PLA sorting for recycling

Experiments performed at the National Test Centre Circular Plastics (NTCP)

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Content

Terminology and abbreviations

Term	Explanation
PMD waste	(= plastic, metaal en drankenkarton) Dutch abbreviation for a waste stream containing Plastic, Metal and Beverage carton.
2D fraction	Foils and other 2-dimensional plastic packaging waste.
3D fraction	3-dimensional (not flat) plastic packaging waste.
Ferro materials	Magnetic metals.
Fines	Waste smaller than 40 mm.
NIR installation	Near-infrared installation. This is used to characterise the plastics.
Non-ferro materials	Non-magnetic metals.
NTCP	National Test Centre for Circular Plastics.
PE	Polyethylene. Plastic primarily used for packaging (plastic bags, plastic films and containers.
PET	Polyethylene terephthalate. Plastic used for bottles and containers for food.
PLA	Polylactic acid. Bio-plastic used for variety of packaging like trays or containers.
PP	Polypropylene. Hard plastic used in many applications like jerry-cans, furniture, boats, cars.
Purity	The share of target waste in the waste stream. E.g. share of PLA in the PLA stream.
Tetra	Material used for beverage cartons.
Yield	The share of the plastic that ends up in the correct stream.

Summary

Introduction

Bioplastic, if produced sustainably, can contribute to the transition to a circular economy, especially when these plastics are recycled as much as possible. BioPE and BioPET are automatically sorted and recycled together with fossil PE and PET in the current recycling system for plastic packaging. After bioPE and bioPET, PLA (polylactic acid) is the third bioplastic on the market in volume. PLA is a bioplastic that can be used for the production of a variety of packaging, for example meat trays and packaging for vegetables and fruit. In the current recycling system for consumer packaging waste in the Netherlands and other countries, PLA is not sorted out and recycled automatically.

It was concluded in a previous study by CE Delft, (2019) that, in theory, sorting out of PLA packaging waste in plastic sorting installations and mechanical or chemical recycling of the sorted out PLA can be interesting, both from an economic and an environmental perspective. CE Delft estimated that the climate impact of mechanical or chemical recycling of PLA is lower than of conventional processing routes like composting or combustion (CE Delft, 2019). The share of PLA in the mix of packaging has to increase to 1 to 5% to make the sorting of PLA economically feasible for industrial sorting installations (CE Delft, 2019).

However, these conclusions are somewhat uncertain because the effectivity of sorting out PLA with a Near Infrared (NIR)-installation is not yet tested in Dutch sorting installations with Dutch packaging waste. To tackle these uncertainties, a PLA sorting experiment is performed in the National Test Centre for Circular Plastics (NTCP) in Heerenveen. This installation is built as a model for Dutch sorting installations. The experiment focused on 3D PLA materials, so no PLA foils are investigated.

The main research question for the experiment is:
How well can 3D PLA be sorted out of Dutch PMD waste with a higher share of PLA and how does this affect other sorted out plastic streams (especially PET)?

Based on stakeholder interviews and literature research we also looked at the possibilities for actual recycling of the sorted PLA.

Experimental set-up

The testing line of the NTCP resembles the testing line of industrial plastic sorting plants in the Netherlands. It contains all the sorting steps that can be found in an industrial size installation. An optical sorter with NIR and visual camera's is used to sort out plastic by material type. Experiments are performed with both source-separated PMD waste and post-consumer separated PMD waste, which is obtained from Omrin (a waste management company with an industrial plastic sorting plant).

Two different sorting sequences are used to investigate which sorting sequence is optimal: one sequence with PLA sorted out *after* PET and one sequence with PLA sorted out *before* PET.

The source-separated PMD waste contains 5% PLA and the post-consumer separated PMD waste contains 4% PLA. This higher volume of PLA is reached by adding PLA packaging material to the waste and by mixing this with the waste. Four types of PLA packaging materials are used, shown in Figure 1.

Figure 1 - PLA packaging types

Transparent cup (0.0086 kg)	Transparent lid (0.0031 kg)	Transparent tray (0.0142 kg)	Green tray (0.0174 kg)
			

Main results experiment

Several results are interesting: the PLA yield (share of PLA, which is sorted out correctly), the purity of the PLA stream (share of PLA in the PLA stream) and the pollution of PLA in the PET stream (share of PLA in the PET stream). The results for these parameters are summarised in Table 1.

Table 1 – Summary of main results

	Experiment A-2	Experiment A-3	Experiment B-2	Experiment B-3
	Source-separated	Source-separated	Post-consumer separated	Post-consumer separated
	PLA sorting ***after*** PET, PE, PP	PLA sorting ***before*** PET, PE, PP	PLA sorting ***after*** PET, PE, PP	PLA sorting ***before*** PET, PE, PP
Yield PLA	73%	75%	78%	76%
Purity PLA	91%	92%	95%	94%
PLA pollution in PET stream	0.96%	0.03%	0.91%	0.02%
PLA pollution in PP stream	1.09%	0.03%	0.25%	0.00%
PLA pollution in PE stream	0.91%	0.00%	0.53%	0.47%

The PLA yield depends on the type of packaging. The yield is lower for lids and higher for cups and trays. A large share of lids and the trays (10-19%) end up in the lights stream since it is blown out by the wind shifter. Furthermore, a large share of the lids and cups (19-28%) are not sorted out and end up in the residual stream. The colour of the packaging appears to make no difference in this experiment.

Table 2 presents the conclusions about PLA pollution in other streams. The quantitative results of PLA pollution in the streams come from the experiment. The qualitative assessment of the harm of the pollution are conclusions from literature review and stakeholder interviews.

Table 2 - Summary of conclusions PLA pollution in other streams

	PLA pollution (PLA sorted out *after* PET, PE and PP)	PLA pollution (PLA sorted out *before* PET, PE and PP)	Possibility separation of PLA contamination from stream	Limit pollution PLA in stream without affecting recycling
Based on	Results from experiment	Results from experiment	Literature review and stakeholder interviews	Literature review and stakeholder interviews
PET	0.91-0.96%	0.02-0.03%	Difficult. Sink-float separation is not possible. Separation with an additional NIR installation is an option.	Uncertain. For PET bottles, PLA pollution should be below 0.1%. But this is probably higher for other types of packaging (e.g. trays, lids, cups).
PP	0.25-1.09%	0.00-0.03%	May be possible with sink-float separation.	Pollution tests in Germany have shown earlier that up to 3% PLA in PP recyclate did not have any negative effect on the properties of the recyclate (Hiebel et al., 2017).
PE	0.53-0.91%	0.00-0.47%	May be possible with sink-float separation.	Uncertain.

Conclusions experiment

The main conclusions from the experiment are:

- 73-78% of the PLA waste can be sorted out of the stream, and the PLA sorting efficiency of the NIR installation is 84-92%.
- The yield and sorting efficiency depend on the characteristics of the material. The PLA lids, which have the lowest weight, have the lowest yield (43%) and transparent trays have the highest yield (81%).
- The purity of the sorted PLA stream is 91-95%. These numbers are comparable to results from similar studies by WRAP and Tomra.
- If the PLA share in packaging gets higher more of this PLA will be sorted out in other materials streams. The PLA pollution is the highest in the foil stream (7-20%).
  This happens because PLA material is blown out by the windshifter. All types of PLA packaging end up in the foil stream. The trays (transparent and green) make up 85-90% of the PLA pollution in the foil stream and lids make up 8-13% of the pollution.
  The windshifter separates waste based on weight, not on material type. Therefore, we expect that pollution of the foil stream will also occur with lids and trays made from PET, PE or PP. For the metals, Tetra, PE and PP streams, the maximal PLA pollution is in the range 0.9-1.7%
- The PLA pollution in the PET, PE and PP stream can be reduced significantly when PLA is sorted out before these materials. For example, PLA contamination in the PET stream was reduced from 0.91-0.96% to 0.02-0.03% when PLA is sorted out before PET.

Discussion experiment

In general, the experiment was performed as planned and no major problems occurred which could severely affect the results. Therefore, it is expected that the results of the experiment are realistic and representative. However, every experiment has uncertainties and limitations which may affect the results and the answers to the research questions. The most relevant uncertainties/limitations and their effects on the results are discussed.

It was not possible to quantify these uncertainties, since only one experiment was performed for each configuration.

The most relevant uncertainties are:

- Only one experiment was performed with a relatively small sample of waste compared to industrial sorting plants because of limited budget and time. The limited sample size may affect the content of the waste.
- To both streams, 3D PLA material is added and homogeneously mixed in the waste stream. The PLA material is crushed beforehand. The PLA is clean at the start but due to mixing with other plastics the PLA is slightly contaminated. However, the PLA packaging remains relatively clean compared to the input waste stream as it contains less dirt and moisture. We expect that pollution does not affect the recognition of the material by the NIR installation (Masoumi et al., 2012). However, dirt and moisture increases the weight of the packaging which may affect the results.
- The content of each output stream is characterised manually. Manual characterisation might lead to errors. However, we expect that these errors are very small since the PLA pieces were easily recognisable and the characterisation was performed by two or three people.
- The properties (weight, share of PLA) of the source-separated and post-consumer separated waste were not completely identical (5 and 4%). We expect that the PLA pollution in the other streams increases when the share of PLA increases. Furthermore, we expect that the purity of the PLA stream is affected. Therefore, small differences with between the experiments with source-separated waste and the post-consumer separated can also be caused by differences in the PLA content.

When comparing the results of the experiment to other PLA sorting experiments, we come to conclusion that this report presents the first PLA sorting research results in which PLA cups and trays have been sorted out under real-life conditions with a well-adjusted NIR installation. The only other well-documented experiment, by KNOTEN WEIMAR, was subject to a combination of performance-reducing factors that can explain the substantially lower PLA yield and purity obtained, compared to our experiment.

Future research sorting of PLA

In this research it was investigated how much PLA pollutes other plastic streams. However, it is uncertain how much PLA pollution in these streams is acceptable. Much uncertainty is present about the effects of PLA pollution in other plastic streams on the recyclability of these streams. More research is necessary.

If PLA is introduced in the market, guidelines should be added for design, such that the products produced can be proficiently recycled. In general, Design for Recycling does not only improve the recycling of a plastic, but potentially also improves the quality of the output streams during the sorting process. Further research should focus on these guidelines for PLA products.

The performed sorting experiment had some uncertainties. Future sorting experiments could be performed to tackle these uncertainties and increase knowledge about how well PLA can be sorted out. In future sorting experiments, batches of waste from different sorting companies and different periods in the year could be used to assess whether this affects the results. Furthermore, it could be investigated whether optimisation of the NIR installation affects the results.

Recyclability of PLA

Based on stakeholder interviews and literature research we also looked at the possibilities for actual recycling of the sorted PLA. It is difficult to draw definitive conclusions about the recyclability of PLA in post-consumer waste since this does not happen yet and it depends on several factors regarding the waste like the content, quantity and the sorting and recycling technology. More research and recycling experiments are necessary to be conclusive. We expect that in 1 to 2 years' time it is possible to actually perform recycling tests in installations.

More innovation is necessary by mechanical and chemical recyclers to be able to deal with post-consumer PLA, which will always contain some contaminations. At this moment, only isolated PLA streams, like PLA festival cups, are recycled. Some companies, however, are well on their way to provide some of the necessary innovations. Total Corbion has plans to build a new chemical recycling plant for PLA in France (de Bie (Total Corbion), 2020) and Looplife expects that their new mechanical recycling system, which is planned to be ready end 2021 or beginning 2022, can deal with many of the current challenges and is capable of recycling sorted PLA waste (de Jonghe (Looplife), 2020).

Additionally, sorting PLA out of the waste stream and recycling this PLA is not feasible because of the small share of PLA in the plastic mix. Scaling up of the volumes of PLA in the mix is necessary to start PLA recycling. An efficient way to scale up the volume of PLA, while having the lowest impact on the environment, is stimulating the use of PLA packaging for applications where conventional packaging products cannot be recycled properly (Molenveld (WUR), 2021). In this way, you can increase the share of plastic packaging that can be recycled. It is not logical to replace existing plastic packaging by PLA when this type of packaging can already be easily recycled. Wageningen University & Research is currently investigating which types of packaging could be replaced by PLA (or other bioplastics) (Molenveld (WUR), 2021).

Currently, Looplife is one of the few companies involved in mechanical recycling of PLA. Other companies are not involved yet because of the small market share of PLA. We expect that in time, if the market share increases, Dutch recyclers will begin mechanical recycling of PLA as well.

The interviewed parties (de Bie (Total Corbion), 2020, Molenveld (WUR), 2021), expect that both mechanical recycling and chemical recycling of PLA will occur in the future, but that mechanical recycling will be dominant since this is a cheaper process. Organic recycling of PLA is an option until the PLA volume in the market is high enough for mechanical and chemical recycling of sorted out PLA waste to be feasible (Molenveld (WUR), 2021).

Currently, there are no facilities for chemical recycling of PLA in Europe. Total Corbion only has a chemical recycling plant in Thailand. But they plan to build a new chemical recycling plant for PLA in France (de Bie (Total Corbion), 2020). This can stimulate chemical recycling of PLA in Europe.

Samenvatting

Inleiding

Duurzaam geproduceerde bioplastics kunnen bijdragen aan de transitie naar een circulaire economie, zeker als deze bioplastics zo veel mogelijk gerecycled worden. BioPE en BioPET worden gezamenlijk met fossiele PE en PET uitgesorteerd en gerecycled in het huidige recyclingproces voor plastic verpakkingen. PLA (polymelkzuur) is na BioPE en bioPET het meest gebruikte bioplastic qua volume. Het wordt gebruikt voor de productie van verschillende verpakkingen, bijvoorbeeld vleesschalen of verpakkingen voor groente en fruit.
PLA wordt niet uitgesorteerd en gerecycled in het huidige recyclingsysteem voor consumentenafval, niet in Nederland maar ook niet in andere landen.

In een eerdere studie van CE Delft (CE Delft, 2019) werd geconcludeerd dat het interessant kan zijn om PLA-verpakkingen uit te sorteren in plastic sorteerinstallaties en deze PLA vervolgens mechanisch of chemisch te recyclen, zowel vanuit economisch als duurzaamheid perspectief. CE Delft schat in dat de klimaatimpact van mechanisch of chemisch recyclen van PLA lager ligt dan conventionele verwerkingsroutes zoals verbranding of composteren (CE Delft, 2019). Het wordt economisch rendabel voor industriële sorteerbedrijven om PLA uit te sorteren als het aandeel van PLA in de verpakkingsmix toeneemt naar 1 tot 5% (CE Delft, 2019).

