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TESI DI LAUREA in

Gestione dei rifiuti solidi e bonifica dei siti contaminati

DESIGN FOR RECYCLING GUIDELINES ON PLASTIC PACKAGING: OPAQUE PET BOTTLES STUDY CASE

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ABSTRACT

The aim of this thesis work is to describe the current European scenario regarding plastic packaging , stated the last Proposal on Packaging and Packaging Waste published in November 2022 by the European Commission which has set high standards in plastic recycling targets.

Given the increasing number of opaque PET bottles used in the food industry - mainly milk bottles - and currently placed on the market, and the increase in plastic waste from this packaging, the focus has been set on the assessment of its end-of-life. In particular, depending on the collection and sorting processes, the waste can be sent to different treatments: waste-to-energy, mechanical recycling, closed-loop recycling (in which the packaging waste is reprocessed to be used for the same purpose).

From the conducted analysis, the three proposed End-of-life treatments are technologically feasible, among them closed-loop recycling results the most cost-effective and desirable recycling process from the point of view of avoided environmental impacts. Within the scope of closed-loop recycling, a recyclability assessment has been determined, based on the packaging characterisation and the existing guidelines issued by European bodies. Considering the technologies available nowadays, the packaging under study was found to comply with recyclability requirements. Anyway, the environmental impacts and cost-effectiveness of single-stream sorting of this packaging remains to be evaluated.

ABSTRACT

Questo lavoro di tesi è finalizzato a descrivere lo scenario europeo attuale circa gli imballaggi in plastica, in seguito all'emanazione della Proposta sugli imballaggi e rifiuti da imballaggio della Commissione Europea del Novembre 2022, che ha fissato standard elevati per quanto riguarda gli obiettivi di riciclo della plastica.

Dati il crescente numero di bottiglie in PET opaco utilizzate nell'industria alimentare – principalmente bottiglie di latte – e attualmente immesse sul mercato e l'aumento dei rifiuti di plastica provenienti da questo imballaggio, l'attenzione è stata concentrata sulla valutazione del fine vita di questo particolare rifiuto. In particolare, in funzione del processo di raccolta e selezione, il rifiuto può essere avviato a differenti trattamenti: termovalorizzazione, riciclo meccanico, riciclo a ciclo chiuso (nel quale il rifiuto viene impiegato per essere riutilizzato per gli stessi scopi).

Dall'analisi condotta, i tre trattamenti di fine vita proposti sono tecnologicamente fattibili, e tra questi il riciclo a ciclo chiuso risulta il processo più conveniente e auspicabile dal punto di vista degli impatti ambientali evitati. Nell'ambito del riciclo a ciclo chiuso, è stata determinata una valutazione della riciclabilità, basata sulla caratterizzazione dell'imballaggio e sulle linee guida esistenti emesse dagli organismi europei. Considerando le tecnologie oggi disponibili, l'imballaggio oggetto dello studio è risultato conforme ai requisiti di riciclabilità. Restano comunque da valutare gli impatti ambientali e l'efficacia dei costi della selezione single-stream di questo imballaggio.

INTRODUCTION

Following the presentation of the proposed Regulation on Packaging and Packaging Waste by the European Commission and the setting of challenging standards, Article 6 of the aforementioned piece of legislation shows the importance of design related recycling of the packaging we currently use every day. The main focus was on plastic packaging, which has numerous polymers with different characteristics and from which an immense range of products can be covered.

After analysing the last market data relating to plastic packaging, at a global and then European level, characterising the situation in some of the European Member States, we focused on a particular type of packaging, opaque PET bottles, which, according to some recent studies, is expanding in the European markets, thanks to some peculiar characteristics that allow this to be preferred to other polymers previously used for the same purpose.

The topic of the circular economy was introduced, as fundamental pivot in our days in order to minimise the input of resources and the output of waste, air pollution emissions and greenhouse gases.

Challenges linked to the production, consumption and end-of-life plastics could be an opportunity for the European Industry to finally drive Europe through the transition towards a low-carbon and circular economy, providing citizens with a clear and safer environment and sensibilisation through the all possible means we have should be mandatory since our first years of life.

A mention of the circularity of PET was the impetus for introducing the fundamental theme of the thesis work, with particular reference to the definitions of closed and open cycle and DRS, as useful tools for the simplest development of the circular economy.

An overview of European legislation provided a better understanding of the pieces of legislation that are currently concerned with the topic of circularity and sustainability of the collection chain, sortability and mechanical recycling of packaging.

Based on the evaluations published by RecyClass for some of the packaging, after conducting the characterization of a white opaque PET milk bottle, the recyclability assessment of the same was carried out. Based on the current sorting and recycling technology, three different scenarios have been defined on how the packaging could be sorted once it arrives at the plant and the corresponding fate it is destined to. Steps related to the sorting and recycling of plastic packaging have been studied and, through a final analysis, the best scenario has been designated, with the caveat that future analyses should be defined to assess the economic and environmental impacts related to the implementation of the preferred scenario.

INTRODUZIONE

La proposta di regolamento sul Packaging and Packaging Waste da parte della Commissione Europea evidenzia l'importanza design degli imballaggi che utilizziamo quotidianamente al fine del loro recupero. La maggiore attenzione è stata posta sugli imballaggi in plastica, che sono costituiti da numerosi polimeri con differenti caratteristiche.

Nel presente elaborato, dopo aver analizzato alcuni aspetti relativi gli imballaggi in plastica, ci si è concentrati su una particolare tipologia di imballaggio: le bottiglie in PET opaco, che, secondo alcuni recenti studi, costituiscono una frazione merceologica in espansione nei mercati europei, grazie ad alcune caratteristiche peculiari che permettono di preferirlo ad altri polimeri precedentemente utilizzati per lo stesso scopo.

Un quadro completo sulla legislazione Europea ha permesso di inquadrare meglio i pezzi di legislazione che ad oggi sono interessati dal tema della circolarità e sostenibilità della catena di raccolta, selezione e riciclo meccanico degli imballaggi.

Un accenno all'economia circolare del PET è stato il punto di slancio per introdurre il tema fondamentale del lavoro di tesi, con un particolare riferimento alle definizioni di ciclo chiuso e ciclo aperto e di DRS (Deposit Refund System), come strumenti utili al più semplice sviluppo dell'economia circolare.

'Sulla delle linee guida emanate da RecyClass per alcuni imballaggi, dopo aver condotto la caratterizzazione di una bottiglia di latte in PET bianco opaco, è stata effettuata la valutazione della riciclabilità di tale rifiuto.

Sulla base dell'attuale tecnologia di selezione e riciclaggio, sono stati definiti tre diversi scenari per il recupero di tali imballaggi. In particolare, sono state studiate le fasi relative alla selezione e al riciclo degli imballaggi in plastica e, attraverso un'analisi finale, è stato designato lo scenario migliore, con la postilla di dover definire analisi future per valutare gli impatti economici e ambientali legati all'attuazione dello scenario preferito.

Le sfide relative alla produzione, al consumo e al fine di vita della plastica possono essere un’opportunità per l’industria Europea per condurre finalmente l’Europa verso un’economia circolare con bassa impronta di carbonio, fornendo ai cittadini un ambiente più chiaro e più sicuro e promuovendo una sensibilizzazione attraverso tutti i mezzi possibili che dovrebbe essere obbligatoria dai primi anni di vita di ciascuno di noi.

CHAPTER 1. PLASTIC PACKAGING

1.1 Plastic composition and polymers

Plastics are a group of polymers, either synthetic or naturally occurring that can be easily modelled and shaped according to the different scopes for which they are meant. A Polymer (from Greek πολύς = many and μέρος = part or unit) is a substance made by many repeating units, which are called monomers.

Naturally occurring polymers include tar, shellac, tortoiseshell, animal horn, cellulose, amber, and latex from tree sap. Synthetic polymers include polyethylene (PE) mostly used in plastic bags, polystyrene (PS) used to make Styrofoam cups; polypropylene (PP) used for fibres and bottles; polyvinyl chloride (PVC) used for food wrap, bottles, and drain pipe; polytetrafluoroethylene (PTFE), or Teflon, used for nonstick surfaces[1].

Many polymers are hydrocarbons that contain only carbon and hydrogen, other polymers may also contain oxygen, chlorine, fluorine, nitrogen, silicon, phosphorus, and sulphur.

Monomers can be chemically joined together following two different procedures:

1. addition polymerization
2. condensation polymerization

The first one occurs when monomers join by adding on to the end of the last monomer in the chain. PE, PS and acrylic are formed by this addition polymerization. They are easily processed, reprocessed or recycled because

[1] Science History Institute - https://sciencehistory.org/education/classroom-activities/role-playing-games/case-of-plastics/science-of-plastics/ - 17/09/2023

they have thermoplastic nature, which is easy to be modelled using the heating or cooling.

During the condensation polymerization, monomers joint together but they eliminate a small molecule. Nylons, some polyesters, and urethanes are examples of this kind of polymerization. These polymers can be thermoplastic or thermosetting, but once a thermoset polymer is formed, it cannot be melted and reformed, unlike the thermoplastic polymers.

Polymers show some characteristics that can cover a wide range of colours and their properties sometimes can also be incremented by using some additives. Because of their huge flexibility, plastics are unique materials that can be used in lots of specific applications. General properties of the polymers can be listed as follows:

- Resistance to chemicals
- High insulation against heat and electricity
- Lightness in mass
- Various degrees of strength
- Flexibility in processability (fibres, sheets, foams, intricate molded parts)

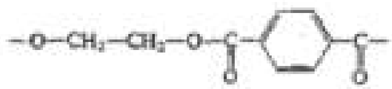
Polyethylene (PE), polyethylene terephthalate (PET), polypropylene (PP), polyvinyl chloride (PVC), and polystyrene (PS) are resins. These are often used in packaging.

1.1.1 Plastic packaging

Plastics and plastic resins are used today for many purposes, including packaging, which still remains the most requiring sector among the plastic applications in EU27+3, with a percentage of 39,1%.

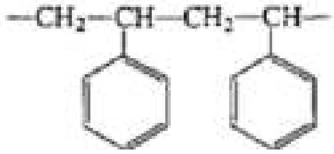
As can be seen from the table below[2], most uses are concentrated in beverage bottles, shampoo containers, plastic bags, rigid microwaveable containers, cups, toys, food contact containers.

Table 1 - Plastic resins recycling codes

Recycling code	**Polymer and structure**	**Uses**
	 Poly (ethylene terephthlate) (PET)	Bottles for soft drinks and other beverages
	 High-density polyethylene	Containers for milk and other beverages, squeeze bottles

[2] Images source: The Sioux Lookout Bulletin - https://www.siouxbulletin.com/what-do-the-plastic-recycling-symbols-actually-mean - 17/09/2023 and Science History Institute - https://sciencehistory.org/education/classroom-activities/role-playing-games/case-of-plastics/science-of-plastics/ - 17/09/2023

	$-CH_2-CH(Cl)-CH_2-CH(Cl)-$ Vinyl/polyvinyl chloride	Bottles for cleaning materials, some shampoo bottles
	$-CH_2-CH_2-CH_2-CH_2-$ Low-density polyethylene	Plastic bags, some plastic wraps
	$-CH_2-CH(CH_3)-CH_2-CH(CH_3)-$ Polypropylene	Heavy-duty microwavable containers

	 Polystyrene	Beverage/foam cups, toys, window in envelopes
	All other resins, layered multi-materials, some containers	Some ketchup bottles, snack packs, mixture where top differs from bottom

Among the polymeric materials, PET is one of the most used polymers in the packaging field, due to its good mechanical properties as well as its processability (Singh et al., 2021)[3]. The main application of PET packaging is bottles for beverages (Malik et al., 2017)[4]. Furthermore, PET can be easily recycled as almost the entire bottles' production industry for drinks, therefore, the use of recycled PET (named Re-PET or R-PET) as an alternative to "virgin" PET or glass-made bottles significantly rose up in the last decades due to its indefinitely recyclability.

It should be remembered also the reasons why PET is the sixth polymer per importance and the "king of the bottled drinks end-segment":

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[3] Singh, A.K., Bedi, R., Kaith, B.S. – 2021 - Composite Materials Based on Recycled Polyethylene Terephthalate and their Properties – a Comprehensive Review. Part B Eng, Compos - Elsevier - https://doi.org/10.1016/j.compositesb.2021.108928 - 17/09/2023

[4] Malik, N., Kumar, P., Shrivastava, S., Ghosh, S.B. - 2016 - An overview on PET waste recycling for application in packaging. Int. J. Plast. Technol. 21, 1–24 – Springer Link - https://doi.org/10.1007/ s12588-016-9164-1 – 17/09/2023

- PET is colourless and can be transparent (if amorphous) or translucent (if semi-crystalline). This is a very important characteristic as it allows consumers seeing the content within the bottles.
- PET is lightweight. The weight of a 1L PET bottle designed for containing water is 25 g. For comparison, a 750 mL wine bottle made by glass is 360 g weight, and a 500 mL aluminium can is 18 g weight.
- PET is thermoplastics, robust, semi-rigid to rigid, mechanically-resistant to impact, and stretchable during processing.
- PET shows gas-barrier properties against moisture and CO_2.
- PET is extremely inert compared to the other plastics, and free from plasticizers (on the contrary, in the case of PVC the use of plasticizers is essential).
- In order to improve specific properties, PET can be blended with other polymers (e.g., with PC, PP, PP copolymers, and PBT) or surface modified (through physical and chemical treatments).
- PET can be copolymerized (e.g., PET-G).

Therefore, for all these reasons, PET remains (and will remain) one of the main polymeric materials to be exploited in the packaging industry[5].

1.1.2 Opaque PET bottles

Opaque PET bottles are mostly used to produce plastic milk bottles, traditionally made of HDPE. Using opaque PET for milk bottles shows several benefits:

1. it's a way to save costs, since PET is cheaper than HDPE

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[5] Roberto Nisticò – 2020 - Polyethylene terephthalate (PET) in the packaging industry - Volume 90 - Elsevier - https://www.sciencedirect.com/science/article/abs/pii/S0142941820310333 - 17/09/2023

2. opaque PET reduces the weight of the container by 25%
3. opaque PET eliminates aluminium seal on the bottle
4. opaque PET reduces water consumption by 20%
5. opaque PET reduces energy consumption of the manufacturing processes by 13%
6. between 10-20% w/w of TiO_2 (Titanium dioxide) is used as opacifying agent, which grants a screening effect from UV radiation of the content, minimising gas permeation and glossy white aspect.

1.2 Plastic packaging data

From the **Report on Plastics – the Facts 2022**[6], some data about plastic market have been collected. In a global overview, after a period of "calm" due to Covid-19 pandemic, the plastics production increased from 365.5 million tonnes in 2018 to 390.7 Mt in 2021. Among the production in 2021, 352.3 Mt are fossil-based plastics, which correspond to the 90.2% of the total; 32.5 Mt are post-consumer recycled plastics, which represent 8.3% of the total amount of plastics production and 5.9 Mt are bio-based plastics (including bio-attributed plastics), which are 1.5% of the total plastics amount produced in the world.

The biggest plastic producer in the world is China, which in 2021 produced 32% of the total plastics amount in the world. After China, we have North America[7] (18%), Rest of Asia (17%), EU27+3[8](15%), Middle East, Africa

[6] Plastics – the Facts 2022 edition presents 2021 data for plastics production, demand, conversion and some 2020 European and national end-of-life management figures.
The data presented in this report was collected by Plastics Europe (the pan-European association of plastics manufacturers) and EPRO (the European Association of Plastics Recycling and Recovery Organisations).

[7] Canada, Mexico and the United States

[8] Norway, Switzerland and United Kingdom

(8%), Latin America (4%), Japan (3%), CIS[9] (3%). In the most of cases, from the data, we can say that the production of plastics remained the same, but in few of them, it increased or decreased by a few percentage points.

In 2021, circular plastics represented about 9.8% of the total production. As we can see from the following Figure 1, the biggest percentage of fossil-based plastic produced was represented by PP, followed by PE-LD-LLD, PVC and so on, while PET represented 6.2% of the global plastics production.

Figure 1 - Distribution of the global plastics production by type

Compared to the total 390.7 Mt of plastics produced, the packaging industry had the largest share globally in 2021, accounting for 44%, followed by the other sector applications (as showed in Figure 2).

[9] Commonwealth of Independent States: Azerbaijan, Armenia, Belarus, Kazakhstan, Kyrgyzstan, Moldova, Russia, Tajikistan, Turkmenistan, Uzbekistan and Ukraine

Figure 2 - Distribution of the global plastics use by application

As a comparison between the global and the European plastic production, after Covid-19 pandemic, plastic production in the EU decreased from 58.1 Mt in 2018 to 57.2 Mt in 2021. Among the production in 2021, 50.1 Mt are fossil-based plastics, which correspond to the 87.6% of the total; 5.8 Mt are post-consumer recycled plastics, which represent 10.1% of the total amount of plastics production and 1.3 Mt are bio-based plastics (including bio-attributed plastics), which are 2.3% of the total plastics amount produced in the European Union.

