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Significance of Plastic Recycling with the Focus on Polyesters – Creating a Circular Economy

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Abstract: Plastics materials are essential in every part of our lives, resulting in their increasing production and consumption. Consequently, recycling of plastics has been of great importance in the last decades. Among all types of plastics, polyesters have become very appealing for numerous kinds of applications, making their recycling crucial. Several techniques have been developed for the recycling of plastics with the aim of eliminating the waste accumulated, as well as to create a circular economy.

Keywords: Chemical recycling · Circular economy · Plastic recycling · Polyester

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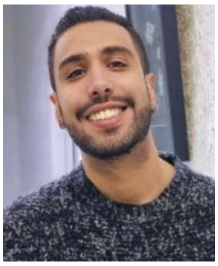

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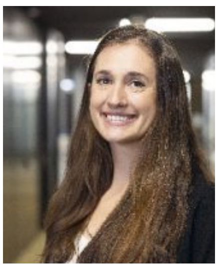

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1. Introduction

It is impossible to find a single moment in our lives that plastics are not present. The tools and equipment we use in our daily routines, the packaging materials that are part of our grocery shopping, the houses we live in, the means of transportation we use - all of them have plastic to a large extent. Plastic has become popular since the 1950s after its large-scale production commenced and it has quickly spread all over the world due to its favourable features. Therefore it is crucial for humanity to understand that plastic is an indispensable part of our lives and we should all educate ourselves about its impact on economy and environment, as well as its life cycle.

Chemically speaking, plastics are synthetic or semi-synthetic materials that are constructed from very large molecules called polymers. Polymers are built up from monomers which are small molecules with binding sites. Upon their bonding to each other in different ways monomers can generate polymer structures with different shapes and sizes, which allows the production of different classes of plastics with different structures, properties and applications.[1] There are seven most common types of plastics that are widely produced in the industry: polyethylene terephthalate (PET), high density polyethylene (HDPE), polyvinyl chloride (PVC), low-density polyethylene (LDPE), polypropylene (PP), polystyrene (PS) and the others (Fig. 1). They can take part in the production of items for various purposes; such as clothing, packaging, storage, and construction.

Due to our need for all these types of plastics, the global plastics production reached 460 million tonnes in 2019, which is two times more than that of 2000,[2] and is expected to triple in the next 30 years.[3] Unfortunately, most of the post-consumer plastics end up in landfills or they are incinerated after their use. To date, seven billion tonnes of plastic waste has been generated and less than 10% of it has been recycled, creating the issue of single-use plastics.[4] Plastic packaging represents a crucial portion of single-use plastics and only 5% of it is currently recycled, causing a loss of USD 80-120 billion to the world economy annually.[5] The circular plastic economy presents a feasible option as a substitute for the current linear system, which involves the production, utilization, and disposal of plastic. The primary objective of the circular economy is to enhance the quantity of plastic that undergoes reuse or recycling and returns to the system.[6]

The plastics industry relies mainly on fossil-hydrocarbon based fuel sources, such as oil and gas. Currently 4–8% of global oil is consumed for plastic production every year and this number is expected to reach 20% by 2050 to meet the demand for plastics, if necessary actions are not taken.[3] This will result in CO_2 emissions from oil refining, production and incineration and it's foreseen that 15% of our annual carbon budget will be occupied by that – the same as driving 51 million passenger cars for 1 year.[3] The aquatic ecosystem is also under threat due to the leakage of at least 8 million tonnes of plastics into the ocean each year, adding over 150 million tonnes of plastic waste that is already present today.[3] Therefore, we need to have awareness about the production and consumption of plastics, and it is of great importance that we make the reuse and recycling of plastic a part of our lives.

Due to their favourable physical and chemical characteristics, polyesters are among the most used plastics all over the world. One of the most important members of this family is PET, which is commonly used in the production of different items including bottles, packaging and clothing through its favourable chemical characteristics. PET waste is among the most generated plastic waste worldwide due to its wide number of applications (Fig. 2(a)).[7] Very importantly, it's the most circularly recycled plastic among all the others thanks to the developing technologies, resulting in having the highest portion of recycling capacity in Europe (Fig. 2(b)).[8]

The purpose of this review is to provide a comprehensive overview of plastic recycling with a particular emphasis on polyesters and the most popular member of this family, PET. Furthermore, it aims to highlight the importance of promoting circular economy principles to ensure sustainable utilization of polyesters and minimize environmental impact, as well as a call for action for stakeholders, including governments, industry, and consumers.

