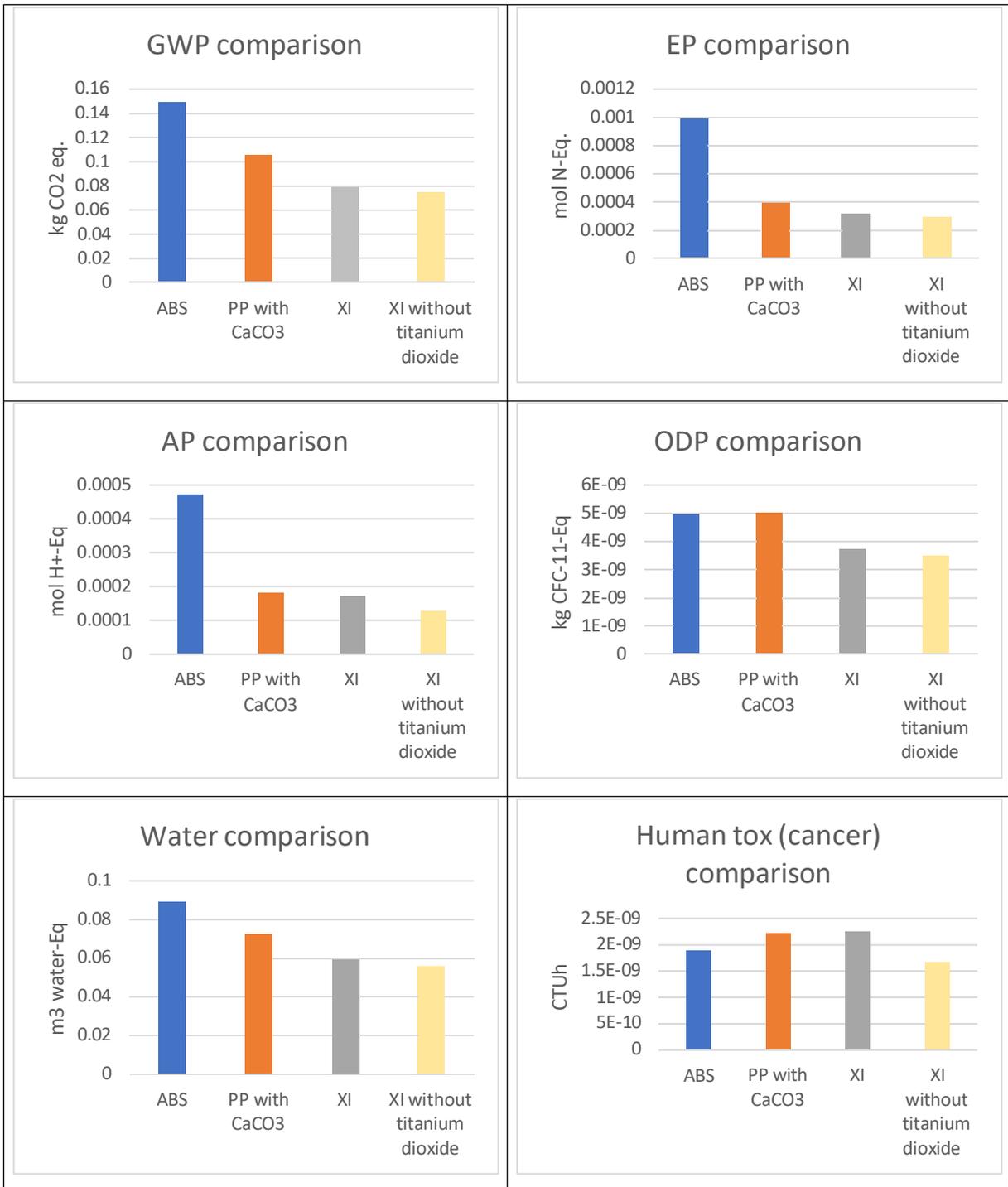
In case 1, the ABS product reflects the product 1 shown in Figure 8, but it also includes the incineration process. The two compounds, on the other hand, follow the processes of product 2 shown in Figure 8 as they are produced mainly from recycled material.



**Figure 8: Processes scheme case 1**

#### 2.1.1 Midpoint

Below are shown the midpoint indicators comparison of the three different materials and of the compound XI without titanium dioxide. It was decided to also compare the compound XI without titanium dioxide since the analyses showed that titanium dioxide contributes substantially to the midpoint indicator human health.



