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Review

Plastics today: Key challenges and EU strategies towards carbon neutrality: A review☆

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ABSTRACT

Never as today the need for collaborative interactions between industry, the scientific community, NGOs, policy makers and citizens has become crucial for the development of shared political choices and protection of the environment, for the safeguard of future generations. The complex socio-economic and environmental interconnections that underlie the EU strategy of the last years, within the framework of the Agenda 2030 and the green deal, often create perplexity and confusion that make difficult to outline the definition of a common path to achieve carbon neutrality and "net zero emissions" by 2050. Scope of this work is to give a general overview of EU policies, directives, regulations, and laws concerning polymers and plastic manufacturing, aiming to reduce plastic pollution, allowing for a better understanding of the implications that environmental concern and protection may generate from a social-economical point of view.

1. Introduction

In 2021, the Intergovernmental Panel on Climate Change (IPCC), the United Nations body entitled to assess the causes and effects of climate change, reported: "Emissions of greenhouse gases from human activities are responsible for approximately 1.1 °C of warming since 1850–1900, and over the next 20 years, global temperature is expected to reach or exceed 1.5 °C of warming" (IPCC report, 2022).

According to IPCC reports, for each degree of temperature rise, wheat crops decreased by 5%, so that maize, wheat, and other important harvests recorded 40 Mt/y reduction between 1981 and 2002 due to climate warming (IPCC Special Report, 2018). Human activities and earth exploitation, such as for example urbanization, overpopulation, industrialization, pollution and deforestation have reached a non-return point; thus, a sound and clear directive framework is mandatory to stop global warming. As set by the Paris Agreement in 2015 and COP26, COP27 (Climate Change Conference, 2015, Climate Change Conference, 2021, Climate Change Conference, 2022), it has become crucial to limit temperature increase within 1.5 °C and reach carbon neutrality by 2050 to guarantee a decent life for future generations. Climate changes, natural catastrophes, health pandemics are becoming more and more frequent, clearly indicating that humanity must adopt more sustainable approaches (Luzi et al., 2019; Aontee and Sutapun, 2013), rethinking development models in a circular economy prospective (Lackner, 2015; Alaerts et al., 2018; Lambert and Wagner, 2017; Gironi and Piemonte, 2011; McKeown and Jones, 2020).

Never as today, Covid-19 pandemic and unstable geographical situations should have taught humanity that efficient use of resources brings net savings and competitiveness for economy, public authorities, and consumers. Improving the efficiency of products and processes adopting recovery and recycling strategies will contribute to reduce EU dependence on the import of raw materials, contributing to the transition to a smart, sustainable, and inclusive growth as set by the goals of the ONU Agenda, 2030.

In this scenario, policy makers have a crucial point in re-directing and establishing future trends and market policies, to achieve the transition to a greener and more sustainable society and economy. Therefore, the industry, the scientific community and policy makers

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must work to develop and promote innovative and environmentally friendly products and processes.

The EU's long-term budget, within the EU Recovery Action Plan coupled with NextGenerationEU (NGEU Next Generation EU, 2020), is the largest financial package ever allocated (€2.018 trillions) which will help rebuild Europe after COVID-19 for a greener, gender equal, and resilient Europe. For instance, for the plastic industry the pandemic and lockdown measures had a significant impact on feedstock availability, plastics production and use. In most sectors, plastics use declined in line with the reduction in demand and production, especially for large-scale plastics-using sectors such as motor vehicles, trade and construction. According to 2022 OECD report, global plastics use in 2020 decreased by 1 Mt which is 4.5% below the pre-COVID projections for 2020 (Global Plastics Outlook, 2022). In this sense, the EU Recovery Plan is a unique opportunity to promote sustainable recovery from all prospective, i.e., economic, social, and environmental.

Within this wide panorama, where all spheres of society and economy are involved in a historical transition for a better future for all, this paper will focalize on one specific manufacturing compartment, the plastic industry, analysing in detail how the Agenda 2030and EU Directives are influencing its future trends and destiny. At European level, numerous initiatives and policies promote the recovery and recycle of polymers (both bio and fossil-based) reducing consumption of natural resources, energy, water, and Greenhouse Gases (GHG) emissions, in line with the principles of circular economy. However, while various stakeholders solicit to take substantial actions, at economic, environmental, and social levels, difficulties remain in determining which should be the right pathways to be undertaken. Since stakeholders, policy makers, industry and society at large need to be involved to undertake adequate initiatives for climate mitigation, a shared view of potential scenarios and implications must be achieved, otherwise convergence and collective action could be lost. Scope of this review is to give an overview of the overall strategic asset of the EU to achieve the goals of the Agenda 2030 and a net zero waste plastic industry by 2050, highlighting the pros and cons that EU environmental strategies generate from a socio-economical point of view. Awareness of the legislative framework, monitoring tools, and industry undertakings is strategic to gain stakeholders, civil society and decision makers consent, so that actions and resolutions could be better polarized and collective actions should not be lost.

