REPORT

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Date
2023-11-03

Reference

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Recycling of PET bottles

Background

Returpack owns and handles the bottle deposit-return system (DRS) in Sweden. They handle the deposit machines, transport and sorting. Washing and processing of the collected bottles are done at Returpacks partner Veolia. Veolia has an advanced washing line which is capable to produce food grade recycled PET. As a result of high quality rPET an increased use of recycled PET in new bottles have been observed, and during the last 3-4 years some companies have started to use 100% recycled PET in their bottles. Since the introduction of 100% recycled PET in the bottles Returpack has noted a change in the quality of the recycled material. The observed effect is mainly optical making the rPET slightly darker (lower L value) and more yellow (higher b+ value) (Figure 1). Now, Returpack wants to investigate how the amount of recycled PET effects the general rPET stream in order to give recommendations to their members.

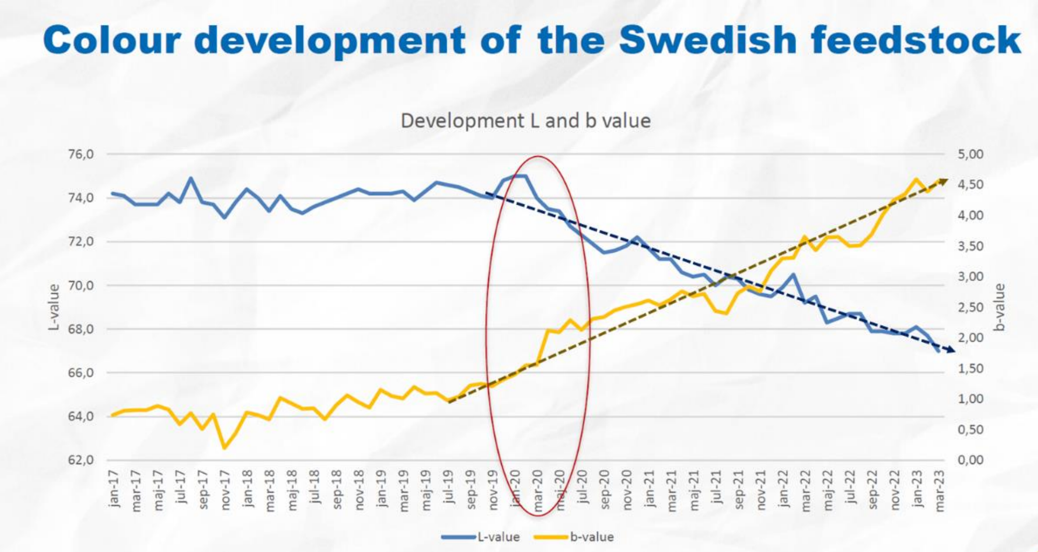

Figure 1, Historical L and b value out from Returpack. The graph has been provided by Returpack.

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Work description

To investigate how the amount of rPET used in new bottles effect the quality of rPET stream from Returpack a literature review was suggested. The review should give insight into what effects the quality of rPET, how to retain a high quality and a suggestion on the what the limit of rPET in new bottles should be. The aim of the work can be summarized into four questions:

1. How does 100% rPET affect the visual quality of the recycled material.
    a. How does the coloring of bottles affect? (e.g. light blue color used in some bottles for mineral water)
    b. What role does the source of rPET play
2. What are the systemic risks of using 100% rPET?
    a. What happens when 100% rPET circulates a few turns?
3. What could be an appropriate amount of rPET to use?
    a. How can the environmental benefits of deposit systems be maximized?
    b. How should quality be guaranteed/controlled?
    c. Are there other packaging requirements that should be introduced, such as design or material in bottles.
4. Identify any gaps and uncertainties in the literature that may need to be supplemented or verified with practical experiments for adaptation to the Swedish deposit system.