In 2021, circular plastics represented about 12.4% of the total production. As we can see from the following Figure 3, the biggest percentage of fossil-based plastic produced was represented by PP, followed by PE-LD-LLD, PVC and so on, while PET represented 5.3% of the plastics production in EU.

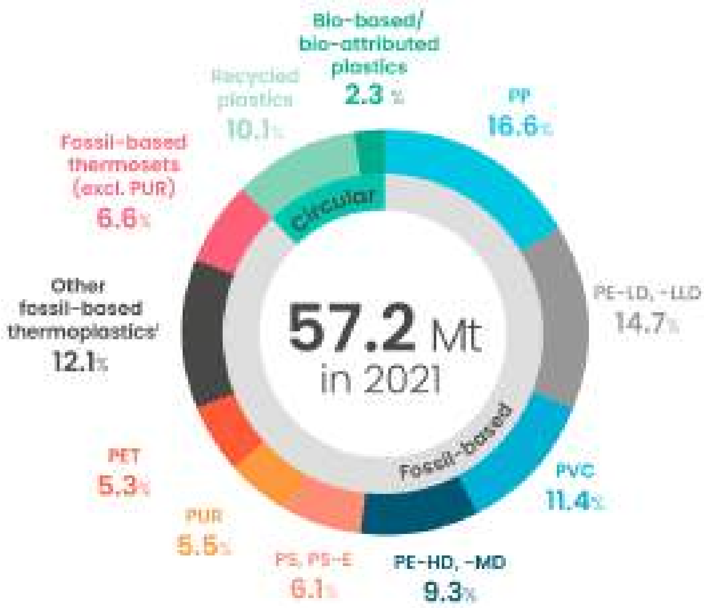

Figure 3 - European plastics production by type

In 2021, among the European recycled plastics use, post-consumer plastics represented 5.5 Mt, which correspond to the 9.9% of the total amount of recycled plastics (55.6 Mt). The remaining 90.1% was represented by fossil-based plastics and it continued to grow in the agriculture, building and construction and packaging sectors, from 2018 to 2021, as Figure 4 shows:

Figure 4 - Post-consumer recycled content evolution per applications (EU27+3)

Going into the details with packaging waste collection, in 2020, 17.9 million tonnes of post-consumer plastics packaging waste were collected in the EU27+3. 10 Mt were collected via separate waste collection, and, as we can see from Figure 5, this system allowed a high percentage of recycling, accounting 80% and the only 2% went to the landfill, which is a great result. About the rest of the collection (7.9 Mt) which was collected via mixed waste collection, only 1% went to the recycling process, while 62% went to energy recovery and 37% to the landfill, which is a very high percentage. It is clear that mixed waste collection can't be listed in the circular value chain of sustainability.

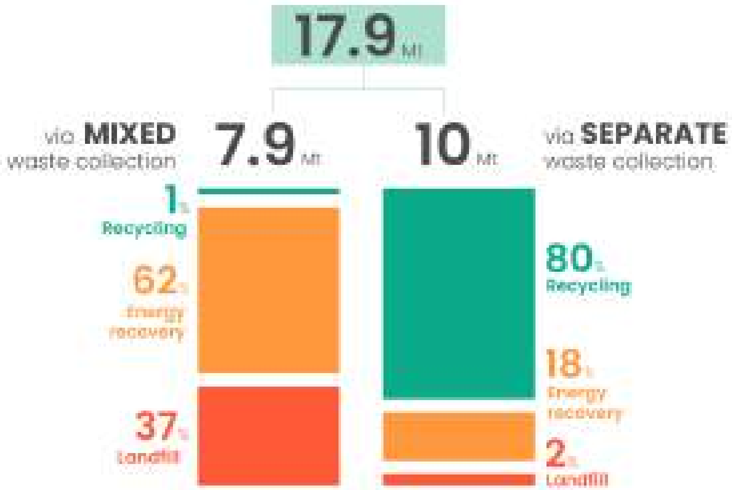

Figure 5 - Mixed and separate post-consumer plastics PACKAGING waste collection in 2020 (EU27+3)

In 2020, the overall European recycling rate for post-consumer plastics packaging reached 46% (under the former Packaging and Packaging Waste Directive (PPWD) calculation methodology), compared to 42% in 2018, which means an increase of about 9.5%. Since 2006, this data has more than doubled, counting a Compound Annual Growth Rate of 5.4%.

Figure 6 shows the post-consumer plastics packaging waste treatment per country in 2020. As we can see, five States of the EU (The Netherlands, Germany, Czech Republic, Belgium, Spain) +UK in 2020 were already over the target sets by 2025 (50%) and The Netherlands had already far exceeded the target sets by 2030 (55%) by the PPWD (Directive EU 2018/852).

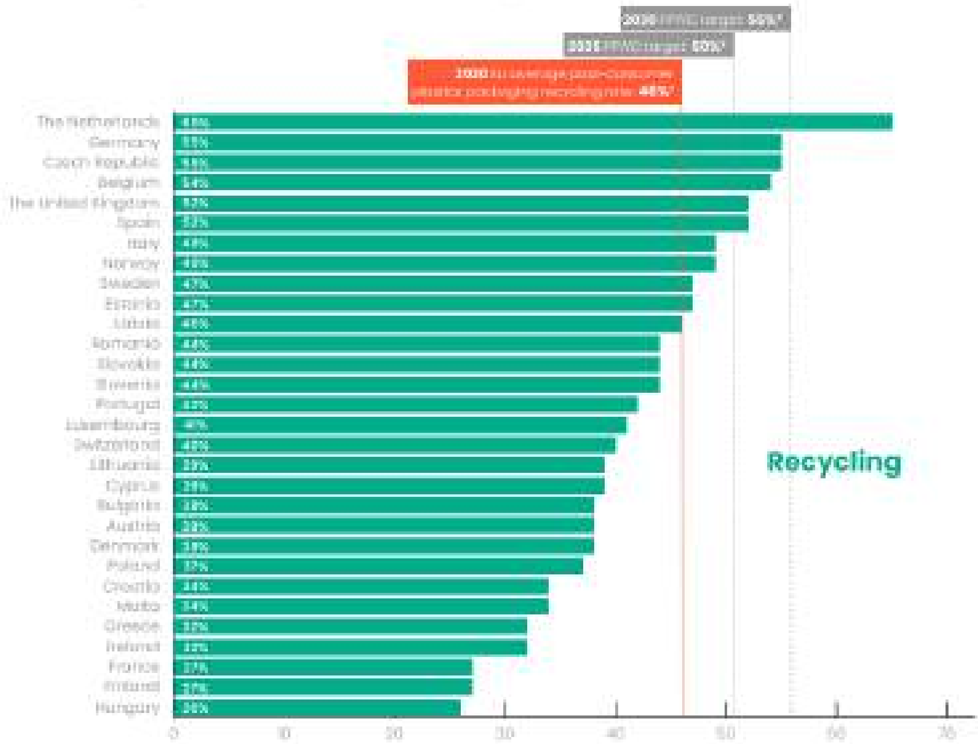

Figure 6 - Post-consumer plastics PACKAGING waste treatment per country in 2020 (EU27+3)

1.2.1 Opaque PET bottles – Global and European data

Going into details related to the PET products placed on the market in 2020, according to the **PET MARKET IN EUROPE - STATE OF PLAY 2022**[10] report, 97% of the whole PET end market is involved in packaging, 3% is other applications. Among the packaging, 64% is represented by bottles (beverage), 20% by trays, 7% by flexible packaging , 6% by bottles (non-beverage).

PET bottles are, in the majority of cases, transparent, but they started to be implemented as opaque PET, more used in milk, fresh cream and oil packaging in some European countries; opaque PET bottles account approximately 2% in the PET bottles value chain, while in the following

[10] by Eunomia and Plastic Recyclers Europe in partnership with PETCORE Europe, NMWE and UNESDA Soft Drinks Europe

figure, other plastic applications are shown as part of the placed-on-the-market packaging. PET trays are blisters or thermoformed/thermoset food trays and flexible PET packaging can be made up of mono-material or multi-material flexible films.

The trend that reports the place on market from 2018 to 2020 for the above-mentioned categories of PET packaging in shown in Figure 7:

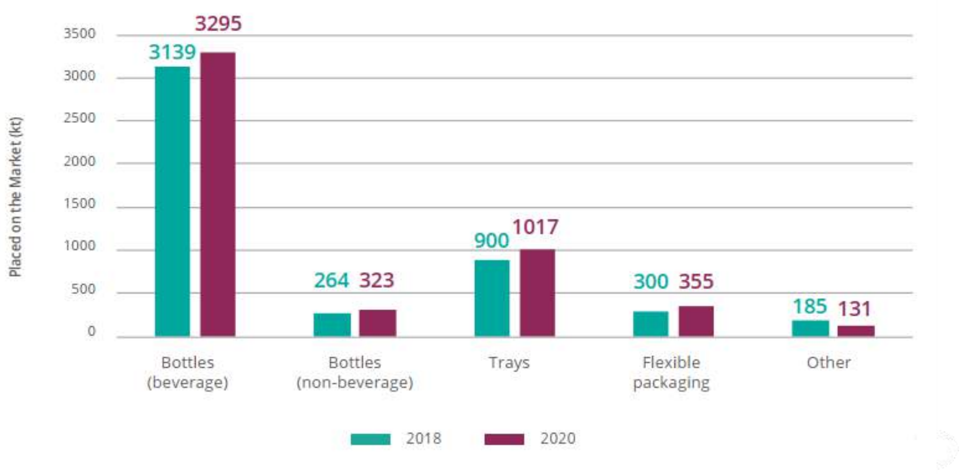

Figure 7 - Changes in Placed on the Market Tonnages per Application, 2018 versus 2020

If we have a look at the sorting data about PET bottles and trays in 2020, as we can see in Figure 8 these data are divided by country and, for instance, opaque PET bottles are sorted in a very low percentage in only few EU countries, such as Italy (2%), Hungary (2%) and Overall (1%). Currently, it is known that also France, Portugal and Belgium are having approaches to this plastic stream[11].

[11] Petcore Europe - May 2023 Newsletter Additional Edition – https://www.petcore-europe.org/news-events/506-latest-news-from-petcore-europe-march-2025.html - 17/09/2023

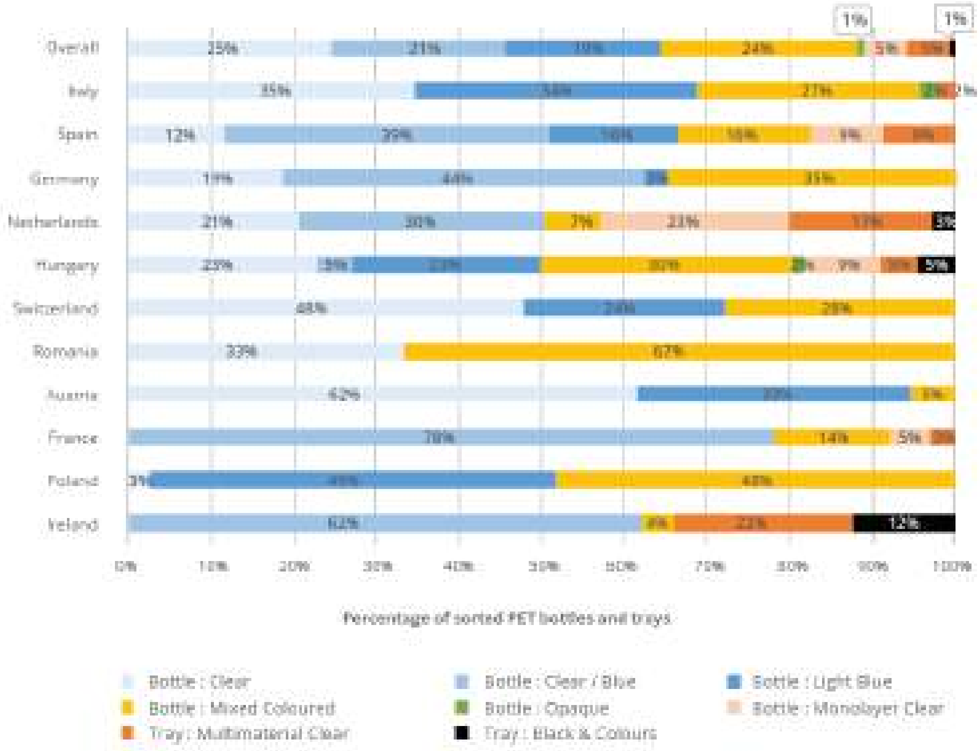

Figure 8 - Proportions of Sorted Colours of PET Bottles and Trays in Countries with Available Data 2020

1.2.2 Opaque PET bottles - Italian data

Some Italian data on opaque PET have been collected through the analysis of the report[12] from CORIPET[13], redacted in May 2022. The consumer input of CORIPET consortium members in 2021 is shown in the table below, taken from the study conducted by Plastic Consult on behalf of the jointly commissioned CORIPET/COREPLA.

[12] Coripet – 2022 - RELAZIONE SULLA GESTIONE 2021 e PIANO SPECIFICO DI PREVENZIONE 2022-24 – Coripet - https://coripet.it/wp-content/uploads/2022/09/Relazione_Ambientale_al_31-12-2021_e_PSP.pdf - 17/09/2023

[13] the Italian voluntary consortium recognised by the Ministry of the Environment between manufacturers, converters and recyclers of PET bottles

Table 2 - Plastic Consult, feb. 2022 - Reconstruction of percentages of CPL-PET released for consumption by CORIPET consortium members

Released for consumption by type of CPL-PET	Total in 2021
CPL-PET opaque / with opaque label, capacity between 0.5 and 5 litres	6,785.3 t
TOTAL CORIPET[14]	192,078.1 t
TOTAL OF THE RELEASED FOR CONSUMPTION	447,350 t

The cost of sorting services incurred by the consortium in 2021 amounted to EUR 30.3 million, invested in the sorting of 134,616 tonnes of CPL[15] PET and the separation of 36,022 tonnes, related to the dispersion of CPL PET into PLASMIX. This is a waste that should be avoided as it ends up in the waste-to-energy plants.

CORIPET CPL PET sorting in 2021 accounted the reported data:

Table 3 - CORIPET CPL PET product

CPL PET product	Quantities (tonnes)
Clear blue	72,968
Coloured	29,561
Transparent	30,245
Opaque/silvered	1,624

We can see that, out of the total, which accounts 134,398 tonnes, the about the 2% of CPL PET product is opaque PET.

[14] The release for consumption is represented by the quantities sold on the national market by CORIPET consortium members
[15] acronym standing for 'Plastic Containers for Liquids', also recognized as bottles

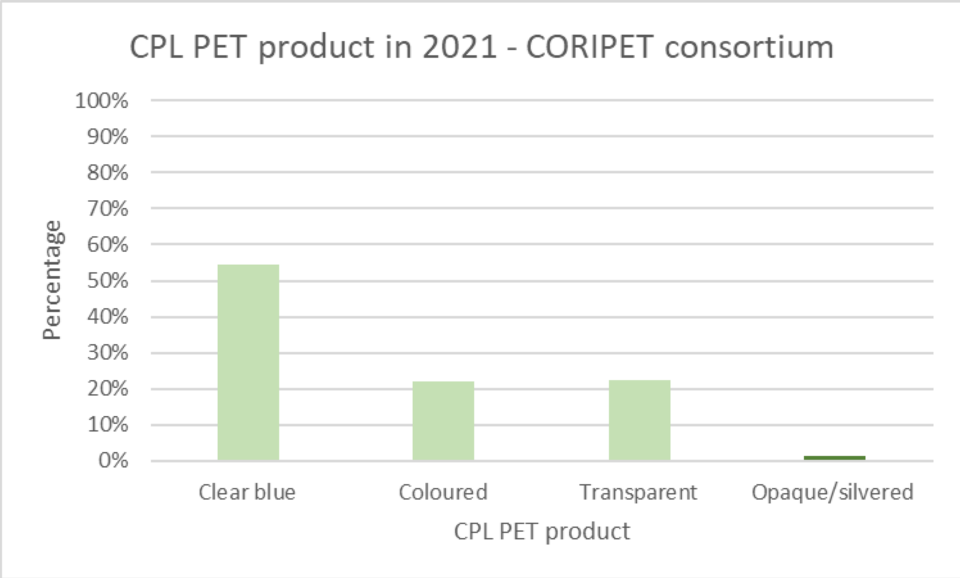

Figure 9 - CPL PET product in 2021 - CORIPET consortium

It has been reported that in 2019[16], in Italy, only 50% of CPL PET have been collected and sent to the recycling plants. This means that out of 460.000 tonnes of PET plastics, 230.000 tonnes were not recycled. In 2018, Corrado Dentis, CORIPET president, stated that, in order to be in line with the targets set by the EU equals to 90% of plastics sent for recycling, it is necessary to increase the volume of the recyclates, especially in the field of PET bottles, and, going into details, of opaque PET bottles. In 2019, opaque PET bottles in Italy represented 20.000 tonnes out of the total. Dentis also considered that, to reach a high collecting and sorting – therefore recycling - standard, it needs to be created a different stream of opaque PET bottles, in order to reach at least the 60% of opaque PET bottles collected to be recycled.