2. Method

In this study, different European actions on plastic and EU Directives and Legislations regarding polymer production and plastic manufacturing, together with the impact of raw materials used, and waste management/recycling were mapped using a combination of different keywords such as Authors used relevant keywords and search term concerning, such as "European Union," "EU directives," "plastic regulations," "plastic waste," "plastic pollution," "polymer", "plastic", "post-consumer waste", "pollution", "marine litter/littering", "waste management", "microplastics", "greenhouse gasses", "single use plastics (SUP)". The research was carried out using academic search engines or database that includes literature on the topic, such as Google Scholar, Scopus, and Web of Science. In order to find the most updated data and regulations, we also searched websites of relevant organizations, such as the European Commission portal (https://commission.europa.eu/index_en), European Law portal (EU law portal, 2021), European bioplastics (European Bioplastics portal), The European Parliament (https://www.europarl.europa.eu/portal/en), The European Commission press corner (https://commission.europa.eu/index_en), The Council of the European Union (Council of the European Union portal), DG Environment (https://commission.europa.eu/about-european-commission/departments-and-executive-agencies/environment_en), the European Environment Agency (EEA, European Environmental Agency portal), the European Chemicals Agency (ECHA, https://echa.europa.eu/it/home), Statista (Statista portal), Eurostat (Eurostat portal,) and World Bank (World bank portal). Once we had identified relevant sources, we reviewed references within to identify additional sources that may be relevant, and exclude all the directives, law and regulation that are no more active. Other reporting items for systematic reviews, such as Prisma and Swot analysis, were not considered adequate for the specific review (Papamichael et al., 2023; Voukkali et al., 2022).

Impact and fate of plastic litter released in the environment, was excluded from our analysis as according to the authors EU Directives and Laws should prevent plastic litter entering the environment. A brief discussion of the problem of plastic pollution and waste management, together with possible alternatives such as plastic recycling, is reported before the discussion on EU regulatory.

3. The plastic facts

Presently over 360 Mt of fossil-based polymers are produced yearly, to produce polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), polystyrene (PS), polyvinylchloride (PVC) employed for the packaging (39.9%), constructions (19.8%), automotive industry (9.9%) and electronic devices (6.2%) (Ferreira-Filipe et al., 2021; /Plastics Europe, 2022) (Fig. 1). Biobased plastics such as polylactic acid (PLA) (Asgher et al., 2020), polybutylene succinate (PBS) (Mochane et al., 2021; Rafiqah et al., 2021), polyhydroxyalkanoate (PHA) (Visco et al., 2022; Al Battashi et al., 2021; De Donno Novelli et al., 2021; Saratale et al., 2021), and polyethylene furanoate (PEF) (Al Ghatta et al., 2021; Filiciotto and Rothenberg, 2021; Rosenboom et al., 2018) are gaining interest at industrial level (Gatto et al., 2021; Ahmed et al., 2018) as alternative to fossil-based polymers. Although their promising features, the biggest limitations to the use of biopolymers derive from their availability and costs. According to the latest European Bioplastics report, EU total production capacity of biopolymers is expected to reach 6.3 Mt by 2027 which is totally insufficient as compared to market needs (Bioplastics market data,). For these reasons, to date over 99% of plastic manufacts are still fossil-based .

Since the production of Bakelite, the first synthetic polymer, in 1907 and successive extraordinaries discoveries such as the stereospecific polymerization for the synthesis of isotactic polypropylene (commercialized as Moplen), for which Giulio Natta and Karl Ziegler were awarded the Nobel Prize in Chemistry in 1963, polymers and plastic materials became increasingly popular as substitutes for materials such as steal, wood, cardboard, leather and further opening up the frontiers to new unprecedented materials and manufacts (Beghetto et al., 2021a; Meyer et al., 2021; Geyer et al., 2017).

Nevertheless, nothing was yet known on their resilience in the environment due to low biodegradability and as a result, plastics accumulated in landfills or in natural environments, polluting marine waters, freshwater ecosystems, and soil (Besseling et al., 2017a; Jahnke et al., 2017; Blettler et al., 2018; Bläsing and Amelung, 2018; Chae and An, 2018a,b; Beghetto et al., 2019; Zubris and Richards, 2005).

Popularity of plastic manufacts started its decline when in 1997 Charles Moore, a yachtsman on his way home to Los Angeles, discovered the first Great Pacific Garbage Patch. The patch is now estimated to be made up of 1.8 trillion pieces of plastic (79.000 Mt) and has a surface larger than Italy and Germany put together (about 660.000 km^2) (Fig. 2) (National Geographic, 2019).

In 2004, Richard Thompson, Professor of Marine Biology, was the first to describe their long-term accumulation and coin the term 'microplastics' in his landmark paper, 'Lost at Sea: Where Is All the Plastic?' (University of Plymouth, 2020).

As public concern on plastic pollution was increasing, EU was facing a difficult management of end-of-life plastics which could only be incinerated or landfilled. Between 2004 and 2016, EU countries were exporting 2.2–2.5 Mt waste yearly to Turkey and Asian countries such as China, Malaysia, Indonesia, Vietnam, India (Statista, 2022).