De voorgaande conclusies zijn echter onzeker omdat de effectiviteit van het uitsorteren van PLA met een Near Infrared (NIR)-installatie nog niet was getest in een Nederlandse sorteerinstallatie met Nederlands afval. We hebben een PLA-sorteerproef gedaan in het Nationaal Testcentrum Circulaire Plastics (NTCP) in Heerenveen om deze onzekerheden te verminderen. De sorteerinstallatie van het NTCP is gebouwd als model voor Nederlandse sorteerinstallaties. Bij dit experiment hebben we alleen gekeken naar 3D PLA materiaal, dus niet naar PLA-folies.

De hoofdvraag van het experiment is:
Hoe goed kan 3D PLA uitgesorteerd worden uit Nederlands PMD-afval met een hoger aandeel PLA, en hoe beïnvloedt het hogere aandeel PLA andere uitgesorteerde plasticstromen zoals PET?

Of uitgesorteerde PLA te recyclen is, is besproken in interviews met stakeholders en onderzocht in de literatuur. De voornemens om dit experimenteel te testen zijn niet uitgevoerd omdat dit nog niet mogelijk was in huidige installaties.

Opzet experiment

De testinstallatie van het NTCP komt overeen met de installaties van industriële plasticsorteerders in Nederland. Het bevat dezelfde sorteerstappen als een installatie van industriële grootte. Een optische sorteerder met een NIR-installatie en visuele camera's wordt gebruikt om het plastic uit te sorteren per type. We hebben experimenten uitgevoerd met brongescheiden en nagescheiden PMD-afval van Omrin (een afvalverwerker met een industriële plasticsorteerinstallatie.

Twee verschillende sorteervolgordes zijn toegepast om te onderzoeken welke volgorde optimaal is: een volgorde waarbij PLA uitgesorteerd wordt *na* PET en een volgorde waarbij PLA uitgesorteerd wordt *voor* PET.
Het brongescheiden PMD-afval bevat 5% PLA en het nagescheiden PMD-afval bevat 4% PLA. PLA-verpakking zijn toegevoegd aan de rest van het afval om dit hogere aandeel PLA te krijgen. Vervolgens is alles goed door elkaar gemixt. Vier soorten PLA-verpakkingen zijn gebruikt. Deze zijn te zien in Figuur 1.

Figuur 1 - Soorten PLA-verpakkingen

Doorzichtige beker (0,0086 kg)	**Doorzichtige deksel** (0,0031 kg)	**Doorzichtige schaal** (0,0142 kg)	**Groene schaal** (0,0174 kg)
			

Belangrijkste resultaten experiment

Verschillende resultaten zijn interessant: de opbrengst van PLA (het aandeel van PLA dat correct uitgesorteerd wordt), de zuiverheid van de PLA-stroom (aandeel PLA in de PLA-stroom) en de PLA-vervuiling in overige stromen (aandeel PLA in deze stromen).
De resultaten voor deze parameters zijn samengevat in Tabel 1.

Tabel 1 - Samenvatting van belangrijkste resultaten

	Experiment A-2	**Experiment A-3**	**Experiment B-2**	**Experiment B-3**
	Brongescheiden	Brongescheiden	Nagescheiden	Nagescheiden
	PLA uitsorteren ***na*** PET, PE, PP	PLA uitsorteren ***voor*** PET, PE, PP	PLA uitsorteren ***na*** PET, PE, PP	PLA uitsorteren ***voor*** PET, PE, PP
Opbrengst PLA	73%	75%	78%	76%
Zuiverheid PLA	91%	92%	95%	94%
PLA-vervuiling in PET-stroom	0,96%	0,03%	0,91%	0,02%
PLA-vervuiling in PP-stroom	1,09%	0,03%	0,25%	0,00%
PLA-vervuiling in PE-stroom	0,91%	0,00%	0,53%	0,47%

De opbrengst van PLA is afhankelijk van het soort materiaal. De opbrengst is het laagste voor deksels en hoger voor bekers en schalen. Een groot gedeelte van de deksels en schalen (10-19%) wordt weggeblazen door de windshifter en eindigt in de stroom met lichte materialen. Daarnaast wordt een groot gedeelte van de deksels en bekers (19-28%) niet uitgesorteerd waardoor het in de residu-stroom eindigt. Het lijkt erop dat de kleur van de verpakking geen verschil maakt in dit experiment.

Tabel 2 geeft de conclusies met betrekking tot PLA-vervuiling in andere stromen.
De kwantitatieve resultaten van PLA-vervuiling in de stromen volgen uit het experiment. De kwalitatieve beschouwing van de gevolgen van deze vervuiling volgen uit literatuur-onderzoek en interviews met stakeholders.

Tabel 2 - Samenvatting conclusies PLA-vervuiling in andere stromen

	PLA-vervuiling (PLA uitgesorteerd *na* PET, PE en PP)	PLA-vervuiling (PLA uitgesorteerd voor PET, PE en PP)	Mogelijkheden om PLA-vervuiling te verwijderen uit de stroom	Limiet PLA-vervuiling in stroom zonder dat het recycling beïnvloedt
Gebaseerd op	**Resultaten experiment**	**Resultaten experiment**	**Literatuuronderzoek en interviews met stakeholders**	**Literatuuronderzoek en interviews met stakeholders**
PET	0,91-0,96%	0,02-0,03%	Moeilijk. Zink-drijfscheiding is niet mogelijk. Scheiding met een extra NIR-installatie is een optie.	Onzeker. Voor PET-flessen moet de vervuiling minder zijn dan 0,1%. Maar voor andere verpakkingen (zoals schalen, deksels en bekers) is waarschijnlijk meer vervuiling mogelijk zonder nadelige effecten op het recycling-proces.
PP	0,25-1,09%	0,00-0,03%	Wellicht mogelijk met zink-drijfscheiding.	Testen in Duitsland hebben aangetoond dat tot 3% PLA in het PP-recyclaat geen negatief effect heeft op de eigenschappen van het recyclaat (Hiebel, et al., 2017).
PE	0,53-0,91%	0,00-0,47%	Wellicht mogelijk met zink-drijfscheiding.	Onzeker.

Conclusies experiment

De belangrijkste conclusies van het experiment zijn:

- 73-78% van het PLA-afval kan uitgesorteerd worden en de PLA-sorteerefficiëntie van de NIR-installatie is 84-92%.
- De opbrengst en de sorteerefficiëntie zijn afhankelijk van de karakteristieken van het materiaal. PLA-deksels, die het lichtst zijn, hebben de laagste opbrengst (43%) en doorzichtige schalen de hoogste opbrengst (81%).
- De zuiverheid van de PLA-stroom is 91-95%. Deze cijfers zijn vergelijkbaar met eerdere studies van WRAP en Tomra.
- Als het aandeel van PLA bij verpakkingen hoger wordt, dan eindigt meer van dit PLA in uitgesorteerde stromen van andere plastics. De vervuiling van PLA is het hoogste bij de folies (7-20%) doordat PLA-materiaal weggeblazen wordt door de windshifter.
  Dit gebeurt met alle soorten PLA-verpakkingen. De schalen (zowel doorzichtig als groen) dragen het meest bij aan de PLA-vervuiling bij de folies (85-90%). We verwachten dat de vervuiling van de foliestroom ook plaatsvindt met andere plasticsoorten (PET, PE of PP) aangezien deze scheiding plaatsvindt op basis van gewicht en niet op basis van materiaalsoort. De maximale PLA-vervuiling in de non-ferro, Tetra, PE- en PP-stroom zit in de range 0,9-1,7%.
- De PLA-vervuiling in de PET-, PE- en PP-stroom kan significant verminderd worden door PLA uit te sorteren voor deze materialen. Zo wordt de vervuiling in de PET-stroom bijvoorbeeld gereduceerd van 0,91-0,96% naar 0,02-0,03% als je PLA uitsorteert voor PET.

Discussie experiment

Over het algemeen verliep het experiment volgens plan en waren er geen grote problemen die de resultaten ernstig kunnen beïnvloeden. Daarom verwachten we dat de resultaten van het experiment realistisch en representatief zijn. Toch heeft elk experiment onzekerheden en beperkingen. Zo ook deze. Het was niet mogelijk om deze onzekerheden te kwantificeren aangezien er slechts één experiment uitgevoerd is per configuratie.

De belangrijkste onzekerheden zijn:

- Er is slechts één experiment uitgevoerd met een relatief kleine sample van afval vanwege beperkte tijd en budget. De beperkte grootte van de sample kan invloed hebben op de inhoud van de afvalstroom.
- 3D PLA-materiaal is toegevoegd aan beide afvalstromen (bron- en nagescheiden). Vervolgens zijn het PLA materiaal en de rest van het afval goed gemixt. Het PLA materiaal is verpletterd voor het toegevoegd wordt. Maar het materiaal is nog wel schoon. Het wordt wel lichtelijk vervuild door het mixen van het PLA-materiaal met de rest van het afval, maar het blijft relatief schoon ten opzichte van echt afval. We verwachten dat vervuiling geen effect heeft op de herkenning van materialen door een NIR-installatie (Masoumi et al., 2012). Maar vervuiling en vocht verhogen het gewicht van het materiaal wat wel effect kan hebben op de resultaten.
- De inhoud van elke stroom is handmatig bepaald. Dit kan leiden tot menselijke fouten. Maar we verwachten dat deze fouten beperkt zijn aangezien het PLA-materiaal makkelijk te herkennen was en het bepalen van de inhoud door twee of drie personen gedaan is.
- De eigenschappen (gewicht, aandeel PLA) van het bron- en nagescheiden afval waren niet compleet identiek. Het brongescheiden afval had een hoger aandeel PLA (5%) dan het nagescheiden afval (4%). We verwachten dat de vervuiling van PLA in andere stromen toeneemt als het aandeel PLA in het afval toeneemt. Daarnaast verwachten we dat dit invloed heeft op de zuiverheid van de PLA-stroom. Dit kan kleine verschillen tussen de resultaten van bron- en nagescheiden afval hebben veroorzaakt.

Als we de resultaten van dit experiment vergelijken met andere PLA-sorteerexperimenten, komen we tot de conclusie dat dit het eerste experiment is waarbij PLA-bekers en -schalen uitgesorteerd worden in reallife omstandigheden en met een goed ingestelde NIR-installatie. Het enige andere experiment, van KNOTEN WEIMAR, had last van meerdere factoren die de resultaten negatief beïnvloedden. Deze factoren verklaren de substantieel lagere opbrengst en zuiverheid van PLA in het experiment van KNOTEN WEIMAR ten opzichte van ons experiment.

Vervolgonderzoek uitsorteren PLA

In dit onderzoek is onderzocht in hoeverre PLA andere uitgesorteerde plasticstromen vervuilt. Maar het is nog onzeker hoeveel PLA-vervuiling in deze stromen acceptabel is en wat het effect is van PLA-vervuiling op de recyclebaarheid van deze stromen. Hier is meer onderzoek voor nodig.

Als het marktaandeel van PLA groeit zijn er richtlijnen nodig voor het ontwerp van PLA-verpakkingen, zodat de verpakkingen goed gerecycled kunnen worden. Dit noemen ze 'Design for Recycling'. Dit zorgt niet alleen voor meer recycling van plastic maar kan ook bijdragen aan de kwaliteit van het sorteerproces. Meer onderzoek is nodig voor specifieke richtlijnen voor PLA.

Het sorteerexperiment dat we hebben uitgevoerd had meerdere onzekerheden. In de toekomst zijn meer sorteerexperimenten nodig om deze onzekerheden te onderzoeken en beter te begrijpen hoe goed PLA uitgesorteerd kan worden. Zo kan afval van verschillende bedrijven en verschillende periodes in het jaar gebruikt worden om te onderzoeken of dit de resultaten beïnvloedt. Daarnaast kan onderzocht worden of verdere optimalisatie van de NIR-installatie de resultaten verbetert.

Recyclen van PLA

We hebben gekeken naar de mogelijkheden om het uitgesorteerde PLA te recyclen. Hiervoor hebben we literatuuronderzoek gedaan en stakeholders geïnterviewd. Het is nog niet mogelijk om definitief te concluderen of PLA uit nagescheiden afval goed gerecycled kan worden aangezien dit nu nog niet gedaan wordt en dit van verschillende factoren afhangt, zoals de inhoud van het afval, de hoeveelheid en de techniek die gebruikt wordt voor het uitsorteren en recyclen. Meer onderzoek en recycle-experimenten zijn hiervoor nodig. We verwachten dat het binnen één of twee jaar mogelijk is om dit soort recycle-experimenten uit te voeren.

Meer innovatie bij mechanische en chemische recyclers is noodzakelijk om nagescheiden PLA te kunnen verwerken aangezien dit altijd vervuiling zal bevatten. Op dit moment worden alleen geïsoleerde PLA-stromen, zoals PLA-festivalbekers, gerecycled. Sommige bedrijven hebben al wel flinke stappen gezet om recyclen van nagescheiden PLA mogelijk te maken. Total Corbion heeft plannen om een nieuwe fabriek in Frankrijk neer te zetten voor chemische recycling van PLA (de Bie (Total Corbion), 2020). Looplife verwacht dat hun nieuwe systeem voor mechanische recycling van PLA, die volgend jaar klaar moet zijn, uitgesorteerd PLA kan recyclen (de Jonghe (Looplife), 2020).

Het uitsorteren en recyclen van PLA is op dit moment nog niet rendabel vanwege het kleine aandeel van PLA in de plasticmix. Het marktaandeel van PLA moet opgeschaald worden om PLA-recycling van de grond te laten komen. Een efficiënte manier om de hoeveelheid PLA op te schalen, met de kleinst mogelijke milieu-impact, is het stimuleren van het gebruik van PLA-verpakkingen bij toepassingen waar de conventionele producten niet gerecycled kunnen worden (Molenveld (WUR), 2021). Op deze manier vergroot je het aandeel van plasticverpakkingen dat gerecycled kan worden. Het is niet nodig om verpakkingen die nu al gerecycled worden te vervangen door PLA. Wageningen University & Research (WUR) onderzoekt momenteel welke typen verpakkingen vervangen kunnen worden door PLA (of andere bioplastics (Molenveld (WUR), 2021).