Literature review

PET recycling systems

There are a different systems for PET bottle recycling, the deposit-refund system (DRS) (used by Returpack) where only PET bottles connected to a specific system is collected. The other system is the co-collection system where the bottles are sorted out from a stream of other plastic types (Chacon, et al., 2020). In the deposit-refund system the bottles have certain specifications that needs to be fulfilled, for instance, the glue for the labels needs to be dissolved in a hot wash, no PVC in labels or other parts of the bottle, no metal foil, no EVOH barrier, no water soluble inks, only PET as bottle material and PE or PP as lid material (Returpack, 2023). There are also specifications for colour and size. These specifications makes recyclates from this stream free from many problematic impurities. In the co-collection system the requirements for the bottles are not restricted in the same way, which results in bottles with more contaminations (Brouwer, et al., 2016). The rPET from this system are not food safe (according to EU 2022/1616) and cannot be used in new drinking bottles, they are therefore excluded as an input material for new PET bottles for food or drink. However, the effect of the contaminants from this stream has been investigated in multiple reports and articles and can be a useful input on understanding how different contaminations effect the recycling.

To further understand how rPET effects the recycling quality the sorting and washing systems needs to be understand.

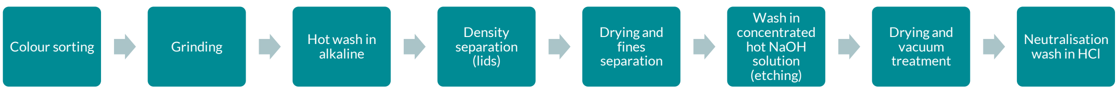

Figure 2, *Process scheme for treatment of PET* (Milton, 2021) (Pinter, et al., 2021)

The process used at Returpack and Veolia ensures that the quality of rPET is safe for food contact applications. The crucial step in the process is the wash in concentrated NaOH where the surface of the material is etched resulting in a pristine material. Although this process results in a clean PET fraction there is a risk that the mechanical properties of the PET are decreased. In order to minimise the degradation risk, washed and dried flakes are mixed with virgin pellets in the bottle production. If flakes needs to be converted to pellets a solid state polymerisation step (SSP) is typically applied in order to regain the properties and to increase the molecular weight (increase IV). The SSP processes can also help remove any volatile substances (acetaldehyde, benzene, ethylene glycol etc) (Welle, 2014).

Contaminations in PET recycling

As mentioned in previous section the contaminations of rPET is dramatically effected by how the bottles have been collected. The contaminations associated with deposit-refund (DRS) system are mainly

- Degradation products such as acetaldehyde, ethylene glycol, diethylene glycol, 2-methyl-1,3-dioxolane, dimers and trimers (Chacon, et al., 2020; Pinter, et al., 2021; Thoden van Velzen, et al., 2020).
- Other contaminants can be as PE or PP from caps, glue from label adhesive or labels. Although most of these are considered to be removed in the separation and washing processes.
- Particle contamination has also been found in rPET from DRS system. The origin of the particles are unknown however they are believed to originate from beverage residues, grime or packaging related contaminants not separated in the process (Brouwer, et al., 2019). According to Brouwer et al there is an opinion among representatives in the PET recycling industry that direct milling causes dirt to be trapped and unable to remove in the washing step.
- Chlorine content, mainly from PVC but can also originate from PVdC has been discussed in the literature as a critical contamination (Dvorak, et al., 2013). These contaminations are among other things thought to produce benzene in PET recycling. Data shows that the chlorine amount from DRS systems are negligible (Brouwer, et al., 2019). PVC and PVdC is not accepted in the Returpack DRS.

In co-collection systems there are much wider range of contaminants besides the ones mentioned for DRS. The majority of contaminants comes from other plastics/polymers used in the packaging such as PVC, PA, EVOH, PS, PE and PP (Chacon, et al., 2020; Thoden van Velzen, et al., 2020; Pinter, et al., 2021). There is also a larger variation of product residues. These contaminations are more difficult to separate in the standard PET recycling process which means they will result in a more significant effect on the rPET. It is clear from the literature that co-collected PET has significantly higher amount of particles, even after wash and SSP.

Properties effected by recycling

There are several different properties that can be effected during recycling of PET. It can be mechanical, processing, thermal, chemical or visual properties. However when investigation rPET used in the bottle DRS there are a few that that have a more significant effect on PET. The section below describes some of the most relevant properties and how they are effected by recycling.