By the end of 2017 China filed a notification with the World Trade

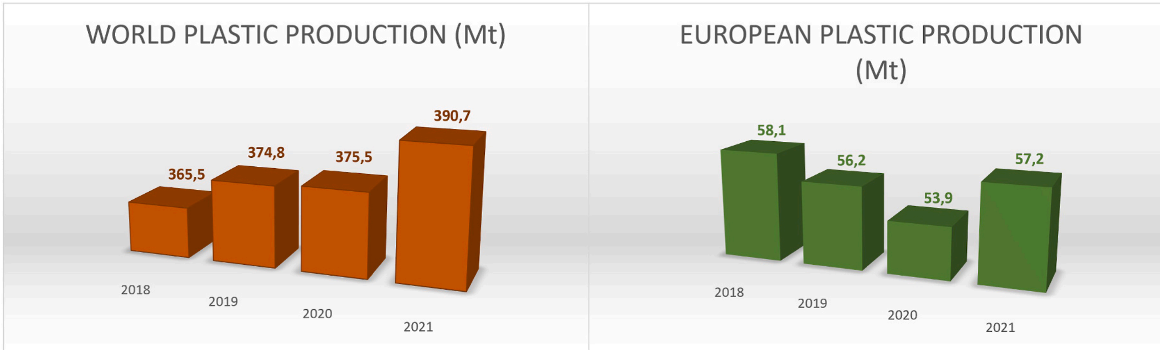

Fig. 1. A) World and b) EU plastic production in Mt/year. The above data include plastics production from polymerization and production of mechanically recycled plastics. Polymers that are not used in the conversion of plastic parts and products (i.e. for textiles, adhesives, sealants, coatings, etc.) are not included.

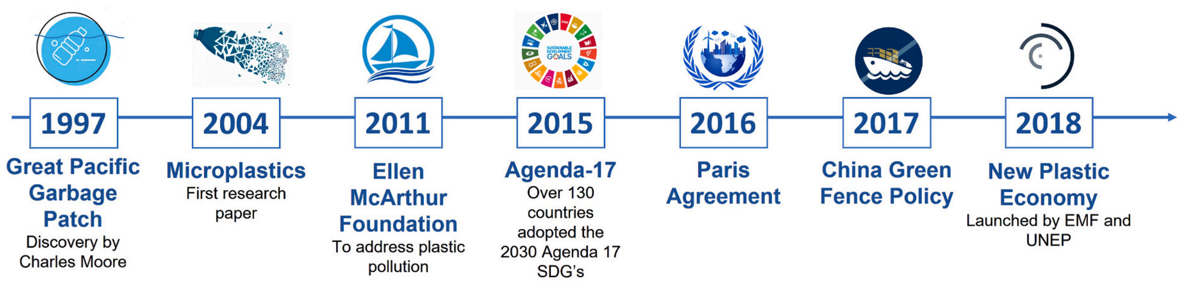

Fig. 2. Overview of Plastic production historical events.

Organization, 2017 to ban trade of four classes and 24 kinds of solid waste, including all plastic scrap and unsorted paper waste (World Trade Organization, 2017). Consequently, EU plastic waste export decreased of over 39%, thereby overloading the EU waste management system and incinerators, pushing the EU to implement a great number of directives and laws to face the problem of plastic management and pollution, as further described below.

It has been estimated that in the last 65 years, over 4900 Mt of the 8300 Mt of fossil-based polymers produced were landfilled, incinerated, or dispersed in the environment (Gilbert, 2017; Streit-Bianchi et al., 2020;Sole et al., 2019). Despite improvements in waste management through the years, worldwide 32% of plastic packaging ends up in the environment, polluting oceans, land, animals, and humans. It is estimated that since 2010 over 12.7 Mt of plastics were leached into the oceans yearly (Ellen MacArthur Foundation, 2016; Jambeck et al., 2015; Geyer et al., 2017).

Since plastic pollution largely contributes to the difficult climatic conditions which life on earth is increasingly experiencing the use, recovery, and recycling of plastics must be rethought and redesigned with a circular integrated approach (https://emf.thirdlight.com/link/faarmdpz93ds-5vmvdf/@/preview/1?o). It is only through a radical change in production, within the boundaries of eco-design and adequate waste management that zero waste production and environmentally sustainable management cycles may be achieved (Tang et al., 2021; Liang et al., 2021; Basuhi et al., 2021; Ahmed et al., 2018b).

All this in mind, strategies to reduce plastic pollution should promote plastic recovery and recycling, in place of energy production or landfill (Visco et al., 2022), together with the production of biodegradable biobased plastics (European Bioplastics Report, 2022) and eco-design of easily recyclable products (European Parliament and the Council, 2022a).

