The Transition Institute 1.5
L'ambition d'une véritable transition

WORKING PAPER

#4 - 04/2025

Barriers and levers to recycling poly(ethylene terephthalate) bottles

Laurianne VIORA

Mines Paris, PSL University, Centre for Materials Forming (CEMEF), UMR CNRS 7635, 06904 Sophia Antipolis, France

laurianne.viora@minesparis.psl.eu

DOI : 10.23646/7g7p-2j09

MINES PARIS | PSL | TTI.5 The Transition Institute

TABLE OF CONTENTS

I. Introduction

Historically, the very first plastic bottles were made from Polyvinyl Chloride (PVC)[1]. However, this material, once heated, degrades into toxic byproducts[2,3]. Meanwhile, a final post-condensation step (SSP)[4] allowed for the creation of sufficiently long chains to use Polyethylene Terephthalate (PET) in plastic bottles, whereas it had previously been reserved for making textile fibers. The development of the injection-blow molding process also enabled a diversification of uses. In the 1980s, PET eventually replaced PVC, which was more dangerous for health. In addition to a reduction in bottle weight and minimal health risks, PET bottles have many advantages: transparency, high mechanical strength, and excellent impermeability to gases and water. However, like many other plastics, PET does not naturally decompose, contributing to the currently criticized plastic pollution. Moreover, to create such a resin, the chemical industry uses terephthalic acid and ethylene glycol, both derived from the petroleum industry. The notion of recycling emerged out of the need to preserve resources and manage the end-of-life of waste (to limit plastic pollution). Additionally, PET is a polyester, and its final synthesis step at high temperature allows the chain lengths necessary for industrial applications. But how is the recycling of these bottles deployed? Despite increasingly strict legislation, why is the bottle-to-bottle PET recycling rate still so low? What are the barriers to its expansion? And what are the levers and opportunities to develop it?

II. From PET synthesis to bottle collection: a diversity of stakeholders

Like any object created by humans, plastic bottles must be managed throughout their entire lifecycle: design, manufacturing, usage, collection, and waste treatment. Despite evolving legislation, plastic bottles are considered single-use packaging, which drastically shortens their usage phase and places significant emphasis on the end-of-life stage of the material.

1. Synthesis of virgin PET

The processes for synthesizing PET and manufacturing plastic bottles, while perfected over the years, have been proven for over 30 years. PET is obtained through the esterification of ethylene glycol (EG) with terephthalic acid (TA), followed by the polycondensation of the newly formed monomer[2,5,6]. Sometimes, dimethyl terephthalate (DMT) can be used in a transesterification reaction. The first step involves the reaction of monomers to create Bis(2-Hydroxyethyl) terephthalate (BHET) prepolymers (**Figure 1.a**). As this step is reversible, byproducts such as water or methanol are removed by heating and/or vacuuming. This first step is followed by an initial polymerization reaction via polycondensation (**Figure 1.b**), and then a second reaction to increase the viscosity and reach a Polymerization Degree (DP) of 100 using primarily antimony-based catalysts[7]. Finally, a Solid State Post-Condensation (SSPC) step at 200-240°C and 100 kPa for 5-25 hours produces chains of sufficient molecular weight for bottle applications (DP > 150). PET is thus obtained in the form of pellets[2,5,6].

The last two steps use catalysts, mainly antimony trioxide or antimony compounds with ethylene glycol[2].

To limit the crystallization of PET upon cooling, a copolymer based on diethylene glycol (DEG) can be synthesized, which adds flexibility to the chains by disrupting their ordered structure, slowing down crystallization[6,8–10]. Isophthalic acid and cyclohexane dimethylene glycol can also be added[2,10.] Some additives may be used in the plastic: carbon particles for faster heating, colorants for differentiation, etc. PETG, which contains a glycol like cyclohexane dimethanol (CHDM) instead of ethylene glycol (EG), can also be used to hinder the crystallization of PET, lower the melting point and viscosity, thus making molding easier[11,12]. These copolymers lead to a loss of chain linearity, with segments containing different atomic configurations.

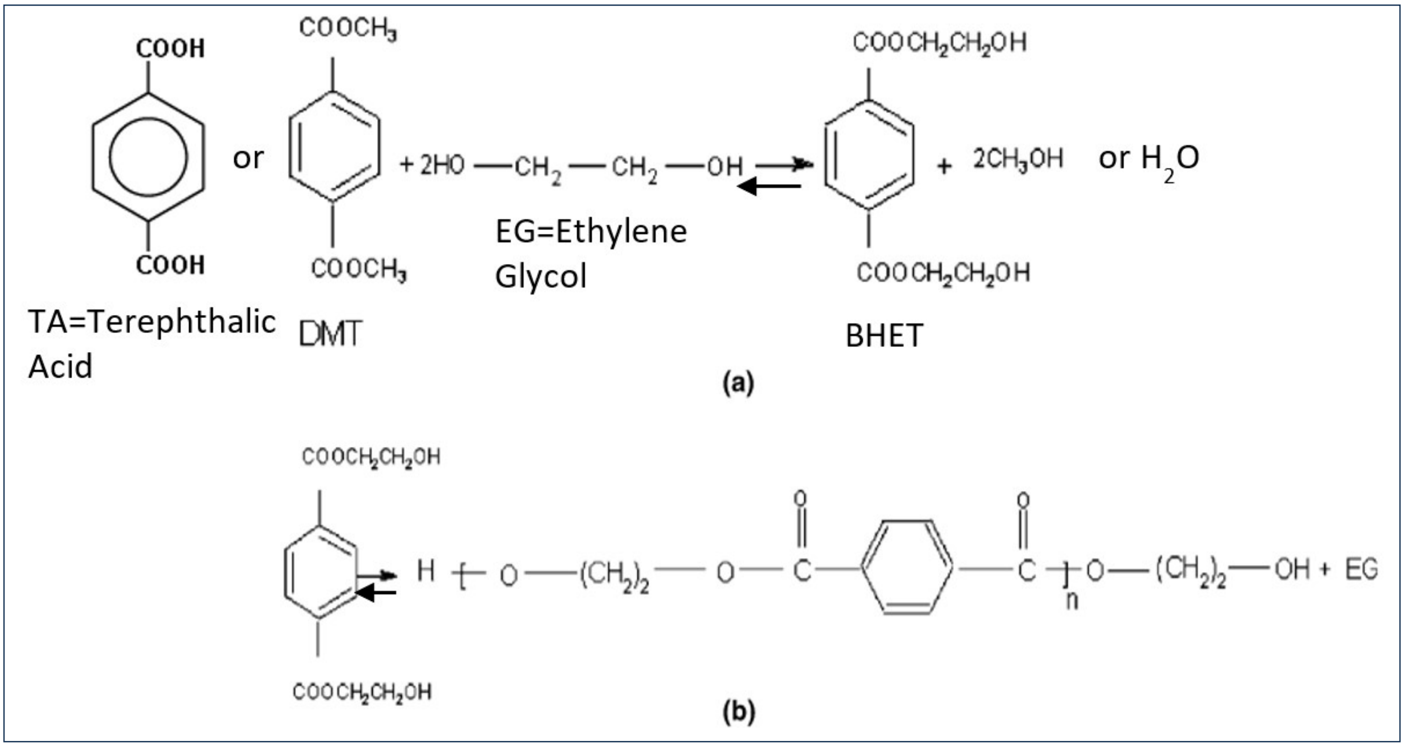

Figure 1. PET synthesis reactions: a. (trans)esterification; b. condensation reaction according to Awaja et al.[2]

The bottles are then formed using the Injection Stretch Blow Molding (ISBM) process, patented in 1973[7]. The pellets, after drying, are placed in an injection hopper with a low-speed screw but high torque[7], at temperatures between 270 and 290°C[2,13]. The fluid polymer can then be injected into a cold mold at temperatures between 5 and 50°C[2,14–16], forming a preform – a tube with a collar and neck with threads, whose geometry allows the future bottle’s closure system to fit.

