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Short Communication

# Closing the loop on plastic packaging materials: What is quality and how does it affect their circularity?

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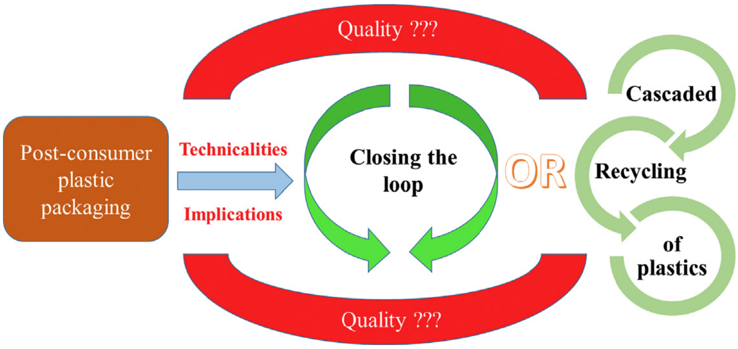
## HIGHLIGHTS

- Plastics recyclability is largely dependent on their quality.
- Technicalities define the ability of plastic materials to be properly recovered.
- Cascading of recycled plastics should be pursued as an alternative pathway.
- Plastic packaging should be redesigned, improving sorting and reprocessing systems.
- Transitioning towards a circular economy requires the exploitation of all available routes.

## GRAPHICAL ABSTRACT



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## ABSTRACT

While attention on the importance of closing materials loops for achieving circular economy (CE) is raging, the technicalities of doing so are often neglected or difficult to overcome. These technicalities determine the ability of materials, components and products (MCPs) to be properly recovered and redistributed for reuse, recycling or recovery, given their remaining functionality, described here as the remaining properties and characteristics of MCPs. The different properties of MCPs make them useful for various functions and purposes. A transition, therefore, towards a CE would require the utmost exploitation of the remaining functionality of MCPs; ideally, enabling recirculation of them back in the economy. At present, this is difficult to succeed. This short communication article explains how the remaining functionality of MCPs, defined here as quality, is perceived at different stages of the supply chain, focusing specifically on plastic packaging, and how this affects their potential recycling. It then outlines the opportunities and constraints posed by some of the interventions that are currently introduced into the plastic packaging system, aimed at improving plastic materials circularity. Finally, the article underpins the need for research that integrates systemic thinking, with technological innovations and policy reforms at all stages of the supply chain, to promote sustainable practices become established.

## 1. Introduction

With concepts such as dematerialisation, factor 4, factor 10, eco-efficiency and industrial ecology becoming ever increasingly attractive to businesses, getting the accreditation of becoming more 'sustainable' and/or 'green' requires a shift towards more systemic practices. This is what the circular economy (CE) aims to achieve of which systemic

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**Nomenclature**

| | |
|---|---|
| ca. | circa |
| CE | circular economy |
| EC | European Commission |
| EoL | End of Life |
| HDPE | high density polyethylene |
| LDPE | low density polyethylene |
| MCPs | materials, components and products |
| MRF | material recovery facility |
| PAHs | polycyclic aromatic hydrocarbons |
| PBDD/F | polybrominated dibenzo-*p*-dioxins and furans |
| PBDEs | polybrominated diphenyl ethers |
| PE | polyethylene |
| PET | polyethylene terephthalate |
| PLA | polylactic acid |
| PP | polypropylene |
| PS | polystyrene |
| PVC | polyvinyl chloride |
| PVOH | polyvinyl alcohol |
| r-PET | recycled polyethylene terephthalate |
| SoC | substances of concern |
| VOCs | volatile organic substances |

nature requires both the ecosystem and its individual components to change. While governance, revised regulations and new business models become increasingly popular in making the transition to a CE, the technicalities (e.g. lifestyle patterns and behaviours, organisational and infrastructural barriers, and composition and functionality) of doing so are often overlooked or not properly accounted. However, these technicalities control to a large extent the successful transition from a linear to a circular economy; amongst them, the ability of materials, components and products (MCPs) to be properly recovered and redistributed for reuse, recycling, or recovery (Fig. 1).