For this purpose, CORIPET promoted the installation of eco-compactors in the whole country. Eco-compactors are machines that citizens can use to

[16]Daniele Autieri – 2019 - Bottiglie in Pet opaco, è l'ora del riciclo – La Repubblica - https://ricerca.repubblica.it/repubblica/archivio/repubblica/2019/05/06/bottiglie-in-pet-opaco-e-lora-del-riciclоAffari_e_Finanza26.html - 17/09/2023

collect PET bottles and this process leads to a better collection by streams and a better quality of the recyclates.

In 2021, according to the Environmental Report from CORIPET, 442 eco-compactors were installed, in order to collect PET bottles, which also involve opaque PET bottles. Data are shown in Table 4.

Table 4 - eco-compactors in Italy

Zone	Eco-compactors number
North of Italy	221
Centre of Italy	93
South of Italy	128

The eco-compactors scenario seems to be similar to the DRS system that will be mentioned in the following paragraphs, but the difference is that the second system is meant to get back a part of the money spent by the consumers in the moment that they bring back the bottle to the machine, while for the eco-compactors system no refund is foreseen. Therefore, in order to increase this collection system, in some spots, in Italy, CORIPET promoted the “Contest – Segui una nuova rotta” which gives to the consumers that participate to the collection through eco-compactors points that can be converted into vouchers and prizes.

CHAPTER 2. LEGISLATIVE FRAMEWORK

The first packaging and management of packaging waste regulations were proposed by EU in 1980s, concerning liquids for human consumption containers, included in the Council Directive 85/339/EEC. The aim of this Directive was to harmonise existing national policies, even if, in the end, it didn't have been as effective as it was supposed to be. Therefore, the European Parliament and the Council adopted a new piece of EU law in 1994, named Directive 94/62/EC on packaging and packaging waste ('PPWD' or 'the Directive').

In the EU legislative framework, the **Waste Framework Directive (2008/98/EC)** sets some basic waste management concepts and definitions. The most important statement discussed and determined in the Directive is the five-step "waste hierarchy", which determines the order of preference for managing and disposing of waste:

1. Prevention: whose aim is to prevent the production of the waste
2. Preparing for reuse: which means that products or components of products that have become waste can be re-used without any other pre-processing.
3. Recycling: which is any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes.
4. Material or Energy recovery: any other recovery operation not designed as recycling processes.

5. Disposal: which means any operation which is not recovery even where the operation has as a secondary consequence the reclamation of substances or energy.

The targets set by the Waste Framework Directive are the following[17]:

- by 2020, the preparing for re-use and the recycling of waste materials (such as paper, metal, plastic and glass) from households shall be increased to a minimum of overall 50 % by weight
- by 2020, the preparing for re-use, recycling and other material recovery, including backfilling operations using waste to substitute other materials, of non-hazardous construction and demolition waste shall be increased to a minimum of 70 % by weight
- the preparing for re-use and the recycling of municipal waste shall be increased to a minimum of 55 %, 60% and 65% by weight by 2025, 2030 and 2035 respectively.

The Waste Framework Directive is going to be reviewed in 2023, in order to better assess the impacts including the stakeholder consultations.

In December 2015, the European Commission adopted the **EU Circular Economy Action Plan,** in which the assessment of the entire plastics value chain plays a key role. Among the sustainability principles promoted by the EU Commission the following aspects must be regulated:

- improving product durability, reusability, upgradability and reparability, addressing the presence of hazardous chemicals in products, and increasing their energy and resource efficiency;
- increasing recycled content in products;
- enabling remanufacturing and high-quality recycling;

[17] European Commission - Waste Framework Directive - https://environment.ec.europa.eu/topics/waste-and-recycling/waste-framework-directive_en - 17/09/2023

- reducing carbon and environmental footprints;
- restricting single-use and countering premature disuse;
- introducing a ban on the destruction of unsold durable goods;
- incentivising product-as-a-service or other models where producers keep the ownership of the product or the responsibility for its performance throughout its lifecycle;
- mobilising the potential of digitalisation of product information, including solutions such as digital passports, tagging and watermarks;
- rewarding products based on their different sustainability performance, including by linking high performance levels to incentives.

In order to set a robust framework around plastic packaging topic, the EU Circular Economy Action Plan aims at contributing to the more sustainable use of plastics, by setting mandatory requirements for recycled content and plastic waste reduction measures and a list of actions to reduce the presence of microplastic in the environment, such as restricting the presence of added microplastics, developing labelling, standardisation, certification and regulatory measures to increase the capture of microplastics and harmonising methods to counteract the release of microplastics, even by better spreading scientific knowledge related to the risk that microplastics bring to the environment and human health.

In 2020 the EU Commission adopted a **new Circular Economy Action Plan**, which requires that, by 2030, all packaging (not only plastics) on the EU market is re-usable or recyclable in an economically viable way. Its measures have been adopted in 2022 (including the revision of EU rules on Packaging and Packaging Waste).

Presented by the EU Commission in 2019, the **European Green Deal** commits to climate neutrality by 2050. In September 2020, EU Commission proposed new EU target to reduce net emissions by at least 55% by 2030. In July 2021, the EU Commission presents a package of proposals to change our economy in order to reach the climate targets by 2030. The foreseeing in 2030 is a reduction of emissions of at least 55% compared to 1990 levels in Europe.

2.1 Current European legislation on plastic packaging

The **Single Use Plastic Directive (EU) 2019/904** has been adopted by the European Parliament and the Council of the European Union with the aims to prevent and reduce the impact of the single-use plastic products on the environment (especially the aquatic one) and on human health and to promote the transition to a circular economy with innovative and sustainable business models, products and materials contributing to the efficient functioning of the internal market. 'Single-use plastic product' means a product that is made wholly or partly from plastic and that is not conceived, designed or placed on the market to accomplish, within its life span, multiple trips or rotations by being returned to a producer for refill or re-used for the same purpose for which it was conceived[18].

The Directive (EU) 2019/904 makes restrictions on some single-use plastic products that cannot be placed on the market, such as cutlery, plates, straws and cotton bud sticks, beverage stirrers, sticks to be attached to and to support balloons and their mechanisms, food containers made of expanded polystyrene, products made from oxo-degradable plastic, beverage containers made of expanded polystyrene, including their caps and lids, cups for beverages made of expanded polystyrene, including their covers and lids.

It also sets standards for SUP bottles:

1. **collection target of 90%** recycling for SUP plastic bottles by 2029 (with an interim target of 77% by 2025)

[18] Single Use Plastic Directive (EU) 2019/904, Art. 3 – Definitions – Eurlex - https://eur-lex.europa.eu/eli/dir/2019/904/oj - 17/09/2023

2. these bottles should contain at least **25% recycled plastic** in their manufacture by 2025 (for PET bottles), and **30%** by 2030 (for all bottles).

According to the Directive (EU) 2019/904, Member States shall take the necessary measures to achieve an ambitious and sustained reduction in the consumption of the single-use plastic products, in line with the Union's waste prevention objective. In order to achieve the proposed objectives, Member States may adopt measures such as DRS and the establishment of separate collection targets for relevant EPR schemes.

The directive have been transposed into national law by 3 July 2021 and the market restrictions and marking of product rules have been applied from the same date as well, while the product design requirements for caps and lids of SUP beverage containers apply from 3 July 2024.

The **Packaging and Packaging Waste Directive 94/62/EC** aims to protect the environment and ensure the proper functioning of the internal market, harmonising national measures concerning the management of packaging and packaging waste.

The legislation was revised in 2018, setting ambitious targets for recycling of packaging waste, which were supposed to achieve, for instance, at least 70% by weight of all packaging waste recycled by the end of 2030.

The **Regulation (EU) 2019/1020 on market surveillance and compliance of products** aims to improve how the free movement of goods principle works by strengthening market surveillance of products covered by EU harmonization legislation. This must ensure a high level of protection of health and safety, in general and in the workplace, and protect consumers, the environment, public security and other public interest. It lays down rules and procedures for economic operators and establishes a system for their cooperation with supervisory authorities and controls on products imported into the EU.[19]

The **Food Contact Materials Regulation (EU) 2022/1616** lays down the rules for:

- the sale of plastic materials and articles manufactured with a suitable recycling technology from waste plastic that are intended to be or can be reasonably expected to come into contact with food;
- the development and operation of recycling technologies, processes and installations to produce that recycled plastic;
- the use of plastic materials and articles in contact with food which have been, or are intended to be, recycled.

Waste management operators must ensure the collected plastic waste:

- originates only from municipal waste or from specific food retail or other food businesses, collected with a certified collection system, subject to possible exceptions;
- contains only plastic materials and articles meeting the requirements of Regulation (EU) No 10/2011 on plastics that come into contact with food;

It has also to be collected separately or with a recycling scheme managed by a single entity in which the participants subject to the rules of that scheme ensure that the plastic is not contaminated.

Suitable recycling technologies:

- must ensure recycled plastic materials

[19] Regulation (EU) 2019/1020 — market surveillance and compliance of products - https://eur-lex.europa.eu/legal-content/en/LSU/?uri=CELEX:32019R1020&qid=1690455298535 – 17/09/2023

- are microbiologically safe
- do not release their constituents into food in amounts that could endanger human health or change, to unacceptable levels, the composition of the food or its colour, aroma, taste and texture (organoleptic characteristics)
- have labelling, advertising and presentation that does not mislead the public

Moreover, they are:

- categorised according to factors such as type, collection and origin of the input material and the intended use of the recycled plastic,
- listed in Annex I to the regulation and may also be individually authorised by the European Commission.

To be placed on the market, recycled plastic materials and articles must contain the necessary documentation, instructions and labelling and be manufactured by one of the following:

- a suitable technology listed in Annex I
- a novel technology in accordance with the procedure set out in Chapter IV

EFSA (European Food Safety Authority) has to assess the process and determine whether the process can apply the suitable recycling technology so that the plastic materials are safe, and issues a scientific opinion concerning the recycling process. [20]

[20] Regulation (EU) 2022/1616 on recycled plastic materials and articles intended to come into contact with foods - https://eur-lex.europa.eu/legal-content/en/LSU/?uri=CELEX:32022R1616&qid=1690445775307 – 17/09/2023

2.2 Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on packaging and packaging waste

The **Proposal for a Regulation on packaging and packaging waste, amending Regulation (EU) 2019/1020 and Directive (EU) 2019/904, and repealing Directive 94/62/EC,** has been published in November 2022.

Pursuant to Article 3, 'packaging' means items of any materials that are intended to be used for the containment, protection, handling, delivery or presentation of products and that can be differentiated into packaging formats based on their function, material and design.

Article 6, on the recyclability of packaging, states that all packaging shall be recyclable, where recyclable means that the packaging complies with:

(a) it is designed for recycling;
(b) it is effectively and efficiently separately collected
(c) it is sorted into defined waste streams without affecting the recyclability of other waste streams;
(d) it can be recycled so that the resulting secondary raw materials are of sufficient quality to substitute the primary raw materials;
(e) it can be recycled at scale.

Point (a) shall apply from 1 January 2030 and point (e) shall apply from 1 January 2035.

'Design for recycling' means design of packaging, including individual components of packaging, in order to ensure its recyclability with state-of the-art collection, sorting and recycling processes.

It has been defined also that the Commission shall establish the methodology to assess if packaging is recyclable at scale. That methodology will be based on:

(a) amount of packaging placed on the market in the Union as a whole and in each Member State;
(b) amounts of separately collected packaging waste per packaging material listed in Table 1 of Annex II:
(c) recycling rates of packaging waste per packaging type listed in Table 1 of Annex II;
(d) installed infrastructure capacities for sorting and recycling in the Union as a whole for each packaging type listed in Table 1 of Annex II.

Table 1 of Annex II reports the following packaging referred to in Article 6:

Category No	Predominant packaging material	Packaging type	Format (illustrative)	Colour
1	Glass	Glass	Bottles, jars, flacons, cosmetics pots, tubs etc. made of glass (soda lime silica)	
2	Glass	Composite packaging, of which the majority is glass	Bottles, jars, flacons, cosmetics pots, tubs	
3	Paper/cardboard	Paper/cardboard packaging	Boxes, trays, grouped packaging	
4	Paper/cardboard	Composite packaging of which the majority is paper/cardboard	Including beverage cartons, plates and cups, i.e., metallised or plastic laminated paper/ card, liquid paperboard, paper/cardboard with plastic liners/ windows	
5	Metal	Steel	Rigid packaging formats (aerosols, cans, paint tins, boxes, etc.) made of steel, including tinplate	
6	Metal	Composite packaging, of which the	Drums, tubes, cans, boxes, trays, etc.	

Figure 10a - Indicative list of packaging materials, types and categories referred to in Article 6

		majority is steel		
7	Metal	Aluminium	Rigid formats (food and beverage cans, bottles, aerosols)	
8	Metal	Aluminium	Semi rigid or flexible formats (containers and trays, tubes, foil)	
9	Metal	Composite packaging of which the majority is Aluminium	Drums, tubes, cans, boxes, trays, etc.	
10	Plastic	PET - rigid	Bottles and flasks	Transparent clear/ light blue
11	Plastic	PET - rigid	Bottles and Flasks	Transparent other colours
12	Plastic	PET - rigid	Rigid packaging other than bottles and flasks (Includes pots, tubs and trays)	Transparent
13	Plastic	PET - flexible	Films	
14	Plastic	HDPE - rigid	Containers and Tubes	natural /clear
15	Plastic	HDPE - rigid	Containers and Tubes	coloured
16	Plastic	PE - flexible	Films	natural /clear
17	Plastic	PE - flexible	Films	coloured
18	Plastic	PP - rigid	Containers and Tubes	natural /clear
19	Plastic	PP - rigid	Containers and Tubes	coloured
20	Plastic	PP - flexible	Films	natural /clear
21	Plastic	PP - flexible	Films	coloured

Figure 10b - Indicative list of packaging materials, types and categories referred to in Article 6

22	Plastic	HDPE and PP - rigid	crates and pallets	
23	Plastic	PS - rigid	Rigid packaging (except EPS and XPS)	
24	Plastic	EPS - rigid	Fish boxes/ white goods	
25	Plastic	XPS - rigid		
26	Plastic	Other rigid plastics including. PVC, PC - rigid	Rigid	
27	Plastic	Other flexible plastics including multilayer plastic films and multi material materials - flexible	Pouches	
28	Wood, cork	Wooden packaging, including cork	Pallets, boxes	
29	Textile	Natural and synthetic textile fibres	Bags	
30	Ceramics or porcelain stoneware	Clay, stone	Pots, containers, bottles	

Figure10c - Indicative list of packaging materials, types and categories referred to in Article 6

From 1 January 2030, packaging shall not be considered as recyclable if it corresponds to grade E under the design for recycling criteria established in a delegated act that the Commission is empowered to adopt.

In Annex II, Table 2 the Recyclability performance grades are listed, based on the assessment of recyclability per unit, measured in weight, which corresponds to a percentage related to the Class Grade:

Recyclability Performance Grade	Assessment of recyclability per unit, in weight
Grade A	higher or equal to 95 %
Grade B	higher or equal to 90 %
Grade C	higher or equal to 80 %
Grade D	higher or equal to 70 %
Grade E	lower than 70 %

Figure 11 - Recyclability performance grades

Article 6 states that, where a unit of packaging includes separate components, the assessment of compliance with the design for recycling requirements and with the 'at scale recyclability' requirements shall be done separately for each separate component and this means that each component shall be compatible with the state of the art collection, sorting and recycling processes.