The preform is then conveyed to the bottle filling unit, where it is heated by infrared radiation beyond its glass transition temperature (Tg). In the second step, the preform is stretched and blown to its final shape by pressing the walls of the blown envelope against the cold mold[2,7], creating a microstructure induced by stretching that is fixed by the contact of the warm walls with the cold mold[2,6], which gives the bottle excellent mechanical and barrier properties[2]. The bottles are then filled with the desired liquid.

Finally, the bottles are fitted with a closure system or "cap," often made of Polypropylene (PP), sometimes of Polyethylene (PE), and occasionally containing silicone[17]. They are also labeled with Poly(styrene) (PS) labels, and more recently PE and PP labels[17]. These materials are advantageous because they can be easily removed by density separation during the recycling process[5].

2. Usage

After being transported to the distribution point, plastic bottles continue their journey with the user, who often consumes the entire contents of the bottle and then disposes of it.

The contents are diverse, as PET is resistant to many substances: water, acids, sugary drinks, carbonated beverages, etc[5,18,19]. This variety of uses, determined by the manufacturer, explains the diversity of PET types available on the market, even though PET is the plastic with the fewest additives.

The user, before discarding the bottle, might repurpose it for other uses: as a water bottle, for storing household products[2,5,20], as a container for cigarette butts[21], etc. Some unconventional uses can more easily pollute the material.

Finally, the user may decide to reuse the bottle for more permanent purposes: as a flower pot, water diffuser for plants, house bricks, or insulation.

3. Collection and treatment: a matter of public policy

Like other household waste, the end-of-life of plastic bottles can be managed in various ways. They can be collected through an organized system with other household waste or brought by citizens to designated collection points (curbside collection). They may also be returned for deposit[5]. Finally, some bottles are discarded in the streets or nature, accounting for about 1% of all bottles and 19% of bottles consumed outside the home in France in 2023[19]. The 8 million tons of plastic that end up in nature each year worldwide degrade into plastic particles, even micro or nanoparticles[22]. These particles are then ingested by marine organisms, poisoning them[23].

In France, the collection system has evolved: in the 1960s, a deposit system for glass reuse was widely used[24]. In the 1990s, the public authorities decided to invest in recycling, including collection by voluntary drop-off points to recover and resell the materials from waste, including plastic bottles[25]. The user thus brings the bottle to a container (voluntary drop-off point) or to a yellow bin (curbside collection) dedicated to various packaging (since 2022), as in Spain. In France, 90% of bottles are collected from households[26]. In Germany, the Netherlands, Denmark, the UK, and Northern European countries, the bottle deposit system has been in place since the 2000s and is spreading across Europe[3,17,27,28]. In the US, both systems coexist. In countries such as Egypt or India, collection occurs in the streets by sorting the accumulating waste. PET, being of commercial value, is valuable for local low-income families to recover. The deposit system has the advantage of achieving nearly 100% PET bottle recovery at this stage. With curbside collection or drop-off point systems, recovery rates are lower[5].

Currently, the PET bottle collection rate in France still only reaches 60%[29,30], compared to 98% in Germany for all materials or 88% in Croatia for plastic bottles in 2020. In Europe, the average collection rate for both bottles and trays is 60%, with 50% of PET effectively recycled across all PET bottles and trays in all sectors[28,31]. In 2020, PET bottles in Europe contained an average of 17% recycled PET[16]. The rest of the recycled bottles and trays is primarily used in fiber applications (33% of all bottles on the market)[31]. In Germany, 40% of PET bottles are recycled into new bottles[32].

Elsewhere in the world, varied rates are reported. In Japan, since 2011, the collection rate has exceeded 90%[33]. In 2021, 69% of the PET collected in Japan was effectively recycled, and 33% of the total recycled PET flakes were used to make new bottles[33]. In Brazil, 56.4% of PET was collected in 2021, and 29% of the collected PET was used in bottle application[34]. Finally, in the United States, decisions are also being made in this direction through national recycling programs (National Recycling Goal), aiming for 50% collection by 2030[35]. Major PET bottle manufacturers are considering more drastic percentages, such as 50% recycled PET by 2030, and even 100% in the case of Danone[36].

These collection rates have encouraged PET producers and processors to work together on decontamination processes, enabling the use of recycled PET for bottle applications[5].

III. Recycling and the Quality of rPET

As previously mentioned, the use of PET requires many stakeholders. This is why waste management organizations interact with a variety of actors, such as businesses, individuals, and communities, from PET recyclers to manufacturers of hollow bodies or thermoformed parts[18]. Mechanical recycling of plastic bottles for bottle-to-bottle use has existed since 1991, when the U.S. Food and Drug Administration (FDA) approved the use of recycled plastics in bottles. Indeed, decontamination systems are sufficiently effective to not endanger consumers[5]. However, some macroscopic contaminants that do not affect food safety may remain in the PET.

The following sections aim to understand the recycling process steps and the quality of the resulting PET.

1. The Technical Reality of Recycling

Once the bottles are collected, they are separated from other materials in the stream to obtain bales concentrated with PET bottles. Sorting can be manual or optical (via Fourier-transform near-infrared spectroscopy (FT-NIR) and spectrocolorimetry)[37]. Optical sorting, now widespread in France, accelerates sorting speeds with excellent identification yields[37,38], equivalent to or greater than manual sorting (90% recovery of PET in the best cases[39]). 90% of PET bales contain 30 to 40% of objects other than bottles, such as PET trays, PET sheets, or aluminium cans[37]. Sorting center checks verify the quality of sorted objects approximately every 5 hours to maintain consistent quality[37].

Next, in the mechanical recycling process, the PET bales undergo further sorting. These machines are regularly checked. The waste is ground, and then the flakes are washed in an aqueous alkaline solution[5]. This step separates polyolefins (PE, PP) by density and removes glue residues. The flakes are then dried and analyzed by infrared spectroscopy to remove remaining polymers, oxygen absorbers, and nylon-based additives (via Raman spectroscopy). The flakes are then dried and extruded through a particle filter to continue decontaminating the PET[17]. Ultimately, 71% of the collected bottles end up as flakes[28]. Finally, the granules obtained during the extrusion step are dried and undergo a post-condensation process under conditions similar to virgin PET. This final step also contributes to PET's success, as it helps restore the macromolecular size necessary for bottle applications. The chemical nature of PET thus facilitates the regeneration of these properties.