3.1. *Waste management of fossil based plastics*

Plastic management and disposal is a matter of strategic importance from an ecological, social, economic and, last but not least, ethical point of view (Brouwer et al., 2018; Filho et al., 2019; Van Eygen et al., 2018; Hsu et al., 2021; Balwada et al., 2021; Lombardi et al., 2021), posing serious dilemmas on the management of huge volumes of fossil-based plastic waste (Paganelli et al., 2015; Diggle and Walker, 2022). As known mismanaged plastic waste can easily leach in the environment and cause dangerous impacts in the marine environment (Chatziparaskeva et al., 2022b; Lamb et al., 2018;Jahnke et al., 2017; Koelmans et al., 2014), freshwater ecosystems (Blettler et al., 2018; Rodrigues et al., 2018; Besseling et al., 2017b), soil (Bläsing and Amelung, 2018; Chae and An, 2018a,b; Scheurer and Bigalke, 2018; Zubris and Richards, 2005) and food chain (Garcia et al., 2021; Lusher et al., 2017; Romeo et al., 2015).

However, plastics can make a major contribution towards circular economy, helping to achieve resource-efficient recycling processes. Therefore, there is an urgent need to increase the efforts for recycling of plastic waste as a major counteraction to prevent plastic pollution. According to literature data, world-wide plastic waste comes from three regions: 57 Mt from East Asia and the Pacific, 45 Mt from Europe and Central Asia, and 35 Mt from North America (Das et al., 2021). In 2020, more than 29 Mt of post-consumer plastic waste was collected in EU, 10.2 Mt of which were sent to recycling facilities inside and outside Europe, 23% of which were landfilled and 40% sent to energy recovery operations.

It should be mentioned that, depending on the process employed, for each ton of post-consumer plastic waste incinerated, between 1 and 4 ton of CO_2 are produced, while recovery and recycle of this waste to produce new plastic manufacts contributes only 10% of the overall CO_2 burden from virgin naphtha (Cabernard et al., 2022). Considering these data, it is evident why the legislator is pushing towards the improvement of post-consumer plastic management, recovery, reuse, and recycling, as well as eco-design of easily recyclable materials, drastically reducing GHG emissions (https://journals.openedition.org/factsreports/5102).

The reason why, in EU only about 37% of post-consumer plastics are recycled is a consequence of the complexity of the different materials available on the market, leading to sorting difficulties, reducing their recyclability. For example, composites are highly performing materials which nonetheless are not recyclable. The great diffusion of composites in the energy production sector (just think of wind turbine blades and composite solar panels) makes it necessary to develop a general circular business model, as well as quality protocols relating to the end-of-waste criteria for each individual mixture of material used (Chatziparaskeva et al., 2022a). Today plastics are recycled mainly by mechanical recycling: i) post-consumer plastics require to be separated from non-plastic components (metal, glass, dirt) and then different plastics are collected separately by optical, manual, float/sinking techniques, ii) shredding and grinding, iii) extrusion (Beghetto et al., 2021b) (Fig. 3).

Recently chemical recycling is gaining increasing interest as a complementary strategy to mechanical recycling, improving the percentage or recycled plastic waste (Huang et al., 2022; Davidson et al., 2021; Thiounn and Smith, 2020; Scrivanti et al., 2019; Scrivanti et al., 2018). Chemical recycling is a process which allows to degrade polymers in a chemically controlled manner, recovering monomers and oligomers which can be used to produce new polymers or other chemicals and is therefore more versatile than mechanical recycling.

3.2. Europe actions on waste management and circular economy

Since the adoption of the first Environmental Action Program (EAP) in 1973 (European Parliament, 1973), it appeared evident that the EU environmental policy would inevitably have to face the problem of reconciling environmental protection and preserving free market initiatives, guaranteeing Member States independence (Chisholm, M., 1994; Collins and Earnshaw, 1993). Consequently, EU strategies should promote the development of a unified policy program, preserving Member State sovereignty, maintaining a certain degree of flexibility, and therefore having limited authority (European Parliament, 1997). For this reason, most of EU environmental legislations have been enacted in the form of directives, allowing national governments to preserve considerable control of domestic implementation within an agreed EU agenda (Bailey, 1999).

Nonetheless, the European Commission (EC) has the right to ensure uniform application throughout Europe of the standards laid down in legislations, as set out in Art. 130 R (4) of the amended Treaty of Rome, and Art. 3 B of the Maastricht Treaty stating that "The Commission shall take action … only if and so far as the objectives of the proposed action cannot be sufficiently achieved by the Member States and can therefore, by reason of the scale or effect of the proposed action, be better achieved by the Union." (European Communities, 2002).

In fact, urgency in taking actions against climate change has, in recent times, brought the EU to prevail in favour of environmental policies, rather than Member States independence. This has generated confusion and disappointment of some Member States towards specific EU directives and regulations in view of the strong socio-economic impact generated, as discussed below.

3.3. EU directives and laws relative to polymers and plastics production and use

Different directives and Regulations are specifically focused on the quality and safety of packaging (see below). Directives and EU legislations inherent with the polymers and plastic manufacturing regulate many different aspects such as compliance of starting materials, industrial production emissions, health of labourer and consumers, food contact requirements, recovery, and recycling of post-consumer waste. All these directives, outlined in this chapter, build up a regulatory system enabling EU and Member states to safeguard the environment and health of EU citizens.