Op dit moment is Looplife een van de weinige bedrijven dat bezig is met mechanische recycling van PLA. Andere recyclingbedrijven zijn hier nog niet mee bezig omdat het marktaandeel PLA nog klein is. We verwachten dat in de toekomst ook andere Nederlandse recyclingbedrijven PLA mechanisch gaan recyclen als het marktaandeel van PLA groeit.

De geïnterviewde partijen (de Bie (Total Corbion), 2020, Molenveld (WUR), 2021) verwachten dat zowel mechanische als chemische recycling van PLA een rol zal spelen in de toekomst, maar dat mechanische recycling dominant zal zijn omdat dit een goedkoper proces is. Organische recycling van PLA is een tussenoptie totdat er genoeg PLA is om mechanische en chemische recycling rendabel te maken (Molenveld (WUR), 2021).

Op dit moment kan PLA niet chemisch gerecycled worden in Europa. Total Corbion heeft alleen een chemische recyclingfabriek in Thailand. Maar ze hebben plannen om een nieuwe chemische recyclingfabriek voor PLA te openen in Frankrijk (de Bie (Total Corbion), 2020). Dit kan het chemische recyclen van PLA in Europa stimuleren.

1 Introduction

1.1 Background

Bioplastic, if produced sustainably, can contribute to the transition to a circular economy, especially when these plastics can be recycled as much as possible. BioPE and also bioPET are automatically sorted and recycled together with fossil PE and PET in the current recycling system for plastic packaging. After bioPE and bioPET PLA is the next bioplastic on the market in volume. PLA is not automatically sorted out and recycled.

PLA (polylactic acid) is a bioplastic that can be used for the production of a variety of packaging, for example meat trays and packaging for vegetables and fruit. Currently the market share of PLA is only 0.1-0.4%, but PLA producer Total Corbion estimates that until 2030 the market share could increase to 10 to 20% of all packaging excluding bottles. For the total consumer packaging market, the share could be 7 to 15% (CE Delft, 2019). Therefore, PLA can contribute to the transition of fossil plastics to bioplastics and to the transition to a circular economy.

Currently, PLA is not sorted out of the waste streams for recycling. In a previous study, CE Delft investigated whether sorting PLA out and recycling is environmentally and economically feasible, by investigating the corresponding costs, profits and environmental benefits (CE Delft, 2019). It was concluded that, in theory, sorting out of PLA packaging waste in plastic sorting installations and chemical recycling of the sorted out PLA can be interesting, both from an economic and an environmental perspective. If the share of PLA in the packaging mix increases to 10%, the potential CO_2-eq. reduction is 16 kton/year compared to waste incineration. The share of PLA in the mix of packaging has to increase to 1 to 5%[1] to make the sorting of PLA economically feasible for industrial sorting installations (CE Delft, 2019).

However, the conclusions of CE Delft, (2019) are somewhat uncertain because the effectivity of sorting out PLA with a Near Infrared (NIR) installation is uncertain in Dutch sorting installations with Dutch packaging waste. The possible advantages of sorting out of PLA, both from an economic and environmental perspective, depend on the following aspects:

- **The PLA yield.** This is the share of the total amount of PLA that ends up in the PLA stream. A higher yield results in more PLA that is sorted out and higher economic and environmental benefits. Furthermore, a higher yield means less PLA pollution in other streams.
- **The purity of the PLA stream.** The quality of the PLA stream depends on the purity, so the pollution of other materials in the PLA stream. Low purity of the PLA stream may affect the PLA recycling. When the purity is too low, additional sorting steps might be necessary.
- **The pollution of other plastic streams by PLA.** Higher shares of PLA in PMD waste can lead to higher PLA pollution in other sorted plastic streams (e.g. PET) which affects the recyclability and value of these streams.

[1] This mainly depends on the development of the market price of lactic acid.

Pollution tests in Germany have shown earlier that up to 3% PLA in PP recyclate and up to 10% in PS recyclate did not have any negative effect on the properties of the recyclate (Hiebel et al., 2017). Furthermore, PLA may be separated from PP and PS with sink-float plastic separation.

PET and PLA cannot be separated with sink-float separation. PLA pollution in the PET stream may affect the recyclability of the PET stream. However, the largest share of the PET stream is currently incinerated in waste incineration plants since the quality of the recycled product is poor and the mass yield is too low when mechanical recycling is applied. It may be possible to recycle a share of the PET trays in the future when additional process steps are added (Thoden van Velzen E.U. et al., 2020). It is uncertain how much PLA pollution in the PET stream is acceptable without affecting the recycling process.

For PET bottles, the PLA pollution should be lower than 0.1% (Alaerts et al., 2018). However, the quality requirements for PET bottles recycling are very high and PET bottles are collected separately with a deposit system, so this does not apply to the source-separated and post-consumer waste investigated in this experiment. For PET trays, the PLA pollution limit is expected to be higher.

Because of the fear of PLA pollution in PET and the uncertainty about the allowed pollution, the PLA pollution in PET is a focus issue of this research. We therefore also investigate a scenario with PLA sorting before PET sorting to try to reduce this pollution.

Some experiments are performed to assess the effectivity of sorting out PLA in other countries, for example in Germany (KNOTEN WEIMAR, 2017). However, no unambiguous conclusions can be drawn from these experiments. Furthermore, no experiments were performed in the Netherlands. Therefore, a sorting experiment has been performed to tackle these uncertainties and increase the knowledge about the waste processing route of PLA in the Netherlands. This experiment focuses on rigids, so only 3D PLA materials are used. PLA foils are not included. The experiment is performed at the National Test centre Circular Plastics (NTCP) in Heerenveen, the Netherlands. The results of this experiment are compared to results of previous PLA sorting experiments, like the experiment in Germany (KNOTEN WEIMAR, 2017).

1.2 Goal and research questions

The report constitutes of two parts. The first part of the report focuses sorting of PLA. An experiment is performed to investigate this. The second part of the report focuses on recycling of PLA, both mechanical and chemical recycling. This part is based on interviews and literature research.

The goal of the sorting experiment of part one is to increase understanding about how well PLA can be sorted out in an industrial sorting installations when the share of PLA in PMD waste increases. Therefore, the main research question of the experiment is:
How well can 3D PLA be sorted out of Dutch PMD waste with a higher share of PLA and how does this affect other sorted out plastic streams (especially PET)?

Several sub-questions will be reviewed to answer the main research question. Additional sub-questions are answered to increase understanding of the sorting process:
- What is the PLA yield?
- What is the purity of the PLA stream?
- What is the PLA pollution in the other output streams?
- What is the impact of changing the sorting sequence in the plastic sorting installation?
- Are the results affected by the type of input waste (either source-separated or post-consumer separated household waste)?
- Are the results affected by the type of PLA packaging?

The main goal of the second part is to investigate the benefits of PLA recycling, how PLA recycling works and investigate the requirement for the quality and purity of the PLA stream. Several expert interviews are conducted for this part.

1.3 Reading guide

The report constitutes of two parts. Chapter 2 to 5 are related to the PLA sorting experiment. Chapter 6 is related to recycling of PLA. The report is built up as follows:
- In Chapter 2, the setup of the experiment at the NTCP is described and the experiment which is performed is explained.
- The main results of the experiments are presented in Chapter 3.
- In Chapter 4 the representativeness of the experiment and uncertainties are discussed and the results are compared to other PLA sorting experiments.
- Chapter 5 constitutes the main conclusions drawn from the results.
- Chapter 6 discusses mechanical and chemical recycling of PLA and requirements for the quality of the PLA stream.

2 Short experimental description

This chapter contains a short description of the experiment. Section 2.1 contains a description of the set-up and Section 2.2 contains a description of the experiments performed with the set-up. A more elaborated description of the experiment is included in in the report of the NTCP in Appendix A.

2.1 Set-up

2.1.1 Testing line

The experiment was performed at the National Test center Circulaire Plastics (NTCP) in Heerenveen, the Netherlands. The NTCP developed a sorting line (as shown in Figure 2) for sorting of plastics which resembles industrial sorting installations in the Netherlands, but on a smaller scale and fully designed and equipped for performing research and tests.
The sorting line consists (among other things) of a screen, windshifter, suspension magnet, ballistic separator and a NIR installation.

In an industrial sorting installation several NIR installations are lined up on the sorting line, one for each material type. In the sorting line of the NTCP only one NIR installation is present. In order to mimic the industrial sorting process the testing line is designed to loop the waste stream. After one full loop, when all the waste has passed the entire installation, the settings of the NIR installation are changed and a different material is sorted out.

Figure 2 - Sorting line NTCP

2.1.2 NIR installation

An optical sorter equipped with a NIR installation and RGB determines the material type of a piece of plastic by measuring its optical spectrum. The optical spectra of all types of plastics that have to be sorted out are present in a database, which is also used by industrial sorting installations. When the measured NIR spectrum is within the threshold of the spectrum of the material which has to be sorted out (as given in the database), the piece of plastic is blown out of the stream.

For this experiment, the producer of the NIR installation added software to separate PLA using an existing PLA database, which is also used by industrial sorting installations.
The software used to recognise and sort out the PLA material is trained based on a generic PLA database and was not specifically trained for the four products in this experiment.

2.1.3 Waste stream

PMD waste streams from an industrial sorting installation (Omrin) are used for the experiment, both source separated and post-consumer separated waste. 212.6 kg (6 big bags) of source separated waste (separated by consumers) and 95.8 kg (3 big bags) of post-consumer sorted waste (separated by machines) is used. Less post-consumer sorted waste was used because of a limited amount of time (consequences are discussed in Chapter 4).

To both streams, 3D PLA material is added and homogeneously mixed in the waste stream. The PLA material is crushed beforehand. The PLA is clean at the start but due to mixing with other plastics the PLA is slightly contaminated. However, the PLA packaging remains relatively clean compared to the input waste stream as it contains less dirt and moisture. In the source separated stream, 5%[2] of PLA was added, and in the post-consumer separated stream 4% of PLA was added. The shares of PLA in the streams differ because of a calculation error. The PLA stream consists of transparent cups, transparent lids, transparent trays and green trays, as shown in Figure 3.

Different types of packaging were chosen with different colour, weight and shape to investigate whether the sorting of PLA is influenced by these factors. For both waste streams, the weight distribution of the packaging types is equal, as shown in Table 3. Not enough material of the transparent lids was present for an equal distribution. Therefore, additional transparent trays were added.

Figure 3 - PLA packaging types

Transparent cup (0.0086 kg)	**Transparent lid** (0.0031 kg)	**Transparent tray** (0.0142 kg)	**Green tray** (0.0174 kg)
			

2 Weight percentage.

Table 3 – Weight distribution PLA packaging types

	Source-separated waste (5% of total weight)	Post-consumer separated waste (4% of total weight)
Transparent cups	24%	24%
Transparent lids	8%	8%
Transparent trays	43%	43%
Green trays	25%	25%

2.2 Experiments

2.2.1 Configurations

Experiments were performed with two batches of PMD waste, one batch with source-separated waste (separated by consumers) as input stream (Experiment A) and one batch with post-consumer separated waste (separated by machines) as input stream (Experiment B).

Three runs are performed with both batches. The same configurations (i.e. sorting line sequences) are used for both batches of waste. The description of the three runs is given below. The summary and the classification of the experiments are given in Table 4. The sorting sequences of the three runs are visualised in Figure 4.

Run 1

In Run 1, the PMD waste stream is used as input. In chronological order, the fractions smaller than 40 mm are sorted with a screen, foils are sorted with a windshifter, ferrometals are sorted with a suspension magnet and 2D fractions are sorted with a ballistic separator. The output (3D fraction) of Run 1 is used as input for Run 2 and Run 3.[3]

Run 2

In Run 2, the output stream of Run 1 (3D fraction) is further sorted into tetra, non-ferro, PET, PP, PE and PLA output streams, respectively, using the NIR[4] installation. In Run 2, the main goal is to get a PLA stream with high purity. Therefore, the PLA is sorted out last.

Run 3

Run 3 is the same as Run 2, except that a different sequence of sorting steps is used. In Run 3, the main goal is to minimise the PLA pollution in other streams, especially the PET stream. Therefore, the PLA is sorted out before PET, PP and PE, respectively.

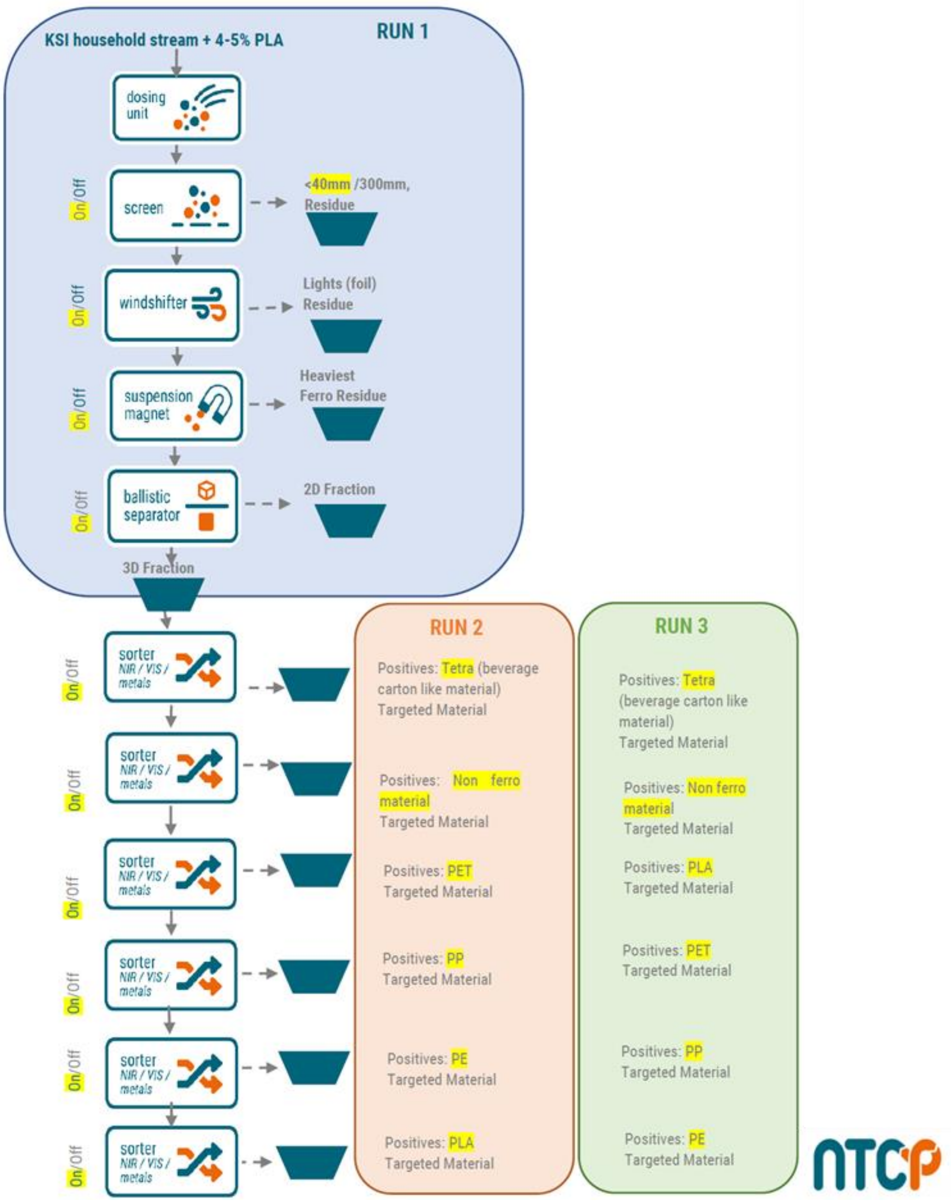
[3] All the output waste streams of Run 2 are mixed manually and used as input for Run 3. Consequentially, Run 2 and Run 3 both use the same waste stream (output of Run 1) as its input.