In the case of chemical recycling, a depolymerization step allows the recovery of the original monomers by adding water (hydrolysis), methanol (methanolysis), or ethylene glycol (glycolysis)[2,3,5]. During purification steps by distillation or crystallization, contaminants of all kinds are removed[5]. The resulting material, regenerated from the polymerization of the purified monomers, can be considered equivalent to virgin PET: the properties derived from it are those of virgin PET. The main barrier to chemical recycling remains its cost[2].

2. Quality of Mechanically Recycled PET

The quality of PET obtained after all these steps can be compromised. It is primarily affected by the degradation state of used bottles, the quality of bales leaving sorting plants, and the recycling process itself[17,18,40].

Molecular contaminants from heterogeneous uses of PET bottles (cleaning products, gardening materials, etc.) can render recycled materials unsuitable for food packaging applications. It is therefore essential to ensure that PET purification technologies are efficient enough to remove these potentially adsorbed molecules[5].

Once the molecules making PET unsuitable for reuse in packaging are removed, three main factors affect the quality of rPET: size, architecture of the macromolecular chains, and the presence of contaminants. The resulting quality of rPET is affected in terms of rheological, mechanical, barrier, optical, and thermal properties.

a) Degradation of rPET: Reduction of Molecular Weight and Chain Architecture Changes

Degradation Mechanisms

The polycondensation reaction used during PET synthesis is a reversible reaction[5]. PET molecules can react with water (hydrolysis[6]), methanol (methanolysis), or glycols (glycolysis) to reform ethylene glycol and terephthalic acid (or dimethyl terephthalate)[2,5,7]. Hydrolysis, in particular, is favored at temperatures above the glass transition temperature (Tg) [7] and can be activated with 0.01-0.02% water in PET[41]. PET is also very sensitive to heat and shear in the presence of oxygen: under these conditions, chain scissions occur[7,37,42–46]. These scissions result in a decrease in chain length, forming low-molecular-weight compounds (**Figure 2**). This significant decrease in molecular weight is even more pronounced as the phenomenon accelerates itself[47]. The carboxylic acid formed catalyzes the chain breakage reaction. Additionally, this reaction leads to the formation of acetaldehyde (**Figure 2**), which gives a fruity taste to PET containers[2,6,7], as well as other volatile organic compounds (VOCs)[41], which can be easily removed. In contrast, in the absence of oxygen, chains tend to elongate and cross-link[43]. These phenomena occur mainly during extrusion and injection processes[2].

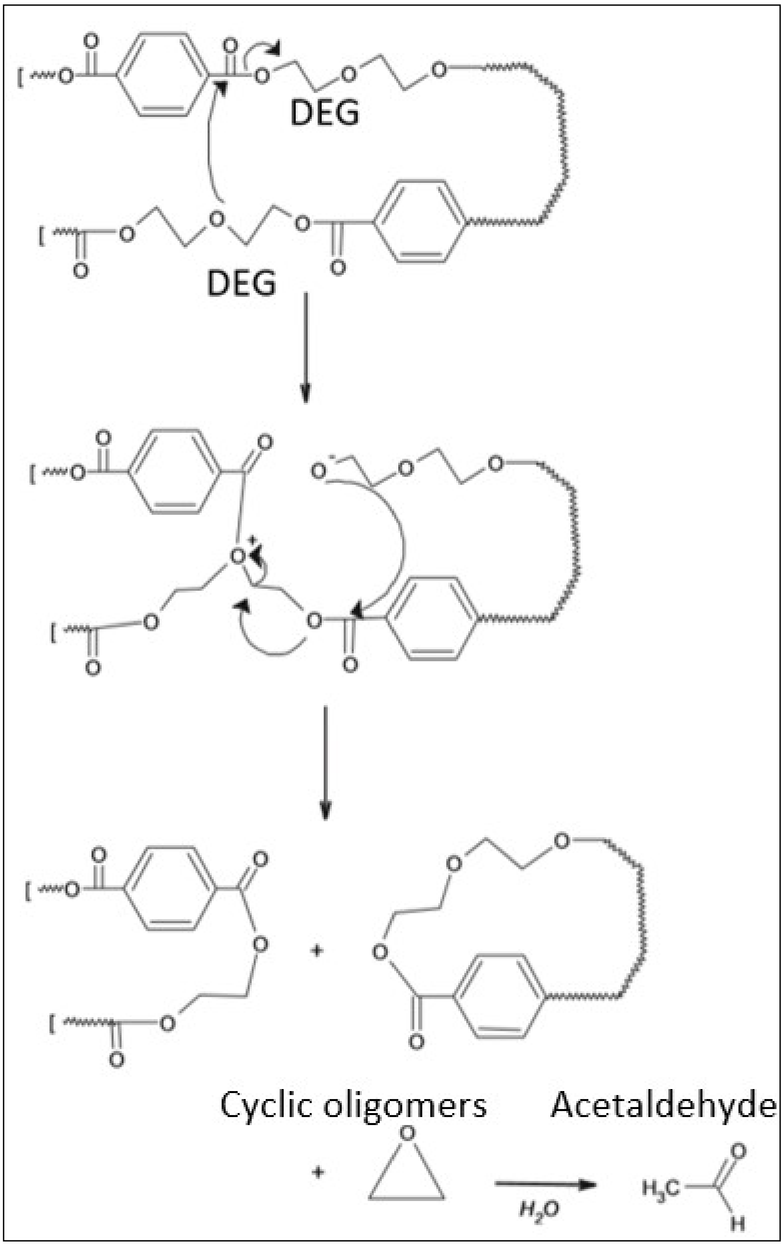

Figure 2. PET degradation mechanism from the DEG units according to Lecomte[9]

The addition of diethylene glycol into the chain creates weak points in the PET chain during thermo-oxidative degradation. Lecomte[9] demonstrated that Poly (Diethylene Glycol Terephthalate) degrades before PET (at 250 and 370°C for the former; 345 to 480°C for the latter), releasing cyclic oligomers initially, followed by benzoic acid, vinyl benzoate, CO2, and acetaldehyde (final step in **Figure 2**). Chain segments containing isophthalic acid also degrade faster than other esters in the PET chain[48]. These two comonomers, which are used to delay cold crystallization by adding disorder to the chain, no longer perform their function and accelerate chain size reduction.

Consequences

This decrease in molecular weight is manifested by a reduction in melt viscosity[2,43,45]. PET may become unsuitable for bottle applications without further treatment. Indeed, a viscosity index (IV) between 0.7 and 0.86 dL/g is often required for bottle applications. For specific applications, such as carbonated beverage bottles, an IV greater than 0.8 dL/g is necessary[3,6,37,49]. PET from mechanical recycling can show a low IV around 0.52 dL/g[49]. This reduction in molecular weight reduces elongation properties and fracture resistance[2].

These phenomena also lead to discoloration, toward a yellowish hue, due to the formation of vinyl compounds from ethylene glycol groups or stilbene and quinone formation. Degradation of sections containing diethylene glycol is also responsible for the formation of chromophores that contribute to the color change of mechanically recycled PET[3,10,50].