Colour

The colour of rPET material is typically measured using CIELab space (Figure 3). CIELab is a colour space with three axis, L (light/dark), a (red/green) and b (blue/yellow). This is an effective measurement to determine the quality of the rPET. The measurement can be done both on pellets, plates or on the bottle.

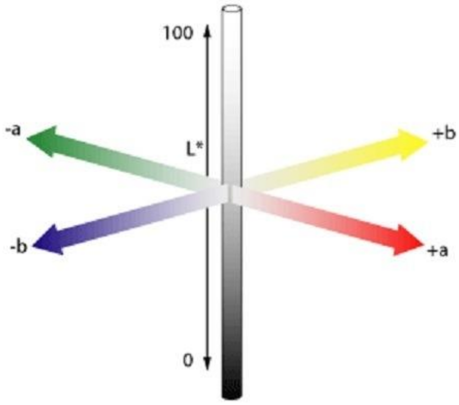

Figure 3, *Representation of CIELab space*

PET is known to easily be miscoloured during the processing (Yang, et al., 2010) and which also is observed in rPET where is typically gets more yellow (higher b value) and/or gets a darker colour (lower L value). This is data that Returpack also has noted in there material stream, that is, as the amount of rPET used in new bottles the rPET is getting darker and more yellow.

According to the literature, the yellowing of the rPET mainly arises from degradation products in the rPET (Brouwer, et al., 2016; Chacon, et al., 2020; Brouwer, et al., 2019). The degradation products are mentioned above however it seems that diethylene glycol (DEG) has the largest impact on the yellowness (Rieckmann, et al., 2013). Rickaman et al showed that the yellowing of PET is strongly dependent on the amount of DEG, processing temperature and the amount of oxygen present. It is not believed that the DEG it self is responsible for the yellow colour but through its reaction with the polymer backbone that is generating conjugated molecules such as benzophenone, stilbenes and biphenyls which are molecules that are known to cause yellowing (Chacon, et al., 2020)

The observed decrease in L value that means the material is getting darker is associate with number of particles in the rPET. Chacon et al has tested how a variety of visual properties are effected by the amount of particles, and has clearly demonstrated that an increasing amount of particles results in lower L value (Chacon, et al., 2020). However when the authors compares L value and yellowness with increasing amount of rPET from DRS they observe a decrease in L value and particles but no change in yellowness. This is believed to be caused by additive that masks the yellowness, this can typically be from light blue bottles. It is observed that the same blue colour additives also could be responsible for an increase in amount of particles thereby also the decrease in L value.

In a thesis work done by Cornelia Milton (Milton, 2021) supervised by Returpack it is demonstrated that when doing a roast test (EPBP, 2010) on 100% rPET from bottles its notably decreases the L value compared to the reference and 50% rPET. The value from 100% rPET also increases the standard deviation of the samples. This shows that rPET have a significant effect on visual appearance however this experiments cannot be compared to the processing that is done in the actual recycling system, where the PET is washed using advanced washing, pre-dried and treated with SSP.

Haze

Haze is a measure of how milky the bottle looks, it is usually measured using a haze-metering device, typically HazeGuard. An increase in haze can be related to changes in the crystallinity that occurs because of contaminations in the rPET. The contaminations can act as nucleation points, slightly increasing the crystallinity which scatters the light making the material more opaque (more on this under Thermal properties). Haze have been shown to significant be affected by particle contamination especially other polymers (Brouwer, et al., 2016).

Intrinsic viscosity (IV)

IV is a commonly used number for determining the processing properties of PET. The number is associated with the molecular weight of PET and is often determined by using the ASTM D4603-03 standard which involves dissolving the PET and let it pass through a capillary. Typical IV numbers for PET ranges from 0.5 to 1 dL/g depending on application. For bottle application IV is usually around 0.8 dL/g. An IV lower than 0.7 dl/g would make bottle processing more difficult (Chairat & Gheewala, 2023).