In order to improve recycling targets and promote recycling, Article 46 of the proposal of PPWR sets the recycling targets that must be achieved in 2025 and in 2030, which can be compared to the existing in 2020:

Table 5 - Recycling targets from Article 46 of the PPDR proposal

	In 2020 (%)	**In 2025 (%)**	**In 2030 (%)**
All packaging waste	55	65	70
Plastic	22.5	50	55
Wood	15	25	30
Ferrous materials	50 (included Al)	70	80
Aluminium (Al)	-	50	60
Glass	60	70	75
Paper and cardboard	60	75	85

Currently, after a stakeholder consultation, the European Commission is working on its new project, driven by the JRC (Joint Research Centre) on the definition of design for recycling criteria, that will be consolidated in a delegated act, as stated by the Proposal.

2.2.1 "Recyclable" and "Recyclable at Scale" definitions

A global definition of "recyclability" of plastics packaging and products is an integral step to harmonize the worldwide plastics recycling industry. This definition has been developed by The Association of Plastics Recyclers (APR) and Plastics Recyclers Europe (PRE) in 2018. In order to be defined "recycled" [21]:

1. The product must be made with a plastic that is collected for recycling, has market value and/or is supported by a legislatively mandated program.
2. The product must be sorted and aggregated into defined streams for recycling processes.
3. The product can be processed and reclaimed/recycled with commercial recycling processes.
4. The recycled plastic becomes a raw material that is used in the production of new products. This definition does not intend to restrict innovation. For innovative materials to be recyclable, it shall be demonstrated that they are collected and sorted in sufficient quantities and are compatible with existing industrial recycling processes or have sufficient material quantities to justify operating new recycling processes.

[21] RecyClass methodology – definition of "recyclability" - https://recyclass.eu/get-certified/recyclability/#1 – 17/09/2023

From Article 3 (32) of the Proposal[22] from the EU Commission, 'recycled at scale' means collected, sorted and recycled through installed state-of-the-art infrastructure and processes, covering at least 75 % of the Union population, including packaging waste exported from the Union that meets the requirements of Article 47(5).

2.3 Extended Producer Responsibility (EPR) schemes

Extended Producer Responsibility (EPR) is an environmental policy tool which places the responsibility for managing the post-consumer state of a product's life cycle on the producer, in order to meet EU and national recycling and recovery targets. To do so, PPWR proposal requires to set up return systems or collection, reuse, recovery, recycling systems.

EPR schemes are set up at national level to help producers and importers meeting the European obligations. In the most of cases, the responsibility for meeting recycling targets is assigned to the producers, but, anyway, the practices on how to implement EPR can vary from country to country, depending on the involved actors (producers, local authorities, private or public waste management companies or consumers) and on the requirements that EPR schemes have to meet to operate.

CITEO[23] (France) and CONAI[24] (Italy) both use eco-modulation of EPR fees in order to provide specific cost incentives for producers to ensure that products are designed to meet recyclability criteria. Eco-modulated fees

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[22] Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on packaging and packaging waste amending Regulation (EU) 2019/1020 and Directive (EU) 2019/904, and repealing Directive 94/62/EC, Art. 3 (32) – Definitions – Eurlex - https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52022PC0677 – 17/09/2023

[23] CITEO is a company set up by companies in the consumer goods and distribution sectors to reduce the environmental impact of their packaging and paper, by offering them solutions for reducing, reusing, sorting and recycling.

[24] CONAI is a private, non-profit consortium that is the instrument in Italy through which producers and users of packaging ensure the achievement of the recycling and recovery targets for packaging waste set by law.

should be used across all EPR schemes as an important way to help meeting increased targets for the recycling of plastic packaging. It is important, however, that modulation criteria are harmonised across Member States. Without a unified approach, there is the potential for schemes to become increasingly diverse, complicating the landscape for producers and possibly introducing conflicting requirements that packaging formats are unable to meet. The PPWR proposal aims at harmonizing, monitoring and reporting obligations, including EPR schemes.

EPR fees will provide an additional economic impetus for compliance and increased clarity as to the roadmap for investments in circular packaging design and innovative sorting and recycling technologies.

CHAPTER 3. CIRCULAR ECONOMY AND RECYCLING OF PLASTIC PACKAGING

3.1 Circular economy and PET circularity

The “circular economy” is a production and consumption model which minimises the input of resources and the output of waste, air pollution emissions and greenhouse gas. This model relies on long-lasting design, maintenance, repair, re-use and recycling, which keeps resources in production and consumption for as long as possible[25]. The idea of “circular economy” gets in contrast with the idea of the “linear economy”, which is a model based on the extraction, use and throwing away of the resources – model that today is not environmentally sustainable anymore.

As we can see in Figure 12, the circularity process starts with raw material[26] extraction; after that, the idea of the product comes to be designed, created and remanufactured. As the product is ready to be launched on the market it comes to be bought and consumed, and the cycle ends up with the transformation of the product in waste. The aim of the circular economy is to turn the waste into secondary material that can be re-used for the same or different scopes. The residual waste should be very low percentage or ideally zero.

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[25] Ekaterina Karamfilova – 2022 - Revision of Directive 94/62/EC on packaging and packaging waste – European Parliament - https://www.europarl.europa.eu/RegData/etudes/BRIE/2022/734698/EPRS_BRIE_734698_Revision_Directive_Packaging.pdf – 17/09/2023

[26] according to Wikipedia definition: “A raw material, also known as a feedstock, unprocessed material, or primary commodity, is a basic material that is used to produce goods, finished products, energy, or intermediate materials that are feedstock for future finished products.”

Figure 12 - Circular Economy by CEN-CENELEC

In this regard, mention should be made of the definitions of “pre-consumer waste” and “post-consumer waste”[27].

Pre-consumer waste is a material that was discarded before it was ready for consumer use. Pre-consumer waste is the reintroduction of manufacturing scrap back into the manufacturing process. Pre-consumer waste is commonly used in manufacturing industries and it is often not considered as recycling in the traditional sense. Examples: shavings, sawdust, walnut shells, fly ash, over-issue publications, textile clippings, obsolete inventories.

Post-consumer waste is a material discarded after someone uses it. Post-consumer waste has served its intended purpose, passed through the hands of a final consumer, and has been discarded for disposal or recovery. Quite commonly, it is simply the garbage that individuals routinely discard, either in the trash can or a dump, or by littering, incinerating, or pouring down the

[27] Wesam Mohamed Edited by: Dr. Wesam Taha, Urban Sophist - 2016 - Pre & Post Consumer Waste Definition – ResearchGate - https://www.researchgate.net/publication/312498203_Pre_Post_Consumer_Waste_Definition - 17/09/2023

drain. In the case of paper, pre-consumer waste would be that which was printed but never used. Such as newspapers that were never bought by a consumer. Post-consumer waste in this example would be the newspaper that was bought and read and then discarded. Examples: Include Construction and Demolition Debris, materials collected through recycling programs, Discarded products (e.g., furniture, cabinetry, decking), and Landscaping waste (e.g., leaves, grass clippings, tree trimmings). (ISO 14021)[28].

Frans Timmermans, the Commission's vice-president in charge of overseeing the European Green Deal[29] said that "*To achieve climate-neutrality by 2050, to preserve our natural environment, and to strengthen our economic competitiveness, requires a fully circular economy*".

To better understand the idea of how circular economy can be efficient in the daily applications, the tools, such as "closed loop scheme" and "open loop scheme" must be mentioned.

When we talk about a "closed loop recycling scheme", we are referring to a manufacturing process that uses the same post-consumer material in order to create a new version of the same product. In the specific case of the PET bottles, for instance, starting from the PET bottle production, it goes ahead with the bottling and distribution from the suppliers to the sellers, then the consumption from the consumers, the separate collection (when a Deposit for Refund scheme is not available). After the collection, the PET bottle is not anymore a consumer responsibility, but it is picked up and laid to the sorting centre. The next step in the agreement between the sorting plant and the recycling plant must be recycling the post-consumer material and getting the best quality of the recyclate.

[28] CEN Cenelec – 2021 - The EU's Circular Economy Action Plan – CEN Cenelec https://www.cencenelec.eu/news-and-events/news/2021/briefnews/2021-02-03-eu-circular-economy-action-plan/ - 17/09/2023

A “open loop recycling scheme” is a recycling process where the products are reprocessed and used in purposes different from the previous one. In the PET bottle recycling scheme, the process for an open loop is the same as the closed loop scheme, except for the last step, in which the product coming off from the recycling plant is not used again to start a new cycle, but this material is supposed to be part of another product made by recycled plastic, for instance recycling PET bottles could be used into fibres for carpets. Even if open loop recycling scheme has a valuable impact on the environment, it has always to be preferred to the utilization of virgin plastic feedstock.

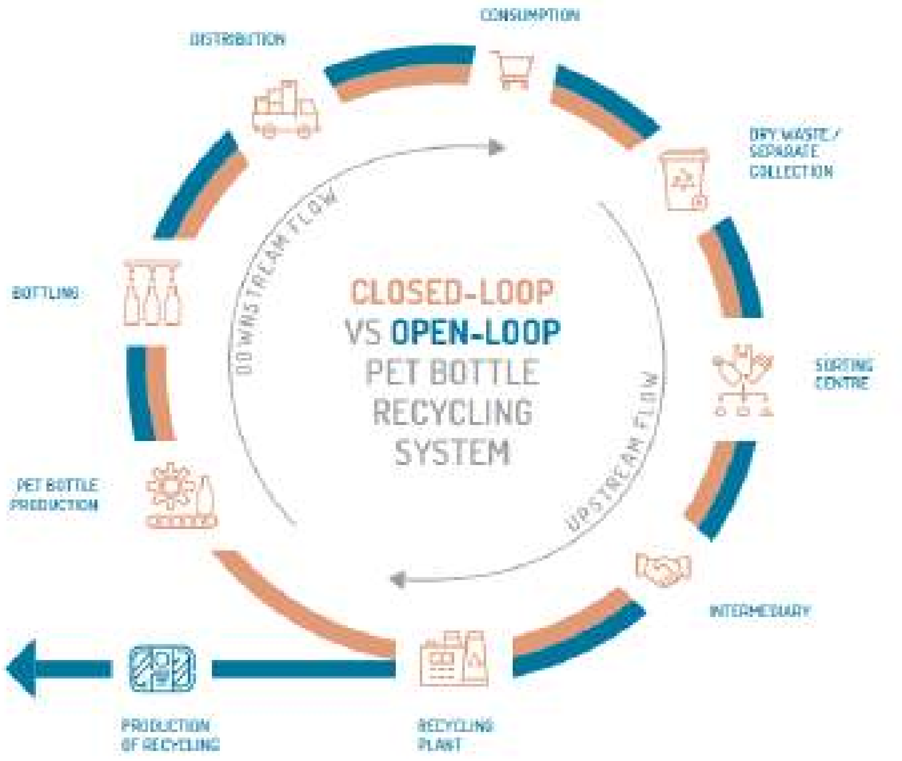

Figure 13 - Closed loop and open loop PET bottle recycling system by RecyClass

In some cases, some packaging cannot be designed for closed loop recycling schemes, so the design choice should fall into a “multiple-step cascaded recycling process”, in which a material can be used until its quality becomes too low to be used and it goes to energy recovery.

Figure 14 - cascade open loop scheme by RecyClass

In the circular economy system, plastics are produced, converted, used and managed in a sustainable way[30]. This means avoiding (or, at least, reducing) the use of the fossil-based feedstocks and preferring to them the use of circular feedstocks, creating eco-designed products respecting the recycled content rates, facilitating re-use and repair.

According to the Circularity Report from Plastics Europe 2022, the trend towards higher circularity of plastics increased from 2018 to 2020. Plastics production (polymerisation) has decreased by 10.3%.

At the same time, the post-consumer plastics waste quantities sent to recycling have increased by 8.5%.

Quantities sent to landfill decreased (- 4.3%) and energy recovery remained the same for the first time since 2006. As a consequence, the supply of postconsumer recycled plastics increased by 11% compared to 2018, and their use into new products rose from about 4 million tonnes to 4.6 million tonnes – an increase of 15%. This demonstrates an initial shift towards a higher share of recycled plastics in the manufacturing of new products (from 7.2% in 2018 to 8.5% in 2020).

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[30] Plastics Europe – 2022 - Plastics in a circular and climate neutral economy – Plastics Europe - https://plasticseurope.org/wp-content/uploads/2022/06/PlasticsEurope-CircularityReport-2022_2804-Light.pdf - 17/09/2023

Figure 15 - Evolution of plastic circular economy from 2018 to 2020 by PRE

Nowadays, still the biggest part of plastics is produced from fossil-based feedstock. To reach the goals of the Paris[31] Agreements and the Glasgow Climate Pact[32] and the EU's 2050 climate-neutral ambition, new investments and innovative recycling technologies must be committed.

Carbon Capture and Use is also a promising technology to create new feedstock while capturing CO_2 emissions and avoiding their emission in the atmosphere.

In the **How circular is PET?** report[33] it is mentioned that the majority of PET is not currently managed in a circular model and the system leakage is

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[31] The Paris Agreement is the first-ever universal, legally binding global climate change agreement, adopted at the Paris climate conference (COP21) in December 2015. It sets out a global framework to avoid dangerous climate change by limiting global warming to well below 2°C and pursuing efforts to limit it to 1.5°C. It also aims to strengthen countries' ability to deal with the impacts of climate change and support them in their efforts. Source: https://climate.ec.europa.eu/eu-action/international-action-climate-change/climate-negotiations/paris-agreement_en

[32] The 26th UN Climate Change Conference (COP26) to discuss about how to accelerate the measures towards the goals of the Paris Agreement and the UN Framework Convention on Climate Change in November 2021.

[33] from Eunomia and Zero Waste Europe - 2022

relevant. The strongest limitations which influence the current circularity of PET concern the collections, the availability of recyclers, the contaminants from collections, the product design and material quality and the rPET economics. Regarding PET bottles, the European average Collection Rate is 96% for countries who adopted DRS (Deposit Refund System)[34] and 48% for countries without DRS, while the Recycling Rate for both beverage and non-beverage bottles in around 50%, calculated considering the weight of PET material after being washed and flaked and the weight of the PET bottles placed on the market.

Figure 16 - Estimated market shares of bottle types and colours

From Figure 16, we can see that most bottles placed on the market are used for beverage purposes (92%), while 8% are used for non-beverage scopes. From the first application, 78% of PET bottles are clear/light blue bottles, 20% are coloured bottles and 2% are opaque bottles, but the opaque PET bottles are foreseen to grow (and are already growing) in terms of production al placing on the market. Manufacturers of recycled PET (rPET) bottles require rPET derived from beverage bottles that meet food safety standards, which is more easily reached in DRS collection systems, since there's no contamination. The meeting of the standards is also easier when we talk about clear or light blue PET bottles, rather than coloured and opaque PET bottles, because the higher the amount of colouring, the fewer (and darker coloured) the applications for which rPET can be used, except if we are talking about a

[34] Reference paragraph 3.1.1

bottle-to-bottle scheme for opaque PET bottles, that today has started to be considered, since the amount of the PET bottles in some countries is increasing in the different applications, especially in dairy bottles production.

In the last years, it was thought that opaque PET bottles should have been collected in separated collection streams, as they used to contaminate the clear and light blue PET bottles stream in the separate collection system, and after being separated, the end-of-life of this waste should have been the landfill or incineration. Nowadays, fortunately, the view is different, since the stakeholders recognized the properties of opaque PET bottles and the items are put on the market more easily, some countries where the use of these products is quite widespread, such as France, Italy, Portugal, Belgium[11] are trying with new approaches to separate the white opaque PET bottle stream from the transparent one, to finalize the sorting to a bottle-to-bottle scheme for opaque PET, that will be better analysed in the following chapters of this work.

3.1.1 Deposit Refund Scheme (DRS) – European overview

From the **Deposit Refund Scheme in Europe** report[35] by ACR+, a Deposit Refund Scheme is *a system whereby a consumer pays an additional (visible) amount of money – a deposit – for the packaging containing the beverage and can claim this money back if he returns it to an approved collection point*.

It is an effective mean to ensure extended producer responsibility[36]. Compared with other collection systems, it has better treatment effect on scattered and hard-to-regulate solid waste. Beverage packaging has become a

[35]Bilyana Spasova - 2019 – Deposit Refund Systems in Europe – ACR+ https://www.acrplus.org/images/technical-reports/2019_ACR_Deposit-refund_systems_in_Europe_Report.pdf - 17/09/2023
[36] Reference paragraph 2.3

key application area in deposit-refund system because of its large quantity, dispersed consumption and high pollution intensity[37].

Figure 17 below, from the Eunomia report[38], gives a big picture of DRS status in EU27+3. Iceland, Denmark, Sweden, Norway, Finland, Estonia, Lithuania, Croatia, Germany, Netherlands, Slovakia have already an established DRS. In Ireland, Scotland, Latvia, Romania, Turkey, Malta, political decisions have been taken in 2022; Hungary and Greece have discussed for it and suppose to adopt the system by 2023. The scheduled deadline for Poland, Portugal, UK is 2024 and for Austria and Cyprus it's 2025. In Belgium, France, Spain, Slovenia, Bulgaria and Czech Republic the DRS is in discussion, while for Italy and Luxembourg the status is currently unknown.