The blowing properties are also affected. Deloye[15] showed that reduced molecular weight is a significant factor in the increased volume of bottles produced. It is also accepted in the literature[51] that shorter chains cause rigidity during hot stretching, requiring greater deformation. This has also been noted in CEMEF studies[52,53]. Recycled PET bottles also show a higher rate of explosion during production when using low-viscosity PET[50].

b) Contamination and Its Effects

Where Does Contamination Come From?

Contaminants can be divided into two main categories: those that affect the quality of the beverage in the bottles (acetaldehyde, limonene, toluene, etc.) and those that change the technical properties of the bottle (other polymers, metals, papers, fibers, glues, dust, etc. [3,40,50,54,55]), which are generally larger. The literature addresses both aspects, with special focus on the former due to their potential hazards[56-59]. Its presence and its diffusion properties has been studied[44,60].

Contaminants affecting the technical properties of the bottle can originate from the bottle components (closure system [caps and rings], labels, inks, etc.), sorting rejects (objects that were not properly separated during initial sorting, such as bottles made from other materials than PET, PET trays, bottles with barrier layers), or external contamination (mainly dust). Two studies show that the composition of contaminants does not exceed 1%[61,62]. Some purification systems can make PET 99.9% pure[11]. The remaining fractions are mostly polymers (Polyvinyl Chloride (PVC), Polyethylene (PE), Polypropylene (PP), Polystyrene (PS)) and other contaminants like paper and metal[62].

These contaminants then appear as opaque particles, often black, known as "black specks." They have been observed during melt filtration. rPET suppliers estimate that they originate from PVC degradation, PET particles, or paper. These visible contaminants have been studied by Thoden, Brouwer, and Alvarado Chacon[3,40,50]. They were also the subject of the thesis on "the impact of contaminants on the injection process of bottle blowing"[53] which justifies this working paper.

Consequences

Contaminants have multiple consequences on the material[2,47,54], sometimes contradictory.

Most contaminants lower viscosity due to chain cuts or increased free volume[54,56,63,64]. This chain cleavage is facilitated by contaminants with acidic functions such as acetic acid or hydrochloric acid, originating from the degradation of closure systems based on poly(vinyl acetate) and poly(vinyl chloride)[2]. However, PE or PP, when present in more than 5%, increases viscosity because polyolefins are more viscous than PET[65]. Recycled PET shows greater sensitivity to hydrolysis and thermal degradation. This could be due to the higher specific surface area of rPET flakes and contaminants, which increase water molecule absorption[54,63]. PVC is also a degradation catalyst by forming associated carboxylic acid[47].

Moreover, the presence of contaminants facilitates both cold and hot crystallization, as evidenced by increased crystallinity, higher crystallization temperature, and reduced cold crystallization temperature[3,11,43,47,52,64,66]. This is observed for most contaminants except PE and PP, which reduce crystallinity[65], or EVOH, whose cold crystallization temperature is higher[3].

These two effects—decreased chain size and increased crystallinity—lead to an increase in Young's modulus, but also a reduction in maximum stress, elongation, or impact resistance[47,61,67-70]. The hypothesis of polymer incompatibility is also considered[64]. In the case of polyolefins (PE and PP), elongation at break may be facilitated[65,71]. The effectiveness of the SSP process is also diminished in the presence of contaminants.

rPET becomes yellow or changes color during recycling[3,4,11,27] and becomes opaque. Opacification may result from immiscibility phenomena or increased crystallization, as in the case of PLA[11,17,56,64]. The number of particles and the nature of the contaminants affect this property[3,11,17,50,72,73].

Regarding bottle blowing, a contamination proportion below 0.07% does not prevent bottle formation, but it requires adjustments in process conditions, particularly to find the right temperature and conditions for obtaining the same microstructure. Recycled PET tends to absorb more infrared energy than virgin PET[53,74] and crystallizes for greater deformation when stretched beyond their glass transition temperature under the same stretching conditions[53,66]. The use of digital twins directly adapted to blow-molding machines is being studied[75].

3. Solutions to These Issues

To restore the desired molecular masses, it is possible to add chain extenders or stabilizers during the extrusion step or to use the post-condensation system (SSP)[2,37,46].

Thoden et al.[3] and Brouwer et al.[62] have shown that the deposit return system results in fewer contaminations compared to co-collection via voluntary contribution. Cleaning systems, decontamination, and property restoration through SSP are also highly effective, at least in Europe, although they do not eliminate all contaminants[2,3,5,27,58]. Stakeholders at the end of the supply chain (PET producers, retailers, and brand owners) have all noted discoloration ranging from blue/gray to yellow/brown, including dark brown[17]. To combat the discoloration of rPET, Wrap suggests addressing the various actors in the supply chain. Raw material and bottle producers can avoid adding carbon black or using PE or PP labels. They should also stop using excessive amounts of dyes, even though this is somewhat advised in a study on 11 recycling cycles[76]. It also appears crucial that waste management improves the sorting of waste. This proposal is also supported by Brouwer et al.[40]. Finally, it is recommended that flake processors remove particles larger than 2 mm.

A laboratory study[76] on 11 artificial recycling cycles also showed that the addition of brightening agents, acetaldehyde sensors, the use of SSP, and the addition of 25% virgin PET help maintain the entire bottle manufacturing specification: viscosity above 0.8 dL/g, L* above 70, and b* below 2.

Although degradation reactions can be used beneficially in chemical recycling of PET, these reactions must be strictly avoided in mechanical recycling, especially for bottle applications. Therefore, before any preform injection (the part intended to be blown), the pellets are dried for a short time at medium temperature and under vacuum before being melted (at 140 to 170°C for 3 to 7 hours)[2,49]. After recycling, the flakes are also dried for this purpose.

IV. The Recycled PET Market

PET, since the onset of plastic recycling, remains the most recycled polymer today.

Since the 1990s, recycled PET (rPET) has been approved for manufacturing new bottles5, and the number of studies on recycling has been increasing[43]. In Europe, the demand has stabilized in recent years[28]. However, there has been a 5% increase in PET bottles put on the market between 2018 and 2020[28] and a 13% increase for trays[28].

To develop the rPET sector, it is essential to know whether there is a market for it[63]. Since the 1990s, the interest in using recycled PET in bottles has been growing[4]. However, manufacturing rPET remains more expensive than producing virgin PET.

1. European and Global Policies

As a result, the European Union (EU) has taken the lead and is requiring industries to incorporate rPET into their bottles. The goal is no longer just recycling but also using recycled material to make PET more attractive and to develop recycling chains in order to reduce the use of virgin PET and, at the same time, plastic pollution.

To this end, in 2019, the EU adopted a directive on single-use packaging[77]. It states that by 2025, PET bottles must contain 25% rPET, and by 2030, all plastic bottles must contain 30% recycled plastics. This directive applies to the global bottle market, so some bottles will have a higher percentage, others lower, but the minimum target of 25% rPET must be achieved by 2025. Collection must also improve: 77% of bottles must be collected across Europe by 2025, and 90% by 2029.

Following the announcement of these constraints, the production of recycled PET in Europe (excluding textiles) increased by 3.8%, rising from 1.08 million tons to 1.32 million tons between 2018 and 2020[28]. The collection rate, however, still only reaches 60% of rigid PET packaging[28]. It can be estimated that PET bottles in Europe contained an average of 17% recycled PET in 2020[16].