In the waste management industry, the remaining functionality (i.e. described via the remaining properties and characteristics) of MCPs, defined here as quality, is the foremost critical factor. It is a measure of ensuring consistent provision of high value outputs to recyclers, hence meeting their specifications and helping them maintain a credibility and reliability status in the market. In the reprocessing industry, quality of MCPs is a measure of gaining competence over virgin material, safeguarding consistent supply and reducing risks associated with resource demand and price volatility. It appears that quality of MCPs recovered from waste can be a way to measure the extent to which synergistic relationships between waste management, recyclers and (re)manufacturing industries are established, promoting sustainable resource management.

Metals, paper, glass and plastics are materials considered to enable a circular way of management (EC, 2016), due to their high recyclability potential. The European Commission (EC) has classified plastics amongst the five priority areas, where progress needs to be made towards a circular reality, recently launching a relative strategy (EC, 2018). Plastics due to their light weight nature, flexibility, and durability, are particularly effective in packaging applications, with over a third of plastic material demand being used for plastic packaging applications (PlasticsEurope, 2016). The short-lived nature of plastic packaging however, creates a great demand in the collection and recycling of this material, both for recovering and redistributing it back into the production chain, as well as for protecting the environment from its inappropriate disposal and leakage (Jambeck et al., 2015). Yet, only a small percentage of plastic packaging production (approx. 14%) is recycled in a global scale (Ellen MacArthur Foundation, 2017).