PET is a stable polymer at room temperature but when processed PET is highly sensitive to moisture as it undergoes hydrolysis in the presence of water at elevated temperature. Hydrolysis cuts the polymer chains making them shorter which results in a lower IV number (Masmoudi, et al., 2018). This also happens in the recycling processes of PET and is the main cause of the decreased IV for rPET. In order to improve the IV, a process called solid state polymerisation (SSP) has been developed as a part of the PET recycling schedule (Welle, 2011). SSP is used in the production of PET and involves heating the PET above its glass transition temperature but below its melting temperature under high vacuum. This process helps extract ethylene glycol out of the PET which helps the polymer chain reconnected increasing the molecular weight and also the IV number. This process has also been shown to remove volatile contaminants in PET (Welle, 2014). The process is so effective it is often possible to get rPET to the same IV as virgin PET-bottle grade (Pinter, et al., 2021)

SSP is essential for using a high amount of rPET in new bottles, however the processes also increase the risk of producing yellowness if not performed at the correct temperature and vacuum. As mentioned in the text about colour Rieckman et al has shown that temperature and oxygen concentration in presence of DEG can significantly affect yellowness (Rieckmann, et al., 2013).

Particles in solution (Partisol)

Partisol is a fairly rare measurement that is performed by only a few companies, such as Getec (former Emmtec) in Holland. The technique is based on dissolving the PET in hexafluoroisopropanol (HFIP), and pushing the solution through a cuvette and taking images of the solution. Using programming 10 000 images are taken and number, shape and size of particles in the images are analysed and summarised. The results can be presented in different ways for instance number of particles with a specific size or shape, however in the literature the results from these measurement are often presented as total amount of particles per 10 000 images (PPTI) (Chacon, et al., 2020).

rPET in almost all cases have increased amount of particles compared to virgin PET (1525 PPTI) (Table 1). However there is a substantial difference between how the rPET have been collected (Chacon, et al., 2020), DRS collection have a significant lower amount of particles than co-collected bottles. As discussed in the contamination section the particles in DRS collected bottles are believed to originate from remaining product residues and not a complete separation of other packaging materials such as labels, caps, glues or liner. In the co-collected bottles the same contaminants are present but in this case also additional contaminants for instance barrier materials (EVOH, PA, PVdC), none water soluble glues and a variety of other plastic materials can be included (Brouwer, et al., 2016). Brouwer et al have modelled a predication that if 100% rPET is used in new bottles there is a linear accumulation in particles with increasing recycling cycles, but if the content of rPET is decreased to 75% the accumulation reaches a plateau at around 4-5 cycles and roughly 30 000 PPTI. At 50% rPET the plateau reached about 10 000 PPTI and at 25% rPET it levels out at 5000 PPTI. Pinter et al have studied the effect of reprocessing 75% rPET from the Swedish DRS system 11 times and found no accumulation of contaminants, no decrease in IV and no significant change in colour, however they did not study number of particles.

Table 1, Number of particles and visual data on PET with different amount of rPET origination from different collection system. The table is reconstructed from (Chacon, et al., 2020).

Sample (amount rPET)	Source	Type	All particles (PPTI)	Haze (%)	L*	a*	b*	ΔE
Virgin	-	-	1525	0.7	95.5	0.04	2.4	-
25%	A	Mono collected	5932	1.1	94.3	−0.13	2.6	1.2
50%	A	Mono collected	10 557	1.7	93.5	−0.24	2.6	2.1
75%	A	Mono collected	18 261	2.8	91.9	−0.39	2.4	3.6
100%	A	Mono collected	22 908	3.6	90.7	−0.54	2.7	4.9
25%	B	Co-collected	16 715	2.0	94.6	0.04	3.3	1.5
50%	B	Co-collected	29 543	3.7	93.6	−0.22	4.1	2.5
75%	B	Co-collected	43 779	5.0	92.8	−0.45	4.9	3.7
100%	B	Co-collected	62 752	6.6	91.7	−0.72	5.8	5.2
25%	C	Co-collected	13 387	1.8	94.3	−0.15	3.2	1.5
50%	C	Co-collected	24 877	3.3	92.9	−0.30	3.9	3.0
75%	C	Co-collected	35 452	4.7	92.0	−0.38	4.2	4.0
100%	C	Co-collected	51 303	6.2	91.1	−0.48	4.5	4.9