The compound XI has the lowest environmental impact in all midpoint indicators except for the indicator human tox – cancer, where ABS has the minimum impact. For this indicator the compound XI has a 19% higher impact in comparison to ABS. Also, the piece in PP with CaCO<sub>3</sub> has a higher impact in this category than ABS and the value is similar to the one of the compound XI.

For the compound XI, the two processes with the largest contribution to human toxicity are polypropylene recycling with 31% of total impacts and titanium dioxide production with 26% of total impacts. Therefore, the case without titanium dioxide was also analyzed in the study. Titanium dioxide was removed from the composition of compound XI. The weight percentage of titanium dioxide is only 2% of the total product weight.

Anyway, the removal of titanium dioxide from the compound XI significantly changes the overall impact of this indicator, which has in this case a 12% lower impact than ABS.

Another possible cause of the different impact results for the indicator human toxicity is the difference in weight of the three materials. The two compounds have greater weight than the ABS product. Two other processes that contribute substantially to the impacts of this indicator are injection molding and incineration. For these two processes, the only parameter that differs in the three models is weight. In these two processes a greater weight causes greater impacts. Therefore, the difference in weight of materials contributes to vary the impacts of this indicator.

The following table shows the midpoint impacts of the two compounds in comparison to ABS, which is used as reference product. In Table 13 and Table 14, compound XI without titanium dioxide was also included to understand how it would behave.

**Table 13: Comparison of the impact of the midpoint indicators of the two compounds with those of ABS for case 1**

	<b>PP&amp;CaCO3% respect to reference product ABS</b>	<b>XI% respect to reference product ABS</b>	<b>XI% without titanium dioxide respect to reference product ABS</b>
GWP	-29%	-49%	-50%
EP	-59%	-67%	-70%
AP	-61%	-63%	-73%
ODP	+5%	-24%	-29%
Dissipated water	-19%	-35%	-38%
Human tox (cancer)	+17%	+19%	-12%

The two compounds have lower environmental impacts than ABS in most of the impact categories.

The compound XI has more than 60% less environmental impact than ABS in the categories acidification potential and eutrophication potential.

Ozone depletion potential is the category where XI shows the least improvement in comparison to ABS. Anyway, XI has a reduction of 24% in comparison to ABS. On the contrary, the compound with PP and calcium carbonate has an increase of 5% in this category compared to ABS. The injection moulding process accounts for around 40% of the impacts for both materials. The second process with the largest contribution to ozone depletion for the compound with PP and calcium carbonate is the production of calcium carbonate (20%), which is not present in the compound XI.

The two compounds use around 35% less water than ABS. In the life cycle of the ABS product, more than 50% of the water is used to produce ABS.

The climate change impact (GWP) of the compound XI is 49% lower than ABS. Again, the process that contributes most to climate change in the ABS life cycle is ABS production (60%). The other process with a high contribution to the global warming for all three materials is incineration. Incineration is the process with the highest CO<sub>2</sub> emissions for the life cycles of