2. French Policy

France has transposed part of these objectives into the Anti-Waste and Circular Economy (AGEC) law, which stipulates that collection must increase (77% by 2025, 90% by 2029)[30].

According to studies conducted by ADEME[29] in 2023, the current policy in France will not meet the EU's objectives or those set by the AGEC law, which align with EU targets. Therefore, the introduction of a deposit return system is being considered, as it has proven effective in countries that use it to achieve or come close to their collection targets[32]. Additionally, an upcoming European legislative proposal specifies that if the 90% collection target for plastic bottles is not met by 2029, member countries will have to implement a form of deposit return system[32]. Other levers are also being explored26.

a) Exploratory Levers: An Ambitious Strategy

Nine levers (excluding deposit return) have been identified by a working group to increase collection near household points (SPPGD)26. These include: 1) Implementing incentive-based pricing; 2) Expanding sorting mandates to all packaging; 3) Increasing the density of collection points for proximity collection; 4) Improving door-to-door collection services; 5) Shifting to multi-material collection; 6) Conducting targeted assessments of household waste and corrective actions; 7) National/local communication campaigns on sorting actions; 8) Improving sorting performance at sorting centers; and 9) Sorting bio-waste at source.

Regarding consumption outside the home, three levers were identified: 1) Developing sorting in public spaces; 2) Implementing selective collection in businesses; 3) Establishing a collection system with rewards.

These levers must be maximized to meet the targets set by French and European policies.

b) The Deposit Return System in France: A Well-Researched Project

Two types of deposit return systems can be implemented: the first is considered "manual," and the second "automated." The manual system involves store employees scanning each item upon return. The automated system uses a machine for this process. This type of system could be further developed: the consumer could scan himself the unique barcode of his product via an app and place it in a sorting bin. In all cases, the consumer receives the deposit they paid at the time of purchase[78]. This financial incentive would increase collection rates and reduce littering[32].

Both systems would help achieve the collection targets. However, exploratory levers add further uncertainties regarding deployment and their effect[29].

V. Conclusion

PET recycling, while beneficial, is a complex process that requires the involvement of many stakeholders to ensure the reuse of this material. For bottle applications, public authorities must implement systems that promote collection, either through a separate PET collection system like a deposit return system or through exploratory levers, to meet the targets set by the EU.

The advantage of a deposit return system is that it guarantees the quality required to reuse rPET in new bottles. Additionally, to maintain properties suitable for bottle applications, the systematic drying of flakes or pellets before shaping is essential to prevent the degradation of PET chains. The use of post-condensation or chain-extending steps should be implemented to ensure a sufficient molecular weight for bottle applications. Despite the various recycling steps that reduce contaminants, the yellowing of recycled material is inevitable and must be compensated for with the use of brighteners. Furthermore, rPET processors must keep in mind that recycled materials tend to crystallize more in static conditions, absorb more infrared energy, and require adjustments during blowing. These effects are minimized if the molecular masses are very close to those of virgin PET and the number of contaminants is limited.

Beyond the technical aspects, legislation is a lever to promote recycling. Through laws, industries are required to use recycled material as a raw material in PET bottles. The law also ensures a substantial supply of rPET by encouraging the development of collection systems. Thus, European public authorities' encouragement, the development of separate collection systems (deposit return), and the deployment of new sorting and recycling technologies, along with optimized blowing processes, should promote the widespread use of recycled PET in France.

VI. Bibliography

(1) Leclerc, M. « L'arrivée de la bouteille en PET ». LSA. November 20, 2008. https://www.lsa-conso.fr/l-arrivee-de-la-bouteille-en-pet,101773 (accessed 2023-10-16).

(2) Awaja, F.; Pavel, D. Recycling of PET. *Eur. Polym. J.* **2005**, *41* (7), 1453–1477. https://doi.org/10.1016/j.eurpolymj.2005.02.005.

(3) Thoden van Velzen, E. U.; Brouwer, M. T.; Molenveld, K. *Technical Quality of rPET : Technical Quality of rPET That Can Be Obtained from Dutch PET Bottles That Have Been Collected, Sorted and Mechanically Recycled in Different Manners*; Wageningen UR Food & Biobased Research, 2016.

(4) Finch, C. A. Plastics Recycling Products and Processes Edited by R. J. Ehrig Hanser Publishers, Munich, 1992. Pp. Xiii + 289, Price DM98.00. ISBN 3-446- 15882-0. *Polym. Int*. **1993**, *30* (3), 426–426. https://doi.org/10.1002/pi.4990300329.

(5) Welle, F. Twenty Years of PET Bottle to Bottle Recycling—An Overview. *Resour. Conserv. Recycl*. **2011**, *55* (11), 865–875. https://doi.org/10.1016/j.resconrec.2011.04.009.

(6) Plantamura, B. Soufflage de corps creux bi-orientés. *Tech. Ing.* **2012**, *Matériaux | Plastiques et composites*.

(7) Nisticò, R. Polyethylene Terephthalate (PET) in the Packaging Industry. *Polym. Test*. **2020**, *90*, 106707. https://doi.org/10.1016/j.polymertesting.2020.106707.

(8) Fann, D.-M.; Huang, S. K.; Lee, J.-Y. Kinetics and Thermal Crystallinity of Recycled PET. II. Topographic Study on Thermal Crystallinity of the Injection-Molded Recycled PET. *J. Appl. Polym. Sci.* **1996**, *61* (2), 261–271. https://doi.org/10.1002/(SICI)1097-4628(19960711)61:2<261::AID-APP8>3.0.CO;2-N.

(9) Lecomte, H. A.; Liggat, J. J. Degradation Mechanism of Diethylene Glycol Units in a Terephthalate Polymer. *Polym. Degrad. Stab.* **2006**, *91* (4), 681–689. https://doi.org/10.1016/j.polymdegradstab.2005.05.028.

(10) Romão, W.; Franco, M. F.; Corilo, Y. E.; Eberlin, M. N.; Spinacé, M. A. S.; De Paoli, M.-A. Poly (Ethylene Terephthalate) Thermo-Mechanical and Thermo-Oxidative Degradation Mechanisms. *Polym. Degrad. Stab.* **2009**, *94* (10), 1849–1859. https://doi.org/10.1016/j.polymdegradstab.2009.05.017.

(11) van Dongen, C.; Dvorak, R.; Kosior, E. *Design Guide for PET Bottle Recyclability*; UNESDA, EFBW, 2013; p 38. https://www.academia.edu/5808788/Design_Guide_for_PET_Bottle_Recyclability_Written_by_Cees_van_Dongen_Coca_Cola_Europe (accessed 2023-10-16).

(12) *Qu'est-ce que c'est le PETG?* https://filament2print.com/fr/blog/49_petg.html (accessed 2024-05-06).

(13) *Précis de Matières plastiques - AFNOR*. https://enseignants.nathan.fr/catalogue/precis-de-matieres-plastiques-afnor-livre-de-l-eleve-9782095014490.html (accessed 2024-01-09).

