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The challenge of plastics in a circular perspective

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Although plastic is a very important material in our economy and lifestyle, we need to deal with its pervasive impact and the huge amount of plastic waste produced, especially in the urban context. In Italy, the production of plastic waste is about 4.8 million tons with a share of 31.4% sent for recycling, 32.8% sent to Waste to Energy facilities and 35.8% sent to landfill. The negative effects of plastic waste have to be mitigated by means of prevention and other measures aimed at a transition to sustainable production and consumption patterns. The presented perspective takes advantage of the work done in the framework of the Italian Circular Economy Stakeholders Platform (ICESP) and identifies regulatory and technical criticalities in the sector, while defining strategic actions to be implemented along the entire value chain of plastics in the short, medium and long term perspective, with the aim of outlining possible mitigation solutions. From the snapshot of the ongoing advancement of the circular economy in the plastic sector, within the Italian urban context, suggestions can be gained for a strategy based on a systemic life cycle approach.

KEYWORDS

plastics, circular economy, recycling, sustainable resource use, plastic waste management

Introduction

In the last decades, in spite of their reliance on fossil resources, plastic materials have been ubiquitously used worldwide, due to the large range of possible applications. In high technological sectors, for instance, plastics are fundamental to substitute metals or other limited resources. Even more, the COVID-19 pandemic has increasingly boosted the demand for Single Use Plastic (SUP) items, required for personal protective equipment (Patrício Silva et al., 2021). As a consequence of the "take-make-use-dispose" linear economic system, the amount of plastic waste produced at a global scale is rising dramatically, at a rate even larger than forecasted, with adverse environmental impacts that are plain for all to see (Ng et al., 2018; Ocean Conservancy, 2021).

The transition to a circular model, in which resources and by-products undergo multiple production and consumption cycles, is an option to balance our use of finite natural resources while making our economic system more resilient (Oliveira et al., 2021). Thus, the application of the Circular Economy (CE) model to the plastics industry

cannot be subjected to further delays and, as a first step, the correct management of plastic waste, consisting in the conversion of waste into resources, becomes a priority. Effective and efficient recycling is widely acknowledged to mitigate the negative effects of plastic waste and has to be continuously improved, especially if considering that, at the moment, landfill and incineration are the most widespread practices for treating plastics at their end of life (Shamsuyeva and Endres, 2021). Nonetheless, recycling is not the top option in the waste hierarchy and, by itself, it is not enough (European Parliament and the Council of the European Union, 2008). Circular economy goes well beyond the end-of-life treatments, calling for a radical change of the production and consumption patterns, based on the adoption of the Reduce, Reuse and Recycle (3R) paradigm, that has been progressively extended to 6Rs to also include Recover, Redesign and Remanufacture (Jawahir and Bradley, 2016). In such a way, closed-loop systems become a driving force for sustainable manufacturing. Prevention of plastic waste production as well as an enhanced eco-design are gaining importance as crucial steps for making progress toward circularity, in particular the reduction of the material engaged and its simplification in disassembly that facilitates recycling. At the moment, however, the application of a circular model to plastics remains quite challenging.

This perspective intends to be a snapshot of the ongoing advancement of the circular economy in the plastic sector, within the Italian urban context, from the privileged standpoint of the Italian Circular Economy Stakeholders Platform (ICESP – www.icesp.it). In the framework of ICESP, the working group dedicated to plastics gathers all the relevant Italian stakeholders, including producers, recyclers, transformers, research bodies and citizens associations. It thus becomes possible to share different expertise and perspectives, with the aim of creating synergies in a common holistic approach and addressing criticalities and bottlenecks in the implementation of a circular model for plastics. After a general overview of the sector, the activities of ICESP and its analysis of the current situation will be detailed in the following sections.

Plastics in figures

The value chain of plastics includes different levels, from the production of plastic raw materials, the conversion to plastic products, the consumption and use phase by private and industrial end-users up to the waste collection and the end-of-life management (by means of landfilling, energy recovering or recycling). According to Paletta et al. (2019), the main actors involved in the entire value chain are:

1) Plastic raw materials producers, mainly represented by big petrochemical companies producing monomers and chemically bonding them into polymers. The different types of plastics that can be derived, such as polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polyethylene terephthalate (PET), polystyrene (PS) or polycarbonate (PC), depend on the different combinations of monomers and their blending with oxygen, chlorine, fluorine and nitrogen;
2) Plastic product manufacturers or converters, with the largest demand coming from the market segments of packaging (39.6%), building and construction (20.4%), automotive (9.6%), electrical-electronic applications (6.2%) and minor contributions from other sectors (household, leisure and sports, agriculture, furniture, medical etc.);
3) Recyclers, dealing with the end-of-life management. In particular, packaging is the largest contributor to post-consumer plastic waste generation, mainly due to its short 'in use' lifetime and high use and consumption, but it is also the most recyclable waste, thanks to the kind of high-quality polymers, products "eco-design" and recycling process optimisation that is adopted (Lombardi et al., 2021).