[4] Near Infrared.

Table 4 – Summary and classification of the experiments

Experiment name	Type of waste	Waste stream	Description of sorting sequence
Experiment A-1	Source-separated	Household waste	Sorting of 2D and 3D fraction
Experiment A-2		3D fraction only (output of A-1)	PLA sorting *after* PET, PE, PP
Experiment A-3			PLA sorting *before* PET, PE, PP
Experiment B-1	Post-consumer separated	Household waste	Sorting of 2D and 3D fraction
Experiment B-2		3D fraction only (output of B-1)	PLA sorting *after* PET, PE, PP
Experiment B-3			PLA sorting *before* PET, PE, PP

Figure 4 - Experimental set-up of three runs. The same setup is used for Experiment A (source-separated input waste) and Experiment B (post-consumer separated input waste)



2.2.2 Measurement method

For each loop, the sorted out material is collected, weighed and investigated. The following measurement steps are performed:

1. The total mass of each stream is measured.
2. The PLA is manually collected from each stream using visual inspection. The four PLA packaging types (as described in Section 2.1.3) are weighed separately.
3. The composition[5] of the non-PLA waste is only categorised for the output stream where PLA is the target material. For the other output streams, the non-PLA waste was not further categorised, as this is not the scope of the research and would be very time consuming.

[5] Foils, lights, ferro, PET, PE, PP, etc.

3 Results

The experiments are performed to investigate how well PLA is sorted out in an industrial plastic sorting installation. This can be determined with the following indicators. The yield of PLA and the purity of the PLA stream indicate whether sorting out of PLA can be profitable. Furthermore PLA can contaminate other plastic streams which can reduce the value of these streams, especially for PET. The most relevant results are summarised in Table 5. The mass balances for all experiments are given in Section 3.1.
The results are discussed in more detail in Section 3.2 to Section 3.5. The results for each output stream for all experiments are given in the NTCP report in Appendix A.

Table 5 – Summary of main results

	Experiment A-2	**Experiment A-3**	**Experiment B-2**	**Experiment B-3**
	Source-separated	Source-separated	Post-consumer separated	Post-consumer separated
	PLA sorting ***after*** PET, PE, PP	PLA sorting ***before*** PET, PE, PP	PLA sorting ***after*** PET, PE, PP	PLA sorting ***before*** PET, PE, PP
Yield PLA	73%	75%	78%	76%
Purity PLA	91%	92%	95%	94%
PLA pollution in PET stream	0.96%	0.03%	0.91%	0.02%
PLA pollution in PP stream	1.09%	0.03%	0.25%	0.00%
PLA pollution in PE stream	0.91%	0.00%	0.53%	0.47%
PLA pollution in foils stream	10.4%	10.4%	10.1%	10.1%
PLA pollution in 2D stream	0.0%	0.0%	1.0%	1.0%
PLA pollution in tetra stream	2.5%	1.3%	0.1%	0.2%
PLA pollution in metals stream	0.5%	0.1%	0.0%	0.2%

3.1 Mass balance

Figure 5 - Results (mass balance) of Experiment A (source-separated waste)

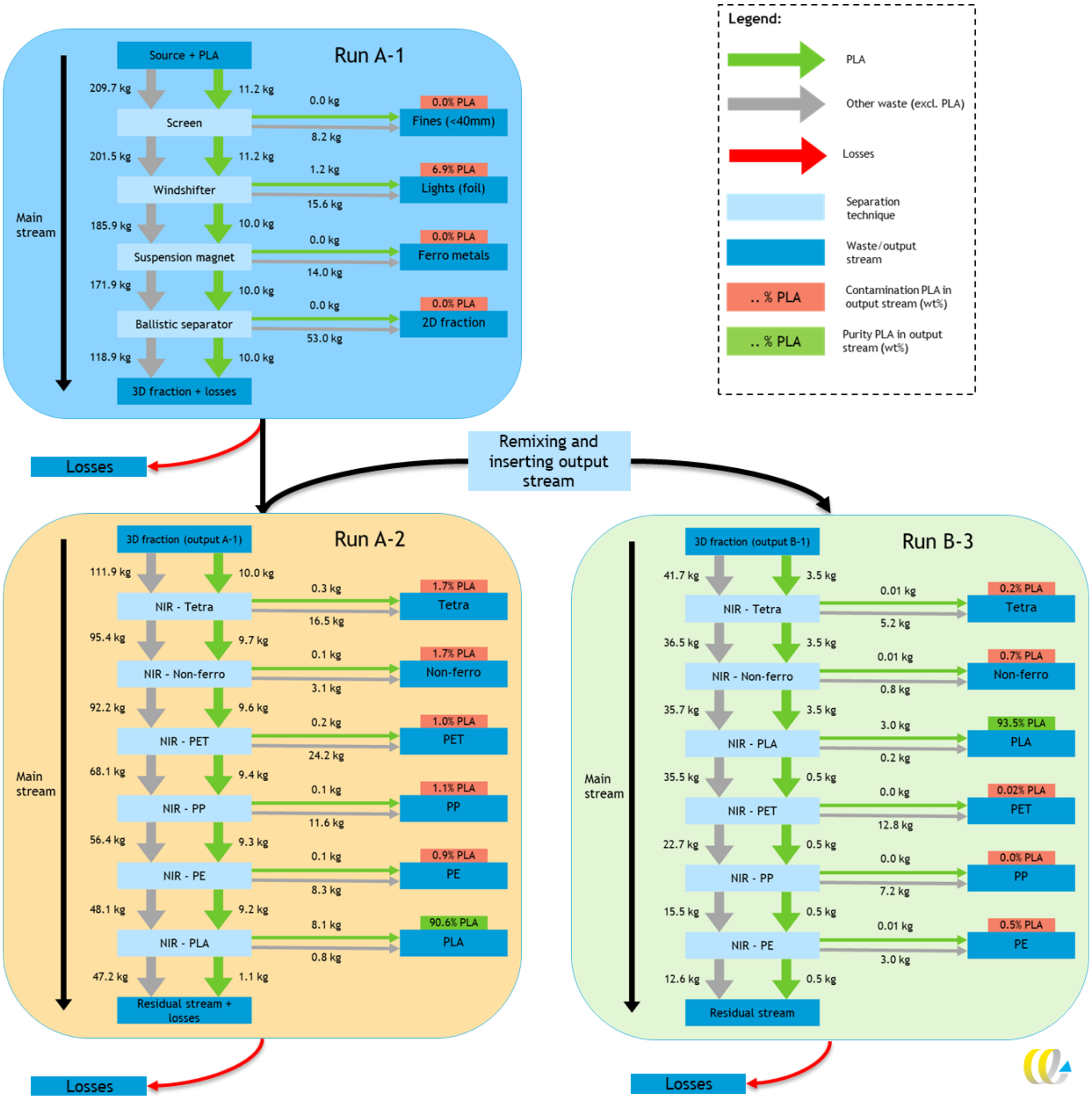
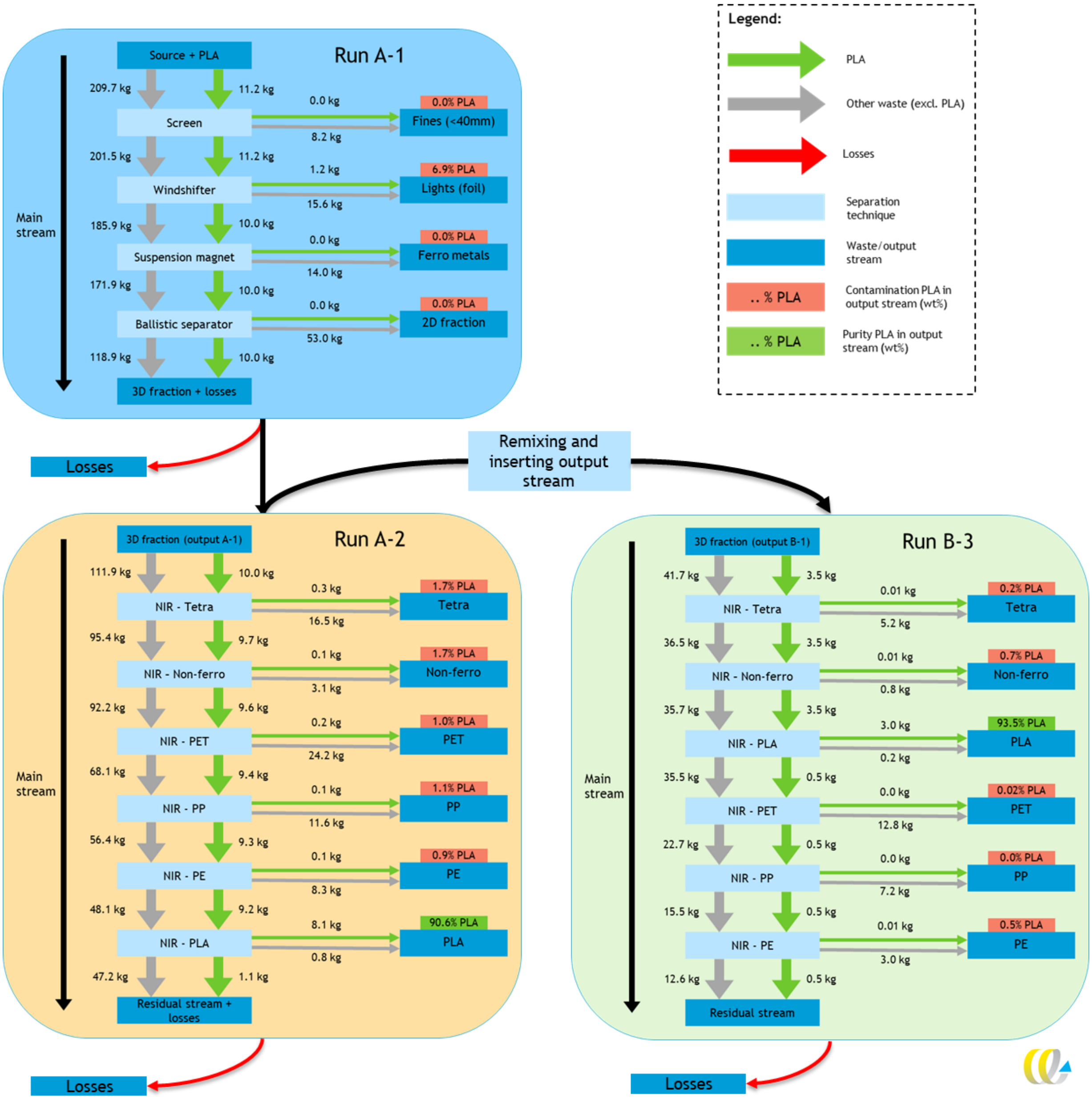


Figure 6 - Results (mass balance) of Experiment B (post-consumer separated waste)



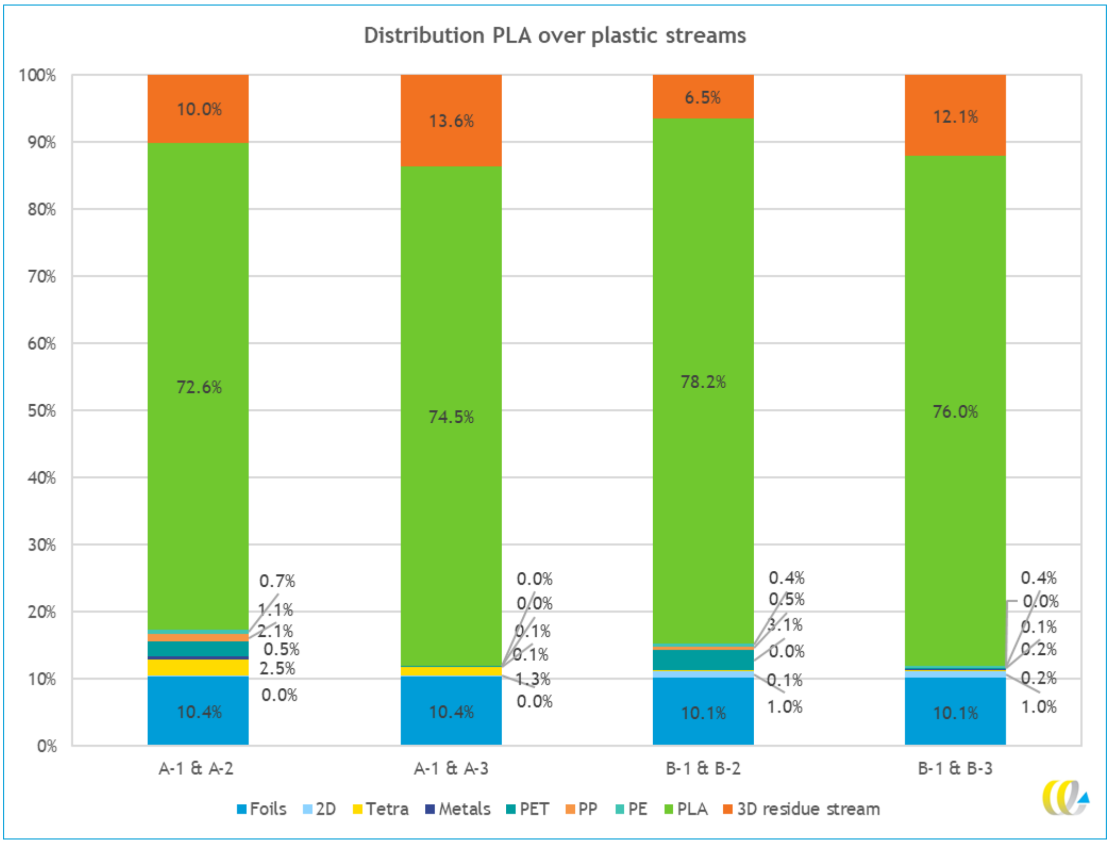
3.2 Yield

To investigate whether it is feasible to sort out PLA from waste streams, it is important to examine which fraction of the total amount of PLA in household waste can be sorted out. It can be seen in Table 5 that, in the conducted experiments, 73 to 78% of the PLA has ended up in the PLA stream. There is no clear difference between the yields of different sorting sequences.