(14) Billon, N.; Haudin, J.-M.; Vallot, C.; Babin, C. Stretch Blow Molding of Mineral Filled PET. *Int. Polym. Process*. **2015**, *30* (4), 487–499. https://doi.org/10.3139/217.3066.

(15) Deloye, E. Effet de l'architecture de chaîne sur le comportement en injection soufflage de copolyesters PET. - Etude expérimentale. phdthesis, École Nationale Supérieure des Mines de Paris, 2006. https://pastel.hal.science/tel-00200808 (accessed 2024-01-08).

(16) Trotignon, J.-P.; Verdu, J.; Dobraczynski, A.; Piperaud, M. *Matières plastiques: structures-propriétés, mise en oeuvre, normalisation*; AFNOR, 2006.

(17) Dvorak, R.; Kosior, E.; Fletcher, J. Wrap: *Improving Food Grade rPET Quality for Use in UK Packaging - Free Report*; WRAP, 2013; p 58. https://www.en.nvc.nl/news/item/wrap-improving-food-grade-rpet-quality-for-use-in-uk-packaging-gratis-rapport-in-het-engels/ (accessed 2023-10-06).

(18) Clark, D. Processing *PCR: How It's Done at a Leading PET Bottle Maker*. https://www.ptonline.com/articles/processing-pcr-how-its-done-at-a-leading-pet-bottle-maker (accessed 2023-09-27).

(19) ADEME. *Comportement d'achat et de tri des bouteilles en plastique pour boisson selon les lieux de consommation*. La librairie ADEME. https://librairie.ademe.fr/dechets-economie-circulaire/6350-comportement-d-achat-et-de-tri-des-bouteilles-en-plastique-pour-boisson-selon-les-lieux-de-consommation.html (accessed 2024-05-09).

(20) Cincotta, F.; Verzera, A.; Tripodi, G.; Condurso, C. Non-Intentionally Added Substances in PET Bottled Mineral Water during the Shelf-Life. *Eur. Food Res. Technol.* **2018**, *244* (3), 433–439. https://doi.org/10.1007/s00217-017-2971-6.

(21) agence, O.-F. avec. *#FillTheBottle. Ramasser les mégots et remplir une bouteille, le challenge pour alerter les fumeurs*. Ouest-France.fr. https://www.ouest-france.fr/environnement/pollution/fillthebottle-ramasser-les-megots-et-remplir-une-bouteille-le-challenge-pour-alerter-les-fumeurs-6467569 (accessed 2024-05-06).

(22) World Economic Forum, Ellen MacArthur Foundation and McKinsey and Company. *The New Plastics Economy: Rethinking the Future of Plastics*; 2016. https://www.ellenmacarthurfoundation.org/the-new-plastics-economy-rethinking-the-future-of-plastics (accessed 2024-01-09).

(23) World Wildlife Fund. *The problem with plastic in nature and what you can do to help*. World Wildlife Fund. https://www.worldwildlife.org/stories/the-problem-with-plastic-in-nature-and-what-you-can-do-to-help (accessed 2024-01-09).

(24) Durbecq, N. *La consigne du verre bientôt de retour en France*. Sciences et Avenir. https://www.sciencesetavenir.fr/nature-environnement/la-consigne-du-verre-bientot-de-retour-en-france_172190 (accessed 2024-05-28).

(25) MK, 20minutes. *Le verre consigné a (enfin) fait son grand retour*. www.20minutes.fr. https://www.20minutes.fr/economie/consommation/4043915-20230708-zero-dechet-comment-verre-consigne-enfin-fait-grand-retour (accessed 2024-05-28).

(26) ADEME. *Prospective sur les leviers (hors consigne) d'amélioration des performances de la collecte sélective*. La librairie ADEME. https://librairie.ademe.fr/dechets-economie-circulaire/6354-prospective-sur-les-leviers-hors-consigne-d-amelioration-des-performances-de-la-collecte-selective.html (accessed 2024-05-09).

(27) Snell, H.; Nassour, A.; Nelles, M. Qualitative Comparison of Polyethylene Terephthalate Flakes from Various Collection Systems in Germany. *Waste Manag. Res*. **2017**. https://doi.org/10.1177/0734242X16686413.

(28) PETCORE; NMWE; UNESDA Soft DrinkEurope. *PET MARKET IN EUROPE STATE OF PLAY - 2022*; 2; 2022; p 48. https://petcore-europe.org/news-events/409-pet-market-in-europe-state-of-play-2022.html (accessed 2023-08-16).

(29) ADEME. *Réduction, réemploi et recyclage des emballages ménagers : l'ADEME présente 8 nouvelles études*; Dossier de presse; ADEME, 2023; p 16. https://presse.ademe.fr/2023/06/reduction-reemploi-et-recyclage-des-emballages-menagers-lademe-presente-8-nouvelles-etudes.html (accessed 2024-05-03).

(30) Harscoet, E.; Ollion, L.; Deprouw, A.; Vaz, A.; Strahm, A.; Pasquier, S.; Parisot, F. *Perceptions et pratiques en cas de mise en place de la consigne pour recyclage sur les emballages de boisson en France - Synthèse; 2023*; p 34. https://librairie.ademe.fr/dechets-economie-circulaire/6351-perceptions-et-pratiques-en-cas-de-mise-en-place-de-la-consigne-pour-recyclage-sur-les-emballages-de-boisson-en-france.html (accessed 2024-05-09).

(31) Grant, A.; Lahme, V.; Lugal, L. *How Circular Is PET?*; Eunomia, Zero Waste Europe, 2022. https://zerowasteeurope.eu/library/how-circular-is-pet/ (accessed 2024-05-29).

(32) Mugnier, E.; Abraham, C.; Lavaud, G.; Aybriot, E.; Garcia Zuluaga, M.; Rahier, L. E.; Parisot, F. *Benchmark européen des dispositifs de consigne pour réemploi et/ou recyclage des emballages*; 2023; p 32. https://librairie.ademe.fr/dechets-economie-circulaire/6357-benchmark-europeen-des-dispositifs-de-consigne-pour-reemploi-et-ou-recyclage-des-emballages.html (accessed 2024-05-09).

(33) Japan. *Actual Volume of Collected PET Bottles and Collection Rate/Uses of Recycled PET Flakes | The Council for PET Bottle Recycling*. https://www.petbottle-rec.gr.jp/english/actual.html (accessed 2023-08-23).

(34) Abipet. 12° *Censo da Reciclagem do PET no Brasil*. https://abipet.org.br/wp-content/uploads/2022/12/Infografico_12_Censo_da_Reciclagem_no_Brasil-Novembro_2022.pdf.

(35) Smith, R. L.; Takkellapati, S.; Riegerix, R. C. Recycling of Plastics in the United States: Plastic Material Flows and Polyethylene Terephthalate (PET) Recycling Processes. *ACS Sustain. Chem. Eng*. **2022**, *10* (6), 2084–2096. https://doi.org/10.1021/acssuschemeng.1c06845.

(36) EUNOMIA. SCI - C&I Issue 3 2022 - *Bottle recycling report*. https://www.soci.org/chemistry-and-industry/cni-data/2022/3/bottle-recycling-report (accessed 2023-10-17).