As such, the value chain linked to plastic production and processing employs over 1.5 million people in EU with a capacity of turnover of 350 billion euros for only year 2019, and a contribution of 30 billion euros to EU public finances (Plastics Europe, 2020).

In 2019, global plastics production almost reached 370 million tons, while in the European Union it reached nearly 58 million tons (16%). In 2018, in the EU, only 29.1 million tons of post – consumer plastic were collected, out of which only 32.5% was sent for recycling and 42.6% for energy recovery, while 24.9% was still sent to landfill (Plastics Europe, 2020).

Focusing on the Italian numbers and figures, the plastics industry dimension is very relevant and not replaceable within the manufacturing sector. Indeed, it employs nearly 150 thousand people with a turnover of 40 billion euros and involving 10 thousands of companies, mostly SMEs. In a comparative perspective, its volume is second only to Germany, with excellent performance at global level. On the other hand, in 2019, the production of plastic waste consisted of nearly 4.8 million tons with a share of 31.4% sent for recycling, 32.8% sent to Waste to Energy facilities and 35.8% sent to landfill (Plastics Europe, 2020).

At the same time, the extensive use of plastic and the exponential increase in waste deriving from this material have had a pervasive impact on the environment and health. Very large quantities of plastic waste end up on land and sea: it is estimated that, globally, 5–13 million tons of plastics, corresponding to 1.5%−4% of global plastics production, end up in the oceans every year, accounting for over 80% of marine litter (Jambeck et al., 2015).

The urban areas, which by definition, are the center of creativity, innovation and growth, play a fundamental role in the

global economy: according to United Nations, in 2018, 55% of the population resides in urban areas with a continuous rising trend that reaches a projection of 68% for 2050 (UN, 2018). Consequently, they are also the center of services and products consumption, thus being responsible for the generation of a considerable amount of plastic waste: an estimated 60% of plastic marine debris derives from urban centers (Lebreton and Andrady, 2019).

The environmental consequences of plastics production and use are huge. In addition to the degradation of natural systems, the ocean in particular, due to the leakage of plastics, the emission of greenhouse gases (GHGs), deriving from plastics production and after-use incineration, is also a main issue. According to EEA (2020), 13.4 million tons of CO_2, corresponding to 20% of the chemical industry's emissions in Europe, are emitted by plastics production every year. If the entire value chain of plastics is accounted for, the total emissions of GHGs reach an estimated value of 208 million tons in the European Union (EU) in 2018 (ETC/WMGE, 2021). Indeed, the emission of GHGs start with the extraction of oil and gas and a large amount of indirect emissions depend on the energy requirements in the refining operations, such as steam cracking. Moreover, health and environmental impacts are caused by substances of concern, emitted during the oil and gas extraction phase, such as nitrogen and sulfur oxides (NO_x, SO_x), particular matter (PM), volatile organic compounds (VOCs), heavy metals and other toxic substances, which accumulate in living organisms, endangering their health. Although the main part of GHGs emissions is associated to the production phase, the conversion of polymers into products and the management of plastics at the end-of-life are responsible for around 40% of the total emissions in the plastics value chain. In particular, the management of plastics waste (by means of landfilling, incineration or recycling) determines how the carbon content returns to the environment. Considering average values of polymer types and production techniques, 2.9 kg of carbon dioxide equivalent (CO_2 eq) are released into the environment for each kg of virgin fossil-based plastic product placed on the market. Moreover, additional 2.7 kg of emissions will derive from its incineration (ETC/WMGE, 2021). Therefore, accounting for the incineration of 20 – 30 million tons of plastic waste annually, it is estimated that 50–80 million tons of CO_2 are emitted per year in Europe (EEA, 2020), due to the incineration of plastic waste, whereas recycling can reduce emissions by 1.1–3.0 tons of CO_2 eq (Ellen MacArthur Foundation, 2016). Instead, when plastic waste is landfilled, the release of CO_2 eq into the atmosphere is slower and the decomposition may require hundreds of years, leaving many doubts about the final fate of leakages.