Thermal properties (melt temperature and crystallisation)

PET is a semi-crystalline polymer which means that it can form a crystal structure during cooling or heating. The thermally formed crystalline parts of PET scatters light making the material more opaque, which is unwanted in PET bottles as it results in a hazy bottle. How PET crystallise depends on a variety of parameters such as cooling time, molecular weight, particles/impurities , co-polymer content and stretching. The melting temperature (Tm) of PET is defined as the peak temperature where the crystals in the PET dissolves into an amorphous state. The amount of energy required to melt the crystals can be related to the amount of crystals in the polymer, this is usually referred to as crystallinity. Crystallisation temperature (Tc) is typically define as the peak temperature where crystals are formed. For PET crystallisation can also occur upon heating, which is called cold crystallisation. The cold crystallisation takes place between the glass transition temperature and melting temperature.

Differential Scanning Calorimetry (DSC) is the preferred method for determining these transitions.

The behaviour of the thermal properties of rPET have been studied in the literature and it has been demonstrated that the crystallisation temperature of rPET is significantly higher than for virgin PET (Romão, et al., 2010). The reason for this could be an increase of particles and impurities in rPET which can act as nucleation sites for crystallisation resulting in quicker crystallisation. The quicker crystallisation can also be effected if the polymer chains are shorter and therefore can move more easily in the melt. A faster crystallisation also results in slightly higher crystallinity (Romão, et al., 2010; Höög, 2021).The effect with higher crystallisation temperature and crystallinity could result in a an increased haze. No reports have been found connecting the crystallinity to an increased haze, however in the paper by Chacon et al (Table 1) an increase in particles also increases the haze, although there are no evidence that the crystallinity is the reason for the increased haze (Chacon, et al., 2020).

In a presentation from Norner received from Returpack DSC is used to characterise raw material (blown bottles) by determining crystallisation temperature and melting temperature. They observed a 5 °C difference in Tc between 80% rPET and 100 % rPET and suggest that if Tc is higher than 189 °C it is probably a 100% rPET. This is a study done on only a few samples and the results would need a larger study to be confirmed.

This method could be a good complement to control the incoming material to Returpack, as the members of Returpack can check their bottles in order to confirm that there not using 100% rPET. However more data is needed to confirm these initial tests. In the presentation only one sample per grade was tested and it is not clear whether the same rPET is used on all the tests.

Results/Outcome

The following section discuss the questions presented in introduction in relation to the findings in the litterature review.

1. **How does 100% rPET affect the quality of the recycled material.**
   100% rPET have a negative effect on colour and accumulation of particles. It seems that the processes for cleaning the materials are not enough to remove the contaminants that occurs in these materials. The use of 100% rPET does not affect IV to a significant extent which means the mechanical properties of the rPET is acceptable even after recycling multiple times. But the decrease in optical properties will significantly change the quality of the rPET and limits the use. The optical effects will get worse for each recycling step until it is no longer usable. Although the scenario presented in the literature describes a system using only 100% rPET the deteriorating effect is also seen at Returpack where only 33% (2020) of the bottles is using 100% rPET, which point to that even a smaller amount of 100% rPET can have an effect on the total quality.

   a. **How does the light coloring of bottles affect? (e.g. light blue color used in some bottles for mineral water)**
      The light blue colour used in certain bottles have a positive effect on yellowness as its masking the yellow tone, however it also decrease the L value making the bottles darker (Brouwer, et al., 2016). In the thesis project by Cornelia Milton (Milton, 2021) it was demonstrated that the light blue colour additive only had minor effect on the L value, however this study was

performed on bottles before processing. The processing step might cause the additives react causing a lower L value. Pinter et al was using a acetaldehyde blocking agent that also had a blue toner which resulted in maintain the yellowness to a low level and did not affect L-value.

b. **What role does the source of rPET play**
It is clear from multiply papers and report that DRS collected rPET is significantly more clean than co-collected systems. In the co-collected system there are less requirements on packaging design and material which leads to a broader variation in contamination. Another source of contaminations is other types of product residues and other plastic packaging.