(37) Ragaert, K.; Delva, L.; Van Geem, K. Mechanical and Chemical Recycling of Solid Plastic Waste. *Waste Manag.* **2017**, *69*, 24–58. https://doi.org/10.1016/j.wasman.2017.07.044.

(38) Adarsh, U. K.; Kartha, V. B.; Santhosh, C.; Unnikrishnan, V. K. Spectroscopy: A Promising Tool for Plastic Waste Management. *TrAC Trends Anal. Chem.* **2022**, *149*, 116534. https://doi.org/10.1016/j.trac.2022.116534.

(39) Gottesman, R. T. Separation of Poly (Vinyl Chloride) from Poly(Ethylene Terephthalate) and Other Plastics Using Automatic Sortation Devices. *Makromol. Chem. Macromol. Symp.* **1992**, *57* (1), 133–143. https://doi.org/10.1002/masy.19920570112.

(40) Brouwer, M. T.; Alvarado Chacon, F.; Thoden van Velzen, E. U. Effect of recycled content and rPET quality on the properties of PET bottles, part III: Modelling of repetitive recycling. *Packag. Technol. Sci.* **2020**, *33* (9), 373–383. https://doi.org/10.1002/pts.2489.

(41) Nait-Ali, L. K.; Colin, X.; Bergeret, A. Kinetic Analysis and Modelling of PET Macromolecular Changes during Its Mechanical Recycling by Extrusion. *Polym. Degrad. Stab.* **2011**, *96* (2), 236–246. https://doi.org/10.1016/j.polymdegradstab.2010.11.004.

(42) Vilaplana, F.; Karlsson, S. Quality Concepts for the Improved Use of Recycled Polymeric Materials: A Review. *Macromol. Mater. Eng.* **2008**, *293* (4), 274–297. https://doi.org/10.1002/mame.200700393.

(43) Paci, M.; La Mantia, F. P. Competition between Degradation and Chain Extension during Processing of Reclaimed Poly(Ethylene Terephthalate). *Polym. Degrad. Stab.* **1998**, *61* (3), 417–420. https://doi.org/10.1016/S0141-3910(97)00227-9.

(44) Pennarun, P. Y.; Dole, P.; Feigenbaum, A. Functional Barriers in PET Recycled Bottles. Part I. Determination of Diffusion Coefficients in Bioriented PET with and without Contact with Food Simulants. *J. Appl. Polym. Sci.* **2004**, *92* (5), 2845–2858. https://doi.org/10.1002/app.20202.

(45) Nait-Ali, K. L.; Bergeret, A.; Ferry, L.; Colin, X. Chain Branching Detection by Cole–Cole Modeling of Rheological Properties Changes during PET Mechanical Recycling. *Polym. Test.* **2012**, *31* (3), 500–504. https://doi.org/10.1016/j.polymertesting.2012.01.006.

(46) López, M. del M. C.; Ares Pernas, A. I.; Abad López, M. J.; Latorre, A. L.; López Vilariño, J. M.; González Rodríguez, M. V. Assessing Changes on Poly(Ethylene Terephthalate) Properties after Recycling: Mechanical Recycling in Laboratory versus Postconsumer Recycled Material. *Mater. Chem. Phys.* **2014**, *147* (3), 884–894. https://doi.org/10.1016/j.matchemphys.2014.06.034.

(47) Torres, N.; Robin, J. J.; Boutevin, B. Study of Thermal and Mechanical Properties of Virgin and Recycled Poly(Ethylene Terephthalate) before and after Injection Molding. *Eur. Polym. J.* **2000**, *36* (10), 2075–2080. https://doi.org/10.1016/S0014-3057(99)00301-8.

(48) Holland, B. J.; Hay, J. N. The Thermal Degradation of PET and Analogous Polyesters Measured by Thermal Analysis–Fourier Transform Infrared Spectroscopy. *Polymer* **2002**, *43* (6), 1835–1847. https://doi.org/10.1016/S0032-3861(01)00775-3.

(49) Mancini, S. D.; Zanin, M. Consecutive Steps of PET Recycling by Injection: Evaluation of the Procedure and of the Mechanical Properties. *J. Appl. Polym. Sci.* **2000**, *76* (2), 266–275. https://doi.org/10.1002/(SICI)1097-4628(20000411)76:2<266::AID-APP16>3.0.CO;2-Q.

(50) Alvarado Chacon, F.; Brouwer, M. T.; Thoden van Velzen, E. U. Effect of Recycled Content and rPET Quality on the Properties of PET Bottles, Part I: Optical and Mechanical Properties. *Packag. Technol. Sci.* **2020**, *33* (9), 347–357. https://doi.org/10.1002/pts.2490.

(51) *Soufflage de corps creux bi-orientés*. Techniques de l'Ingénieur. https://www.techniques-ingenieur.fr/base-documentaire/materiaux-th11/plasturgie-fabrications-de-corps-creux-de-films-et-de-fils-42149210/soufflage-de-corps-creux-bi-orientes-am3700/ (accessed 2023-08-16).

(52) Rohart, V.; Combeaud, C. Stretchability above Glass Transition of Mechanically Recycled Poly(Ethylene Terephtalate), PET. *Polymer* **2022**, *257*, 125218. https://doi.org/10.1016/j.polymer.2022.125218.

(53) Viora, L. Influence des contaminants contenus dans des Poly(Ethylène Téréphtalate) recyclés mécaniquement sur le procédé d'injection-soufflage de bouteilles. Thèse de Doctorat Mécanique Numérique des Matériaux, Université Paris sciences et lettres, 2024.

(54) Giannotta, G.; Po', R.; Cardi, N.; Tampellini, E.; Occhiello, E.; Garbassi, F.; Nicolais, L. Processing Effects on Poly(Ethylene Terephthalate) from Bottle Scraps. *Polym. Eng. Sci.* **1994**, *34* (15), 1219–1223. https://doi.org/10.1002/pen.760341508.

(55) La Mantia, F. P.; Vinci, M. Recycling Poly(Ethyleneterephthalate). *Polym. Degrad. Stab.* **1994**, *45* (1), 121–125. https://doi.org/10.1016/0141-3910(94)90187-2.

(56) La Mantia, F. P.; Botta, L.; Morreale, M.; Scaffaro, R. Effect of Small Amounts of Poly(Lactic Acid) on the Recycling of Poly(Ethylene Terephthalate) Bottles. *Polym. Degrad. Stab*. **2012**, *97* (1), 21–24. https://doi.org/10.1016/j.polymdegradstab.2011.10.017.

(57) Pennarun, P. Y.; Saillard, P.; Feigenbaum, A.; Dole, P. Experimental Direct Evaluation of Functional Barriers in PET Recycled Bottles: Comparison of Migration Behaviour of Mono- and Multilayers. *Packag. Technol. Sci*. **2005**, *18* (3), 107–123. https://doi.org/10.1002/pts.680.

(58) Welle, F. Simulation of the Decontamination Efficiency of PET Recycling Processes Based on Solid-State Polycondensation. *Packag. Technol. Sci.* **2014**, *27* (2), 141–148. https://doi.org/10.1002/pts.2013.