Figure 17 - Status of DRS Discussions in the EU27+3

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[37] Guangli Zhou, Yifan Gu, Yufeng Wu,
Yu Gong, Xianzhong Mu, Honggui Han, Tao Chang – 2020 - A systematic review of the deposit-refund system for beverage packaging: Operating mode, key parameter and development trend – Science Direct - https://www.sciencedirect.com/science/article/abs/pii/S0959652619345305 - 17/09/2023

[38] Reference paragraph 1.2.1

The PET collection rate has been reported in Figure 18 from PRE:

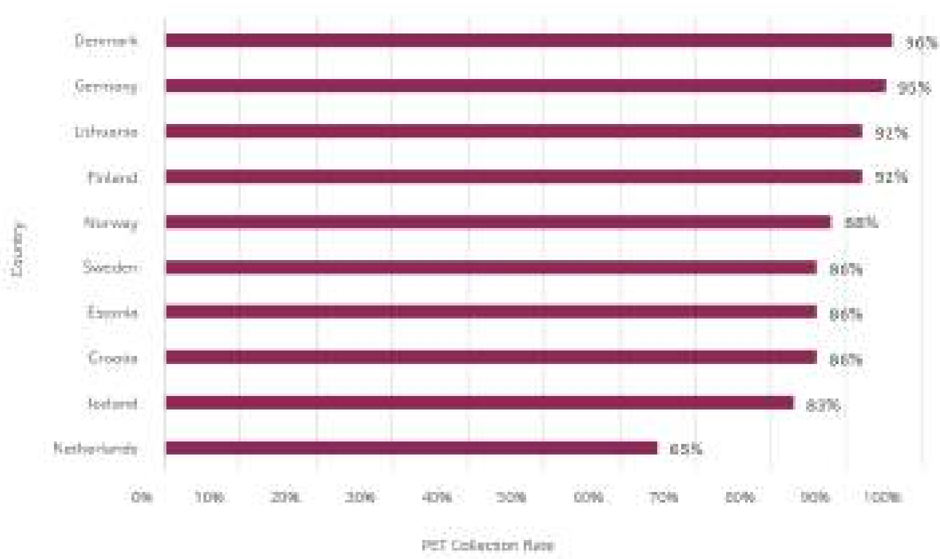

Figure 18 - PET Collection Rates Across Countries with DRS Systems that Include PET

It is clear, from the data, that countries that have implemented DRS systems show high collection rates (the most of them accounts above than 80%).

The result of the study conducted by the authors and above-mentioned[30] shows that although the operation mechanism of beverage packaging deposit-refund system varies greatly in different countries, there are also some common problems in the integration with intelligent collection, promote ecological design[39] and develop a multi-profitable circular business model.

It is surely a system which foster the spread of circular economy, although some Member States still struggle to adopt it because the collection targets

[39] The concept sustainable design and build (SDB) is the advancement of science and engineering principles performed by scientists, consultants, architects, engineers, construction managers, policymakers, and investors to secure a more ecologically balanced planet Earth.
Sustainable Design and Build, 2019 – ScienceDirect - https://www.sciencedirect.com/topics/engineering/ecodesign - 17/09/2023

for PET bottles are fully achieved and they don't consider that this system could be ad added value in the value chain.

However, in the countries where in has been adopted the authors believe that the increasing of the application of Internet communication technology and Internet of Things technology can make the whole process more controllable and verifiable.

3.2 Recycling of plastic packaging

One of the priorities of the European Commission is to minimize waste generation and to promote resource efficiency, which could be achieved by increasing the recycling post-consumer plastic packaging waste (Thoden van Velzen et al., 2019)[40].

Indeed, plastic packaging, and the main polymers used in packaging such as polyethylene terephthalate (PET), polypropylene (PP), high-density polyethylene (HDPE), polystyrene (PS), low-density polyethylene (LDPE), represent the majority of the plastics that are collected for recycling due to their widespread use (Paletta et al., 2019)[41]. In Europe, the recycling rate of post-consumer plastic packaging waste has reached 46% in 2020 (Plastics Europe, 2022), which is still not enough to meet the 50% target by 2025 set by the European Commission's Packaging and Packaging Waste Directive (European Commission, 2018).

[40] Thoden van Velzen, E.U., Brouwer, M.T., Feil, A. – 2019 - Collection behaviour of lightweight packaging waste by individual households and implications for the analysis of collection schemes – Science Direct - https://www.sciencedirect.com/science/article/abs/pii/S0956053X19302351 - 17/09/2023

[41] Paletta, A., Leal Filho, W., Balogun, A.L., Foschi, E., Bonoli, A. – 2019 - Barriers and challenges to plastics valorisation in the context of a circular economy: case studies from Italy. J. Clean. Prod. 241, 118149 – Science Direct - https://www.sciencedirect.com/science/article/abs/pii/S0959652619330197 - 17/09/2023

Recycling process usually includes: collection, sorting, and recycling[42] (that could be either mechanical or thermo-chemical). In the specific case of plastic waste, mixed plastics from municipal solid waste are usually recycled in suitable Material Recovery Facilities (MRFs) following separate collection. These plants allow the sorting of individual plastics with variable performance depending on the technologies adopted (Gadaleta et al., 2020).[43] The MRFs have to sort and to separate this mixed waste streams in order to convert them into secondary raw materials (Gaustad et al., 2012)[44]. Where this sorting is not possible, the non-recyclable stream (PLASMIX[45]) is transferred to incineration plants for energy recovery.

A waste-to-energy plant consists of a process by which the delivered waste is incinerated at very high temperatures (900°-1200°). The heat produced by combustion is used to generate steam, which is then sent to a turbine to generate electricity or is fed into the district heating network.

On this purpose, it needs to be mentioned that the waste stream that arrives to the incineration plant is not useful anymore for food contact purposes, since it has been mixed with the rest of the waste in the upcoming stream.

Legally speaking, food contact packaging containing recycled content can only be made up by not contaminated food contact material.

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[42] Does PET trays sorting affect the sustainability of plastic waste? An LCA and cost-revenue approach - George Barjoveanu , Giovanni Gadaleta, Giusy Santomasi, Sabino De Gisi, Michele Notarnicola, Carmen Teodosiu – 2023 – Science Direct - https://www.sciencedirect.com/science/article/abs/pii/S0048969723038457 -17/09/2023

[43] Outlining a comprehensive techno-economic approach to evaluate the performance of an advanced sorting plant for plastic waste recovery - Giovanni Gadaleta, Sabino De Gisi, Silvio M.C. Binetti, Michele Notarnicola – 2020 – Science Direct - https://www.sciencedirect.com/science/article/abs/pii/S0957582020316098 - 17/09/2023

[44] Gaustad, G., Olivetti, E., Kirchain, R. – 201 - Improving aluminum recycling: a survey of sorting and impurity removal technologies. Resour. Conserv. Recy. 58, 79–87 – Elsevier - https://tarjomefa.com/wp-content/uploads/2016/09/5306-English.pdf - 17/09/2023

[45] PLASMIX is the extremely heterogenic plastic waste resulting from the mechanical recycling of packaging. Recycling options for PLASMIX are currently limited.

Nowadays, in more than two decades of technological development, MRFs are characterized by an automated sorting process with a high degree of technical complexity, that has increased the sorting efficiency (Serranti and Bonifazi, 2019)[46].

The sorting process consists of different steps, listed below[47]:

– **Ballistic separation**: packaging is separated according to their shape and size. In this step, packaging with a small size or volume are less extracted (e.g. pods and bottles < 20ml or films with size < size A5).

– **Metals separation**: plastic packaging containing metallic elements (steel or aluminium) can be oriented with plastics or metals according to the quantities of metal and depending on the machine settings (for example: PET jars with a steel hinge or mixed aluminium cans /plastic)

– **Optical sorting**: with infra-red sorting technologies, plastics can be separated by resin (PET, HDPE, PP, etc.). Some elements may interfere and reduce the efficiency of optical sorting: sleeves made of a material that is different from packaging body, complex trays made of several plastic resins, black packaging, etc.

– **Manual sorting**: the human eye is still essential to ensure a good quality of materials sorted out of sorting centres.

– **Baling**: the sorted materials are compacted and baled, then shipped to the regenerators.

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[46] Serranti, S., Bonifazi, G. – 2019 - Techniques for separation of plastic wastes – Science Direct - https://www.sciencedirect.com/science/article/abs/pii/B9780081026762000025#:~:text=Separation%20technologies%20are%20divided%20into,magnetic%20and%20Eddy%20current%20separators – 17/09/2023

[47] COTREP - https://www.cotrep.fr/en/plastics-sorting-and-recycling-in-france/

Figure 19 - General sorting process in sorting facilities. Source: COTREP [48]

Mechanical recycling consists of the following steps:

– **Opening of bales**: packaging bales are opened and packaging item are unpacked.

– **Optical & metals sorting**: as in sorting centres, plastic regenerators are equipped with optical sorters and metal detectors to perform new sorting operations and eliminate unwanted materials.

– **Shredding**: packaging is then shred into flakes of about one centimetre. The presence of elements other than plastic (glass beads, metal element) can damage equipment.

– **Washing**: the flakes are washed. Depending on the ink, pigment or glue used, some particles can disturb the regeneration or pollute the washing water.

– **Flotation**: flakes are separated according to their density, those with a density greater than 1 sink while those with a density less than 1 float. At a PET regenerator, the sinking material is of interest (PET density> 1)

[48] Images source: web

– **Optical sorting of flakes**: some regenerators are equipped with optical sorting equipment that allows to sort the flakes according to their material and colour.

– **Extrusion / Granulation**: some regenerators can perform an extrusion / granulation step which consists of heating the flakes together. The melt, thus produced, then passes through a die to produce spaghetti, which is cut into small pieces. These are called plastic pellets and can be directly used in plastics processes.

Figure 20 - General process of plastic regeneration. Source: COTREP [49]

Thermo-chemical recycling is a process that converts polymeric waste by changing its chemical structure and turns it back into substances that can be used as raw materials for the manufacturing of plastics or other products. There are different chemical recycling technologies, such as pyrolysis, gasification, hydro-cracking and depolymerisation[50].

[49] Images source: web
[50] Plastics Europe - https://plasticseurope.org/sustainability/circularity/recycling/chemical-recycling/ - 17/09/2023

Pyrolysis is the thermochemical decomposition of organic matter into non condensable gases, condensable liquids, and a solid residual coproduct, biochar or charcoal in an inert environment (i.e., in the absence of oxygen)[51].

Pyrolysis is an interesting technology for plastic waste feeds that are difficult to depolymerize and that are currently not (mechanically) recycled but incinerated and/or dumped to landfill such as mixed PE/PP/PS, multilayer packaging, fibre-reinforced composites, polyurethane construction and demolishing waste[52].

Gasification is generally defined as a thermochemical conversion (750–850 °C) of carbonaceous compounds including biomass and organic wastes into gas mixtures, consisting of carbon monoxide (CO), hydrogen (H2), carbon dioxide (CO2), methane (CH4), nitrogen (N2), usually named syngas, and smaller liquid (tar) and solid fractions (Sikarwar et al., 2016)[53].

Hydrocracking is a two-stage process combining catalytic cracking and hydrogenation, wherein heavier feedstocks are cracked in the presence of hydrogen[54].

Depolymerisation consists of breaking the chemical bonds of the polymer in order to obtain the monomer, either using chemical agents (solvents, water, alcohols) or heat. The monomers thus obtained are then purified before they

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[51] Environmental Materials and Waste - 2016 – Science Direct - https://www.sciencedirect.com/topics/earth-and-planetary-sciences/pyrolysis - 17/09/2023

[52] Kim Ragaert, Laurens Delva, Kevin Van Geem – 2017 - Mechanical and chemical recycling of solid plastic waste – Science Direct - https://www.sciencedirect.com/science/article/abs/pii/S0956053X17305354 - 17/09/2023

[53] Bioresource Technology - 2021- Science Direct - https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/gasification - 17/09/2023

[54] Encyclopedia of Energy - 2004 – Science Direct - https://www.sciencedirect.com/topics/physics-and-astronomy/hydrocracking - 17/09/2023

can be polymerised again. They are then injected into traditional production processes as a secondary raw material (recycled material)[55].

Mechanical recycling is the current industrially ubiquitous technique for the recovery of waste polymers. Contaminations in the mixed plastics types in waste affect the product quality and give rise to limited economies of scale and fluctuating price of recycled materials. These potential limitations have led to the growing interest in a currently less frequently used type of recycling, which is chemical recycling. This type of recycling has high potential for heterogeneous and contaminated plastic waste material, where separation is either not economically viable or not completely technically feasible[44], but where CO_2 footprint as well as a cost analysis have to be conducted. Furthermore, the feasibility of chemical recycling on an industrial scale, with large amounts of output of recycled materials and a positive recycling value, remains questionable[56].

3.2.1. Opaque PET bottles recycling

Clear light blue coloured bottles are the easiest packaging to recycle, mainly because they are easy to empty, and usually employed in closed loop recycling of food grade packaging, where the contaminants cannot exceed 5%. An additional reason is that PET is considered the most promising food-packaging plastic for recycling because it is capable to absorb post-consumer contaminations at lower levels, compared to other plastics.

The presence of opaque PET bottles within a clear and transparent PET bottles recycling stream can affect the clarity and transparency of the rPET (recycled PET), although it would be interesting trying to find out methods and technologies to recyclate as well this stream which is going to increase more

[55] Plastics e Mag – 2021 - https://plastics-themag.com/Converting-the-old-into-a-virgin-plastic - 17/09/2023
[56] FEAD – 2019 - Chemical recycling - https://fead.be/position/chemical-recycling-2/ - 17/09/2023

and more. Data reported in the Preliminary note 2[57] from COTREP[58]'s research show that, from a study on the composition of bales conducted in 2014[59], dairy opaque PET accounts for 5% of the coloured PET streams, which represents a stock of approximately 2000 tonnes.

The proportion of opaque PET in coloured bales has grown from 7% in 2012 to 10% in 2014.

The counterpart of opaque PET is its difficulty in being recycled by conventional processes used for transparent PET (r-T-PET), especially the bottle-to-fibre recycling process, which represents around 44% of its market share. The French packaging compliance organisation Eco-Emballages stated that above a threshold of 15% by weight, the presence of recycled opaque PET (r-O-PET) in the PET bottle-to-fibre recycling stream leads to a series of difficulties during the filament manufacturing and significant deterioration of the mechanical properties of the fibres.

The main issue concerning the recyclability of opaque PET bottles is related to the presence of opacifiers, such as Titanium dioxide (TiO_2), which can be added in varying concentrations and additives, such as carbon black, mica, silica. Their scope is to create barrier properties required for preserving dairy drinks. Without the addition of opacifiers, PET is one of the resins best suited to the recycling process. The use of Titanium dioxide calls for enquiry into the impact of a growing and increasingly significant proportion of this opaque

[57] Cotrep – 2015 - Preliminary note 2 Impact of the increase in opaque PET packaging on the recycling of coloured PET packaging – https://www.cotrep.fr/content/uploads/2019/02/np02-preliminary-notice-impact-of-opaque-pet-on-coloured-pet-recycling.pdf – 17/09/2023

[58] Center of resources and expertise on household plastic packaging recyclability in France, Cotrep has been supporting packaging designers for 20 years in the development of recyclable solutions

[59] Eco-Emballages – 2014 - Results of campaigns to assess the characteristics of dark-coloured PET bales in MRFs
https://www.cotrep.fr/content/uploads/2019/02/np02-preliminary-notice-impact-of-opaque-pet-on-coloured-pet-recycling.pdf - 17/09/2023

PET on current recycling chains and outlets. Opacifiers are present in many types of HDPE packaging, and are well known to recyclers. However, there is a marked difference between the applications and markets for recycled HDPE and those for PET, which tolerate opacifiers to a much lesser degree[60].

Stated the COTREP preliminary note, the main outlets for recycled PET are bottles, fibre and sheet. Opaque PET contain various additives which prevent the material to be used in bottles and sheet applications made from clear PET.

The current packaging sorting system cannot accept the presence of opaque PET in the mixed stream together with pale coloured PET stream, even in small quantities, because it is seen as “contaminant” for the main outlets, which are sheets and bottles. This is even more hampering when a carbon black layer is included in the packaging.

When the mixed stream, containing both pale coloured PET and opaque PET packaging, is detected by the sorting process, recyclers are successful in extracting opaque PET bottles prior the recycling process itself.