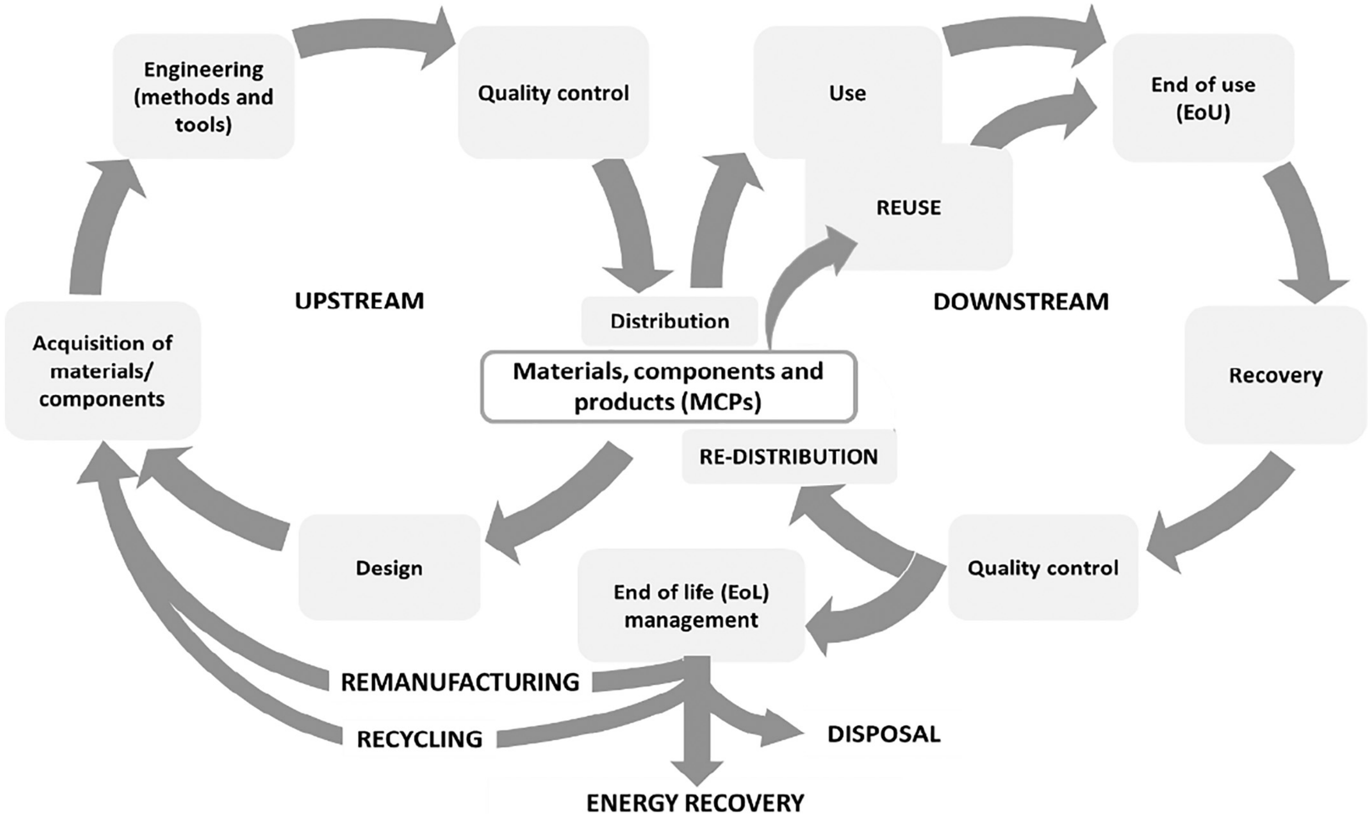

**Fig. 1.** The MCP lifecycle in a CE system.
Adapted by Iacovidou et al. (2017b).

This article aims to communicate that the quality of plastic packaging may change at different stages of the plastic materials lifecycle. These changes however may not always be associated with alterations in material properties, but in the way materials are collected and handled for reprocessing. This is an important distinction, and one that raises questions in regards to how quality is perceived and dealt with by the different actors at the different stages of the supply chain. Specific focus is given in some of the most recent attempts of overcoming technical difficulties encountered in plastic packaging recycling, questioning their potential to integrate design and manufacture with waste management and resource efficiency in the transition to circular economy.

## 2. Challenges and complications on recycling plastic packaging due to transformation of material quality

Plastics are composed of multiple chains (called polymers) made of small molecules (called monomers), connected with chemical bonds. Plastics may come at different structures according to what monomer is repeated in the chain, and the way the chains are linked. Based on the latter, a distinction can be made between thermosets, thermoplastics and elastomers. Thermoset plastics, are formed when their macromolecular chains are cross-linked together permitting no further deformation or shaping; in thermoplastics macromolecular chains are not cross-linked but held together by relatively weak chemical forces (Van der Waals), which means that they can be reversibly re-melted by heating, and re-solidified by cooling, without altering much their mechanical properties (American Chemistry Council, 2018; Ensiger, 2018). Elastomers, are also formed by cross-linked chains, but can be elastically deformed, and return to their original shape after exposure to load (Ensiger, 2018). Thermoplastics can be subdivided into amorphous and semi-crystalline according to whether they have a random or ordered structure, respectively, which affects their properties, e.g. colour, chemical resistance, solubility, thermal stability, density, firmness and strength.

Plastic packaging is generally made of thermoplastic resins, namely the polyethylene terephthalate (PET) (known as type 1); high-density polyethylene (HDPE) (known as type 2); polyvinyl chloride (PVC) (known as type 3); low-density polyethylene (LDPE) (known as type 4); polypropylene (PP) (known as type 5); polystyrene (PS) (known as type 6); and others (known as type 7). The latter category includes multilayer and other plastics that are not generally collected for recycling. The rest of the plastic types can be collected, sorted and then mechanically or chemically reprocessed into flakes and/or pellets that are used as raw materials in the manufacture of new products (e.g. HDPE can be used in drainage and utility pipe manufacture storage tanks and wheelie bins, whereas PP can be used in the automotive sector, as an alternative to wood tiles, and pallets).

In spite of plastics theoretically high recyclability, post-consumer plastic packaging recycling rates remain low and this is mainly associated with quality aspects. But how does the post-consumer plastic packaging quality degrades? As quality depends on the properties of the material, its designed characteristics, and the changes thereof during their use, handling, and reprocessing, it is interesting to look at how each of these steps affects plastic packaging recycling.