The PLA sorting efficiency of the NIR installation is the percentage of PLA that is sorted out by one NIR installation. The efficiency of the NIR installation when separating PLA is higher than the 'PLA yield', as the PLA lost before the NIR installation is not taken into account. The PLA sorting efficiency is 84-92%.

In Figure 7, it is shown in which streams the PLA ends up in each run. 10% of the PLA ends up in the foil stream, which means that it is blown out by the windshifter due to the weight characteristics of the specific packaging material. Furthermore, up to 3.1% of the PLA ends up in the PET stream and up to 2.5% of the PLA ends up in the Tetra stream. The amount of PLA ending up in other streams (metals, PE, PP) is less than 1%. 6 to 14% of the PLA is not sorted out at all and ends up in the residual waste stream.

Figure 7 - Distribution PLA over plastic streams



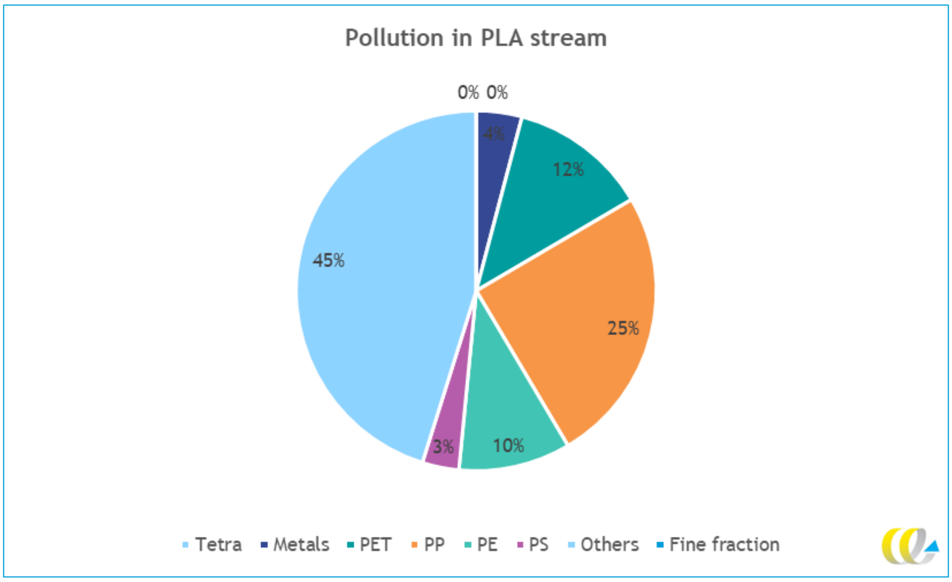
3.3 Purity

The economic value of the PLA stream is affected by the purity, since it affects the recyclability of the stream. The purity of the PLA streams ranges between 91 and 95% for the different configurations. The purity appears to be higher with post-consumer separated waste, but the differences are small and circumstances differed so we cannot be conclusive (we elaborate on this in in Section 4.2.2). There is no indication that the sequence of the sorting steps affects the purity of the PLA stream.

The pollution in the PLA stream ranges between 5 and 9%. The pollution in the PLA stream was characterised. Figure 8 shows that the category 'others'[6] is responsible for almost half of the pollution. Furthermore, PP is a major polluter of the PLA stream.

Materials can end up in the wrong stream by multiple factors, such as faulty registering of the NIR installation, materials sticking together, 'flight behaviour' of lighter materials in the sorting hood, or materials that are partly on top of each other when measured.

Figure 8 - Characterisation of pollution of PLA stream (mean of all experiments)



3.4 Pollution of other streams

An overview of the PLA pollution in all streams is given in Figure 9. The PLA pollution in other plastic streams depends on the share of PLA in the waste. The PLA share was 5% for the source-separated waste (Experiments A-2 and A-3) and 4% for the post-consumer separated waste (Experiments B-2 and B-3). In general, when the share of PLA in the input stream becomes higher, the pollution of PLA in other streams will be higher as well.

[6] Undefined waste, which does not belong in one of the other categories.

Figure 9 - Overview PLA pollution in output streams (wt% PLA in relation to total weight stream)

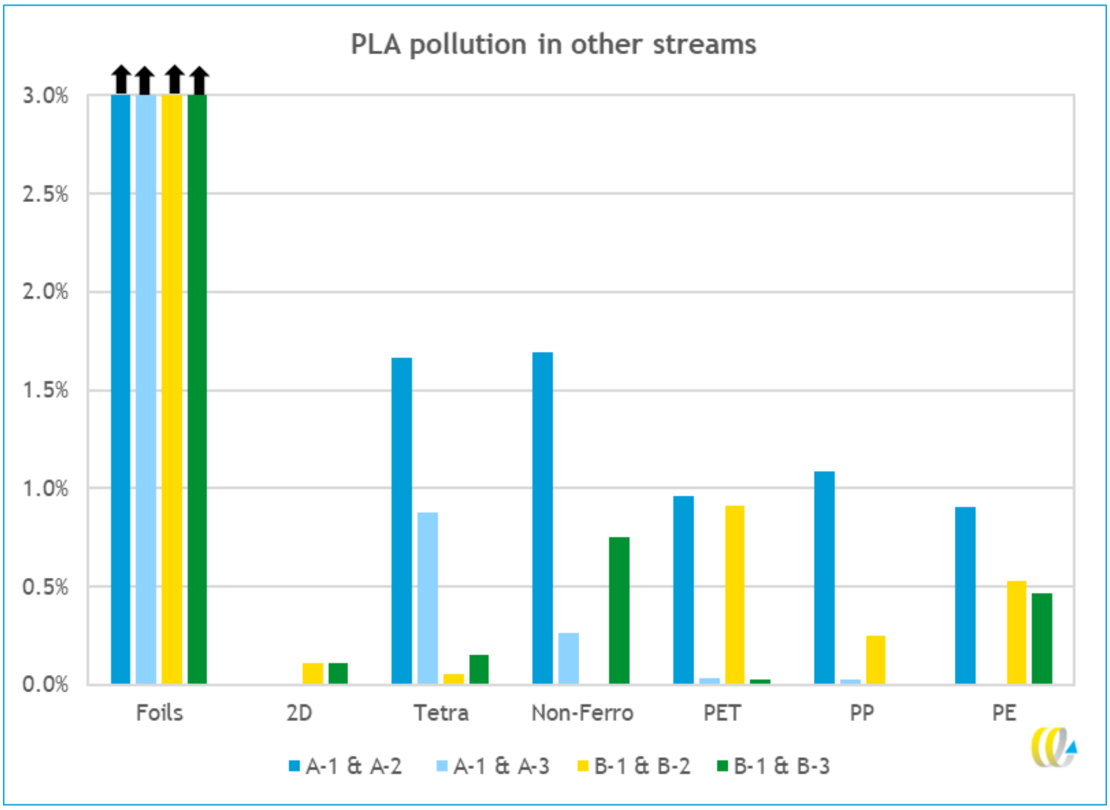


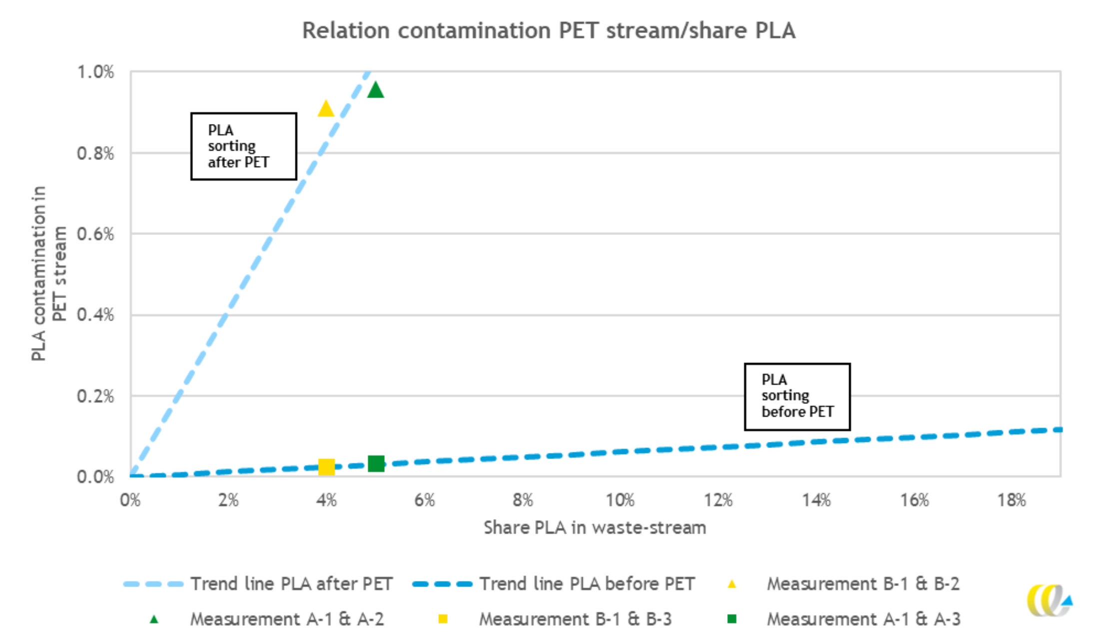
Figure 9 shows that the PLA pollution is the highest in the foil stream (7-20%). Trays (green and transparent) make up 85-90% of the PLA pollution in the foil stream and lids make up 8-13%. For the other output streams the maximal PLA pollution is in the range 0.9-1.7%.

The PLA pollution in the PET stream is 0.91-0.96% when PLA is sorted out after PET (Run A-1 & A-2/Run B-1 & B-2). The PLA pollution in PET is reduced significantly when PLA is sorted out before PET (Run A-1 & A-3/Run B-1 & B-3), to 0.02-0.03%. The same occurs for PP and PE.

This conclusion applies to both source-separated and post-consumer separated waste. There is no indication that the type of waste significantly affects the PLA pollution in the PET stream.

In Figure 10, the relation between the PLA pollution in the PET stream and the share of PLA in the PMD waste-stream is shown. It is assumed that the relation between the PLA pollution in PET and the share of PLA is linear and that the share of PET remains equal.

Figure 10 - Relation PLA pollution PET stream/share PLA in stream for different sorting sequences



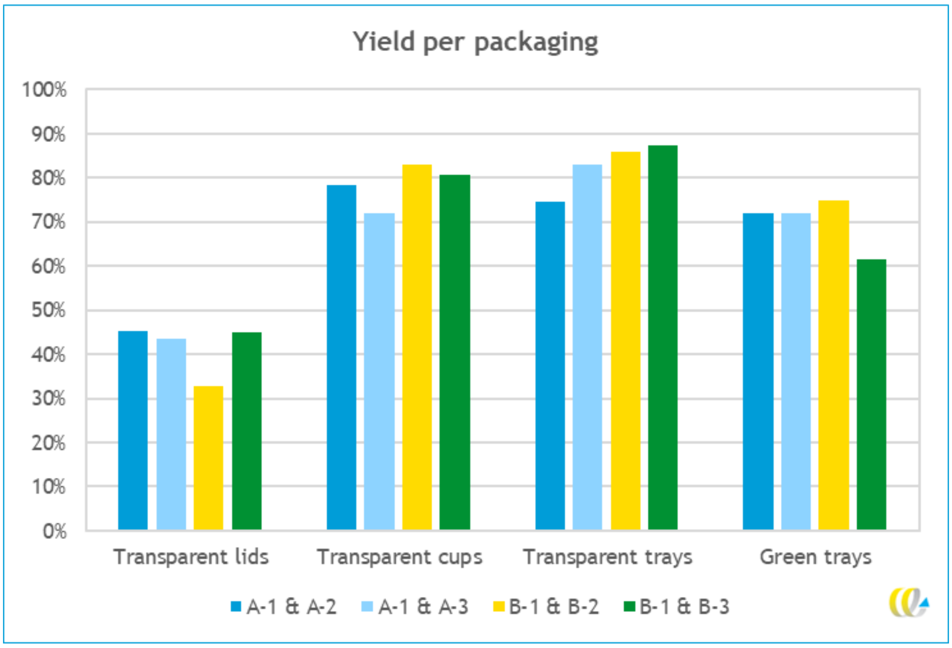
Be aware!: each trend line is only based on two data points, so uncertainties are significant.

The figure shows again that PLA pollution in the PET stream can be decreased to very small amounts when PLA is sorted out before PET. It is important to mention that the trend lines are based on just two measurement, which means that the outcomes have significant uncertainties. Therefore, little value should be given to the exact numbers. However, it can be concluded with fair certainty that PLA pollution in the other plastic stream (e.g. PP, PE and PET) is reduced significantly when PLA is sorted out before the other plastic.