From the abovementioned figures, it is clear that, despite the undeniable advantages that the plastics industry holds, a very accurate action plan is required for reducing the environmental impact of the plastic waste. Although some progress has been made in the last decade, the amount of plastic waste that is landfilled is still too high. Indeed, evidence shows that countries facing restrictions linked to landfilling have higher recycling rates. Therefore, in order to close the loop of the plastic sector, the target of the action plan should be zero landfilling, stemming from an improved separation of waste already at urban level.

Italian circular economy stakeholders platform

The presented perspective takes advantage of the work done in the framework of the Italian Circular Economy Stakeholders Platform (ICESP), an Italian initiative mirroring the European Circular Economy Stakeholders Platform (ECESP – https://circulareconomy.europa.eu/platform/). It is based on stakeholders' engagement and highlights inter-sectorial opportunities and challenges through a meeting point where stakeholders can share their solutions and work together to address specific challenges. It links existing initiatives and supports the circular economy at national, regional and local level. The network works through several working groups, each focusing on different aspects of the Circular Economy, by means of an integrated approach including regulatory, technical and economic aspects. The involvement of all society actors such as industries, research, civil society and institutions, allows to outline possible solutions to be implemented in the short, medium and long term perspective.

One of the ICESP working groups is dedicated to industrial value chains, focusing on six selected sectors which are considered relevant by the European Commission, namely Building&Construction, Fashion, Smart Mobility, Agrifood, Plastics and Waste from Electrical and Electronic Equipment (EC, 2015). Given the high relevance of the plastic sector both in terms of industrial value chain and of urban areas' impact, a focus group is specifically dedicated to plastic and its Circular Economy perspective.

The following sections summarize the ICESP viewpoint and tackle the main issues related to plastics, according to the principles of the Circular Economy, starting from an outline of the institutional and policy drivers of the plastics in the circular transition.

Policy and institutional drivers

The overall inspiration of the EU policies and institutional effort toward reducing the waste, in general, and plastic waste, in particular, is characterized by a clear distinction between material recovery and other types of recovery, in full harmony with the Circular Economy principles and practices. The distinction is reflected in two directions: (1) the positioning of the preparation for reuse and recycling at a higher level in the

waste hierarchy and (2) the exclusion of the quantity of waste used for energy recovery form the calculation of the recycled waste quantity.

The first EU Action Plan for a Circular Economy identified the plastics as a key priority (EC, 2015) and it was followed by a dedicated document. Indeed, in 2018 the European Commission adopted the Plastics Strategy which addresses the challenges posed by plastics throughout the value chain and takes into account their entire life cycle. The strategy is a call to all involved actors to embrace the "circular way" of dealing with plastic: plastic producers and designers, recyclers, civil society, the scientific community, businesses and local authorities (EC, 2018).

In this framework, in line with the first principle of the Circular Economy, namely Reduce, the Single Use Plastics (SUP) Directive (EU Directive 2019/904/EC, 2019), which entered into force on July 2021, bans from the market single use plastic products, such as cutlery, plates, straws etc., and oxo-degradable plastic products. In May 2021, the EC has published the guidelines for its implementation and has included in the ban the organic-based bioplastics, arguing that there are no widely shared technical standards to certify that these are biodegradable in the marine environment in a short period of time, without causing any harm to the environment.

Other two EU laws, directly connected to the plastic, go in the direction of reducing the use (consequently the production) and the incorrect waste management. In fact, the Directive on Plastics Bags (EU Directive 2015/720/EC, 2015) pushes the progressive reduction of the lightweight plastic carrier bags and the Delegated Regulation on Plastic Waste Shipments (EU Directive 2020/2174/EC, 2020) aims at reducing the uncontrolled international trade in plastic waste with consequent uncontrolled management.

Plastic is also dealt with in other EU directives and laws that refer to wider issues. The most important one, the Waste framework directive (EU Directive 2008/98/EC, 2008), encompasses all Circular Economy principles, establishing the waste management in the five-step "waste hierarchy."

The directive sets a number of rules that involve plastic waste treatment such as: (a) separated collection aiming at reuse and recycle with a ban on incineration, unless this is the best option in environmental terms; (b) EU member states are required to fix concrete and measurable goals for separate waste collection setting numbers for different types of waste (including plastics); (c) the share of waste that goes for energy recovery cannot be calculated as part of the quantity that goes for reuse and recycle; (d) regarding the costs, the logic of the "polluter pays" principle is applied.