- ***Materials properties and design characteristics***: understanding which properties are relevant in ensuring good plastic packaging material performance from use towards their end-of-life (EoL) stage, can provide confidence in utilising the recovered plastic resource in the production of new products. The set of rheological, mechanical and structural properties of the plastic packaging materials produced may vary widely depending on the type of plastic used to make them (Hamad et al., 2013). Table 1 shows the different characteristics

**Table 1**
Main characteristics of the thermoplastics mainly used for packaging.
Adopted from: Ensiger (2018).

| Plastic type | Characteristics and properties | Applications |
|---|---|---|
| PET | Semi-crystalline, high density, very hard material that is very tough, strong, and rigid, has very good sliding friction properties, very good dimensional stability, highly stiff with brittle behaviour at temperatures below zero, with good thermal stability, minimal thermal expansion, sensitivity to hot water and steam, relatively high thermal conductivity, low electrical conductivity, good insulation properties, high chemical and wear resistance, and low moisture absorption. | Renowned for its success as a replacement for glass in beverage bottles, due to its dimensional stability, strength and resistance to chemicals; widely used in food and personal care packaging applications as it is an excellent barrier to flavors and is usually transparent. |
| HDPE | Semi-crystalline, translucent, low density and hardness characteristics, but tough with low strength and very low rigidity properties, relatively stiff with low thermal stability and high thermal expansion, high thermal conductivity, low electrical conductivity, relatively good insulation properties, poor chemical and wear resistance, and very low moisture absorption. | Can be a poor barrier for oxygen and other gases, odors and flavors, but is normally used in consumer bags, thermoformed trays for packaging frozen food, films for a variety of uses. |
| PVC | Amorphous, optically transparent, high density, hard, brittle material that is tough, relatively strong and rigid with very good sliding friction properties, very good dimensional stability, relatively stiff with low thermal stability, low thermal expansion, low thermal conductivity, low electrical conductivity, good insulation properties, good chemical and wear resistance, and very low moisture absorption. | The most widely used of the amorphous plastics. It is available in two forms - plasticised (flexible) or un-plasticised (hard, tough) and is used in blister packaging for pharmaceuticals and capsules. |
| LDPE | Semi-crystalline, translucent, with low density and hardness characteristics, very tough (no breaks), but low strength and low rigidity, sensitive to temperature with low thermal stability, no thermal conductivity, high thermal expansion, low electrical conductivity, relatively good insulation properties, poor chemical and wear resistance and low moisture absorption. | Not practical for rigid containers and flexible packages, and is not recommended for oily products. Squeezable tubes and bottles, wrappers and bags, frozen food containers, coating material for bottle cartons. |
| PP | Semi-crystalline, low density, material with better strength, hardness, rigidity, stiffness and thermal stability than PE types (HDPE-LDPE) with sensitivity at temperatures below zero, low thermal conductivity, low electrical conductivity, relatively good insulation properties, good chemical and wear resistance, and low moisture absorption. | Has the lowest density of all thermoplastics, which combined with its excellent fatigue and chemical resistance can make it attractive in many packaging applications, such as closures of all kinds, several boil-in-bag food packages and containers exposed to high levels of thermal and chemical stress |
| PS | Amorphous, optically transparent, high density, hard, brittle material, very tough, relatively strong and rigid, low thermal stability, low thermal conductivity and electrical conductivity, excellent insulation properties, poor chemical and wear resistance to hydrocarbon solvents, good electrical insulation properties and relatively low moisture absorption. | Polystyrene is available in a range of grades which generally vary in impact strength from brittle to very tough. It is used for low strength structural applications when impact resistance, machinability, and low cost are required, such as in vending cups, yogurt containers, bottles for pharmaceutical tablets and capsules, and packaging of fragile products. |

of the most commonly used types of plastics; which can vary from transparent to opaque, and have a different chemical and UV radiation resistance, depending on their structure. During the design stage of plastic packaging components, a number of additives (e.g. plasticizers, flame retardants, antioxidants, acid scavengers, light and heat stabilizers, lubricants, pigments, antistatic agents, slip compounds and thermal stabilizers) are added to the polymeric structures; hence contributing to plastic packaging final properties and improving their performance, functionality and ageing (Hahladakis et al., 2018). These properties and design attributes may affect plastic packaging quality at various stages of its lifecycle.