3.5 Differences between PLA products

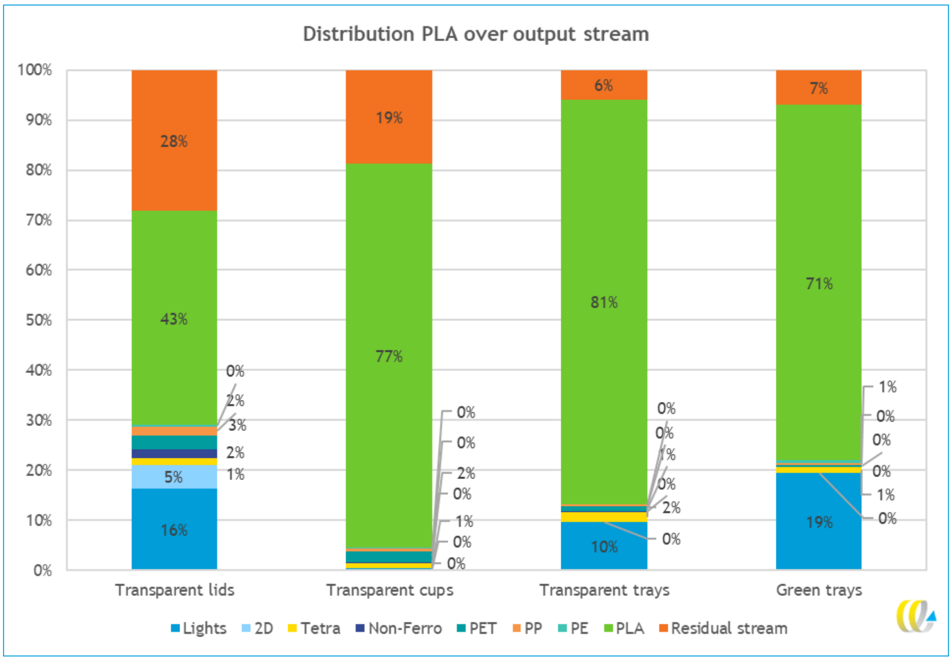
Different types of packaging were used to investigate whether the colour and the shape of the packaging affects the sorting process. Each type of PLA product was measured separately. The yield of the different types of packaging is shown in Figure 11. This yield does not correspond directly to the efficiency of the NIR installation, since a part of the PLA products do not reach the NIR installation as they are sorted out (incorrectly) at previous sorting steps.

Figure 11 - Yield of PLA per type of packaging



The figure shows that the yield of PLA lids is way smaller than the yield of other packaging types. Figure 12 shows in which output stream the different PLA packaging types end up. A large share of lids and the trays (10-19%) end up in the lights stream since it is blown out by the wind shifter. Furthermore, a large share of the lids and cups (19-28%) are not sorted out and end up in the residual stream. The colour of the packaging appears to make no difference in this experiment. This happens less with other types of packaging. The implications of these results are discussed in Section 5.1.

Figure 12 - Distribution PLA over output streams, by packaging type (mean of four experiments)



4 Discussion and uncertainties experiment

The goal of the experiment is to simulate the sorting of future domestic waste with a higher share of PLA. In general, the experiment was performed as planned and no major problems occurred which could severely affect the results. Therefore, it is expected that the results of the experiment are realistic and representative. However, the experiment had some limitations and uncertainties.

The representativeness of the experiment (Section 4.1) and uncertainties and limitations (Section 4.2) will be discussed in this chapter. Furthermore, the results of the experiment are compared to other PLA sorting experiments (Section 4.3).

Since each experiment was only performed once, it is not possible to perform a quantitative uncertainty analysis. Therefore, the limitations and uncertainties will be discussed qualitatively.

4.1 Representativeness

4.1.1 Sorting line

The line of the NTCP was designed to simulate an industrial plastic sorting installation. Even though the line only had one NIR installation and the size of the installation is way smaller, it represents an industrial size equipment properly. A sequence of NIR installations was simulated by using a loop and changing the NIR settings after each loop. The size of the sample was dimensioned to the size of the installation and hence should not affect the results.

4.1.2 NIR installation

For this experiment, the producer of the NIR installation added software to separate PLA using an existing generic PLA database[7], which is also used by industrial sorting installations. As a consequence, the software used in the NIR installation can be considered to be realistic for industrial sorting installations. Further optimisation of the NIR installation could improve the yield, purity and pollution figures, but this was not part of the experiment.

4.1.3 PMD waste stream

The PMD waste streams that are used in the experiment were obtained from waste management company (Omrin). We expect that the PMD waste stream of Omrin is representative for the PMD waste of the Netherlands. However, the material sample taken at one point in time will always differ from the national average since only a small sample is taken. Furthermore, seasonal factors affect and possibly COVID-19 affect the content of the waste stream. This is relevant since the content of the waste stream affects the results. For example, the PLA pollution in the PET stream is affected by the size of the PET stream.

[7] The four target materials of this experiment were not specifically added to the database.

The content of the used waste stream is compared to the average content of Dutch waste in Table 6.

Table 6 - Comparison content PMD waste stream experiment to Dutch average

	Source-separated waste		Post-consumer separated waste	
	Dutch average	Estimation experiment[8]	Dutch average	Estimation experiment
Foils	37%	36%	39%	44%
PET	21%	22%	20%	24%
PE	18%	7%	15%	6%
PP	17%	10%	19%	14%
Others	7%	24%	6%	11%

Source: (Delft, 2018).

The content of the waste stream used in the experiment could not be determined exactly, since the non-PLA waste in each stream was not analysed and some of the plastic waste was not sorted out. Therefore, there is some uncertainty about the content of the used waste stream. However, the results give some indication whether the waste stream is representative.

It can be seen that the used waste stream contained less PE and PP and more 'Others' (e.g. Tetra, metals) than the national average. However, these shares are less relevant since the PLA pollution in the PET stream was the main focus of investigation. The share of PET in the waste stream in this experiment appears to be approximately equal to the Dutch average. Therefore, the results about pollution of PLA in the PET stream are expected to be realistic for the current situation. However, the content of PMD waste streams may change in the future. Therefore, current samples might not be representative for future waste streams.

4.1.4 PLA products

To both streams, 3D PLA material is added and homogeneously mixed in the waste stream. The PLA material is crushed beforehand. The PLA is clean at the start but due to mixing with other plastics the PLA is slightly contaminated. However, the PLA packaging remains relatively clean compared to the input waste stream as it contains less dirt and moisture. We expect that pollution does not affect the recognition of the material by the NIR installation (Masoumi et al., 2012). However, dirt and moisture increases the weight of the packaging which may affect the results.

In some cases, some pieces of PLA ended up sticking together in the installation. However, this also occurred for other materials like PE, PP and PET. Therefore, this is not unrealistic.

It is not possible to determine whether the PLA samples are representative for the future PLA waste. This may affect the results since differences occur between the different PLA products (see results Section 3.5).

[8] This corresponds to the mass of the sorted out waste stream. However, the sorted out waste stream may also contain other types of plastic. Furthermore, not all plastic are sorted out. The fraction which is not sorted out is not taken into account. This means that the mass of the sorted out stream does not perfectly correspond to the actual content. However, it is the best possible approximation.

4.2 Limitations and uncertainties

4.2.1 Human factors: manual measurements and mixing

The content of each output stream is characterised manually, since this is the easiest way. The content of the sorted out stream was poured on the floor and the PLA pieces were collected by visual inspection. Manual characterisation might lead to errors. However, we expect that these errors are very small since the PLA pieces were easily recognisable and the characterisation was performed by two or three people.

After Run 2, the sorted out waste has to be remixed for Run 3. The waste stream should be mixed homogeneously to represent a realistic situation. The mixing was done manually by pouring all waste on the floor, overturning it multiple times and putting it back into the big bags. It is plausible that the waste streams in Run 3 was mixed less homogeneously compared to Run 2 (A-2. However, after the manual mixing, the waste stream ran through the entire loop twice before the sorting process was started which leads to better mixing. Therefore, it is expected that the waste stream was mixed well enough.

4.2.2 Differences between samples Experiment A and Experiment B

The input waste stream for Experiment A (source-separated waste) was different from the input waste sample of Experiment B (post-consumer separated waste). Less post-consumer sorted waste was used because of a limited amount of time. However, we expect that the sample size does not affect the results since we only consider relative shares of PLA in the streams.

Furthermore, the share of PLA in the waste stream was slightly different (5% for A versus 4% for B). We expect that the PLA pollution in other stream increases when the share of PLA increases. Furthermore, we expect that the purity of the PLA stream is affected. Therefore, small differences between the experiments with source-separated waste and the post-consumer separated can also be caused by differences in the PLA content.

4.2.3 PLA detection by NIR installation

No clear differences appear between the PLA pollution in the different streams. This could be an indication that the pollution is not affected by the settings of the NIR installation and implies that the pollution is not caused by the characterisation of the material by the NIR installation, but by the actual sorting by the compressed air blower of the optical sorter which blows pieces of plastic with a positive match from the NIR out of the streams. This can happen when pieces of plastic are stuck together.

After the experiments were finished, single pieces of PLA packaging were inserted into the installation to test how these pieces are registered by the NIR installations. One piece of each type of packaging was tested. The pieces of PLA were registered perfectly by the NIR installation. This also gives a slight indication that PLA pollution in other waste streams is not caused by faulty registering by the NIR installation, but is presumably due to materials sticking together, ‘flight behaviour’ of lighter materials in the sorting hood or materials that are partly on top of each other when measured. However, further research is necessary to be conclusive.

4.3 Comparison with other experiments

In this section, we compare the results of our sorting experiments with reported results from other PLA sorting experiments, which allows us to interpret and validate our results.

4.3.1 Experiment by KNOTEN WEIMAR

The only well-described PLA sorting experiment in which PLA was part of plastics packaging waste from consumers[9] has been carried out by KNOTEN WEIMAR, a German research and consultancy company specialised in environmental technologies, resources and waste disposal. This experiment was part of a research project on PLA disposal, sorting and recycling.

Set-up

Three tests were carried out as part of the experiment:
- Test 1: Normal operation; use of NIR installations to sort out PE/PP, PVC and PET.
- Test 2: Use of NIR installations to sort out PLA.
- Test 3: Use of NIR installations to sort out PLA together with PE/PP.

For each of the tests, 160 kilogram of 3D PLA packaging waste was mixed with about 2 tonnes of lightweight plastic packaging waste from households, resulting in 8% PLA in the input waste stream. The PLA packaging waste consisted of transparent cups, forks and dessert cups, as well as green coloured forks (see Figure 13).[10]

Figure 13 - PLA materials used in the sorting experiment by KNOTEN WEIMAR

Source: (TU Chemnitz, 2017).

The system configuration of the experiment is shown in Figure 14. It includes four NIR installations. In Test 1, NIR 1/2/3/4 were used to sort out PE/PP/PET/PVC, respectively. In Test 2, the four NIR installations were set to detect and shoot out PLA. In Test 3, the four NIRs were set to sort out both PLA and PE/PP. The used line throughput was 10 tonnes of waste per hour.

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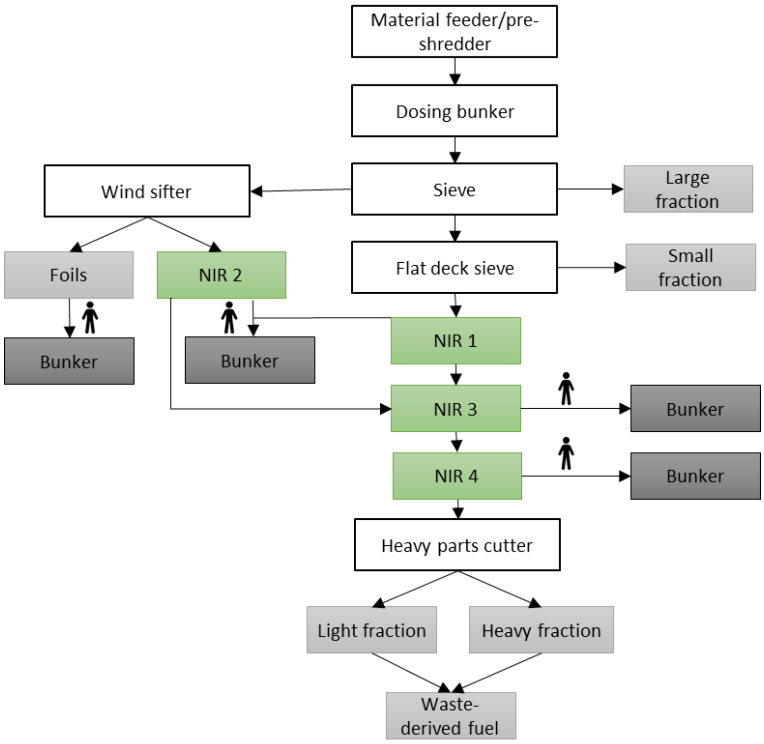
9 A few sources describe tests in which PLA bottles/flakes were sorted from PET bottles/flakes, but this is not representative of the sorting of PLA from consumer plastic packaging waste.

10 The mass percentages of the different package types as part of the whole PLA batch were not reported.

Figure 14 - System configuration of the PLA sorting experiment by KNOTEN WEIMAR



Source: (TU Chemnitz, 2017).

Results

The distribution of the PLA over the output stream for the different tests of the KNOTEN WEIMAR experiment are shown in Table 7.

Table 7 - Distribution of PLA over waste streams in the three tests in the KNOTEN WEIMAR experiment

Waste stream	PLA percentage in the different output streams		
	Test 1 (Normal operation)	Test 2 (Sorting of PLA)	Test 3 (Sorting of PLA + PE/PP)
PLA	-	54.8%	45.8%
PE/PP	2.7%	-	-
PET	0.5%	-	-
PVC	8.9%	-	-
Waste-derived fuel	79.4%	36.8%	45.7%
Small fraction	6.3%	6.2%	6.3%
Heavy fraction	2.2%	2.2%	2.2%
Foils	0%	0%	
Total	**100%**	**100%**	**100%**

Note: In Tests 2 and 3, PE/PP, PET and PVC were not sorted out separately. In Test 3, PE/PP was sorted out together with PLA.
Source: (TU Chemnitz, 2017).

The **Test 1** results indicate in which output streams PLA ends up if it is not sorted out. Most of the PLA ended up at the end of the sorting line, as part of the waste-derived fuel stream. Due to some similarities in the NIR spectra, almost 9% of the PLA was found in the PVC stream.
Test 2 resulted in a PLA yield of about 55%, i.e., 55% of the PLA was sorted out as a separate stream. The purity of the sorted 3D PLA directly after the sorting experiment was 70%. After crushing and wind sifting (post-processing) of the PLA stream, in which mostly dust was removed, the PLA purity was increased to 73%, and after washing and density sorting the purity reached 80% (KNOTEN WEIMAR, 2017).

In **Test 3** a PLA yield of about 46% was obtained, which means that the combined sorting of PLA and PE/PP with NIR installations is possible, but diminishes the yield.