(59) Pelegrín, C. J.; Flores, Y.; Jiménez, A.; Garrigós, M. C. Recent Trends in the Analysis of Chemical Contaminants in Beverages. *Beverages* **2020**, *6* (2), 32. https://doi.org/10.3390/beverages6020032.

(60) Thoden van Velzen, E. U.; Brouwer, M. T.; Stärker, C.; Welle, F. Effect of Recycled Content and rPET Quality on the Properties of PET Bottles, Part II: Migration. *Packag. Technol. Sci.* **2020**, *33* (9), 359–371. https://doi.org/10.1002/pts.2528.

(61) Pawlak, A.; Pluta, M.; Morawiec, J.; Galeski, A.; Pracella, M. Characterization of Scrap Poly(Ethylene Terephthalate). *Eur. Polym. J.* **2000**, *36* (9), 1875–1884. https://doi.org/10.1016/S0014-3057(99)00261-X.

(62) Brouwer, M. T.; Thoden van Velzen, E. U.; Augustinus, A.; Soethoudt, H.; De Meester, S.; Ragaert, K. Predictive Model for the Dutch Post-Consumer Plastic Packaging Recycling System and Implications for the Circular Economy. *Waste Manag.* **2018**, *71*, 62–85. https://doi.org/10.1016/j.wasman.2017.10.034.

(63) Oromiehie, A.; Mamizadeh, A. Recycling PET Beverage Bottles and Improving Properties. *Polym. Int.* **2004**, *53* (6), 728–732. https://doi.org/10.1002/pi.1389.

(64) McLauchlin, A. R.; Ghita, O. R. Studies on the Thermal and Mechanical Behavior of PLA-PET Blends. *J. Appl. Polym. Sci.* **2016**, *133* (43). https://doi.org/10.1002/app.44147.

(65) Itim, B. Influence of Polyolefin Contamination on the Thermal Characteristics of Bottle Grade Recycled Polyethylene Terephthalate. doctoral, London Metropolitan University, 2015. https://repository.londonmet.ac.uk/922/ (accessed 2023-10-18).

(66) Taniguchi, A.; Cakmak, M. The Suppression of Strain Induced Crystallization in PET through Sub Micron TiO2 Particle Incorporation. *Polymer* **2004**, *45* (19), 6647–6654. https://doi.org/10.1016/j.polymer.2004.06.056.

(67) Lusinchi, J. M.; Pietrasanta, Y.; Robin, J. J.; Boutevin, B. Recycling of PET and PVC Wastes. *J. Appl. Polym. Sci.* **1998**, *69* (4), 657–665. https://doi.org/10.1002/(SICI)1097-4628(19980725)69:4<657::AID-APP4>3.0.CO;2-I.

(68) Navarro, R.; Ferrándiz, S.; López, J.; Seguí, V. J. The Influence of Polyethylene in the Mechanical Recycling of Polyethylene Terephtalate. *J. Mater. Process. Technol.* **2008**, *195* (1), 110–116. https://doi.org/10.1016/j.jmatprotec.2007.04.126.

(69) Seier, M.; Archodoulaki, V.-M.; Koch, T.; Duscher, B.; Gahleitner, M. Polyethylene Terephthalate Based Multilayer Food Packaging: Deterioration Effects during Mechanical Recycling. *Food Packag. Shelf Life* **2022**, *33*, 100890. https://doi.org/10.1016/j.fpsl.2022.100890.

(70) Girija, B. G.; Sailaja, R. R. N.; Madras, G. Thermal Degradation and Mechanical Properties of PET Blends. *Polym. Degrad. Stab.* **2005**, *90* (1), 147–153. https://doi.org/10.1016/j.polymdegradstab.2005.03.003.

(71) Avila-Orta, C. A.; Medellín-Rodríguez, F. J.; Wang, Z.-G.; Navarro-Rodríguez, D.; Hsiao, B. S.; Yeh, F. On the Nature of Multiple Melting in Poly(Ethylene Terephthalate) (PET) and Its Copolymers with Cyclohexylene Dimethylene Terephthalate (PET/CT). *Polymer* **2003**, *44* (5), 1527–1535. https://doi.org/10.1016/S0032-3861(02)00832-7.

(72) Awaja, F.; Pavel, D. Injection Stretch Blow Moulding Process of Reactive Extruded Recycled PET and Virgin PET Blends. *Eur. Polym. J.* **2005**, *41* (11), 2614–2634. https://doi.org/10.1016/j.eurpolymj.2005.05.036.

(73) Paci, M.; La Mantia, F. P. Influence of Small Amounts of Polyvinylchloride on the Recycling of Polyethyleneterephthalate. *Polym. Degrad. Stab.* **1999**, *63* (1), 11–14. https://doi.org/10.1016/S0141-3910(98)00053-6.

(74) Le, A.-D.; Gilblas, R.; Lucin, V.; Maoult, Y. L.; Schmidt, F. Infrared Heating Modeling of Recycled PET Preforms in Injection Stretch Blow Molding Process. *Int. J. Therm. Sci.* **2022**, *181*, 107762. https://doi.org/10.1016/j.ijthermalsci.2022.107762.

(75) Han, W.; Kerfriden, P.; Viora, L.; Combeaud, C.; Bouvard, J.-L.; Cantournet, S. Intelligent Control of ISBM Process for Recycled PET Bottles, Materials Research Proceedings; Toulouse, 2024; Vol. 41, pp 1817–1826. https://doi.org/10.21741/9781644903131-201.

(76) Pinter, E.; Welle, F.; Mayrhofer, E.; Pechhacker, A.; Motloch, L.; Lahme, V.; Grant, A.; Tacker, M. Circularity Study on PET Bottle-To-Bottle Recycling. *Sustainability* **2021**, *13* (13), 7370. https://doi.org/10.3390/su13137370.

(77) The European Parliament and the Council of the European Union. *Single-Use Plastics (SUP) Directive - Directive (EU) 2019/904 | Circular Cities and Regions Initiative*; 2019; Vol. L 155/1. https://circular-cities-and-regions.ec.europa.eu/support-materials/eu-regulations-legislation/single-use-plastics-sup-directive-directive-eu-2019904 (accessed 2023-10-09).

(78) Monier, V.; Reinstadler, A.-C.; Louee, N.; Artigue, D.; Durand, J.; Parisot, F.; In Extenso Innovation Croissance. *Faisabilité de la consigne dématérialisée pour les emballages de boisson en France - Synthèse*; ADEME, 2023; p 27. https://librairie.ademe.fr/dechets-economie-circulaire/6355-faisabilite-de-la-consigne-dematerialisee-pour-les-emballages-de-boisson-en-france.html (accessed 2024-05-09).

Ce travail a été réalisé dans le cadre du parcours doctoral de The Transition Institute 1.5 (TTI.5). TTI.5 est un institut de recherche de Mines Paris - PSL dédié à la transition bas carbone.

This work was carried out as part of The Transition Institute 1.5's doctoral track. The Transition Institute 1.5 is a research institute of Mines Paris - PSL dedicated to the low-carbon transition.

CONTACT

the-transition-institute.minesparis.psl.eu

tti.5@minesparis.psl.eu