For example, the EC Regulation 2023/2006, relative to Good Manufacturing Practices (GMP), poses standards relative to materials and objects intended to come into contact with food (Commission Regulation, 2006). The Regulation requires operators in the sector to "establish, implement and enforce an effective and documented quality assurance system" (art. 5.1), which is based on "monitoring the implementation and total compliance with the GMPs" (art. 6.1). GMPs consist of a set of rules that describe the methods, equipment, means and management of productions or services to ensure the appropriate quality standards and stakeholders' satisfaction.

An important milestone was achieved in 2008, when Europe approved Directive 2008/98/EC (European Parliament, 2008), which laid down general minimum requirements for extended producer responsibility schemes (EPR) defined as 'a policy principle to promote total life cycle environmental improvements of product systems by extending the responsibilities of the manufacturer of the product to various parts of the entire life cycle of the product, and especially to the

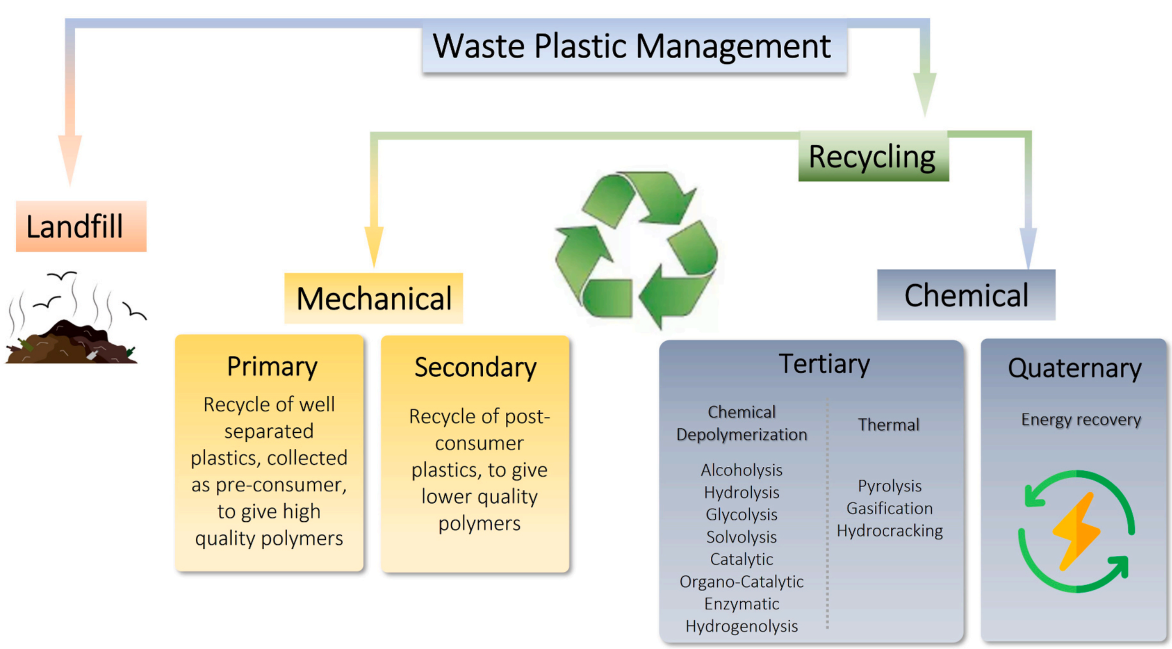

Fig. 3. Overview of plastic recycling techniques.

take-back, recycling and final disposal of the product'. In doing so, EPR legislation, in principle, shifts the responsibility, and costs of negative environmental externalities of products from taxpayers to producers, consistent with the polluter pays principle. The final aim of EPR is to address issues related to resource consumption and growing waste generation; the key rationale behind EPR is that producers are best suited to make the required changes to achieve a reduction in the environmental, social, and economic impacts of their products compared to end-users. EPR is intended to achieve environmental improvements throughout the product life cycle, establish feedback loops, so that improvements in products' design may help optimize their environmental performance and minimize the costs of end-of-life management. EPR has two primary environmental goals: the first to provide incentives for manufacturers to design resource efficient and low impact products by means of 'eco-design', and the second to ensure effective end-of-life collection, environmentally-sound treatment of collected products and improved reuse/recycling.

Nevertheless, EPR policies may impact negatively on smaller producers, who may not have the resources to comply with regulations, facing higher costs, reducing their competitiveness on the market. Further, the cost of compliance may be passed on to consumers through higher prices. To maximize the impact of EPR policies, they should be combined with economic incentives for virtuous companies undertaking environmentally sustainable initiatives, in line with the EU Taxonomy. The EU taxonomy is a classification system, establishing a list of environmentally sustainable economic activities. It could play an important role helping the EU scale up sustainable investment and implement the European green deal (EU taxonomy for sustainable activities).

Over the past 33 years the EPR approach (Directive 94/62/EC, European Parliament and the Council Directive, 1994), has spread to over 400 EP R schemes currently in use globally, most of them in Organization for Economic Co-operation and Development (OECD) countries (Extended Producer Responsibility, 2016).