The bottles used in the Swedish DRS does not necessary come from Swedish bottles. It is most likely that PET bottles with rPET that are on the Swedish market originates from other countries (mostly within EU?). Most of the DRS in Europe are similar but there could be variations in the guidelines. This could result in that PET bottles with rPET originating from another system could have an impact on the Swedish system. European PET Bottle Platform (EPBP) is an industry initiative that provides PET bottle design guidelines for recycling, evaluates PET bottle packaging solutions and technologies and facilitates understanding of the effects of new PET bottle innovations on recycling processes. EPBP and its guideline is widely accepted in many European countries and larger companies. When comparing Returpacks guidelines on transparent PET to EPBP they are very similar, with only a few difference, mainly on the orange part (conditional) where EPBP can accept some metallised labels and PA barrier (if tested). This point to that the negative impact from other DRS in the Swedish system is only minor.

2. **What are the systemic risks of using 100% rPET?**

Using 100% rPET in the DRS creates a risk of miscoloured bottles with a decrease in overall quality. The risk of accumulation of this problem has not thoroughly been investigated, although modelling studies suggest that particle level would increase which likely will lead to stronger discolouration. It is not only particles accumulation that could be problematic, the risk of accumulation of chemical substances that potentially could change the safety and the organoleptic properties of PET should also be considered. No data that supports the URRC process removes any potential chemical within the PET has been found. Generally PET has a low absorption of chemicals into the polymer, which suggest that most of the product contamination would be on the surface of the PET and can be removed by the URRC process. The degradation products which are produced within the PET could be more problematic to remove using the URRC process as it is only cleaning the surface. In a SSP process on the other hand most of the degradation products can be removed.

a. **What happens when 100% rPET circulates a few turns?**
According to Brouwer et al cycling of 100% rPET will lead to linear increase of particles which probably will result in lower L value and increase in yellowness. However if using rPET from DRS the PET could cycle for about 2-5 times before reaching the same number of particles as for co-collected bottles.

3. **What could be an appropriate amount of rPET to use?**

In the literature values between 0 to 100% rPET typically with 25% increments have been studied. In most of the papers and reports 100% rPET is not recommended, however 75% rPET have been shown to retain good enough properties to be used in multiple recycling steps. No data on 80-90% rPET was found in the literature, although it can be calculated using the equation 1 presented in (Brouwer, et al., 2019).

Equation 1: $AP_j^{PET} = \left(AP_{j-1}^{PET} + \Delta AP_{recycling\ process}^{PET}\right) \times RC + AP_{virgin}^{PET} \times (100\% - RC))$

Where AP_j^{PET} is the number of particles in the cycle j, AP_{j-1}^{PET} is the number of particles in previous cycle, $\Delta AP_{recycling\ process}^{PET}$ is the increase in particle per recycling cycle, RC is the amount recycled material and AP_{virgin}^{PET} is the amount of particles in virgin PET.

Using this equation with the values reported in the article the particle accumulation of 80, 90 and 95% can be calculated. In Figure 4 the data have been plotted using PET from DRS and it is evident that up 80% rPET content plateaus in a similar way as 75%. With 90 or 95% content the accumulated particles increases more rapidly and the graph does not level off after 20 cycles. Pinter et al demonstrated that 75% rPET from the Swedish DRS could be recycled up to 11 times without any significant change in colour, IV or contaminants (chemical) (Pinter, et al., 2021). With the data presented above a recommendation of 80% rPET should be a safe and sustainable amount of rPET. It should be noted that the recommendation is per bottle and not in the total input material to Returpack, as described in the presentation sent by Returpack and the thesis work by Corenlia it is not the total amount of recycled rPET that determines the visual quality but it is the amount of bottles that contains 100% rPET.