Some PLA cups were stuck together and could not be shot out with the NIR installations because they were too heavy. These ended up in the heavy fraction (TU Chemnitz, 2017). Also, the NIR installations were not optimally adjusted to the sorting of PLA, as a result of which the air blower was sometimes too slow. Furthermore, many forks ended up in the small fraction, because they were small enough to fall through the sieve, and because they got stuck in waste foils (KNOTEN WEIMAR, 2017). Finally, TU Chemnitz, (2017) mentions a few more factors that may have negatively affected the PLA sorting yield in the sorting tests: the nozzle/jet functioning of the NIR installation, the presence of dust in the system or on the NIRs, manual sorting, and the distribution of waste on the conveyor belt.

4.3.2 Experiment by WRAP (2008)

In the United Kingdom, a sorting test with British plastic packaging waste from households has been carried out by WRAP, a UK-based advisory company engaged in resource efficiency, including re-use and recycling. Unfortunately, the only details of the experimental setup provided in WRAP, (2008) are that sorting tests were performed using different NIR based sorting systems, using a line throughput of 3 tonnes of waste per hour. The average purity of the PLA stream resulting from these tests was 97%.

4.3.3 Tests by TOMRA

TOMRA, a NIR installation supplier, provided the following estimations of the performance of its NIR installation:[11]

- The sorting yield of 3D PLA lies between 80 and 85%, and that the yield of 2D PLA lies several percentage points lower.
- The sorting of 3D PLA results in a purity of the PLA stream above 90%. The purity of a sorted 2D PLA stream is estimated to be a few percentage points lower, as foils are harder to shoot out.

4.3.4 Comparison of results

To compare the results of our PLA sorting experiments with other experiments reported in literature, we have made a high-level overview of the main results. See Table 8.

[11] Personal communication with TOMRA, December 2018. In: CE Delft, (2019).

Table 8 - General comparison of results of 3D PLA sorting experiments

Experi-ment	Run/test	Through-put	PLA yield (% PLA sorted out)*	Efficiency NIR separating PLA (% PLA sorted out)**	PLA purity (% PLA in PLA stream)	Pollution of PET stream (% PLA in PET)
This study	A-2 (source-separated waste, PLA sorted *after* PET/PE/PP)	2 tonnes/hour	73%	88%	91%	0.96%
	A-3 (source-separated waste, PLA sorted *before* PET/PE/PP)		75%	84%	92%	0.03%
	B-2 (post-consumer separated waste, PLA sorted *after* PET/PE/PP)		78%	92%	95%	0.91%
	B-3 (post-consumer separated waste, PLA sorted *before* PET/PE/PP)		76%	86%	94%	0.02%
KNOTEN WEIMAR	Test 1 (normal operation)	10 tonnes/hour	-		-	N/A
	Test 2 (sorting of PLA)		55%		70% (incl. further sorting: 80%)	
	Test 3 (sorting of PLA + PE/PP)		46%		*Mixed with PE/PP*	
WRAP	-	3 tonnes/hour	N/A		97%	N/A
TOMRA	-	N/A	N/A	80-85%	>90%	N/A

Sources: (CE Delft, 2019, KNOTEN WEIMAR, 2017, TU Chemnitz, 2017, WRAP, 2008).

* PLA yield is the percentage of the total input PLA of the experiment which is sorted by the NIR installation.

** The efficiency of the NIR is the percentage of PLA that is sorted out by one NIR installation The efficiency of the NIR installation when separating PLA is higher than the 'PLA yield', as the PLA lost before the NIR installation is not taken into account.

Not all the main PLA sorting performance indicators were reported for all experiments, which limits the scope of the comparison. Furthermore, it should be noted that the experiments have been described in very different levels of detail: very shortly in case of the WRAP and TOMRA experiments, and very extensively in case of KNOTEN WEIMAR and this study. This complicates the interpretation of differences in results. Unfortunately, our results on the pollution of the PET stream with PLA cannot be compared with results from other experiments, because this aspect was not covered in those experiments.

WRAP and TOMRA

In the experiment by WRAP a purity of the sorted PLA stream of 97% was obtained (WRAP, 2008). TOMRA indicated with its NIR installation a PLA purity of more than 90% can be obtained, and a sorting efficiency of 80-85%[12] (CE Delft, 2019). The PLA purity values of both WRAP and TOMRA are in line with the values found in this study. The sorting efficiency of one NIR installation, as indicated by TOMRA, is in line with the results of our experiment.

[12] The sorting efficiency is that same as the PLA yield when only looking at one NIR, and thus discarding the losses that occur before the NIR installation.

KNOTEN WEIMAR

When comparing our experiments with those of KNOTEN WEIMAR, we see that both the PLA yield and the PLA purity values found in the KNOTEN WEIMAR tests were about twenty percentage points lower than the values from our experiments. This is a substantial difference. Examining the details of the KNOTEN WEIMAR study, we find that there are multiple reasons that may have caused a relatively low performance of the PLA sorting system in the KNOTEN WEIMAR experiment (KNOTEN WEIMAR, 2017, TU Chemnitz, 2017) (see Section 4.3.1):

- The NIR installations were not well adjusted to PLA sorting in the KNOTEN WEMAR experiment.
- Different composition of the PLA packaging material. In the KNOTEN WEIMAR experiment PLA cups and forks were used, whereas in our study PLA cups, lids and trays were used. Many forks ended up in other waste streams, because they were so small that they fell through the sieve, and because they got stuck into foils.
- Some PLA cups stuck together, making them too heavy for the NIR installation too shoot out.
- The throughput of waste in the sorting system in the KNOTEN WEIMAR experiment was 10 tonnes/hour, which is five times higher than in our experiment, and also much higher than in the WRAP experiment. According to NTCP, a throughput of 2 tonnes/hour resembles that of a real plastics sorting facility. The higher throughput could be the result of a higher conveyor belt speed and/or a higher density of packaging waste on the belt. Indeed, TU Chemnitz, (2017) did shortly remark that the distribution of waste on the conveyor belt as a factor that may have affected the PLA yield.
- The presence of dust in the sorting system or on the NIRS has also been mentioned as a possible factor affecting the PLA yield and purity. In post-processing steps of the PLA stream, mostly dust was removed, increasing the PLA purity from 70 to 73%.

It is interesting to note that the use of four NIR installations in the KNOTEN WEIMAR experiment did not compensate for the above problems. The KNOTEN WEIMAR results show that the majority of the PLA was sorted out by a single NIR installation. This indicates that the use of four NIR installations instead of one does not do much to improve the PLA yield.

Conclusion of comparison

We conclude that the PLA purity level of 91-95% obtained in our experiment is in line with the values reported by WRAP and TOMRA. Furthermore, the sorting efficiency of the NIR installation (84-92%), is slightly higher than the numbers given by TOMRA. The lower PLA yield and purity found in the KNOTEN WEIMAR experiment compared to our experiments can be explained by a combination of performance-reducing factors in the KNOTEN WEIMAR experiment. Although the relative importance of these factors is unknown, the different composition of the PLA packaging material is probably one of the main causes. Because of the differences in experimental set-up between our experiment and that of KNOTEN WEIMAR and the lack of information on the WRAP experiment, this comparison does not provide enough basis to validate our experiment results. Rather, this study presents the first PLA sorting research results in which PLA cups and trays were sorted out under real-life conditions with a well-adjusted NIR installation.

5 Main conclusions experiment

5.1 Main findings

The main goal of the experiment is to increase the understanding of the sorting out of PLA and to determine whether it can be feasible to sort out PLA when the share of PLA in the PMD waste increases. Therefore, the following research question has been composed: ***How well can PLA be sorted out of Dutch PMD waste with a higher share of PLA and how does this affect other sorted out plastic streams (especially PET)?***

Several sub-questions were composed to answer the main research question. The answers to these sub-questions are given below:

- **What is the PLA yield?**
  The yield of PLA is 73-78%. The yield appears to be slightly higher when PLA is sorted out before PET, PP and PE, but differences are small. The PLA sorting efficiency of the NIR installation is 84-92%.

- **What is the purity of the PLA stream?**
  The purity of the PLA stream is 91-95%. PP, fines and other plastics are the main polluters of the PLA stream. There is no clear indication that the purity of the PLA stream is affected by the sorting sequence.

  The purity of the PLA stream can be improved by additional sorting methods, like sink-float separation for PE, PP, PS and foils. An additional sorting step with a NIR installation can be added for sorting out PET pollution.

- **What is the PLA pollution in the other output streams?**
  The PLA pollution is the highest in the foil stream (7-20%). This happens because PLA material is blown out by the windshifter. All types of PLA packaging end up in the foil stream. The trays (transparent and green) make up 85-90% of the PLA pollution in the foil stream and lids make up 8-13% of the pollution. The windshifter separates waste based on weight, not on material type. Therefore, we expect that pollution of the foil stream will also occur with lids and trays made from PET, PE or PP.

  For the other output streams, the maximal PLA pollution is in the range 0.9-1.7%. The PLA pollution in the PET stream is 0.9-1.0% when PLA is sorted out after PET. The pollution is less than 0.02-0.03% when PLA is sorted out before PET.

- **What is the impact of changing the sorting sequence in the plastic sorting installation?**
  There is no clear indication that the sorting sequence affects the PLA yield and the purity of the PLA stream. However, the PLA pollution in the PET stream is much lower when PLA is sorted out before PET, which improves the recyclability of the PET stream. Therefore, it appears to be preferential to sort out PLA before PET.

- **Are the results influenced by the type of input waste (either source-separated or post-consumer separated household PMD waste)?**
  As can be seen in Table 5, the PLA yield and the PLA sorting efficiency of the NIR installation appears to be slightly higher for post-consumer separated household waste.

Furthermore, the purity appears to be slightly higher. However, the differences are small. Therefore, we expect that the type of input waste does not affect the results. However, it is not possible to be conclusive since the conditions of the experiments were not identical (see Chapter 4).

- **Are the results influenced by the type of PLA packaging?**
  Four types of PLA waste are used in the experiment. 3D packaging were chosen since it is expected that most PLA packaging will be 3D in the future. Different types of packaging were used to investigate whether the colour and the shape of the packaging affects the sorting process.
  The yield of the different types of packaging is given in Section 3.5. It can be seen that the yield of the PLA lids is lower than the other types of packaging for all four experiments. A large share of lids ends up in the lights stream since it is blown out by the wind shifter. This also happens with green and transparent trays. Furthermore, a large share of the lids are not sorted out and end up in the residual stream. This happens less with other types of packaging.

The main research question can be answered based on the answers to the sub-questions. It can be concluded that PLA can be sorted out of PMD waste with 5% PLA successfully and without polluting other streams problematically when PLA is sorted out before PET. At least 73% of the PLA waste can be sorted out and the purity of the PLA stream is over 90%. The PLA pollution in the PET, PE and PP stream can be reduced significantly when PLA is sorted out before these materials.

Table 9 presents the conclusions about PLA pollution in other streams.

Table 9 - Summary of conclusions PLA pollution in other streams

	PLA pollution (PLA sorted out *after* PET, PE and PP)	PLA pollution (PLA sorted out *before* PET, PE and PP)	Possibility separation of PLA contamination from stream	Limit pollution PLA in stream without affecting recycling
Based on	**Results from experiment**	**Results from experiment**	**Literature review and stakeholder interviews**	**Literature review and stakeholder interviews**
PET	0.91-0.96%	0.02-0.03%	Difficult. Sink-float separation is not possible. Separation with an additional NIR installation is an option.	Uncertain. For PET bottles, PLA pollution should be below 0.1%. But this is probably higher for other types of packaging (e.g. trays, lids, cups).
PP	0.25-1.09%	0.00-0.03%	May be possible with sink-float separation.	Pollution tests in Germany have shown earlier that up to 3% PLA in PP recyclate did not have any negative effect on the properties of the recyclate (Hiebel et al., 2017).
PE	0.53-0.91%	0.00-0.47%	May be possible with sink-float separation.	Uncertain.

Future research on sorting of PLA

In this research it was investigated how much PLA pollutes other plastic streams. However, it is uncertain how much PLA pollution in these streams is acceptable. Much uncertainty is present about the effects of PLA pollution in other plastic streams on the recyclability of these streams. More research is necessary.

If PLA is introduced in the market, guidelines should be added for design, such that the products produced can be proficiently recycled. In general, Design for Recycling does not only improve the recycling of a plastic, but potentially also improves the quality of the output streams during the sorting process. Further research should focus on these guidelines for PLA products.

The performed sorting experiment had some uncertainties. Future sorting experiments could be performed to tackle these uncertainties and increase knowledge about how well PLA can be sorted out. In future sorting experiments, batches of waste from different sorting companies and different periods in the year could be used to assess whether this affects the results. Furthermore, it could be investigated whether optimisation of the NIR installation affects the results.

6 Recyclability of PLA

After sorting of PLA from packaging household waste we would like to see that the material is being recycled, either mechanically or chemically. In this chapter we discuss the possibilities for recycling of PLA.

Due to the COVID-19 situation and the current development of installations of stakeholders it was not possible to perform actual tests for this step in this project. Therefore, we explored this step with a literature review. Furthermore we have performed interviews with chemical recycler Total Corbion, mechanical recycler Looplife (de Jonghe (Looplife), 2020) and Wageningen University & Research (Molenveld (WUR), 2021).

First, we give a background on recycling of PLA. After this we elaborate on the potential of mechanical and chemical recycling of PLA and discuss the requirements of the PLA stream. After this we discuss the future of PLA recycling.

6.1 Background

Mechanical recycling is preferred over chemical recycling because the process is less energy-intensive. However, chemical recycling can cope with higher grades of pollution. Additionally, the end-products of chemical recycling generally have a higher quality than end-products of mechanical recycling, comparable to the quality of virgin products. As a result, chemical recycling can be considered to be complementary to mechanical recycling, for example when high quality recycled plastics are required or when dealing with more polluted streams.
Organic recycling, production of biogas from bioplastics by digestion, is a backfall for bioplastics when both mechanical and chemical recycling are not possible, e.g. with small amounts of bioplastics. Composting is the last option, with no environmental benefits.

Currently approximately 10% of the plastics are recycled worldwide and most of the recycled plastics end up in downgraded applications. In the Netherlands, the amount of recycled plastics equals 16% of the plastics demand (Total Corbion, 2020).