Another relevant initiative started in 2008 is the non-legally binding Raw Material Initiative (RMI) (SEC/2008/2741) regarding raw-material extraction also employed for plastic manufacturing (European Parliament and the Council, 2008a). Th e RMI is built on three pillars aiming to ensure continuous access to raw materials in the EU with an environmentally sustainable approach (European Commission, 2011a). Focus of RMI is to ensure competitive and sustainable supply of raw materials from EU sources, to empower resource efficiency and recycling (European Commission and the Council, 2008). In a greement with RMI, the EC adopted a resolution to elaborate, monitor and review policies regarding raw materials and industrial production environmental impact (Steensgaard et al., 2017).

In 2008 the EU waste framework directive (WFD) (Waste Framework Directive, 2008), amended by Directive (2018)/851 (see Section 3.4), provided a strategy intended to reduce waste, limit landfilling, promoting waste management, innovative waste collection and recycling technologies, sustainable behaviours at all levels of civil society. Preventing products and materials from becoming a waste and turning inevitable waste into a resource are key steps to achieve a greener and more circular economy.

The WFD defines a "hierarchy" in waste management, graphically reported in Fig. 4. Best practices, such as waste prevention and re-use, are at the top of the pyramid, followed by recycling, and energy recovery, while landfilling is at the bottom. Most importantly, the WFD reports terms and conditions for a waste to end its waste status and be further reprocessed. In particular, requirements for "End of waste status" by which a waste (in the Directive referred to as "substance") shall cease to be such if: (a) "the substance is commonly used for specific purposes"; (b) "a market or demand exists for such a substance or object"; (c) "the substance fulfils the technical requirements for the specific purposes and meets the existing legislation and standards applicable to products" (d) "the use of the substance will not lead to overall adverse environmental or human health impacts". This directive is of strategic importance to

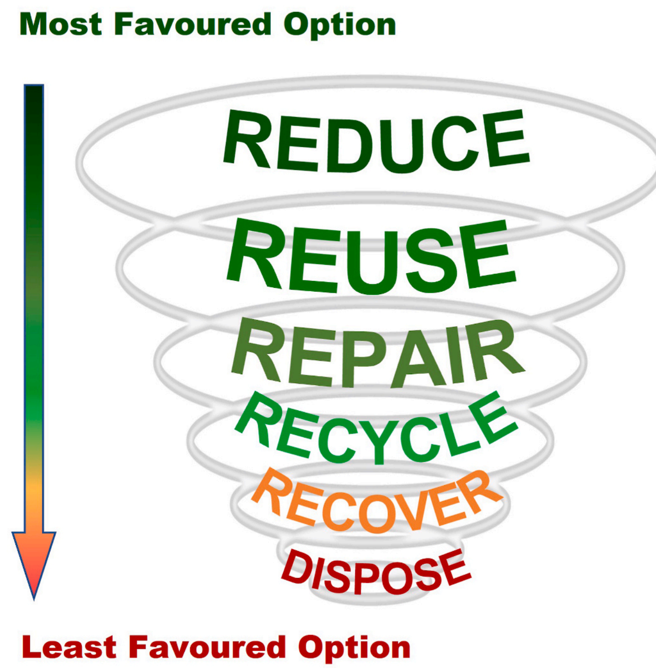

Fig. 4. Pyramid of waste hierarchy.

implement innovative products and processes within the circular economy boundaries, since if waste has to become the future feedstock alternative to virgin fossil based products, wasted substances need to be authorised as secondary primary materials to produce new market opportunities.

In 2010 the EU issued the Industrial Emissions Directive (IED, 2010/75/EU) setting the rules on integrated prevention and control of pollution connected to industrial activities (European Parliament and the Council, 2010). Acco rding to this Directive, the rules are "designed to prevent or, to reduce emissions into air, water and land" as well as "to prevent the generation of waste". Hence Member States are asked to take necessary measures to ensure that industrial installations adopt all necessary preventive measures to minimize pollution and waste adopting Best Available Technologies.

Best available technologies (BAT) were first introduced in 1984 b y the European Economic Community law with Directive 84/360/EEC (European Council Directive, 1984) and applied to air pollution emissions from large industrial installations, substituted in 1996 b y the Integrated Pollution Prevention and Control (IPPC) Directive 96/61/EC (European Council Directive, 1996), widening the scope of BAT to the integrated control of pollution in air, water, and soil. Directive 96/61/EC was further implemented in Directive (2008)/1/EC (European Parliament and the Council, 2008b) and finally led to the Industrial Emissions Directive 2010/75/EU (European Parliament and the Council, 2010). Presen tly over thirty different industries are listed among those for which the Directive 2010/75/EU applies, ranging from Chlor-alkali manufacturing to the polymers production industry, among others (BAT reference document 2020), and BAT are described in reference documents called BREFs (Best Available Techniques, 2019), as defined in article 3 (11) of the Industrial Emissions Directive and in the Commission Implementing Decision Law 2012/119/EU (European Parliament, 2012). The importance of BAT/BREF conclusions, according to article 14 (3) of the Industrial Emissions Directive, is that they define the best existing technical solutions available which should be adopted for new large industrial installations to achieve permit conditions.