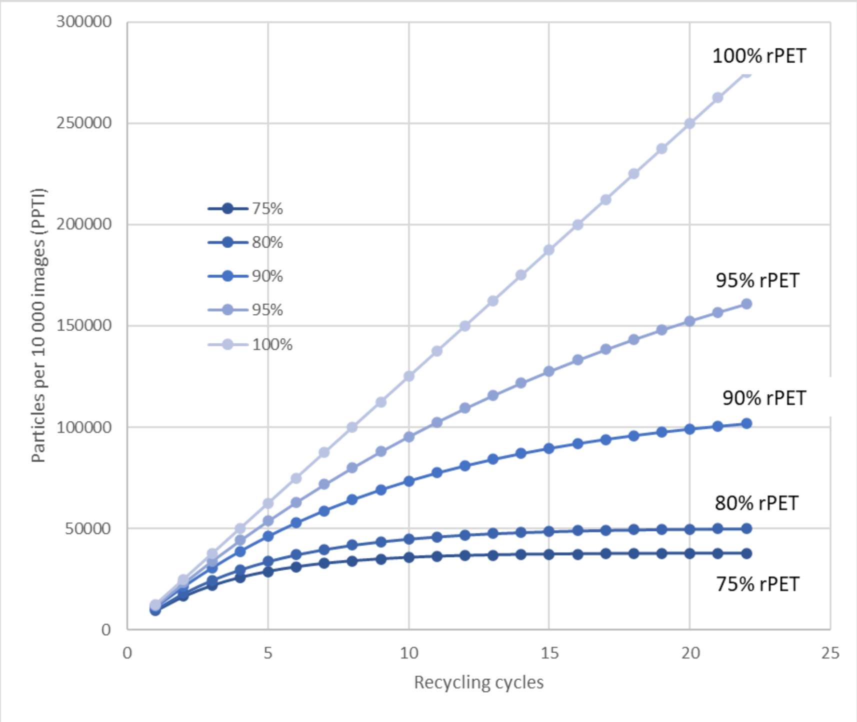

Figure 4, *Calculated accumulation curves using Equation 1.*

The recommendation of 80% is predicted to maintain the visual and mechanical properties, it will probably not decrease the already fallen L to lower value or increasse the b value.

According to the latest data received from Returpack the L value had decreased from around 74 to 67 (between March 2020 and March 2023) and the b value has increased from around 1.5 to 4.5 during the same time. It is not certain that implementing a 80% maximum rPET concentration at this point would improve these values and it could take several years before the values are going back to their original values, *if* they do at all. A suggestion would be to start with 80% and then follow the trend over time, then depending on the trend the amount of recommended rPET can be corrected. In order for better prediction more data on the current and the historical use of rPET is needed.

a. How can the environmental benefits of deposit systems be maximized?

In a perfect world with no degradation or impurities the best way to maximise the system would be for everyone to use 100% rPET in their bottles. This system would then truly be circular, although this would not allow a growing number of PET bottles. However from this report it is evident that 100% rPET is not a good option as the quality of the PET will decrease which eventually would lead to material which no longer can be used. This will inevitably lead to low quality recycling which in the end would anyway require and input of virgin material. Using the suggested 80% rPET would allow for a high degree recycled material while maintain quality and allow for a growing amount of bottles. This would results in a stable recycling system with high amount of recycled content.

In order to determine the true environmental impacts of the deposit system some sort of life cycle assessment (LCA) is needed. Returpack has provided LCA work done on their system. According to Böving et al (Böving, et al., 2019) Returpack sends roughly 50% of their collected transparent/blue PET bottles for URRC processing. By increasing the amount to 80% the GWP (CO_2 eq.) from the Returpacks DRS would decrease by 3.27 % compared to today. Assuming a linear relationship of GWP the increase from 80% to 100% would be approximately 2%. In the same report Böving demonstrates that going from 0% material recycling to the recycling rate used today there is a 95% improvement in GWP. When comparing this increase (95%) to the increase for “optimal” recycling (3.27%) it sems that major improvement in environmental benefits is mostly effected by going from 0 to 50%. With this argument setting a limit to 80% rPET in new bottles will on one hand increase the GWP, but the increase would be minor compared to the GWP increase that virgin PET could generate to compensate for the low quality of a 100% rPET system.

b. How should quality be guaranteed/controlled?