- ***Use and handling***: plastic packaging has a short lifespan and therefore environmental conditions (e.g. oxygen, humidity, UV radiation) have a less important role to play on its quality degradation, given it is stored properly. Defining the quality of a plastic packaging component that enters the waste stream however, can be extremely challenging. This is because quality changes of plastic packaging may not be associated with changes in the plastic packaging properties per se, but with changes in the way plastic packaging, and particularly the high-value streams (e.g. PET and HDPE), are segregated, sorted and recovered for recycling. Consumers are sometimes confused by the types of plastics they can segregate for recycling, and they end up mixing different materials, affecting as such the quality of high value recyclates collected. Plastics that may come in contact with impurities and contaminants during disposal, bear the risk of having these contaminants diffused into the polymeric bulk due to their permeable nature, affecting their recyclability (Hahladakis et al., 2018). In addition, councils may refuse to collect plastic streams that are contaminated with other materials (incl. other plastics) due to the lack of infrastructure to support separate collection of the high-value plastic packaging. These result in plastic streams being diverted to landfill. Even in cases where plastic packaging may reach material sorting facilities, potential contamination of the target streams, e.g. PET and HDPE, with other polymers, makes it unlikely for these to be used for closed loop recycling as they are often incompatible (Hahladakis et al., 2018). This is because contamination even at low levels can lead to poor adhesion properties in the polymeric mixture interface and deterioration in overall macroscopic properties (Vilaplana and Karlsson, 2008). For example, the presence of minor amounts of PVC in a PET bottle batch, can form acids that make PET brittle and yellowish in colour when recycled (Marks & Spencer, 2008). As such, a contaminated batch is more likely to end up in landfill or energy recovery facilities. This results in short to medium term issues for reprocessors facing unanticipated high costs of contamination and further sorting of poor quality plastic packaging, especially when a strong market for products using mixed plastics does not exist.
- ***Processing***: rheological, mechanical and structural properties of plastic packaging materials may change during reprocessing (i.e. mechanical and or chemical). The extrusion cycle is also important in determining changes in plastic packaging characteristics, however in reality this is difficult to determine. Mechanical recycling is the most preferred and used recycling method. When plastic packaging is mechanically reprocessed a number of changes occur because of rheological changes in the structure of the polymer, a few of which are outlined in Table 2 (Hamad et al., 2013). For example, the structural and macroscopic properties of plastics are modified during multiple processing; chain scission decreases the molecular weight of the polymeric chains, which in turn leads to an increase in the degree of crystallinity in semi-crystalline polymers, a decrease in viscosity, which increases the melt flow rate, and deterioration of the mechanical properties (e.g. elongation, impact strength), resulting in a progressive embrittlement of the reprocessed material (Ronkay, 2013; Vilaplana and Karlsson, 2008). Degradation of the material that usually occurs during reprocessing, may often lead to changes in material properties. Although the degradation rate of the materials can be stabilised through the use of additives and/or by mixing the recycled resin with virgin material to diminish the change in properties (Kartalis et al., 2000; Sokkar et al., 2013), these could create other technical constraints for the recyclers. Different resins have different melting points (see Table 1 – thermal stability), and if a batch of mixed plastics that melt at different temperatures are mixed together, some resins may not melt at all, and others may burn, affecting as such feedstock's appearance and performance, and preventing its use in a particular end product. For example, accidental co-melting of a batch of polyethylene packaging with polypropylene, can result in a blend that is useless. Since the same resins may have different properties, markets could potentially ask e.g. for plastic bottles (containers with a neck smaller than the base) to be separated from wide-mouthed containers. For example, HDPE milk jugs are blow-moulded, while HDPE margarine tubs are injection-moulded. These two processes require different fluidity levels, which, if mixed together, produce a fluidity level that may no longer be suitable for re-manufacturing (Waste360, 2016). The additives present in the different types of plastics may also affect their recyclability either directly or by promoting their degradation; whereas a range of hazardous substances (e.g. toxic metals, volatile organic compounds (VOCs), phthalates, polycyclic aromatic hydrocarbons