The role that BAT/BREFs can play in reducing the impact of plastic pollution, clearly emerges from the recently updated BAT/BREF for food, drink and milk industries (FDM). The BAT/BREF reported "to ensure sustainability, the effects of the raw material supply, food processing, transport, distribution, preparation, packaging and disposal must be considered and controlled" and "The FDM sector complies with the requirements of the Directive 94/62/EC on packaging and packaging waste (Directive 94/62/EC, European Parliament and the Council 233 Directive, 1994) by preventing the production of packaging waste, and by reuse and recycling as well as by recovery of packaging waste" (BAT reference documents, 2020).

Of great relevance for the polymers and plastic industry is EU Regulation October 2011 (replacing Directive, 2002/72/EC) (European Commission, 2011b), regarding food contact plastic materials and objects, referred to as MOCA (Materials and objects allowed for food contact). The EU Regulation October 2011 has been subjected to constant revisions as for example EU Regulation 831/2018 and EU 2020/1245, which posed further limitations on materials allowed for food contact packaging (European Commission, 2018, 2020).

The Roadmap to Resource Efficient EU (European Parliament, 2011) was published in September 2011, and represented the first step towards designing a coherent framework cutting across different policy areas and sectors and has become a key action in the EU Green Deal strategy to make EU's economy sustainable by 2050.

In 2019, EU Directive 2019/904 (European Parliament and the Council, 2019a) on the reduction of the environmental impact of certain plastic products was approved. Most commonly known as the Single Use Plastic Directive (SUPD) conceived to minimize marine plastic pollution, promoting the production of re-useable items. It applies to products that are made wholly or partly from plastic and that are not conceived, designed, or placed on the market to accomplish, within their life span, multiple trips or rotations and are not returned to producers for refill or re-used.

In March 2020 the EC adopted the Circular Economy Action Plan COM (2020)98 (European Parliament, 2020a) aiming to implement 35 actions and engaging social economy for its development: "Between 2012 and 2018 the number of jobs linked to the circular economy in the EU grew by 5% to reach around 4 million. Circularity can be expected to have a positive net effect on job creation provided that workers acquire the skills required by the green transition. The potential of the social economy, which is a pioneer in job creation linked to the circular economy, will be further leveraged by the mutual benefits of supporting the green transition and strengthening social inclusion". The Green transition has been further underlined by the European Parliament in the Action Plan (European Parliament, 2020b), where it "calls on the Commission to ensure that the Circular Economy Action plan is linked to implementation of the European Pillar of social right and gender equality strategy and to ensure a just transition; it stresses also the crucial role of social partners in work-related and social aspects of the shift to a circular economy". Additionally, the New Industrial Strategy for Europe COM (2020)102 (European Parliament, 2020c) defined the policy to become more competitive, greener, and circular, passing through secure supply chain of clean-affordable energy and raw/-secondary materials, complying the highest social, labour, and environmental EU standards.

In 2020 the EC also adopted new rules on the export, import and intra-EU shipment of plastic waste. These new rules banned the export of plastic waste from the EU to non-OECD countries, except for clean plastic waste sent for recycling (European Parliament, 2020d). Exporting plastic waste from the EU to OECD countries and imports in the EU will also be more strictly controlled.

The EUis also gradually turning away from Waste-To-Energy (WTE) strategies with major European financial institutions excluding it from financial support. Waste incineration is a carbon-intensive process, discouraging waste prevention and recycling and undermining the efforts to decrease GHGs to reach carbon neutrality.

The existential threat posed by climate change pushed the EU and the Member States to enhance initiatives in favour of climate actions, approving the European Climate Law 2021/1119 (European Parliament and the Council, 2021a) that established the framework to achieve climate neutrality (amending Regulations (EC) No 401/2009 and (EU) 2018/1999, European Parliament and the Council, 2009, European Parliament and the Council, 2018c). Climate actions strengthened by EU directives and laws to help secure EU leadership in global innovation, for all the economic sectors.

The European Climate Law sets a legally binding target of net zero GHG emissions and addresses the targets to be reached by 2050, and in particular.

- 55% net reduction by 2030 of GHG emissions compared to 1990
- Carbon neutrality within 2050
- Commitment to negative emissions after 2050
- Promote stronger provisions on adaptation to climate change
- Promote strong coherence across Union policies with the climate neutrality objective
- Commitment to prepare sector-specific roadmaps setting the path to climate neutrality in different geographical areas.

As a consequence, very important limitations are imposed on some occasions, generating heavy consequences at industrial level and for the market (see section 4).

In 2021 the European Commission further approved EURegulation 2021/783 (European Parliament and the Council, 2021b), in order to facilitate and promote coherence among different project activities and initiatives at regional, national, and international level, to create synergies and to support the uptake and replication of environmentally and socio-economic sustainable solutions. All the initiatives are supported by several entities such as public and private European, National, and regional associations, public administrations, policymakers, and NGOs.