In the outlet for fibre, a test has been conducted by COTREP in order to assess the recyclability of opaque PET for pale coloured PET fibre applications. It comes out that concentrations up to 15-20% of opaque PET in the material are still accepted in terms of mechanical properties. Carbon black layer, instead, is not accepted because it causes the greying of the fibre and this is not compliant with user specifications.

From an economic point of view, the presence of a significant proportion of non-recyclable PET (PLASMIX) in the main applications is likely to reduce the market value of PET bales.

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[60] Cotrep – 2013 - Preliminary note - The impact of the increase in white opaque PET on the recycling of PET packaging – https://www.cotrep.fr/content/uploads/2019/02/np01-preliminary-notice-impact-of-opaque-pet-on-pet-recycling.pdf - 17/09/2023

If the residual waste from any other recycling treatment still contains opaque PET bottles, then it could be sent to the waste-to-energy plant, where it can still either be sorted at the beginning of the plant and sold to the recyclers or be incinerated, in accordance to the waste hierarchy, which always prioritize the recycling and recovery of the waste.

Considering the increasing number of opaque PET bottles in the domestic plastic waste stream, this would mean an increasing amount of PLASMIX being sent for incineration.

3.2.2. Design for Recycling Guidelines

In terms of recycling, as Article 6 of the new proposal for PPWR from the Commission stated, **Design for Recycling Guidelines** should be build up as a fundamental tool that can be used in order to assess the recyclability of packaging. Encourage packaging designers, converters and users to facilitate plastic recyclability is currently a hot topic among the European spectrum of interests.

There are a lot of organizations within the EU framework that are working for long time on the release of the Design Guidelines, or have already published their own works, especially since the PPWR proposal has set new standards that need to be met if the above-mentioned involved stakeholders want to be in line with the circularity mindset.

According to the general objective mentioned in the EU Commission proposal on PPWR, strict measures on the several steps of the plastic recycling value chain must be adopted, in order to make plastic packaging as most recyclable as possible, starting from the design.

The general layout, common to all of the tables published so far that cover different types of packaging, finds that each category of packaging that needs to be assessed is based on a 3-coloumn classification, according to a trafficlight concept, to summarize the different features that can be found on a plastic packaging. In the colour hierarchy:

1. GREEN COLUMN → FULL COMPATIBILITY, meaning that the packaging has the best design features to guarantee the best recyclability and quality of the recyclate.
2. YELLOW COLUMN → LIMITED COMPATIBILITY, meaning that the packaging features have been tested and it is has been proved that they have a slight impact on the recycling process and on the quality of the recyclate, despite they are not the best choice.
3. RED COLUMN → LOW COMPATIBILITY, which mentions the design features that should be avoided, since they have a strong impact on the recycling process and on the quality of the recyclate.

Currently, the JRC (Joint Research Centre), the European research centre from the European Commission, which provides independent, evidence-based knowledge and science supporting EU policies to positively impact society, is collecting feedback from the stakeholders, in order to provide itself to the creation and release of Design for Recycling Guidelines that can cover in a harmonised framework all the packaging mentioned in Article 6, Annex II of the PPWR proposal.

The process must be quite slow, in order to make sure that all the feedback have been considered and can help the EC scientific group to elaborate a work that finally harmonizes the design requirements for packaging.

In spite of this, some European organizations and platforms already released their own Guidelines, based on their experience in the specific sector, after conducting precise scientific analyses.

Currently, studies have been conducted and are still conducted on the assessment of Design for Recycling Guidelines for opaque PET bottles.

Among the entities that are involved in the mentioned process, EPBP published its own guidelines designated with scientific scrupulousness that will be discussed thereafter.

EPBP (European PET Bottle Platform) is a voluntary industry initiative that, among others, developed PET bottle Design Guidelines for Recycling, paying attention to all of the different features that PET bottles can assume (transparent clear/light blue PET bottles, transparent coloured PET bottles, Opaque PET bottles and Opaque White PET bottles), laying the foundations for fully support a circular economy in the European PET value chain.

The following table sets out the Design criteria in order to better assess the recyclability of white opaque PET bottles.

The belonging on the different coloured columns has to be referred to the classification mentioned above. The green column represents the ideal criteria that has to be observed in order to have a completely compliant packaging.

In order to comply with the recycling process, the packaging should be mostly made by PET, in white opaque colour. Multilayer or bi-layer structure or pastel colour can hamper the recycling process, as well as the fluorescent and metallic layer.

SiOx can be accepted as compliant, and also TiO2 should be included into the green column. Carbon plasma-coating, Nylon-MXD6 in a 3-layer structure with up to 5 wt% Nylon-MXD6, PGA multilayer and PTN alloy can hamper the recycling process and the presence of Nylon-MXD6 in a 3 layer structure, with > 5 wt% Nylon-MXD6 or with tie layers, Nylon-MXD6 in a 5 layer structure, monolayer Nylon-MXD6 blend and EVOH implies a low compatibility of the packaging with the design for recycling criteria.

Additives are not accepted in the fully compatibility, but UV stabilisers; AA blockers, optical brighteners and oxygen scavengers are partially compliant.

Bio-/oxo-/photodegradable additives and nanocomposites are marked as hampering (red column).

In the closure system PE and PP together all with density <1 g/cm^3 are classified as "green", while materials with density >1 g/cm^3 (e.g. highly filled PE, metals and non-detaching or welded closures) are marked as "red", probably because of their high weigh in the sortability process that doesn't allow to separate the main body from the closure system.

In liners, seals and valves PE, PE+EVA, PP, foamed PET, all with density <1g/cm^3 and TPS with density <0.95g/cm^3 are accepted, but silicone with density 0.95g/cm^3 and floatable TPE are classified as "yellow" and materials with density >1 g/cm^3 (e.g. PVC, silicone, metals) and Floatable silicone (even with density <1g/cm^3) are marked as low compatible.

PE; PP; OPP; EPS; foamed PET; all with density <1 g/cm^3 labels are accepted as compatible, while lightly metallised labels (density <1 g/cm^3) and paper labels are partially compatible with the recycling process. In the red column, materials with density >1 g/cm^3 (e.g. PVC; PS; PET; PETG; PLA), metallised materials, non-detaching or welded labels, foamed PETG (even with density <1 g/cm^3) and PET with washable inks.

Fully compatible are sleeves with partial bottle coverage in PE, PP, OPP, EPS, foamed PET and LDPET, all with density <1 g/cm^3. Full sleeves translucent for IR detection in PE, PP, OPP, EPS, foamed PET and LDPET, all with density <1 g/cm^3 are classified as mid-compatibility, while there's red light for materials with density >1 g/cm^3 (e.g. PVC, PS, PET, PETG), metallised materials, heavily inked sleeves, full body sleeves, foamed PETG (even with density <1 g/cm^3) and PET with washable inks.

Tamper Evidence Wrap should be made by PE, PP, OPP, EPS, and foamed PET, all with density <1 g/cm^3 for the compliance, while materials with density >1 g/cm^3 (e.g metal, PVC, PS, PET, PETG), metallised materials, foamed PETG (even with density <1 g/cm^3) and PET with washable inks are marked as low compatible.

Adhesives that can be accepted are alkali/water soluble and alkali/water releasable at 60-80°C without reactivation, while the ones that are not accepted are alkali/water soluble, non-releasable or releasable above 80°C.

The inks should be non-toxic and they should follow EUPIA Guidelines. Inks that bleed, that are toxic or hazardous or metallic inks are not compliant with the assessment.

In terms of direct printing, laser marked printing is fine for the evaluation, production or expiry date printing is mid-compatible and any other direct printing is low compatible.

Under "other components" category, base cup, handles or other components which are separated by grinding and float/sink, all with density <1 g/cm^3 and unpigmented PET or with the same base colour as the bottle are classified as compliant. Materials with density >1 g/cm^3(e.g. metal, RFID tags) and non-detaching or welded components are, instead, marked as non-compliant, therefore they go under "red column" category classification.

	YES Full compatibility – materials that passed the testing protocols with no negative impact OR materials that have not been tested (yet), but are known to be acceptable in PET recycling	CONDITIONAL Limited compatibility – materials that passed the testing protocols if certain conditions are met OR materials that have not been tested (yet), but pose a low risk of interfering with PET recycling	NO Low compatibility – materials that failed the testing protocols OR materials that have not been tested (yet), but pose a high risk of interfering with PET recycling
Material	PET		PLA, PVC, PS, PETG, PC, PBT (as a bottle material)
White Opaque			
Size			smaller than 4 cm (when compacted) or larger than 5 litres
Colours	White opaque. (1) (2)	Multilayer or bi- layer structure with white outer layer. Pastel colours. (1) (2)	Fluorescent, metallic. Any other non-white outer layer
Barrier	SiOx plasma-coating	carbon plasma-coating; Nylon-MXD6 in a 3-layer structure with up to 5 wt% Nylon-MXD6 and no tie layers; PGA multilayer ; PTN alloy	Nylon-MXD6 in a 3 layer structure, with > 5 wt% Nylon-MXD6 or with tie layers; Nylon-MXD6 in a 5 layer structure; monolayer Nylon-MXD6 blend; EVOH
Additives		UV stabilisers; AA blockers; optical brighteners; oxygen scavengers	bio-/oxo-/photodegradable additives; nanocomposites
Closure Systems	PE; PP; together all with density <1 g/cm³		materials with density >1 g/cm³ (e.g. highly filled PE; metals); non-detaching or welded closures)
Liners, Seals and Valves	PE; PE+EVA; PP; foamed PET; all with density <1g/cm³; TPE with density <0.95g/cm3	silicone with density 0.95g/cm³; floatable TPE	materials with density >1 g/cm³ (e.g. PVC, silicone, metals); Floatable silicone (even with density <1g/cm3)

Figure 21a - White opaque PET bottles Design for Recycling Guideline from EPBP

Labels	PE; PP; OPP; EPS; foamed PET all with density <1 g/cm^3	lightly metallised labels (density <1 g/cm^3), paper	materials with density > 1 g/cm^3 (e.g. PVC, PS, PET, PETG, PLA); metallised materials; non-detaching or welded labels foamed PETG (even with density <1 g/cm^3); PET with washable inks
Sleeves	sleeves with partial bottle coverage in PE; PP; OPP; EPS; foamed PET; LDPET; all with density <1 g/cm^3	full sleeves translucent for IR detection in PE; PP; OPP; EPS; foamed PET; LDPET; all with density <1 g/cm^3 (INTERIM: Twin-perforated sleeves for household and personal care)	materials with density > 1 g/cm^3 (e.g. PVC, PS, PET, PETG); metallised materials; heavily inked sleeves; full body sleeves; foamed PETG (even with density <1 g/cm^3); PET with washable inks
Tamper Evidence Wrap	PE; PP; OPP; EPS; foamed PET all with density <1 g/cm^3		materials with density >1 g/cm^3 (e.g. metal; PVC; PS; PET; PETG); metallised materials; foamed PETG (even with density <1 g/cm^3); PET with washable inks
Adhesives	alkali/water soluble and alkali/water releasable at 60-80 C without reactivation		alkali/water soluble, non-releasable or releasable above 80oC
Inks	non toxic; follow EUPIA Guidelines		inks that bleed; toxic or hazardous inks; metallic inks
Direct Printing	laser marked	production or expiry date	any other direct printing
Other Components	base cup, handles or other components which are separated by grinding and float/sink - all with density <1 g/cm^3; Unpigmented PET or with the same base colour as the bottle		materials with density >1 g/cm^3 (e.g. metal, RFID tags); non-detaching or welded components

Figure 21b - White opaque PET bottles Design for Recycling Guideline from EPBP

3.2.3 Recyclability assessment

With the aim of achieving compliance with the Guidelines - the future ones to be issued by the JRC and those already defined by other European bodies on the basis of internal analyses - RecyClass has defined a preventive methodology that can guarantee the recyclability of packaging, in accordance with what Article 6 of the PPWR has established.

3.2.3.1 RecyClass methodology

Plastic Recyclers Europe is an European organisation who represents plastic recyclers that reprocess plastic waste into high-quality materials to produce new items. It is the representative of more than 165 companies which take part into the organisation and more than 730 recycling facilities, which means over 30.000 employees.

RecyClass initiative has been promoted by Plastic Recyclers Europe in 2014. In 2019 PRE developed inputs coming from the European plastic recyclers in the RecyClass platform, to which brand owners, raw material producers, converters, retailers and all these actors together with the recyclers take part, and set Design for Recycling Guidelines and a freeware online tool available on RecyClass website which allows to self-assess the recyclability of the packaging. In order to complete the assessment, companies can go ahead to apply for a Recyclability Certification, carried out by an independent and recognized auditor. That certification can be used to make a claim of recyclability in final packaging, which can be identified through a reliable recyclability methodology.

In June 2021, RecyClass published the first claims guidance and logo for recyclability.

In order to pose the foundations for the methodology, RecyClass defined the meaning of "recyclability"[61], transferring it to the definition of a "recyclable packaging", which is ranked in the classification from "A" to " F ".

[61] Reference paragraph 2.2.1

Figure 22 - RecyClass ranking

As we can see from Figure 22, class "A" implies that a packaging is completely recyclable, while class "F" packaging means that it is unrecyclable and the only option is energy recovery.

In the recyclability assessment analysis conducted at the end of this study, it has been evaluated the percentage that corresponds to the recyclability class, according to a range of percentage, which is shown in the following table, defined by RecyClass Methodology:

Table 6 - Recyclability percentage linked to recyclability class in RecyClass Methodology

RECICLABILITY CLASS	RANGE OF PERCENTAGE
A	> 95%
B	90-95%
C	70-90%
D	50-70%
E - F	< 50%

3.2.3.2 Recyclability Certification Schemes

From both previous assessment methodologies, Design for Recycling and Recyclability Rate Certifications can be released. These are procedures that allow the applicant to show externally the RecyClass logo with the class that the packaging achieved in terms of recyclability; this means that the plastic packaging is perfectly compliant with the mechanical recycling process.

The Certification Scheme focuses on the recyclability by considering as main benchmark the ability of the recycled plastic packaging to be reused in Closed-Loop and Cascade Open-Loop applications.

Recyclability of a plastic packaging has to be verified throughout the whole steps of the waste management process, that includes collection, sorting, recycling, in order to make a claim of recyclability in final packaging.

Therefore, certification may be granted to all companies commercialising final plastic packaging, mainly brand owners and retailers but not exclusively.

The Schemes are developed according to the RecyClass Recyclability Methodology and EN 13430 - Requirements for packaging recoverable by material recycling[62].

Packaging either already placed on the European market or not yet placed on market but in their last design stage (no more editable) is eligible for Recyclability Certifications. Semi-finished packaging cannot be assessed with the Recyclability Certification scheme. However, they can be evaluated and receive a Letter of Compatibility.

A Letter of Compatibility is a certified document that allows the evaluation of a semi-finished plastic packaging by an accredited author, that is based on the certification scheme of a Design for Recycling Assessment. It does not allow the use of RecyClass logo, because the latter is allowed only for final packaging certified. The Letter is valid for 3 years and if some modifications on the assessed packaging are done, it has to be evaluated again.

As second eligibility requirement, the packaging should be entirely covered by the Design for Recycling guidelines, meaning that all its features are already known and classified according to their recycling compatibility.

In the following Figure 23, we can see the certification process for both final packaging and semi-finished packaging summarised:

[62] Plastics Recyclers Europe – 2023 - RecyClass Recyclability Methodology – https://recyclass.eu/wpcontent/uploads/2023/07/Recyclass_methodology_version-2.2_June-2023.pdf - 17/09/2023

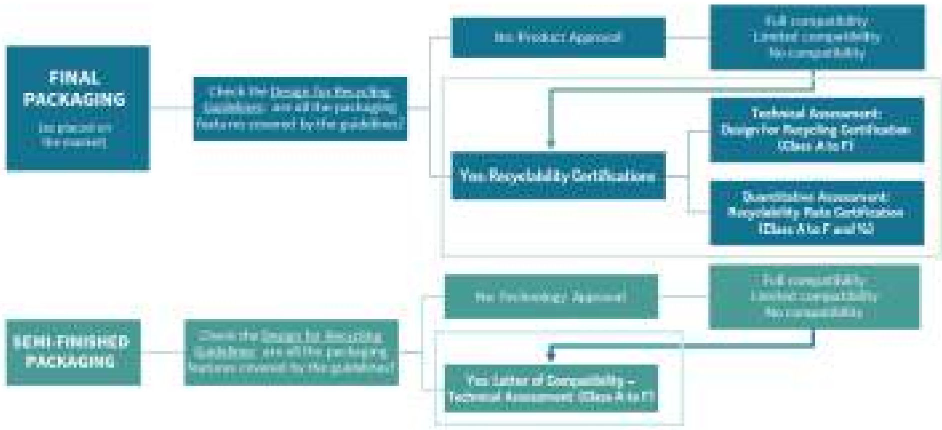

Figure 23 - Recyclability Assessments scenarios by RecyClass

The Certification Schemes give to every single packaging a percentage of compatibility with the recycling process, by assessing a class ranking from A to F. Classes between A, B and C can be rated above 50%, while packaging ranked as D, E and F are rated below 50% and they are not considered as conform.