**Table 2**
Complications and perspectives during plastic packaging recovery and reprocessing.

| Plastic type | Mechanical recycling | Results | References |
|---|---|---|---|
| PET | 1) Blending with HDPE using the extrusion process<br>2) Adding small amounts of virgin PLA | 1) HDPE reduces the melt viscosity of the blend indicating good flow ability<br>2) Lowers the viscosity of the blend, and gives higher thermal sensitivity | 1) (Navarro et al., 2008)<br>2) (La Mantia et al., 2012) |
| HDPE | 1) Reprocessing<br>2) Blending with virgin polyamide | 1) Mechanical properties remain almost unaltered<br>2) Improves the mechanical properties and thermal stability of the blend | 1) (Vilaplana and Karlsson, 2008)<br>2) (Vallim et al., 2009) |
| PVC | 1) Via triboelectrostatic technology | 1) Recovers PVC from plastic composites (e.g. PVC/PET, PVC/PP, PVC/PE or PVC/PS). Recovery of 96–99% with the pure extract content in excess of 90%. | 1) (Lee and Shin, 2002) |
| | 2) Blending with wood fiber | 2) Improves recyclability-composite properties remained stable for up to 5 processing cycles | 2) (Augier et al., 2007) |
| LDPE | Subjected to extensive extrusion cycles (up to 100 cycles). | Increases the viscosity with increasing number of extrusion cycle. Its processing ability is affected after the 40th extrusion cycle. | (Jin et al., 2012; Kabdi and Belhaneche-Bensemra, 2008; Kartalis et al., 2000; Vallim et al., 2009; Waldman and De Paoli, 1998) |
| PP | 1) Reprocessing<br>2) Subjected to injection cycles | 1) Progressive diminution of the elastic modulus<br>2) Decreases the viscosity, and leads to small losses in material strength | 1) (Vilaplana and Karlsson, 2008)<br>2) (Aurrekoetxea et al., 2001) |
| PS | Reprocessing cycles on PS nanocomposites containing 5 wt% organophilic clay | Increases reprocessing ability compared to pure PS | (Remili et al., 2011) |

(PAHs), polybrominated diphenyl ethers (PBDEs), polybrominated dibenzo-*p*-dioxins and furans (PBDD/F)) may either be released during reprocessing contributing significantly to environmental pollution, or partially retained in the recycled plastic affecting its end-use (Hahladakis et al., 2018).

Cascading of recycled plastic packaging to lower grade products is often promoted as the optimal option for recovering its value, especially when contamination and/or degradation occurs. For instance, approximately 80% of r-PET bottles are turned into polyester fibers for carpet, clothing and other non-packaging applications. Other low value applications include plastic pipes, and waste collection bags. However, if a more systematised way of capturing and handling post-consumer plastic packaging is in place it might make it possible to increase closed-loop recycling. Nonetheless, it would still not be feasible for all plastic types to be recycled back to the same product due to their inherent properties and characteristics. But for the plastic types for which such an option is feasible, closed-loop recycling presents an opportunity for recovering their value and enabling sustainable management.

Quality does affect plastic packaging recyclability, and given the right design and technology innovations at the sorting and reprocessing of plastic components, closed-loop recycling can be improved. A better understanding of how quality changes during plastic packaging's lifecycle would enable better handling, sorting and reprocessing to become realised. Current innovations strive to achieve that, by also looking at improved design and capture interventions. But are these set to encourage an increase in the percentage of post-consumer plastic packaging recycling? The next Section looks at some of these innovations and explores how these could potentially help to increase recycling of post-consumer plastic packaging.

## 3. Existing and future improvements in the road to an efficient recovery and recycling of plastic packaging

Currently only ca. 5% of material value of plastics packaging is captured after one use cycle. As such, industries are continuously investing in R&D activities and innovation to develop new technologies that can support and maximise the recovery of plastic packaging material and its embedded value. For example, in the past couple of years innovations made in the recycling of PE films used in packaging, allow almost 100% recycled content in clear PE films (also known as foils)[1]; completely “closing the loop” on plastic films (WMW, 2016). New sorting technologies (e.g. Autosort) for opaque PET, PET trays and food grade recycled PET (r-PET) are promoted to improve sorting of these different types of plastic packaging. Yet, the market penetration of these technologies at different stages of the supply chain is unknown.