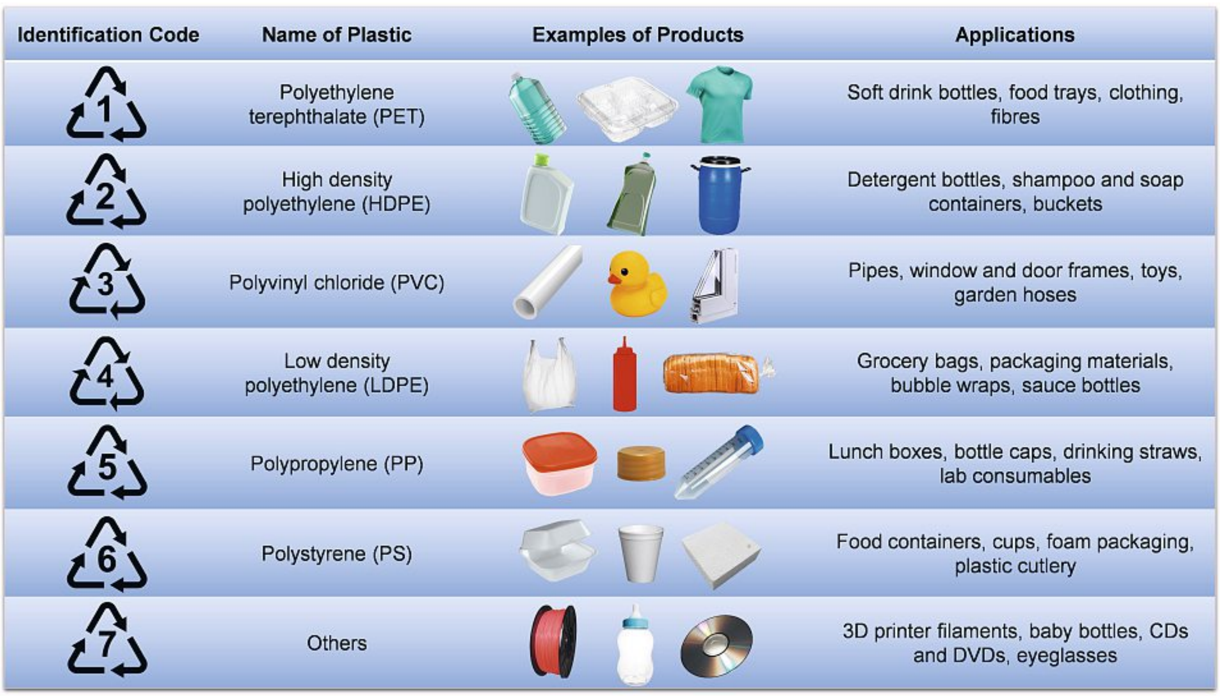

Fig. 1. List of the most commonly used plastics with plastic resin identification codes.