On the other hand, the 2018 amendment of the Packaging and Packaging Waste Directive (EU Directive 1994/62/EC, 1994) has followed the same trend and objective, aiming at preventing the production of packaging waste, and promoting the reuse, recycling and other forms of recovering of packaging waste, instead of its final disposal.

Plastics in the circular economy

The attempts of applying CE models to plastics, thus promoting sustainable production and consumption patterns, are on the rise in the European context and a plethora of initiatives has been undertaken in different countries (King and Locock, 2022). The purpose of the analysis conducted by the ICESP working group is the sharing of best practices and knowledge among stakeholders, at national level, with the aim of a coordinated action to move toward a global circular economy. The novelty of the proposed approach consists in the involvement of all the stakeholders working in the plastics value chain, that allows the identification of the main issues related to the CE of plastics, at regulatory, technical and economic level, based on the expertise and perceptions of the involved stakeholders.

The possible ways to generate additional value from plastic products, once their function has come to an end, and to reintroduce their material or energy content in the production cycle can be clustered as follows:

- Recovery as a raw material (feedstock) for other production sectors;
- Recycling within or in other applications;
- Recovery of biodegradable and compostable bioplastics in the form of compost, as an organic amendment useful for soil fertilization;
- Recovery of energy (both thermal and/or electrical), when the previous three solutions are not viable, only after a careful evaluation of costs and benefits (especially in environmental terms).

The proposed analysis follows the logic and the framework of the European waste hierarchy, which is also the basis of the European regulation and the EU Circular Economy package. The approach is conducted by unraveling the issues related to the different stages of the life cycle, as follows:

Waste prevention

Waste prevention is essential for any waste stream (Minelgaite and Liobikiene, 2019), but it is specifically important for plastic waste, due to its predominant single use, especially after the COVID-19 emergency devices (Patrício Silva et al., 2021). Plastic can turn into waste in a short time or after many years, depending on its use. Plastic packaging turns into waste shortly after purchase, while plastic in construction sector turns into waste after a relatively long period of time. To date, plastic waste is only partially recycled and a small

share undergoes recycling processes in the EU territory through sustainable environmental protection practices and standards (EEA, 2020). The analysis carried out by ICESP pointed out that it is essential to focus on prevention, aiming at changing the consumption patterns, as well as reducing the environmental impacts deriving from the recycling process. The introduction of specific objectives for the plastic use reduction is thus necessary, but unfortunately still not sufficiently widespread. The European Environmental Agency has identified 173 measures that can prevent the generation of waste, out of which 105 refer to the production phase, while 69 refer to the consumption phase (EEA, 2019). The SUP Directive, on the other hand, has been conceived to follow up the prevention strategy.

[Eco] Design for circularity

The importance of eco-design for circularity was strongly underlined by ICESP. It consists in developing new and integrated solutions, aimed at improving efficiency for optimizing resources along the life cycle and recyclability of products. The design for circularity aims at producing plastic products that are more durable, repairable, more easily disassembled and easily separable into parts and components, and finally easily recyclable.

The circularity approach of the eco-design is applied not only to products, but also to processes (Kondoh and Mishima, 2011). Eco-design of processes means applying the same principle of resource efficiency, thus resource use reduction, to the production processes. The application of the eco-design principle to the plastics value chain can contribute to build virtuous and circular schemes capable of extending the life cycle of plastic items.

In particular, design is very important in the packaging sector, leading to a reduction of the quantity of materials used and to a simplification of the disassembly, thus facilitating recycling (Chengcheng, 2022). Considering that plastics are a family of heterogeneous materials, their mechanical and physical properties should be seen as variables rather than constraints. This is true especially regarding the design with the second raw material, where it is essential to characterize a material and find its application in a market (De Giorgi et al., 2020).

Waste collection

The organization of waste collection is the first step in any waste management process, because it determines the composition of the waste streams, thus their suitability for downstream pre-treatment, selection and recovery operations. Cities and municipalities across EU have a number of waste collection plans which ideally should share the objective of maximizing recovery of recyclable materials and the value of waste, preventing these precious resources from being disposed in landfills. In addition, they should be aligned with the downstream infrastructure for pre-treatment and selection, in order to maximize recovery, improve environmental performance and manage costs. From the ICESP working group, it clearly emerged that a critical issue is represented by the so called "plasmix," namely the residue of the selection processes of plastics. This is a waste produced by centers of secondary selection and consists of the sum of extraneous fractions, non-recyclable plastic packaging and selection errors (Cossu et al., 2017).

A particular attention is paid to the collection of WEEE plastic waste, for which the related Directive has a special mention. Anyway, its management is extremely complicated because of the different dimension of the considered waste, the variability of used polymers and the considerable amount of the additives employed (Cafiero et al., 2021).