Opaque PET recovery at material recovery facilities (MRFs) constitutes an important step towards increasing the recyclability of coloured plastics. But how many MRF operators would they invest in such technology? At present only clear, or even translucent, PET is recovered and recycled, due to its high marketability (economic value) and flexibility to be easily recycled into new products and/or dyed (technical value). Coloured plastics are considered to have a lower market value because of their incapability to be dyed into other coloured plastics; hence they can only be used to produce darker shades or black plastic that makes it hard for recyclers to compete with the virgin material market (technical and economic constraints) (Szaky, 2015). Investment in a technology that sorts coloured plastic materials may often not be a justified, viable solution for recyclers, especially when they are unable to find a market for these materials.

Multilayer PET trays, normally used for meat products, are reportedly contaminating the PET bottles stream that MRF operators desperately need to recover. To solve this problem a technology (i.e. Autosort) has been developed to detect and separate multi-layered PET trays from other PET products; maximising the market value of PET bottles and maintaining very high end quality levels (WMW, 2016). Although this technology seems more attractive to invest on, current manufacturing trends that focus on sustainable packaging highlight that lightweight multilayer plastics make little sense (from a sustainability perspective) to produce, as they cannot be recycled. Hence, investment in a technology that may not be needed in the future raises concerns regarding recyclers' investment decisions (PacNext, 2014).

In cases where plastics of high market value and quality are mixed with other plastics of lower quality, a sorting technology that can remove contamination caused by other plastic materials and/or contaminants, constitutes an important innovation. For example a flake sorter that is capable of identifying and sorting flakes as small as 2 mm when processing food grade r-PET, is considered to be an important step towards increasing the quality of the end material and consequently the confidence of the manufacturing companies that would like to increase their products' recycled content. Regene Atlantique (part of the SUEZ Group) that operates a PET recycling plant in Bayonne, France has trialled the flake sorting technology, which was set to remove PVC fragments below 10 ppm, metallic (ferrous and non-ferrous) particles below 3 ppm, and other unwanted materials (incl. coloured plastic) at less than 200 ppm (WMW, 2016). It has reportedly achieved the high quality levels required by some of the biggest soft drinks companies in the world, which indicates that this innovation, at this stage of the supply chain, is one that can potentially increase the recyclability of plastic packaging.

It is crucial when promoting innovation and investment in the plastic packaging recycling industry, to methodically consider the strengths and needs of each key actor at each stage of the supply chain, and provide the innovations that can make a difference in the way plastic packaging is recovered and recycled. Many would argue that better sorting at MRFs would reduce the degree of contamination – and this may be true. However, would it make sense from an economic, environment or social perspective? This is a multifaceted aspect that requires a multidimensional valuation, and any conclusions should only be made when sorting and recycling (downstream) is assessed in combination with aspects faced at the design, use, and collection stages (upstream) of the supply chain.

In the present market, the design of plastic packaging controls to an extent the degree to which this packaging will be recycled. Hence, manufacturers are urged to make design innovations that give plastic the properties required for this to be used in a wide variety of packaging applications, while also offering superior recycling properties. We have briefly mentioned the implications surrounding multi-layered plastics and efforts to phase them out. However, phasing all multi-layered products out may not always be feasible. A particularly challenging case is the plastic packaging used for food and beverages. This packaging is designed based on strict requirements that are aimed at increasing food shelf life while retaining high degree of quality, safety and hygiene.

For example, nylon 6, is a thermoplastic material with great recycling properties that can be ‘infinitely’ recycled in a closed-loop system using a chemical recycling process (Ellen MacArthur Foundation, 2015; NPG-6, 2015). Due to its poor moisture barriers, nylon 6 is used in combination with PE in multilayer films; hence improving its performance and use in various food packaging applications but hindering its recycling. Although, efforts have been made to design reversible adhesives so that multi-material layers can be separated after use; the environmental, economic and technical aspects of such innovations are under scrutiny in order to ensure their feasibility and sustainability in the long-term. And yet, this is only one of the many innovations happening in the design field, e.g. bioplastics, production of polyvinyl alcohol (PVOH), removable coloured coatings, shrink sleeves to replace in-

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[1] PE recycling is a two-stage process: first is PE foils separation from the other in-feed material, and second decontamination takes place to remove all fines and improve the purity of the end fraction.

mould labels, and use of 'self-peeling' labels (WRAP, 2010), constitute a few more innovations that may need to be investigated on their potential to support increased recycling of plastic packaging.