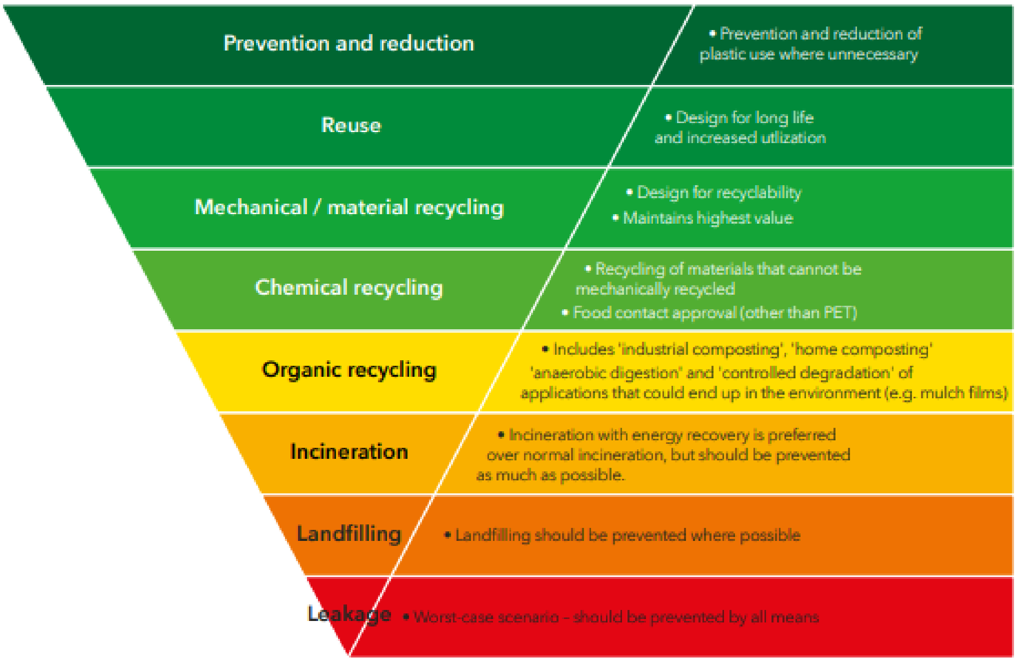
The recycling process for sorted PLA is approximately equal to the recycling process of other plastics, which can be reprocessed with mechanical recycling or chemical recycling. However, at this moment post-consumer PLA is not recycled on a large scale as the volume of PLA is very low compared to other plastics. In order to recycle post-consumer PLA, sorting and recycling companies will likely have to extend their current systems.

Currently, the price of virgin PLA is € 2,000-€ 2,500/ton PLA which is higher than the price of recycled PLA. Therefore recycled PLA has high market potential. In the following sections we will elaborate on mechanical and chemical recycling of PLA.

Broader perspective on recycling
Recycling is one of the end-of-life options for plastics. It can contribute to the circular economy, reduction of greenhouse gas emissions and reduction of plastic waste. However, the process of recycling requires energy and the end-products of recycling generally have lower quality than the original products. Therefore, it is not an ideal solution.

Figure 15 shows a hierarchy for the treatment of (bio-)plastics based on their ability to conserve resources (Total Corbion, 2017). Measures higher in the pyramid are better for the environment and thus preferable. Measures lower in the pyramid should only be applied when measures higher in the pyramid are not possible. Therefore, recycling should only be applied to plastics which use cannot be prevented and which cannot be reused.

Figure 15 – Pyramid of bioplastic waste management (Total Corbion, 2017)



6.2 Mechanical recycling

Karin Molenveld of Wageningen University & Research (2021) and Looplife (de Jonghe (Looplife), 2020) were interviewed about mechanical recycling of PLA. Their contributions are used in this section.

With mechanical recycling plastics are processed into new products by several physical processes. The molecular structure of the plastic remains intact. Usually, the new products have lower quality than the original products.

Mechanical recycling of PLA has environmental benefits compared to other processing routes of plastics, like combustion or composting. The environmental benefit of mechanical recycling of PLA compared to the conventional processing routes (combustion, composting) is estimated between 1.5-1.8 CO_2-eq./kg PLA (CE Delft, 2019).

Mechanical recycling is only possible when plastics are used as monomaterial in packaging (CE Delft, 2019). The sorted PLA has to be processed into flakes and after that into grains/regranulate before mechanical recycling can occur. Before the sorted PLA is processed into flakes, it is shredded and washed, purified (with additional sorting steps) and dried. To process the flakes into regranulate, the flakes are melted. After this, the melted mass is pushed through a small aperture with filters which remove pollution. This is called extrustion. This process produces wisps of PLA which are cooled and cut into regranulate. It is possible to agglomerate the flakes before melting them to get regranulate with higher quality (CE Delft, 2019).

Mechanical recycling company Looplife processes 100-120 tons of PLA each month. Currently, only closed loop PLA streams are recycled, like PLA cups from festivals or football stadiums. These cups are processed into plastic for 3D printers or injection molding applications. In principle, mechanical recycling of sorted PLA from post-consumer waste is possible. However, it is not yet possible for Looplife, but a system which can is currently being developed and they expect it will be finished in the end of 2021 or beginning of 2022 (de Jonghe (Looplife), 2020).

Usually, Looplife creates products with 100% PLA because it is biodegradable. In this case, high purity PLA is necessary. It is possible to have 10% PE or PP pollution in the sorted PLA stream. This does not affect the recycling process since these plastics have comparable melting temperatures. However, the end-product is not completely biodegradable in this case. In general, it is almost impossible to prevent that some pollution ends up in the r-PLA. Therefore r-PLA cannot be used for some applications which require biodegradable plastics, for example in agriculture. But other purposes can deal with a small fraction of PP in PLA.

6.2.1 Requirements PLA stream

Pollution in the sorted PLA stream may affect the mechanical recycling process. The current mechanical recycling facilities are not yet capable of processing sorted out PLA waste because of challenges with pollution. It depends on the type of pollution whether it affects the process. Some of the main challenges which mechanical recyclers face regarding PLA are (de Jonghe (Looplife), 2020):

- Currently only 3D plastics can be processed. Foils and films cannot be washed. Furthermore, a mix of foils and 3D products may lead to problems in the extrusion process. And it is easier to sort out 3D plastics than 2D materials. So recyclers prefer 3D materials.
- It is difficult to recycle food packaging, since nutrient-contamination ends up in in the recycling products and affects the quality (Total Corbion, 2017). Furthermore, it affects the recycling yield. Fat remains can be removed with a warm washing line with friction, but this is a costly process and it may lead to breaking down of the PLA.
- PET contamination may cause problems in the extrusion process since PET has a higher melting point than PLA. Therefore, PET is still solid when it enters the extrusion process and it may block the extrusion filter. This problem could be solved by using filters which continuously remove the PET from the filter. It is not certain how much PET pollution in the PLA stream is acceptable.
  PE and PP pollution are less problematic since these materials have a similar melting

point and these will be liquid in the extrusion process. This does cause a problem for biodegradability.
- It is difficult to remove non-ferro metals from the recycled material without losing a lot of the recyclate. Therefore, non-ferro metal pollution is considered a major problem. Ferro-metals can be removed easily with a magnet and do not cause problems.
- Paper labels on packaging stick and can cause problems in the recycling process. This problem does not occur with PP or PLA labels.

Looplife expects that their new system, which is planned for end 2021 or beginning 2022, can deal with these challenges and is capable of recycling sorted PLA waste (de Jonghe (Looplife), 2020).

6.3 Chemical recycling

Karin Molenveld of Wageningen University & Research (2021) and Total Corbion (de Bie (Total Corbion), 2020) were interviewed about chemical recycling of PLA. Their contributions are used in this section.

With chemical recycling plastics are broken down into its original components with chemical reactions. From these components new products can be created which have a higher quality compared the end-products of mechanical recycling. End-products of chemical recycling have similar quality as virgin products. New plastics can be created when they are broken down into a pure monomer stream.

With chemical recycling, only the target material is recycled. Therefore, it is not suitable for mixed packaging. For example, if a PLA tray consists of only 50% PLA, only 50% of the material ends up in the recycled product (Molenveld (WUR), 2021).
The two main forms of chemical recycling are:
- **Thermal depolymerisation**, or cracking/pyrolysis, is used for chemical recycling of PE and PP. This is an energy-intensive process which requires large-scale facilities to be cost-effective (Total Corbion, 2017).
- **Chemical depolymerisation** can be used for chemical recycling of PLA and PET. This is an easier process and the process does not require large-scale facilities.

Sorted PLA can be depolymerised into PLA components like lactide or lactic acid, which can be inserted into the PLA production process. Chemical depolymerisation of PLA is relatively energy efficient and can be performed in small-scale facilities (CE Delft, 2019).

Chemical recycling of PLA has environmental benefits compared to conventional processing routes like combustion or composting (CE Delft, 2019).

Chemical and mechanical recycling are not entirely different processes. The first steps of processing PLA waste are approximately equal for mechanical and chemical recycling. The sorted PLA stream is processed into flakes and after this into pellets in a mechanical recycling plant. These pellets can be used directly for new products, which is mechanical recycling. However, these pellets can also be sold to chemical recyclers. Chemical recyclers use pellets since PLA with a standardised size is necessary to get a predictable flow of materials in their processes. Homogeneous waste is necessary for practical reasons like transport and processing in the factory. In the future, it may be possible to use PLA flakes instead of PLA pellets for chemical recycling (de Bie (Total Corbion), 2020).

A share of the pollution in the sorted PLA is removed when they are processed into pellets, but not all. Therefore, an additional process step which increases the purity is often necessary before PLA pellets can be used for chemical recycling, for example hydrolysis.

6.3.1 Requirements PLA stream

Pollution in PLA may also affect chemical recycling. Producing new PLA with polymerisation of lactic acid is easier when the lactic acid does not contain pollution. Increased amounts of pollution make it increasingly difficult to polymerise lactic acid. It depends on the type of pollution whether it is problematic for the chemical recycling of PLA (de Bie (Total Corbion), 2020):

- Pollution of metal is a large problem. A few percent of metal seriously affects the process.
- Even small amounts of catalysator, e.g. 0.1%, can seriously affect the chemical recycling process.
- Pollution of PE, PP and wood can be removed relatively easy with sink-float separation since it floats while PLA sinks. Therefore it does not cause major problems.
- Similar to PLA, PET sinks. As a consequence, it cannot be removed easily with sink-float separation. However it may be removed in other ways.

Total Corbion has appliances for cleaning lactic acid. The PLA they receive is pre-processed which decreases the pollution of the PLA pellets and the pellets are processed with hydrolysis to increase the quality before the chemical recycling process. Therefore most of the pollution is removed (de Bie (Total Corbion), 2020).

The amount of pollution which can be processed in a chemical recycling plant depends on the design of the plant. A new factory can be designed with additional appliances to make sure it can deal with higher shares of pollution.

In the current chemical recycling plant of Total Corbion, rPLA is mixed with virgin PLA. Therefore, the rPLA stream is diluted and the quality of the end-product is affected less (Total Corbion, 2017).

Furthermore, the current plant of Total Corbion in Thailand is designed to reprocess their own products which do not comply to the quality standards. These (pre-consumer) products can be reprocessed into products which do comply to the quality standards. It should be noted that the recycling of post-consumer PLA will likely be substantially harder than pre-consumer PLA because of the difference in pollution.

6.4 Design for recycling

If PLA is introduced in the market, guidelines should be added for design, such that the products produced can be proficiently recycled. In general, Design for Recycling does not only improve the recycling of a plastic, but potentially also improves the quality of the output streams during the sorting process. The same general guidelines of traditional plastics also apply to PLA (Total Corbion, 2017):

- use labels which can be washed off easily;
- use mono-materials if possible;
- do not add materials that harm the recycling;
- do not use direct printing on the product.

Furthermore, guidelines should be made specifically for PLA, similar to the existing guidelines for other plastics. For example, paper labels on PLA packaging may cause problems with mechanical recycling. Therefore, a guideline could be that the label should be made of PLA or PE. An example of design for recycling guidelines for PET is given on https://recyclass.eu/recyclass/design-for-recycling-guidelines/.

6.5 The future of PLA recycling

It is difficult to draw definitive conclusions about the recyclability of PLA in post-consumer waste since this does not happen yet and it depends on several factors regarding the waste like the content, quantity and the sorting and recycling technology. More research and recycling experiments are necessary to be conclusive. We expect that in one to two years' time it is possible to actually perform recycling tests in installations.

More innovation is necessary by mechanical and chemical recyclers to be able to deal with post-consumer PLA, which will always contain some contaminations. At this moment, only isolated PLA streams, like PLA festival cups, are recycled. Some companies, however, are well on their way to provide some of the necessary innovations. Total Corbion has plans to build a new chemical recycling plant for PLA in France (de Bie (Total Corbion), 2020) and Looplife expects that their new mechanical recycling system, which is planned for next year, can deal with many of the current challenges and is capable of recycling sorted PLA waste (de Jonghe (Looplife), 2020).

Additionally, sorting PLA out of the waste stream and recycling this PLA is not feasible because of the small share of PLA in the plastic mix. Scaling up of the volumes of PLA in the mix is necessary to start PLA recycling. An efficient way to scale up the volume of PLA, while having the lowest impact on the environment, is stimulating the use of PLA packaging for applications where conventional packaging products cannot be recycled properly (Molenveld (WUR), 2021). In this way, you can increase the share of plastic packaging that can be recycled. It is not logical to replace existing plastic packaging by PLA when this type of packaging can already be easily recycled. Wageningen University & Research is currently investigating which types of packaging could be replaced by PLA (or other bioplastics) (Molenveld (WUR), 2021).

Currently, Looplife is the one of the few companies involved in mechanical recycling of PLA. Other companies are not involved yet because of the small market share of PLA. We expect that in time, if the market share increases, Dutch recyclers will begin mechanical recycling of PLA as well.

The interviewed parties (de Bie (Total Corbion), 2020, Molenveld (WUR), 2021); (Total Corbion, 2017), expect that both mechanical recycling and chemical recycling of PLA will occur in the future, but that mechanical recycling will be dominant since this is a cheaper process. Organic recycling of PLA is an option until the PLA volume in the market is high enough for mechanical and chemical recycling of sorted out PLA waste to be feasible (Molenveld (WUR), 2021).

Currently, there are no facilities for chemical recycling of PLA in Europe. Total Corbion only has a chemical recycling plant in Thailand. But they plan to build a new chemical recycling plant for PLA in France (de Bie (Total Corbion), 2020). This can stimulate chemical recycling of PLA in Europe.

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