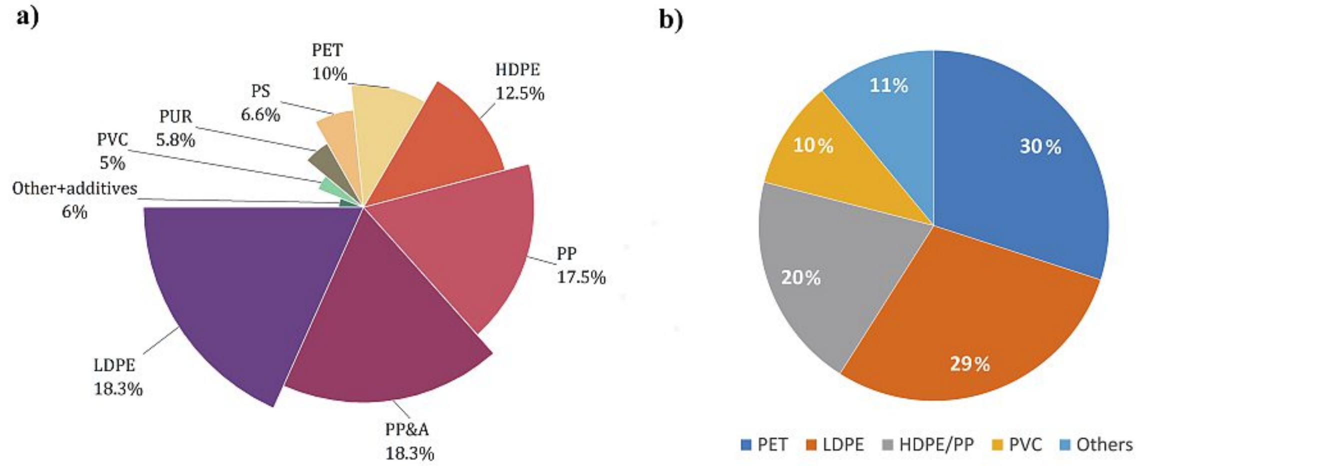

Fig. 2. a) Distribution of plastic waste generated in the world in 2015, PET having a portion of 10% among all types of plastics.[7] b) Share of installed recycling capacity per polymer type in Europe in 2020, showing that recycling of PET is the most developed among all polymers.[8]

2. Plastic Recycling: An Overview

Large scale plastic production increased exponentially in the post World War II years. The fate of plastic was doomed to landfill until the introduction of plastic recycling. The global production of plastics from 1950 to 2015 amounts to 8300 million metric tons of plastic, of which 30% is still in use today, 60% has been discarded and 10% has been incinerated (Fig. 3(a)).[9] Fig. 3(b) shows that while the amounts of plastic generated and recycled are both increasing exponentially, the difference between them is getting wider. By 2050, primary waste generated is expected to be almost three times that of plastics recycled.[9]

2.1 *Methods of Plastic Recycling*

Plastic recycling can be categorized into material recycling and chemical recycling (Fig. 4).[10] Material recycling is mechanical or physical recycling where the molecular structure of the plastic is preserved. Mechanical recycling often involves melting of the polymer and is thus suitable for thermoplastic polymers.[10] Physical recycling involves using heat and solvents to dissolve the plastic waste into a mixture of polymers and additives with no change to the molecular structure of the polymer. Whilst material recycling prevents waste from entering landfill in the short term, it delays the inevitable path to landfill as it can only be carried out a finite number of times. Chemical recycling can take place on a monomer level (depolymerization) or on a molecular level (pyrolysis and gasification). Pyrolysis and gasification break down the polymer to smaller molecules and are often associated with energy recovery from the recycling process. Depolymerization breaks down the polymer to its monomers and re-creates the compound on a molecular level, with no difference between the recycled and virgin material. In this regard, the chemically recycled material has all the benefits of the virgin product but without the production impact of new fossil fuels.[10]

Even though there is widespread collection and sorting of plastics into the classified categories, only two plastics are currently recyclable (PET and HDPE) and two are sometimes recyclable (LDPE and PS).[9] Based on a study of the global production of all plastics ever produced from 1950 to 2015, of the plastics that are recyclable, approximately 20% of PET and 10% of HDPE were recovered through recycling (Fig. 5).[9] The remainder of these plastics were destined for disposal or incineration. Is our current effort to recycle plastic having the desired effect? The trend suggests a move in the right direction, however, an accelerated effort is required to create real circularity.

2.2 *Chemical Recycling vs. Mechanical Recycling*

Currently, mechanical recycling is the main method that is used for material-based plastic recycling, whereas chemical recycling is still under development. Chemical recycling is considered as an advantageous technology for the plastic materials that mechanical recycling cannot handle, due to the reasons below:

i. The quality of the final products in the chemical recycling is better and higher than the products obtained using mechanical recycling. This is because the chemical recycling gives back