The case of bio-based plastics or bioplastics (i.e. polymers made entirely or partially from a renewable, plant-based material), is particularly interesting. This is because as their name implies bioplastics can be considered to be biodegradable; however this is rarely the case as their ability to biodegrade varies widely, with some bioplastics be completely consumed by microorganisms, others be decomposed into small pellets, and others be mechanically recycled. For example, bio-PE and bio-PET cannot be biodegraded, and as such they should be recycled with their conventionally produced counterparts.

Polylactic acid (PLA) made from corn is one of the most versatile bioplastics as it can by composted with other organic wastes, decomposed into small pellets, or recycled. However this type of plastic is currently neither sorted for recycling, nor composted with organic waste, and it often ends up with other plastics diverted for sorting and recycling, contaminating the high-value plastics streams (e.g. PET, HDPE). This affects the recyclability of these streams which may eventually end up in landfill. PLA can be mechanically separated for recycling; however, its low production rate and marketability do not justify the high investment costs required for sorting it out. Alternative, its composting is a least promising option for its management, despite its highly biodegradable nature, and this is because it adds no nutrient value to the compost. As such, a multidimensional valuation of bioplastics development, use and EoL management is increasingly needed.

Production of PVOH also stands out, as this polymer, which first appeared in 1924, is now promoted as a sustainable alternative to both multilayer plastic packaging and bioplastics, creating additional benefits thanks to being water soluble. Dishwasher and laundry detergent tablets are common applications of PVOH that reduce waste and leakage by individually wrapping portions of detergent in the water-soluble film. Other applications include, pouches and films for crisp packets, biscuit wrappers and meat packaging, and also as a plastic window in paper envelopes and bread bags (Nicholls and Baldwin, 2016).

Are these the type of innovations we would essentially like to see promoted in a sustainable society? In a study by Jambeck et al. (2015) it was suggested that plastics with high after-use value are less likely to leak into our oceans, polluting the aquatic and terrestrial environment and biota (Jambeck et al., 2015). Indeed, improving the design of plastic packaging is important in making them bio-benign with less risk of leakage of substances of concern (SoC) (Leslie et al., 2016; Peeters et al., 2014), and advanced biodegradability in aquatic environments (Razza et al., 2015). Enhancing their design to promote after-use value seems to also be a better option in promoting its recoverability and recyclability in the long-term.

For the latter to become realised, plastic packaging must be properly managed at source. This is where the consumers have a key role to play in enabling the systems established in each region to become able to recover the multidimensional value embedded in plastic packaging (Iacovidou et al., 2017b). In Belgium, for example, municipalities have launched pilots to expand the range from PET bottles, HDPE bottles and jars to other plastic packaging such as pots, trays, films, and bags. The comprehensive collection of plastic packaging for recycling is also important in public spaces. For instance, one third of bottled beverages are consumed away from home. Schemes put in place by the local authorities, or even the soft drink manufacturers (e.g. Coca cola) are proved to be instrumental in recovering plastic packaging.

## 4. Conclusions

It is becoming increasingly apparent that when actions on redesigning plastic packaging and improving sorting and reprocessing technologies are considered in concerted, integrated manner, the transition to increasing secondary material recovery and recycling becomes more feasible than ever (Ellen MacArthur Foundation, 2017; Iacovidou et al., 2017a). Exploring the synergies between the two ends of the supply chain – upstream and downstream - enables informed changes on increasing material quality, efficiency and sustainability, to be made.

Disjointed and fragmented efforts of increasing recycling levels at different stages of the supply chain, need to be addressed. A multidimensional value assessment that provides the means of capturing materials and financial flows, and actors interactions and dynamics, becomes an important tool in uncovering where disruptions in the system should, and can, be made. This information can then be used in conjunction with material properties and design characteristics, to create a level playing field for all actors involved in the plastics packaging system, enabling a circular plastics production and management model to prevail.

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