Once the Certification is released, the applicant will receive:

- An audit report, including the recyclability class and recyclability rate of Audited Packaging and reporting its composition. The audit report is identified with a unique certification code.
- The Recyclability Certificate, identifying the recyclability class and recyclability rate achieved by Audited Packaging. As for the audit report, the certificate is identified with the same certification code than the audit report. Auditor shall include an Annex to the certificate if equivalent packaging has been assessed, listing them with unique identifications.
- The RecyClass logo including the recyclability class.

- Tests results, if any performed by the auditor. The certificate is valid for 3 years and guarantees that the packaging is designed to be recycled in Europe. Any change in the packaging design must be communicated to RecyClass in order to revise its recyclability. Retailers, brands, converters and any other companies involved in manufacturing or designing of the packaging can apply for the Certification[63].

RecyClass claims and logo can be used in documentation, websites, product brochures or on-product and certification holders are responsible for the correct use of RecyClass logos.

[63] RecyClass – 2023 https://recyclass.eu/wp-content/uploads/2023/07/Recyclass_methodology_version-2.2_June-2023.pdf - 17/09/2023

CHAPTER 4. OBJECTIVES AND EXPERIMENTAL PLAN

4.1 Scope of the study

The objective of this study will be defining the recyclability assessment of opaque PET bottle, starting from the analysis of opaque PET bottle stream, through the sorting and recycling value chain, giving shape to different sorting scenarios that can lead to diverse quality of the recyclate ending up in the analysis of the existing Design Guidelines related to this specific packaging.

1. **Scenario 1** : opaque PET sorted in a mixed stream together with pale coloured PET stream
2. **Scenario 2**: opaque PET sorted in a mixed stream together with dark coloured PET stream
3. **Scenario 3**: opaque PET sorted as single stream

It will be important to understand which should be the design for recycling criteria that can eliminate (or, at least, minimize) the issues into the sorting/recycling processes and how important the definition of opaque PET bottles Guidelines can be, ending up again with the legislative framework reference.

4.2 Experimental plan

To this end, the study has been organised into the following phases:

1. Characterisation of an opaque PET bottle sample;
2. Analysis and comparison of different sorting scenarios of the end-of-life stream of opaque PET bottles that will lead to different outlets for recyclates;

3. Recyclability Assessment of the opaque PET bottle and comments on the Design Guidelines totally fitting to mechanical recycling.

CHAPTER 5. MATERIALS AND METHODS

5.1 Materials

As a starting step of the study, a milk bottle, as the one reported below, has been collected from the supermarket, in order to analyse an existent product on the Italian market.

Figure 24 – opaque PET bottle sample

The second part has been developed on the basis of literature studies in order to define the state of art of the collection, sorting and recycling technologies of opaque PET bottles and the outcomes, after passing through the processes.

In particular, to define the current scenario, it has been considered an MRF plant[64] in the South of Italy. It is situated in Molfetta (BA) and it is provided by bag opener units, two-dimensional ballistic separators which divide the

[64] Giovanni Gadaleta, Sabino De Gisi, Francesco Todaro, Giuseppe D'Alessandro, Silvio Binetti and Michele Notarnicola - 2023 - Assessing the Sorting Efficiency of Plastic Packaging Waste in an Italian Material Recovery Facility: Current and Upgraded Configuration – ResearchGate – https://www.researchgate.net/publication/368464750_Assessing_the_Sorting_Efficiency_of_Plastic_Packaging_Waste_in_an_Italian_Material_Recovery_Facility_Current_and_Upgraded_Configuration - 17/09/2023

3D, 2D and fine (waste with size < 40 mm) waste flows. Then, different plastic packaging streams can be sorted using an automated sorting chain made up of optical separators. Lastly, a final manual sorting removes any waste that is mistakenly present in other streams, leaving the PLASMIX flow at the end of the sorting line.

On the basis of the existing MRF plants and technologies, different End-of-life treatments scenarios, have been modelled according to the sorting processes.

In order to develop the third phase of the study, RecyClass Methodology, defining the recyclability criteria and assessment has been the key driver to define a Recyclability Assessment on opaque PET milk bottle never been conducted before, as it is still the subject of studies to be further investigated.

5.2 Methods

In this paragraph will be shown the methods followed in the analysis.

5.2.1 Opaque PET bottle characterisation

The first step in order to proceed with the recyclability assessment is a preliminary characterization of the packaging. The opaque PET bottle has been subjected to a lab analysis conducted in the Polytechnic of Bari laboratory, DICATECh (Civil, Environmental, Land, Construction and Chemical Engineering) Department, in order to describe the composition of an opaque PET milk bottle and the evaluation of the percentage of the different polymers that make up the bottle.

It has been weighed on a laboratory scale. Once the weight was known, labels and lids have been removed and respectively weighed. The weight of both, label and lid, has been subtracted from total weight of the bottle and the composition percentages have been deducted.

It has been also calculated the percentage of surface coverage talking about the label and the percentage of different polymers in the composition has been calculated. For this purpose, the bottle was divided into 5 cylinders having the same base area and the volumes of the cylinders have been calculated with the following formula:

$$Vol = \pi r^2 h$$

where:

r = ray of the circle which represents the base of the cylinder

h = high of the cylinder

5.2.2 Scenario assessment

In this specific section of the study, three different scenarios have been hypothesized in the sorting step of the process chain, in order to describe, from a qualitative point of view, which, among them, could be the best option.

- **Scenario 1** : opaque PET sorted in a mixed stream together with pale coloured PET stream
- **Scenario 2**: opaque PET sorted in a mixed stream together with dark coloured PET stream
- **Scenario 3**: opaque PET sorted as single stream

Scenario 1 has been assumed as the current scenario in place in all the Countries that are still not experimenting the single-stream sorting solution and are still sorting the opaque PET as PLASMIX, which goes directly to incineration plant. References have been found in COTREP evaluation of the outlets of different sorting streams. In this case, pale coloured PET stream is the main stream and opaque PET represents the ‘contamination’ in the stream.

Scenario 2 has been hypothesised starting from the literature, as in the previous study case. The French centre of resources and expertise on plastic packaging recyclability identified different potential applications for the above-mentioned packaging, such as:

- fibres “nonwoven” applications and “cut” fibres, in order to substitute virgin fibre used in pillow filler materials, roof insulation and geotextile membranes, carpet underlays
- industrial thermoformed plates and dark-coloured (brown and black) interlayers
- strapping for packaging
- automation and automotive industries
- PET foams, used in construction and padding applications
- miscellaneous products, such as floor tiles and monofilament material for industrial brushes.

According to the studies, after the consultation with the stakeholders, only two of these potential applications have been identified as suitable for opaque PET, even if probably not covering all the tonnage on the market, considering that the amount of opaque PET on the market is going to increase and packers could decide to switch over completely from HDPE to opaque PET. In that case, the proportion of opaque PET in the latter bales of dark coloured PET bottles could exceed 40%, and this would mean big difficulties in industrial recycling processes. In the end, the two identified potential outlets are:

1. Fibre applications (containing a maximum percentage of opaque PET in the bale equals to 15% of the total)
2. Foam applications is the second outlet examined, since PET characteristics, such as light weight, stability, flexibility and thermal

resistance, are completely compliant with PET-based foam manufacturing. PET polymer could be alternative to the polyurethane and PVC which are the most commonly used polymers in the foam applications.

Scenario 3 has been evaluated on the basis of data which describe an increasing trend in the place-on-the-market of this specific packaging. In this scenario, opaque PET is sorted in a single stream and does not account as contamination of a wider pale/dark coloured PET stream, and the purpose leads to a closed-loop scheme for opaque PET bottles, in order to have a higher quality recyclate and avoid to sort out in other outlets or incineration plants.

5.2.3 Recyclability assessment of opaque PET bottles

For the recyclability assessment of the opaque PET bottles, the RecyClass Methodology has been followed.

In RecyClass methodology two types of recyclability assessments are developed:

1. Design for Recycling
2. Recyclability Rate

Both of them consider the sorting behaviour of the packaging and the design issues and incompatibilities that can affect the recycling process.

The first evaluation takes in account:

- if the packaging is mentioned in one of the European packaging waste stream recognized by PRE
- if the packaging is designed to be compatible with the sorting and recycling processes

- if the recycled plastics can be used to replace virgin materials

The recyclability rate is a percentage value, indicated as the ratio between the weight of the recyclable plastic coming from the package and the total weight of the package. To assess this index, formula in Figure 25 is used:

$$Recyclability\ Rate = [(100 - X) * \eta] - Y - Z - V$$

where:

X = weight of non-recoverable non plastic parts

η = sortability of the packaging

Y = design for recycling incompatibilities resulting in loss of material during the recycling process

Z = easy-to-empty index

V = design for recycling incompatibilities resulting a downgrade of the quality of the final material

The formula considers:

- local or European packaging collection
- local or European availability of sorting and recycling infrastructures
- if the packaging can be sorted in line with the Sorting Evaluation Protocol[66]
- if the packaging can be recycled with the same methodology used in order to evaluate the Design for Recycling Assessment

[66] RecyClass - https://recyclass.eu/wp-content/uploads/2021/10/SORTING-EVALUATION-PROTOCOL-FOR-PLASTIC-PACKAGING_FINAL-V1.0.pdf - 17/09/2023

- if the quality of the recycled plastic generated by the packaging can achieve Recyclability Class certification.

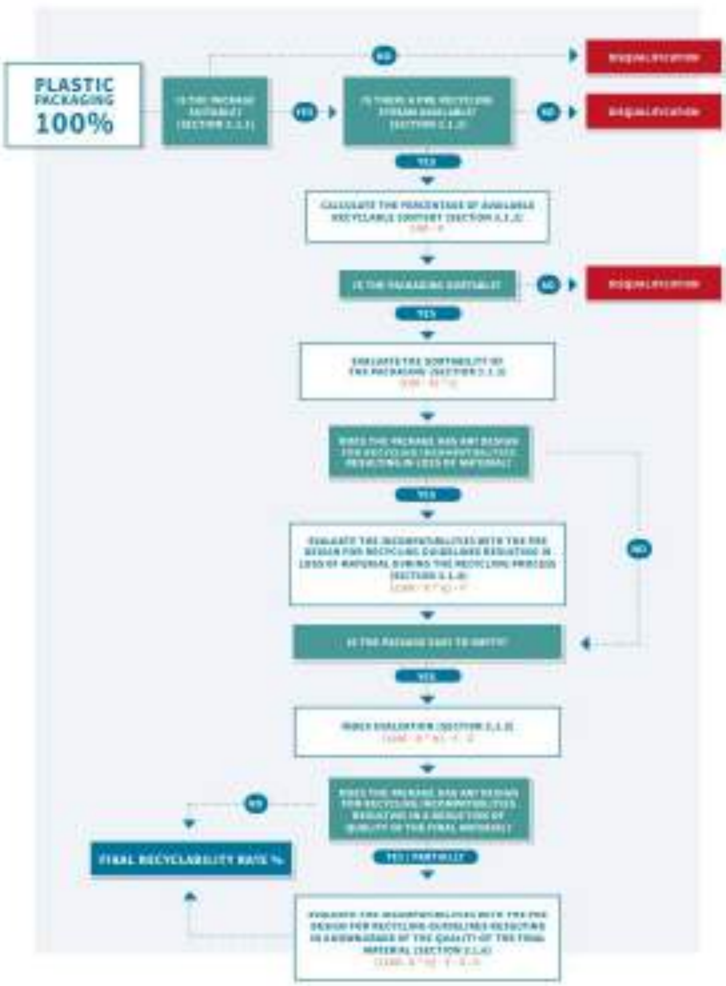

Figure 25 - Formula and evaluation of the Recyclability Rate by RecyClass

Thereafter, the evaluation parameters and criteria that were qualitatively assessed in this thesis work, and the followed RecyClass procedure, on the packaging under study, such as the opaque PET bottle, are reported. Specifically, the parameters evaluated are: composition; suitability; existence of pre recycling stream; presence of recycling plastic content; sortability; design for recycling incompatibilities; easy to empty index; compliance with REACH regulation.

5.2.3.1 Recyclability Assessment following RecyClass methodology

Packaging to be assessed: OPAQUE PET BOTTLE

Figure 26a - white opaque PET milk bottle (source web)

COMPOSITION[67]:

- PET BOTTLE: percentage determined by the procedure described in par. 5.2.1
- HDPE CAP: percentage determined by the procedure described in par. 5.2.1
- PE LABEL: percentage determined by the procedure described in par. 5.2.1

ADDITIONAL INFORMATION:

- PET BOTTLE with/without BARRIER LAYER
- DIRECT PRINTING ON THE BOTTLE
- percentage of WATER-SOLUBLE ADHESIVE (IN HOT ALKALINE WATER)
- percentage of PRINTING ON THE LABEL

1. SUITABILITY

The first question area addresses the overall design of the packaging to assess if it will be sorted into one of the established recycled streams in Europe. Mono-material packaging is preferred. Indeed, the larger is the content of one single polymer in the packaging, the higher its recyclability rate will be.

[67] Reference paragraph 5.2.1

2. PRE RECYCLING STREAM EXISTS

Imagining that the opaque PET bottles stream is recognized as its own collected, sorted and recycled stream with his own bottle-to-bottle outlet in Scenario 3, it would be tagged as "opaque PET bottles" stream.

- 2a – Local collection: to be checked in the Country(ies) of interest

2a criterion, according to the Recyclability rating requirements by RecyClass methodology, is the Local collection, that is based on the following evaluation:

Table 7 - Recyclability rating requirements by RecyClass

CRITERION	ASSESSMENT	DOWNGRADING OR DISQUALIFICATION	SCORE PENALTY	
			CLASS	**RATE**
2a. LOCAL COLLECTION	Packaging which is collected in the countries of interest, based on the auditor knowledge	Disqualification if there is no collection system in place to collect the given packaging in the countries of interest	Class F	"0" factor

- 2b – Local sorting and recycling: to be checked in the Country(ies) of interest.

2b criterion, according to the Recyclability rating requirements by RecyClass methodology, is the Local collection, that is based on the following evaluation:

Table 8 - Recyclability rating requirements by RecyClass

CRITERION	ASSESSMENT	DOWNGRADING OR DISQUALIFICATION	SCORE PENALTY	
			CLASS	RATE
2b. LOCAL SORTING AND RECYCLING	Packaging which is sorted and recycled in the countries of interest, based on the auditor knowledge.	Disqualification if there is no available sorting or recycling infrastructure for the given packaging in the countries of interest.	Class F	"0" factor

The packaging is collected, sorted and recycled in the geographical area of interest.

3. RECYCLABLE PLASTIC CONTENT

Weights of non-recoverable non-plastic parts are removed from the recyclable proportion (adhesive and printing inks), representing 0.5 wt%.

X = 0.5 leading to (100 – 0.5) = 99.5%. Recyclable plastic content > 95% leading to no class penalty.

4. SORTABILITY

In order to evaluate the percentage of opacifier. The coefficient of sortability can be applied as 1, then we should have:

$\eta_{sort} = 1$, leading to $(100 – X) * \eta_{sort} =$ % and no class penalty.

5. DFR INCOMPATIBILITIES

This point identifies the removable Design for Recycling incompatibilities that will get separated by the process, and the Design for Recycling incompatibilities that will get recycled within the stream and will therefore affect the recyclate quality.

- 5a – Removable DfR incompatibilities

The HDPE cap will float and will be recovered as by-product, as well as the PE label because the water-soluble adhesive will allow the PE label to detach from the bottle. Polyolefin weights that will get recycled in a mix of polyolefin stream are therefore only slightly deducted (- 0,25 x wt%).

Y = 4.2%, leading to $[(100 – X) * \eta_{sort}] – Y = 95.5\%$ and no class penalty.

- 5b – Non-removable DfR incompatibilities

The opaque PET bottle is designed with all separable materials/substances.

V = 0%, leading to $[(100 – X) * \eta_{sort}] – Y – V = 95.5\%$ and no class penalty.