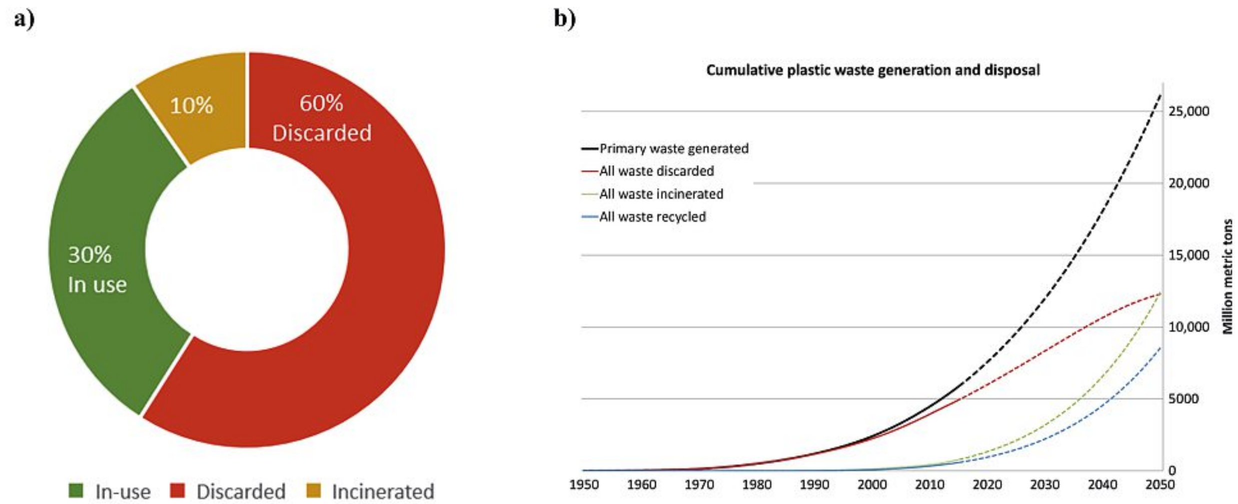

Fig. 3. a) Cumulative plastic waste generation and disposal.[9] b) The fate of the global production of plastics from 1950 to 2015 (adapted from ref. [9]).

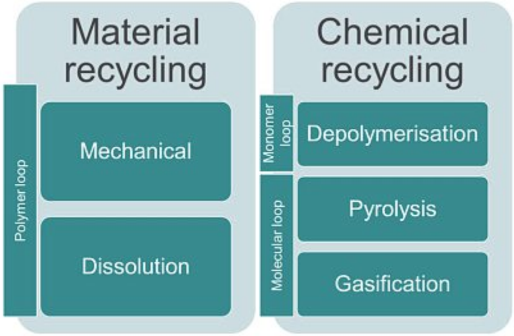

Fig. 4. Two main ways of plastic recycling – material and chemical recycling.[10]

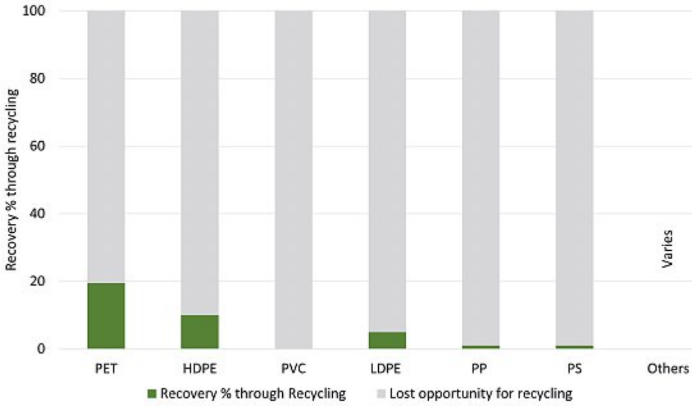

Fig. 5. Recovery of plastics through recycling (adapted from refs. [9] and [10]).

the pure initial monomers that made the polymer, while mechanical recycling gives back polymers with poorer quality (due to the degradation during the process).[11]

ii. Monomers from chemical recycling could be used to produce new polymers for any other application. However, mechanically recycled plastics have limited applications given the contamination that could occur during the process of recycling.[11]

iii. Chemical recycling makes plastics infinitely recyclable in opposition to mechanical recycling.[11]

Nonetheless, mechanical recycling still has a lot of advantages, such as having lower amounts of technical requirements for infrastructure and processes, low cost, and high industrial maturity, making it one of the most common used technologies to recycle plastic.[12] In fact, chemical recycling could be considered as a complementary process to the mechanical one.

2.3 *Different Ways of Chemical Recycling*

Chemical recycling is a chemical operation that is used to break up the bonds of polymers, with the involvement of a catalyst as a reaction-initiator. The most common methods of chemical recycling can be given as pyrolysis and depolymerization (Fig. 4). Plastic pyrolysis is the degradation of the polymer chain into gaseous molecules. It is thermal (or catalytic) decomposition in an oxygen-free or limited oxygen environment. The plastic feed is introduced into a reactor at 450–600 °C to produce an off-gas, which consists of condensable (liquid and wax) and non-condensable (gas) fractions. Depending on the technology, liquid products may be fractionated onsite, usually by distillation, into a range of light, middle and heavy distillate fuel oils.[13] Pyrolysis requires a large amount of energy consumption, which makes it less environmentally friendly compared to depolymerization techniques.