There is no quick test for guaranteeing the quality of the rPET. Multiple analysis needs to be done, the recommendation would be to continue the colour and IV test which is already done today. It is also important the measurements are done over time to monitor the trends. Measuring IV and colour on flakes that has been processed at Veolia might not provide the actual value of quality as the flakes needs to be processed to get a good homogenisation. However the exact value of data might not so important but more how the value change over time. The data provided from Returpack shows CIELab data from flakes, even if does not show the true colour of the rPET it is good enough for screening and to follow the general trend.

Probably there will be variation in the colour due to seasonal fluctuations in consumer behaviour and other variations that can affect the colour, it is therefore important to follow the trends on a longer time scale that only a few months.

An alternative way to monitor quality (colour) is to get information from the members of Returpack. By measuring the output data from members using 80% rPET (or similar) the quality of the input to Returpack could be estimated. According to Returpack website (2023-10-05) there are 540 connected companies using more than 7000 different articles, the website does not reveal whether there are using PET or aluminium, however it can be assumed that the many of articles are PET, which suggest that amount of PET bottles are great. Which means such a test would involve an immense number of measurements and would probably not be feasible. However if Returpack could choose a smaller number of representative members that could send a few bottles to be measured a 3-4 times per year such data collection could be attainable. This data would give valuable information on the quality of rPET that goes in to Returpacks facility without risking contaminations and with known amounts of rPET. An alternative to this is to measure the properties at Returpacks customers after the material have been processed..

Another option would be to do “picking analysis” on the input material to Returpack, however by doing this the bottles would need to be cleaned and the amount of rPET will not be known.

c. **Are there other packaging requirements that should be introduced, such as design or material in bottles.**
The guidelines used at Returpack is at moment already very strict and does not allow any of the reported problematic materials covered in this review. Barriers and other polymers such as PVC and PVdC seems to have the biggest impact on the quality of rPET and these are forbidden in the Returpack system. According to the guidelines labels, liners and caps are allowed to be used using other materials than PET, however these are easy to separate and according to the literature have low impact on the quality.

4. **Identify any gaps and uncertainties in the literature that may need to be supplemented or verified with practical experiments for adaptation to the Swedish deposit system.**

The literature around PET is vast and the quality aspect of different systems have been investigated in many articles and reports. However when it comes to more specific data i.e. how recycling of different grades would affect the Swedish system is more difficult to find. Although there where one published paper (Pinter, et al., 2021) on how the quality of 75% rPET from Returpack is effected by multiple recycling cycles, there is still a lack of information on the real world impacts of such system would look like. To confirm the findings in this literature review a study on how 80% rPET from Returpack would influence the general quality after multiple recycling steps is needed. Such study would however probably not generate that much new information, as it would be similar to the study of Pinter et al, maybe with the addition of partisol analysis some new results might be presented. To truly see the effect of a maximum 80% rPET content the change in quality over time needs to be monitored (as suggested in question 3)

Besides how the limit of rPET would affect the quality of the recycling system there are few missing pieces that would be valuable to investigate:

- Follow up to the Norner experiment using the crystallisation temperature (Tc) to determine rPET content. To understand more about this approach data regarding how the amount of particles is effecting the Tc would need to be investigated. A larger number of tests needs to be performed with known amount recycled content. This should also be complimented with CIElab and haze measurement to understand how crystallisation and particle content impacts visual properties.
- Investigate how 80 and 90% rPET from Returpack effects colour and particles and compare with 100% rPET
- More detailed investigation of how blue and green additives effect colour.
- How effective is the URRC processes on removing degradation products that is generated within the polymer? Especially comparing the chemical cleanliness of URRC processed flakes and SSP processed pellets.

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Polymers, fibers and composites - Polymer Materials and recycling

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Verifikat

Transaktion 09222115557509342852

Dokument

Report Recycling of PET bottles V2 2023-11-03
Huvuddokument
14 sidor
Startades 2024-01-25 20:39:51 CET (+0100) av Mattias Andersson (MA)
Färdigställt 2024-01-25 20:40:21 CET (+0100)

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