Recycle and related technologies

The strategies suggested by the ICESP group stem from an overview of the currently operating recycling technologies, widely described in the pertinent scientific literature (Solis and Silveira, 2020; Bhoi and Rahman, 2022). To date, the largely predominant recycling method is *mechanical recycling*, which consists in separating the different types of plastics in order to process them mechanically, or altering their characteristics only minimally. Nevertheless, there are a number of critical aspects presented by the current state of technology, which are related to thermo-mechanical selection and degradation or to issues related to food contact or bad smells. Another valid and promising alternative is the *chemical recycling*, which consists in breaking the long molecular chains that turn polymers into their basic components (monomers) or other hydrocarbons that can replace those of fossil origin (virgin naphtha). This is done through a number of different technologies developed worldwide. A third way is the *organic recycling*, which is mostly connected to biodegradable and compostable plastics specifically for packaging purposes. Finally, *energy recovery* follows, but it has to be operated only residually and if none of the abovementioned paths are viable. This means that it is not in competition with the proper recycling streams, but only complementary to them.

A special focus on bioplastics and plastic packaging

In the ICESP analysis, bioplastics and plastic packaging have deserved more attention than other products, due to the contribute they can give to limit the environmental impact.

As far as bioplastics are concerned, a first substantial clarification has to be made about biodegradable and compostable bioplastics. It should be noted that, according to the European standard EN 13432 (2002), a material can be considered biodegradable if it degrades by 90%, within 6 months, under certain laboratory conditions (Laboratory test method EN14046, also published as ISO 14855), while it is considered compostable if it is able to disintegrate and no longer be visible in the final compost, in <3 months, during an industrial or domestic composting process, without creating problems in the treatment plant, nor affecting negatively on the quality of the final compost with the possible presence of toxic and/or harmful substances. Therefore, in particular compostable bioplastics may give a relevant contribution to the reduction of environmental impacts, as they can be disposed together with organic waste. This helps increasing the quality of the compost generated, thus offering a simple waste management and, at the same time, a solution for the collection itself (Cucina et al., 2021).

Bioplastics have been present on the Italian market for a long time and their global production shows a growing trend in the years to come. The Italian industry represents an international excellence in this sector, with a crucial role in the context of the circular economy and the bioeconomy. In fact, bioplastics (i) represent the outcome of a process of valorisation of renewable resources, such as waste and waste from agro-industry, (ii) decrease the withdrawal of non-renewable resources and the related pollution and (iii) in turn, can undergo recovery treatment in closed cycles (circular, indeed).

A potential bottleneck in the further development of this sector can be represented by the plants designed to treat organic waste such as food waste, mowing and pruning: greater diffusion on the territory and technological modernization are increasingly necessary, in light of the expected growing volumes and of the new standards required by the European Union on fertilizers.

With reference to plastic packaging, generally, the packaging is inextricably linked to the characteristics of the product it is intended for. Therefore, identifying the best packaging for a specific product is a complex matter. In a circular perspective, the economic charge of overpacking has proved to be an important prevention lever. A number of actions, aimed at reducing the environmental impact of the package, has been identified as follows: (i) simplification of packaging, by eliminating the components that hinder the recycling of the main polymer; (ii) reuse of packaging for multiple life cycles, favoring the situations where the reuse and the implementation of reverse logistics for the return of empty packaging are environmentally, technically and economically sustainable; (iii) development of packaging by using smaller amounts of raw materials, preserving the technical characteristics; (iv) creation of primary and secondary packaging for more efficient logistics, for example by increasing the number of packages that can be transported on a single pallet; (v) design for recycling or design for circularity, i.e., design from scratch of packaging that facilitate selection and recycling operations.

Conclusions

The analysis conducted by ICESP highlighted that a systemic life cycle approach is the game changer to boost plastic value chain toward closing loop systems. The promotion of new conversion and recycling processes of traditional plastics and biodegradable bioplastics, for the sectors in which they represent a real solution, could be core part of a national strategy on the Circular Economy. Starting from the European framework (Green New Deal, Farm to Fork Strategy, Circular Economy Action Plan, Climate Law, Chemical Strategy, Horizon Europe research and innovation fund), such a strategy can enable Italy and Italian urban areas to make a real transition toward a sustainable development model from the economic, social and environmental points of view, thus capitalizing its leadership in the Circular Economy approach.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

RP and GF contributed to conception and design of the study and wrote the first draft of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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