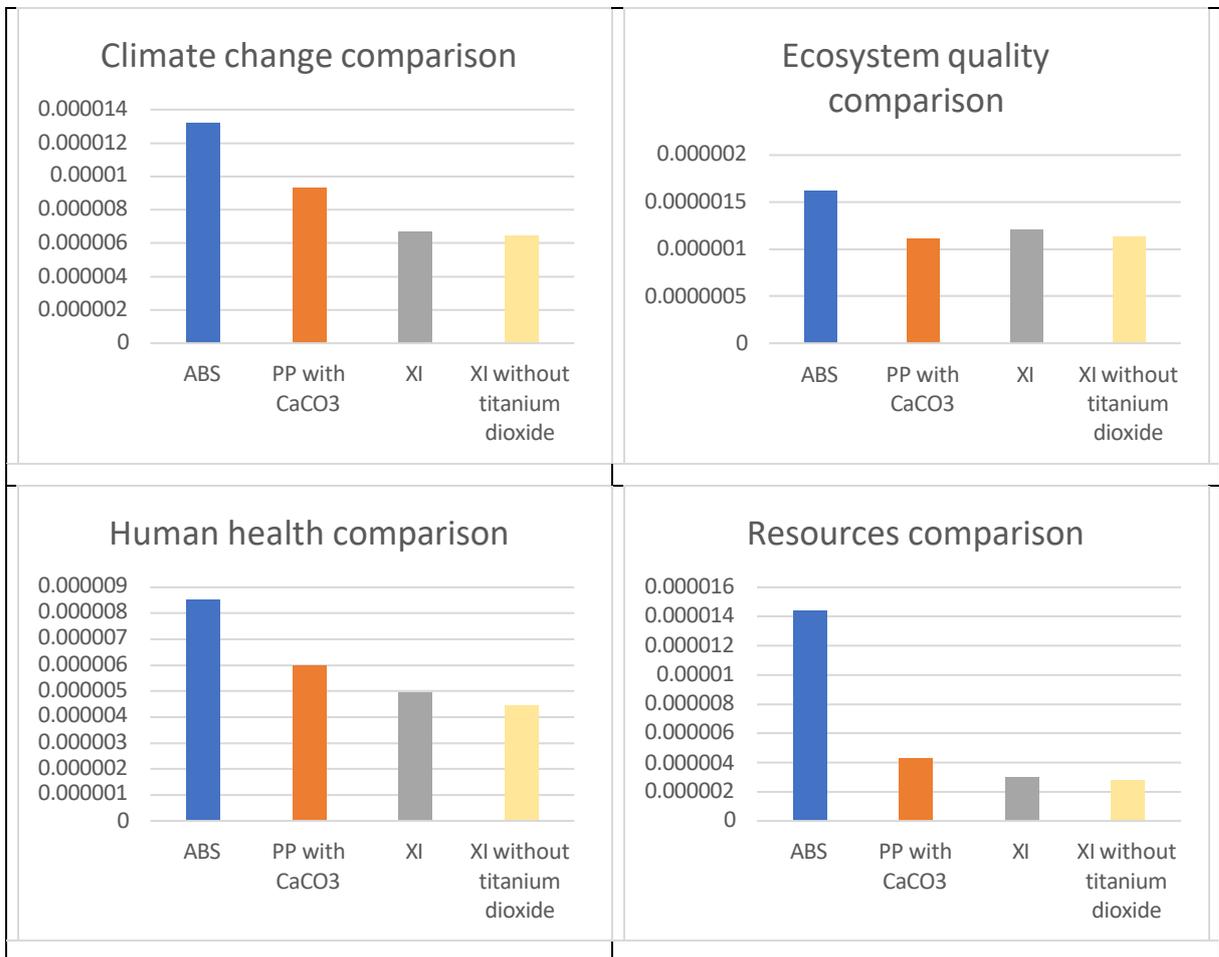
the two compounds. Therefore, recycling the material of the two compounds instead of incinerating it could further reduce the CO<sub>2</sub> emissions.

The removal of titanium dioxide from the compound XI causes a slight improvement in all indicators and changes the ratio of the human tox index in relation to the reference product. With the presence of titanium dioxide in the compound XI the toxicity of the compound was higher than that of the ABS product (+19%). Removing titanium dioxide from the compound XI changes the ratio and in this case the compound also has a favorable impact on the human toxicity indicator compared to ABS (-12%).

The compound with recycled polypropylene and calcium carbonate has a similar impact as the compound XI for the indicator human tox. In the case of the XI compound, human tox is the only indicator with a greater impact than the ABS product. For the compound with recycled polypropylene and calcium carbonate, however, the ozone depletion potential also shows a slightly higher impact (5%) than the product in ABS. The presence of calcium carbonate in the compound contributes substantially to this result.

### 2.1.2 Endpoint

Below are shown the endpoint indicators comparison of the three different materials and the compound XI without titanium dioxide.



The following table shows the endpoint impacts of the two compounds in comparison to ABS, which is used as reference product.

**Table 14: Comparison of the impact of the endpoint indicators of two compounds with those of ABS for case 1**

	PP&CaCO3% respect to reference product ABS	XI% respect to reference product ABS	XI% without titanium dioxide respect to reference product ABS
Climate change	-29%	-49%	-51%
Ecosystem quality	-32%	-25%	-30%
Human health	-30%	-42%	-48%
Resources	-70%	-79%	-81%

The major improvement of the compound XI in comparison to ABS is that 79% less resources are used.