Industrially, there are different chemical processes for the depolymerization of PET plastic, including glycolysis, methanolysis, aminolysis and hydrolysis.[14] While methanolysis is performed at high temperature and pressure conditions (180–280 °C and 20–40 atm), glycolysis requires an interval of temperature ranging from 180–240 °C. These conditions make both technologies not very ecofriendly in terms of energy consumption. In the case of aminolysis, the degradation products of PET find potential uses in other applications such as plasticizers and precursors rather than being involved in PET reproduction again.[15] Hydrolysis has been a developing chemical process for the depolymerization of PET. The resulting monomers of PET hydrolysis, terephthalic acid (TPA) and monoethylene glycol (MEG) can be involved in the polymerization reaction and used for the PET production. While this process has been conducted with a temperature range of 200–250 °C under acid, base or neutral catalysis, different conditions have been under investigation to perform it at milder temperatures, making it an evolving technology.[16]

3. Polyesters: An Important Member of the Plastic Family

The family of polymers can be categorized based on their thermal stability and structure: Thermosets are materials that cannot be melted and thermoplastics are materials that can be melted. Thermoplastics are most widely used and their family groups often begin with 'poly' and end with the name of the repeating monomer. The most commonly used polymers are summarized in Fig. 6, where the six polymers in blue are often identified on packaging to help consumers with appropriate disposal.

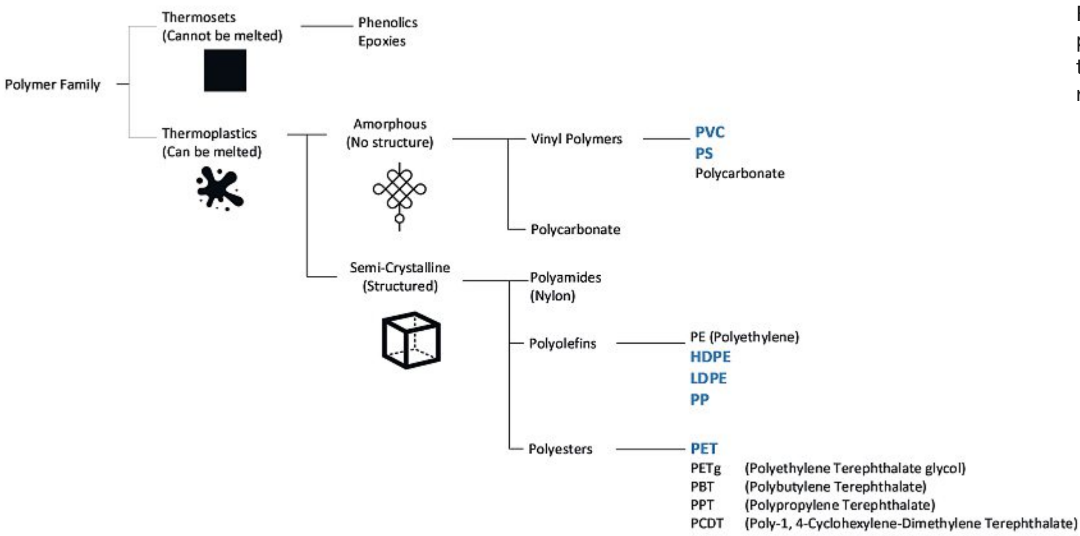

Fig. 6. Examples of common polymers and their place within the polymer family (adapted from ref. [17]).

Polyester is a long chain polymer where the repeating functional groups contain an ester linker, shown in red (Fig. 7). The properties of a polyester vary drastically with the nature of the 'R' group and the number of repeating units 'n'. Manipulating these variables changes the properties of the material, such as strength, durability, flexibility, shape retention, water resistance and stain resistance. As a result of the broad range of applications, polyesters are the most widely used man-made synthetic materials.[18] The most well-known synthetic polyester is PET, which we all know to be the plastic used for bottled water.

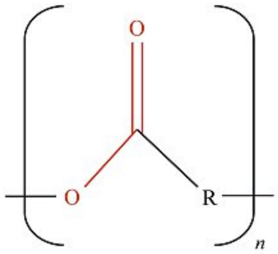

Fig. 7. Chemical structure of polyester.