Criteria 5a and 5b are reported in the following table:

Table 9 – Recyclability rating requirements by RecyClass methodology

CRITERION	ASSESSMENT	DOWNGRADING OR DISQUALIFICATION	SCORE PENALTY	
			CLASS	RATE
5a. DFR INCOMPATIBILITIES (REMOVABLE)	Package designed according to the Design for Recycling Guidelines.	Downgrading accounts for all the parts of packaging such as inks, adhesives, labels, sleeves, valves/seals, caps, etc. that will be separated by the recycling process and will not get recycled.	Strongest class penalty to apply for both criteria 5a and 5b.	"Y" factor to deduct (sum of all penalties)
5B. DFR INCOMPATIBILITIES (NON-REMOVABLE)	Package designed according to the Design for Recycling Guidelines allowing for high quality recycled plastic.	Downgrading of parts of the packaging such as barriers, additives, printing, and all other non-detachable components which will not be separated during the recycling process and will be part of the final recyclate.		"V" factor to deduct (sum of all penalties)

6. **EASY TO EMPTY**

The bottle will be completely emptied after use (Index = 0)

Z = 0, leading to $[(100 - X) * \eta_{sort}] - Y - V - Z = 95.5\%$ and no class penalty.

7. **REACH COMPLIANCE**

All materials comply with REACH. REACH (Regulation on the registration, evaluation, authorisation and restriction of chemicals) is the main EU law to protect human health and the environment from the risks that can be posed by chemicals.

CHAPTER 6. RESULTS AND DISCUSSION

6.1 Results and discussion

6.1.1 Opaque PET bottle characterisation

As mentioned in the methodology followed (paragraph 4.2.1 of 'Methods'), the total weight of the opaque PET milk bottle which has been evaluated accounts 36g, which corresponds to the 100% of the total body. The closure system weighs 3g, which represents the 8.3% of the total body and the label is 1.5g, which represents the 4.2% of the total surface.

The label covers 47.47% of the total surface, calculated as follows:

The bottle was divided into 5 cylinders having the same base area

1. Cylinder 1: ray 7.5 cm, height 4.5 cm
2. Cylinder 2 (covered by label): ray 7.5 cm, height 9.5 cm
3. Cylinder 3: ray 7.5 cm, height 4 cm
4. Cylinder 4: ray 7 cm, height 2 cm
5. Cylinder 5: ray 4 cm, height 1 cm

The volumes of the cylinders have been calculated, the results are here reported:

1. Cylinder 1: 795.21 cm^3
2. Cylinder 2 (covered by label): 1678.75 cm^3
3. Cylinder 3: 704.28 cm^3
4. Cylinder 4: 307.88 cm^3
5. Cylinder 5: 50.27 cm^3

The total volume of the bottle accounts 3536.39 cm^3. The volume covered by the label, as said, covers 1678.75 cm^3. Using a proportion, it is clear that the label surface corresponds to the 47.47% of the total.

$$3536.39\ cm^3 : 100\% = 1678.75\ cm^3 : x(\%)$$

$x(\%) = 47.47\%$ of label covering surface.

6.1.2 End-of-life scenario of opaque PET bottles

In accordance to the waste hierarchy of the Waste Framework Directive, the recycling and recovering steps have always to be preferred to the disposal option.

Pursuant to Article 10.4[68] of the Waste Framework Directive "Member States shall take measures to ensure that waste that has been separately collected for preparing for re-use and recycling pursuant to Article 11(1) and Article 22 is not incinerated, with the exception of waste resulting from subsequent treatment operations of the separately collected waste for which incineration delivers the best environmental outcome in accordance with Article 4."

This means that opaque PET, as any other separately collected waste, cannot be directly sent to the waste-to-energy plant, but it has to be treated, passing by a sorting and a recycling plant.

Stated that and the analysis of the different scenarios presented in the previous chapter, it comes self-evident that the **first scenario** (Scenario 1) has to be avoided, because, as said before, sending waste to the incineration plants should never be the first option in order to treat waste streams. Energy recovery comes, according to the pyramid of the waste hierarchy, after 'prevention', 'preparing for reuse' and 'recycling' steps.

[68] European Commission - Waste Framework Directive - https://environment.ec.europa.eu/topics/waste-and-recycling/waste-framework-directive_en - 17/09/2023 - 17/09/2023

Moreover, as reported in the analysed literature, this profile shows and important contribution in air emissions from waste combustion, and the production of various chemicals needed for the post-incineration treatment of flue gases (such as NOx). For example, the incineration of 1 kg of mixed plastic waste generates 2.34 kg of carbon dioxide in the climate change (CC) category and 2.19∗10-5 kg of Nitrogen in the marine eutrophication (M-Eu) category.

On the other hand, the sorting process of opaque PET within the dark coloured PET stream might be the greatest contributor to the electricity consumption, requested to power all the equipment in the sorting plant, followed by the hot washing water and the chemicals needed for cleaning the recycled plastics[34].

The opaque PET are mixed together with the **dark coloured PET stream**. Some recyclers systematically remove and reject bottles made of opaque PET because their systems are not able to tolerate them. In the systems where they are accepted, opaque PET still doesn't bring any other added value to the quality of the recycled material produced. It has been proved that at its current dilution within the dark coloured PET stream, which is 5% across all sectors – dairy, oils, detergents, cold drinks – the impact of opaque PET remains moderate, which means that it does not create any technical issue on the quality of the recycled dark coloured PET and recyclers can still extract it from the process.

Since the fibre is the main application for this kind of mixed stream, a test has been conducted by COTREP, in order to assess the fibre quality according to two different parameters, such as colour and mechanical properties. It has been found that, up to concentrations of 15-20% of opaque PET in the dark coloured PET fibre applications, mechanical properties are not affected, while variation in colour is not discernible. From a technical point of view, above the mentioned percentage, recycling of the PET blend to produce fibre is no longer possible, because of the excessive proportion of opacifier that creates processability issues and reduces mechanical properties.

However, due to the lack of data on specific waste to energy models, the very high variability of important parameters (energy prices, waste processing tariffs and fate) and the uncertain benefits induced on the environment, the analysis would be only qualitative.

From the literature studies, despite of opaque PET outlets recognized as viable are more than one, it has been established that opaque PET feedstock by the recycling operator are at least one-tenth less than the availability of stock amounts which is growing rapidly.

This means that, instead of incorporating opaque PET into the dark coloured PET stream, new solutions must be found.

Since technology is making great progresses in recycling field**, Scenario 3** must be accepted as the best-case profile among the three hypothesized.

Making opaque PET bottles recyclable in a close-loop scheme decreases the quantity of PLASMIX to be sent to the incineration plants, and therefore, the quantity of residual plastics that cannot be treated and are led to the landfill.

This scenario is already applied and well-consolidated in the case of transparent PET bottles and, in line with this process, opaque PET bottles should be collected, sorted and recycled in order to obtain a bottle-to-bottle cycle.

It is needed to keep in account that the possibility to create more waste streams is the best according to the processability of the plastic waste, but this implies that more organization in the waste treatment plants is needed and, therefore, higher costs have to be taken in consideration.

The outlet, in the end, is the best quality of recycled that can be obtained within a mechanical recycling process, and, considering the increasing trend identified by some of the EU Member States, Scenario 3 has to be implemented in all the plants which currently receive a quite high percentage of opaque PET or, at least, for those which an increasing trend in opaque PET income is foreseen in next months and years.

In order to better recycling opaque PET bottles, and considering the EU willingness in determine the harmonized Design for Recycling criteria, stated that currently there are no Guidelines that can help the manufacturers and recyclers to be driven into the recycling process for this specific waste stream, this thesis work is meant to define, under a qualitative point of view and on the basis of the existing guidelines on transparent and coloured PET bottles, new Guidelines that could give a shape to the design criteria about opaque PET.

In particular, Scenario 3 aims at ending up with a closed-loop bottle-to-bottle scheme for opaque PET bottles, by separating the opaque PET bottles in a single sorted stream.

PET technologies detector mentioned above are nowadays able to select the different packaging by the nature of the polymer, by their size and their colour. Opaque PET can be detected by NIR (Near Infra-Red sorting technology) which separates resins by colour.

Moreover, according to the Food Contact Material Regulation (EU) 2022/1616, containers which are used in food-grade applications before becoming waste, if correctly sorted and collected, can be in the meaning as recycled content for the same scope. In this specific case, opaque PET bottles must be sorted in a unique stream, meaning that they have to be collected in some specific collecting points and facilities which allow then to be used for the same scope at the end-of-life of the product.

In this way, the Titanium dioxide TiO_2 that is contained in opaque PET bottles as opacifier, not only cannot be considered as contaminant for the plastic waste stream, but, based on the percentage of opacifier contained, if the closed loop allows new bottles to be obtained from recycled material, this will already contain Titanium dioxide in itself and there will be no need to add extra quantity, or, if this was necessary, it would certainly be in smaller quantities than the percentage added to the virgin material. It needs to be taken in account that, since the packaging is food-contact, low percentages of TiO_2 are allowed and black carbon layer should be avoided in order to have a more efficient sorting and better quality recyclate, since black PET strongly absorb NIR light, rendering it undetectable for the NIR sorting units.

6.1.3 Recyclability Assessment

Stated that Scenario 3 is the best option among the proposed ones, Recyclability Assessment must be conducted in order to make sure that the packaging is compliant with RecyClass methodology and recyclability design for recycling criteria.

It is important to underline that currently opaque PET bottles are not included into the packaging categories that can be assessed by RecyClass methodology since there’s still a study on the topic that will define the definitive guidelines related to this packaging.

Recyclability assessment can be done along the lines of the RecyClass Recyclability Methodology, Annex V, where some case studies are sorted out in order to show how the evaluation is made.

On the basis of the characterization of the opaque PET milk bottle conducted at the beginning of the study, it is easy to have the composition and additional information relative to the waste.

6.1.3.1 Recyclability Assessment following RecyClass methodology

Packaging: OPAQUE PET BOTTLE

Figure 26b - white opaque PET milk bottle (source web)

COMPOSITION[70]:

- PET BOTTLE: 87.5%
- HDPE CAP: 8.3%
- PE LABEL: 4.2%

ADDITIONAL INFORMATION:

- PET BOTTLE WITHOUT BARRIER LAYER
- NO DIRECT PRINTING ON THE BOTTLE
- 0,1% WATER-SOLUBLE ADHESIVE (IN HOT ALKALINE WATER)
- 0,5% PRINTING ON THE LABEL

1. **SUITABILITY**

The packaging is made of more than 50% of plastic polymer, which is PET. More than half of its surface is made of plastic and the bottle is not coupled with other materials. The packaging is suitable for the analysis.

➤ Interim result = class A and 100%

2. **PRE RECYCLING STREAM EXISTS**

Established in Scenario 3 a single opaque PET bottles stream, it complies with the requisite that a single stream of the packaging exists, therefore the interim result still accounts for 100%.

➤ Interim result = class A and 100%

[70] Reference paragraph 6.1.1

3. RECYCLABLE PLASTIC CONTENT

This section is introduced to make the user of the recyclability tool aware that packaging can be designed with the awareness that the packaging could be not only recyclable but also circular if it is made un by recycled contents.

- Interim result = class A and 99.5%

4. SORTABILITY

It is assumed that the packaging is not made up of carbon black surface, which could hamper the recycling process. No Al layer > 5 micron is foreseen, no full sleeves, opaque PET can be considered as dark colour, but since the stream is sorting such coloured PET there shouldn't be any issue in the sortability process. No multilayers, no metal components, label covering < 50% the bottle surface.

The big difference with the transparent PET bottles is that opaque PET bottles contain TiO_2 which could imply to perform a sorting test,

- Interim result = class A and 99.5%

5. DFR INCOMPATIBILITIES

Design incompatibilities in line with criteria 5a and 5b decrease the previous score by a few points, especially because of the removable incompatibilities, such as Polyolefin weights that will get recycled in a mix of polyolefin stream are therefore only slightly deducted (- 0,25 x wt%).

- Interim result (5a) = class A and 95.5%

Criterion 5b on non-removable DfR incompatibilities does not lower the recyclability score, because there is no design incompatibility that cannot be removed.

- Interim result (5b) = class A and 95.5%

6. **EASY TO EMPTY**

The bottle will be completely emptied after use because milk is a fluid, therefore the easy of empty Index accounts as 0. It makes no change to the score.

▶ Interim result = class A and 95.5%

7. **REACH COMPLIANCE**

All materials comply with REACH. REACH (Regulation on the registration, evaluation, authorisation and restriction of chemicals) is the main EU law to protect human health and the environment from the risks that can be posed by chemicals.

▶ **FINAL RESULTS = CLASS A AND 95.5%**

Figure 27 - RecyClass ranking (source RecyClass methodology)

The hypothesised Recyclability Assessment compliant with RecyClass methodology could be the basis for the Design for Recycling Guidelines that must be planned out in order to facilitate the recycling process of opaque PET bottles.

In conclusion, we can see in the table below, the final results:

Table 10 - Summary of the Recyclability assessment results

CRITERIUM	RESULT	
1. SUITABILITY	100% - Class A	☑
2. PRE RECYCLING STREAM EXISTENCE	100% - Class A	☑
3. RECYCLABLE PLASTIC CONTENT	99.5% - Class A	☑
4. SORTABILITY	99.5% - Class A	☑
5. DFR INCOMPATIBILITY	95.5% - Class A	☑
6. EASY TO EMPTY	95.5% - Class A	☑
7. REACH COMPLIANCE	95.5% - Class A	☑
Opaque PET bottle		High degree of recyclability

It can be concluded that the opaque PET bottles were found to be recyclable following the Recyclass recyclability assessment.

CONCLUSIONS

The Proposal for a Regulation on Packaging and Packaging Waste is a clear call for the need to better manage the entire recycling process chain, especially of plastics, which starts from packaging design.

This thesis work was developed in order to investigate possible recovery scenarios for a particular type of packaging: opaque PET bottles. This waste is characterised by the presence of additives, necessary to protect the perishable content of the bottles, which hinder established recycling processes.

It is precisely starting from the current situation both from a regulatory and technological point of view, relating to actual plants and literature, that this study set out to identify the best scenario for the end-of-life of opaque PET bottles. This study led to identify for opaque PET, the opportunity to create a new stream within the separate collection for better sorting of the packaging.

Therefore, an evaluation analysis has been conducted, with the purpose of testing the recyclability assessment of a white opaque PET bottle.

As the results of the trial show, the recyclability level of an opaque white PET bottle is very high and the packaging still falls within the highest range of categories in the RecyClass characterisation methodology.

An LCA (Life Cycle Assessment) study design, showed that PET white opaque bottles offer a significantly lower carbon footprint over alternative packaging materials, offering the opportunity to save greenhouse emissions, reduce energy consumption and waste generation, and contribute reducing the overall environmental impact of applications made of PET over other materials for similar end products.

It would be interesting, in order to have a complete overview on the topic, to collect other technical information from vendors and recyclers that could help understand how to create a virtuous cycle of recycled opaque PET bottle.

CONCLUSIONI

La Proposta di Regolamento su Packaging e Packaging Waste evidenzia la necessità di una gestione sostenibile basata sul recupero dei rifiuti, soprattutto della plastica, che parte dal design dell'imballaggio.

Il presente lavoro di tesi è stato sviluppato al fine di indagare i possibili scenari di recupero di una particolare tipologia di imballaggio: bottiglie in PET opaco. Tale rifiuto è caratterizzato dalla presenza di additivi, necessari per proteggere il contenuto deteriorabile delle bottiglie, che ostacolano i consolidati processi di riciclo.

È proprio a partire dalla situazione attuale, sia dal punto di vista normativo, che tecnologico, relativo agli impianti reali e alla letteratura, che questo studio si è proposto di individuare lo scenario migliore per il fine vita delle bottiglie in PET opaco. Tale studio ha portato ad individuare per il PET opaco, l'opportunità di creare un nuovo flusso all'interno della raccolta differenziata per una migliore selezione della confezione. È stata condotta, dunque, un'analisi di riciclabilità circa l'imballaggio caso di studio.

Come mostrano i risultati della sperimentazione, il livello di riciclabilità di una bottiglia in PET bianco opaco è molto alto e rientra ancora nella gamma più alta di categorie nella caratterizzazione RecyClass.

Uno studio di design di una LCA (Life Cycle Assessment), ha mostrato che le bottiglie bianche opache in PET producono un'impronta di carbonio significativamente inferiore rispetto ai materiali di imballaggio alternativi, offrendo l'opportunità di risparmiare emissioni di gas serra, ridurre il consumo energetico e la produzione di rifiuti, contribuire a ridurre l'impatto ambientale complessivo degli imballaggi in PET rispetto ad altri materiali impiegati per gli stessi scopi.

Sarebbe interessante, al fine di avere un’analisi completa sull’argomento, collezionare altre informazioni tecniche da venditori e riciclatori che potrebbero aiutare a capire in che modo creare un ciclo virtuoso di bottiglie in PET riciclato bianco opaco.

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