The compound XI has also almost 50% less impact than ABS on the climate change. One midpoint alone contributes to this category, the global warming with units of kg CO<sub>2</sub> eq.

The compound XI shows an improvement also for the categories ecosystem quality and human health.

The results show that the compound XI has better environmental impacts in almost every impact category. Therefore, the compound XI can be a better material choice for the toys.

## 2.2 Case 2: incineration process included only in the ABS model

In case 2, the AS-IS state of the ABS product and a possible future scenario for the two compounds are considered. The incineration process is included in the life cycle of the ABS product, as is currently the case. A future scenario is instead hypothesized for the two compounds. A possible next step in the future is to recycle the material instead of incinerating it. Therefore, the incineration process is not included in the life cycle of the two compounds. This scenario is shown by product 2 in Figure 9.

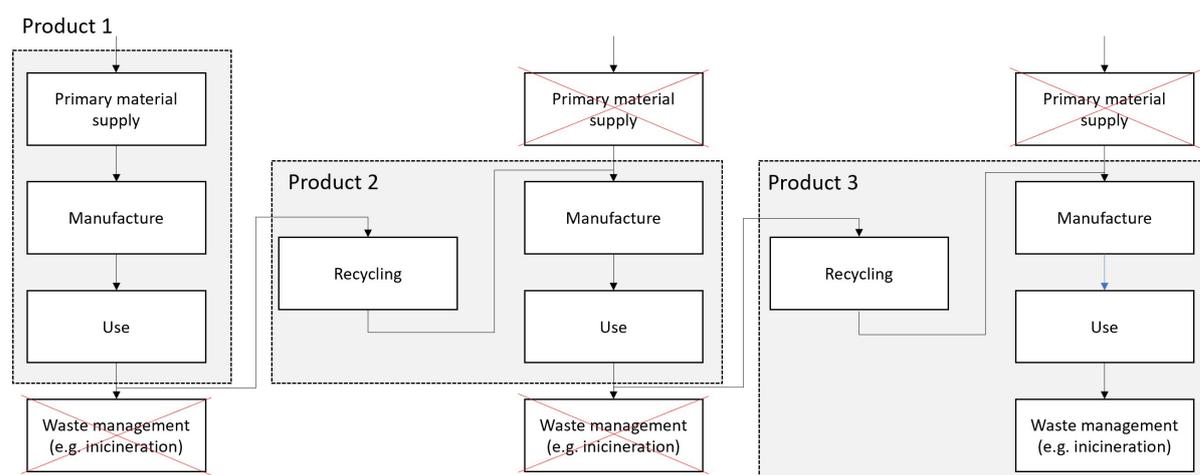


Figure 9: Processes scheme case 2

In this case it is assumed that at the end of life the compounds are recycled and not incinerated. The recycling phase is the first phase of the following life cycle (Product 3) and therefore not included in the considered life cycle (product 2 in Figure 9) as end of life.

The following tables show the midpoint and endpoint impacts of the two compounds in comparison to ABS.

Table 15: Comparison of the impact of the midpoint indicators of the two compounds with those of ABS for case 2

	PP&CaCO3% respect to reference product ABS	XI% respect to reference product ABS	XI% without titanium dioxide respect to reference product ABS
GWP	-68%	-79%	-81%
EP	-66%	-73%	-75%

AP	-64%	-66%	-75%
ODP	-3%	-30%	-35%
Dissipated water	-21%	-36%	-39%
Human tox (cancer)	-4%	+2%	-29%

**Table 16: Comparison of the impact of the endpoint indicators of two compounds with those of ABS for case 2**

	<b>PP&amp;CaCO3% respect to reference product ABS</b>	<b>XI% respect to reference product ABS</b>	<b>XI% without titanium dioxide respect to reference product ABS</b>
Climate change	-73%	-84%	-86%
Ecosystem quality	-33%	-27%	-31%
Human health	-45%	-54%	-60%
Resources	-71%	-80%	-81%

For the midpoint and endpoint, the indicator with the greatest improvement is climate change. The removal of the incineration phase from the life cycle of the compound XI lowered the CO<sub>2</sub> emissions, which are now 84% lower for the endpoint than the ABS life cycle.

Another midpoint indicator that shows a considerable improvement is the human tox indicator which has now almost the same impact as the ABS product.