Polyester and PET are often used synonymously, however, PET is only one type of polyester. Polyester is also often referred to by trade names such as Dacron, Mylar, Terylene and microfiber. Whilst polyester can be found in all aspects of our lives, it is most commonly used in the textile industry. Global textile production in 2021 was 113 million metric tons of which polyester production accounted for 54%.[18]

4. Potential Solutions and Future Development for Polyester Recycling in the Circular Economy

The concept of circular economy for plastic recycling has been gaining importance in addressing the environmental challenges posed by plastic waste. It is an innovative approach that aims to reduce waste and promote sustainability. In the context of plastic recycling, a circular economy model aims to create a closed-loop system where plastic waste is collected, sorted, and processed into new materials instead of following a linear model where plastic is used once and then discarded. These materials can then be used to create new products, reducing the demand for virgin plastics, and minimizing the overall environmental impact. This approach aims to minimize the amount of plastic waste that ends up in landfills and oceans by keeping plastic in use for as long as possible. Through innovative recycling technologies and efficient waste management practices, a circular economy for plastic recycling promotes resource conservation, reduces greenhouse gas emissions, and mitigates the harmful effects of plastic pollution on our planet's ecosystems. By embracing the principles of circularity, we can create a more sustainable and resilient future for generations to come.[19]

As discussed before, chemical recycling offers alternative methods for polyester recycling. This capability of chemical recycling allows for the use of recycled materials in applications with high approval requirements like food and medicine. However, it is worth noting that chemical recycling is still an evolving field. Some of the solutions such as depolymerization and pyrolysis to manufacture new products such as fabrics and bottles are in various stages of development and commercialization. The main problem with existing methods for recycling polyester plastics is their inability to process contaminated items efficiently and effectively with different colours or have been previously transformed into forms such as fibers or textiles.[20]

There are already existing technologies for the degradation of polyester-based plastics. For instance, Carbios founded in 2011 developed biological enzymes C-ZYME and EVANESTO to degrade PET and polylactic acid (PLA) based plastics.[21] The depolymerization technology of Loop Industries breaks down PET plastic into their base building blocks, dimethyl terephthalate (DMT) and MEG.[22] Gr3n SA, a Swiss company, developed a microwave technology by using an alkaline solution at the temperature of 200 °C to degrade PET to its monomers TPA and MEG.[23] However, all these technologies require high temperature for the depolymerization of the polyesters, which results in high cost. Recently, DePoly SA has developed an innovative and cost-effective process that produces TPA and MEG from low value post-consumer PET plastic waste, including mixed colour, multi-layer polyester textile fibers. The remarkable aspect of this process is that it does not require additional heat or pressure, and only includes sustainable and environmentally friendly chemicals. DePoly's technology is very selective to process PET plastic even when it is mixed with other plastics like PE and PP. 100% recycled PET monomers can then be sold back to various industries to produce new virgin PET products. Additionally, this approach enables the industry to utilize their own waste as a resource, which reduces our reliance on oil-based products and contributes to the goal of achieving closing the loop in PET production.[24]

5. Conclusions

In this review, we gave an overview of how plastic is ubiquitous in our daily lives, from clothing to bottles, grocery bags to food containers. The properties that make plastic so useful such as their robustness and long life, also make the disposal of it challenging. We talked about the chemical makeup of the different plastics, homing in on polyester plastic which as well as being one of the most common and useful types of plastic, is the most promising in the focus of establishing circular economy around. Complimenting mechanical recycling of plastic, chemical recycling was described, discussing how the advantages of this innovative technology compared to traditional recycling accelerates circularity for plastics.

With plastic being so integral in our daily lives, but through its production from oil contributing significantly to the climate crisis, the elimination of plastic as a resource though a noble goal is not realistically achievable. The effective commercialization of chemical recycling technology will allow expansion of recycling of plastic waste material that cannot be handled by mechanical recycling. Although mechanical plastic recycling has limitations, the successful recycling of plastic bottles, and production of items such as backpacks is a strong beginning to creating the circular economy.

With many of the innovative chemical recyclers based in Europe, the continent and Switzerland in particular, has a huge opportunity to lead this. In February, the Swiss Federal Council committed itself to the "...reuse of materials and products that are currently being disposed of...", with the aim of creating general conditions of favouring the circular economy.[25] Expanding the current waste disposal system, currently monopolised, is part of that mandate, where the existing framework of waste disposal can be expanded rather than completely liberalised. With the 'Climate and Innovation Act', which aims to reduce its reliance on the oil industry, being passed by nearly 60% of the population, initiatives to expand the recycling system will have the support of the general population.[26]

The key challenge now is to use the momentum that has been built this year, to increase public awareness and participation in the recycling of plastic, expanding the current recycling collection systems in place, and through initiatives at local, cantonal and federal level, educate the general population in creating a circular economy for all types of plastic.

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