### 3. Conclusion

The study analyzed and compared the environmental impacts of three different materials to understand which material has the least ecological impact. The three materials which were analyzed are: acrylonitrile butadiene styrene (ABS), the compound composed of recycled polypropylene (PP) and calcium carbonate, and the compound composed of recycled polypropylene and wood (XI).

Each material was analyzed according to its life cycle with the cradle-to-grave approach. The steps from raw material extraction through to final disposal were considered with exception of the distribution and use steps which were excluded from the study.

The study includes the analysis of six midpoint indicators using the "EF2.0 midpoint" method and four endpoint indicators using the "Impact2002+ endpoint" method.

Two scenarios were evaluated in the analysis. The first scenario includes the incineration process in all three models. While the second scenario only includes the incineration process in the ABS model. In this second case, it is assumed that the materials of the two compounds are recycled and not incinerated. According to the "recycled content approach", the recycling of the material is attributed to the next life cycle in which the material will be used and therefore has no impact in the current life cycle.

For the first scenario the analysis shows that for the ABS life cycle, the material production is the phase with the greatest ecological impact in all four endpoint indicators and also in five out of six midpoint indicators (except for the indicator ozone depletion). For the midpoint indicators, the material production accounts between 50% and 62% of the total impacts, except for the ozone depletion. The indicator ozone depletion potential is the only indicator that shows a different proportion. For this indicator, the life cycle phase with the greatest impact is the injection moulding, which accounts for 33% of the total impacts, whereas the ABS production accounts for 27% of the total impacts.

In the first scenario, for the model of the compound composed of recycled polypropylene and calcium carbonate, the injection moulding has the highest impact for two midpoint indicators which are: ozone depletion and dissipated water. The injection moulding accounts between 14% and 73% of the total impacts. For global warming the life cycle stage with the greatest impact is incineration (55%). Polypropylene recycling, on the other hand, has the greatest impact on the human tox indicator and accounts for 35% of the total impact.

In this model, injection moulding has the greatest impact on the resources. For the climate change the incineration phase accounts for most of the impacts and for the indicator ecosystem quality the drying process after the extrusion process has the highest impacts. Extrusion is also the process that has the highest impact on human health.

The last analyzes model in the first scenario is the compound XI, which is composed of recycled polypropylene and wood fibers. It shows a trend of indicators like the model of the compound composed of recycled polypropylene and calcium carbonate. The difference is that for this model the impacts are lower than for the other compound. For the human tox indicator, the recycling process has the highest impact and accounts for 31% of the total impacts. In this case there is another phase with a high impact which is the production of titanium dioxide. It accounts for 26% of the total impacts. In the compound XI, titanium dioxide represents 5% by

weight of the material. Despite the low percentage of titanium dioxide, this has an important effect on the human tox indicator.

A comparison of the three models was also carried out. The two compounds have lower environmental impacts than ABS in most of the midpoint impact categories.

The comparison of the impacts of the three materials shows that the compound XI has the lowest environmental impact in all midpoint indicators except for the indicator human tox – cancer. For this indicator the compound XI has a 19% higher impact in comparison to ABS and also the other compound shows a 17% higher impact compared with ABS. A critical element identified in the compound XI for this indicator is titanium dioxide. The removal of titanium dioxide from the compound XI significantly changes the overall impact of human tox, resulting in a 12% lower impact than ABS.

Ozone depletion potential is the category where XI shows the least improvement in comparison to ABS. Anyway, XI has a reduction of 24% in comparison to ABS. On the contrary, the compound with recycled polypropylene and calcium carbonate has an increase of 5% in this category compared to ABS.

One important note is that the different impacts of extrusion, injection molding and incineration of the three different models are only due to the different weights of the three pieces.

In the second scenario, the removal of the end-of-life phase (incineration) in the two compounds has a significant impact on the global warming potential. The endpoint climate change impact of the compound XI is 84% lower than the one of ABS and the one of the compound with recycled polypropylene and calcium carbonate is 73% than ABS.

The study showed that from an ecological point of view the use of compound XI might be a better choice for the production of Geomag toys rather than the use of ABS.

Some processes, such as toy distribution, were excluded in the study. Therefore, a possible next step is to add the distribution process into the product life cycle to understand and quantify its impact. The impacts of the distribution process could vary for the three models due to the difference in weight of the three materials.