The year 2022 has ended with the proposal of a regulation by the European Parliament on packaging and packaging waste (PPWD, COM (2022) 677) (European Parliament and the Council, 2022b) amend ing EU Directive 2019/904 (European Parliament and the Council, 2019a), EU Regulation 2019/1020 (European Parliament and the Council, 2019b), Directive EU/2018/852 (European Parliament and the Council, 2018b) and repe aling Directive 94/62/EC (European Parliament and the Council, 1994).

The PPWD directive focuses on strengthening and standardizing among Member states measures to prevent packaging waste through a series of requirements for producers and distributors, aiming to reduce packaging, by means of recycling, reuse, and eco-design. In this connection, COM (2022) 677 begins stating the reasons for and objectives of the proposal as follows: "The Packaging is necessary to protect and to transport goods. The manufacturing of packaging is also a major economic activity in the EU. However, regulatory approaches differ from one Member State to another, which creates obstacles that prevent the internal market for packaging from fully functioning. Differences relate, for example, to packaging labelling, strategies for recyclable or reusable packaging, approaches to extended producer responsibility (EPR), fees and marketing restrictions for certain packaging formats. Such discrepancies create legal uncertainty for businesses, leading to lower investment in innovative and environment-friendly packaging and new circular business models". Further COM (2022) 677 states: "Packaging is .... One of the main users of virgin materials (40% of plastics and 50% of paper) and accounts for 36% of municipal solid waste. The increased use of packaging coupled with low reuse and recycling rates hamper the development of a low-carbon circular economy". From 2012 till 2020, the share of unrecyclable packaging has grown significantly (IPCC report, 2022; EU law portal, 2021; EU taxonomy for sustainable activities). Furthermore, technically recyclable packaging is often not recycled because the processes needed for its collection, sorting and recycling are not available or economically inconvenient.

All this in mind, targets for all Member states have been established for packaging and plastic recycling according to PPWD, which are.

- By December 31st, 2025, at least 65% weight of all packaging waste must be recycled.
- By December 31st, 2030, at least 70% weight of all packaging waste must be recycled.
- By December 31st, 2025, at least 50% weight of all plastic waste must be recycled.
- By December 31st, 2030, at least 55% weight of all plastic waste must be recycled.

By doing so the EC makes a fundamental step in preventing post-consumer mismanagement, responsible for over 40% of non-recyclable plastics, and promotes the adoption of unambiguous, consistent, and unique labelling for packaging all over the EU. Moreover, within the PPWD and COM (2022) 682 (European Parliament and the Council, 2022c), sp ecific indications on the framework for setting eco-design requirements for sustainable bio-based, biodegradable and compostable plastics are given. A number of conditions need to be met for bio plastics to have positive environmental impacts. In particular, biomass used to produce biobased plastics must be sustainably sourced, with no harm to the environment and in respect of the 'cascading use of biomass' principle, which favours the use of agro-industrial waste or by-products as feedstock. In addition, to fight greenwashing and avoid misleading consumers, producers need to avoid generic claims on plastic products such as 'bioplastics' and 'biobased'.

3.4. *The Agenda 2030 and EU green deal*

In 2015, all European Member States adopted the Agenda 2030providing a shared standpoint for peace and prosperity for people and the planet. The Agenda 2030 highlights 17 Sustainable Development Goals (SDGs) based on 169 targets (Fig. 5) (ONU Agenda 2030). Ambitious climate policies, economic development, education, technological progress, and less resource-intensive lifestyles, are crucial elements of the 17 goals, which are divided in four main pillars. Goals 1 to 7 fall under the social pillar of sustainable development. These refer to household targets, no poverty, nutrition, health, education, gender, clean water and sanitation and access to sustainable energy. Goals 8 to 12 fall under the economic pillar and provide targets for the economy in terms of decent work, economic growth, innovation, infrastructure, income inequalities, sustainable cities, and responsible consumption and production. Goals 13, 14, and 15 form the environmental pillar and provide targets for the care of our planet in terms of climate, life under water and land. Goals 16 and 17 refer to governance goals and specifically peace, institutions, and Global partnerships to pursue and achieve the SDGs goals. Each goal contains a list of tasks which came into effect on the January 1, 2016 and will guide decision making over a period of 15 years.

Analysing the Agenda focusing on polymers and the plastic industry, the most relevant points are.

- SDG 12: "Ensure sustainable consumption and production patterns by reducing industrial waste production, water consumption and substituting fossil-based polymers with highly sustainable bio-polymeric ones" with particular attention to targets 12.2 to 12.5 on the achievement of sustainable management and efficient use of natural resources, development of environmentally sound management of chemicals and all wastes throughout their life cycle, reduction of chemicals release to air, water and soil, reduction of waste generation, in favour of recycling, and reuse.

SDG12 is one of the most relevant points for the plastic industry because it wants to guarantee sustainable models of production and consumption, in favour of people's well-being and with a view to a circular economy (see also section 4.1).

- SDG 13 & 14: "Take urgent action to combat climate change and its impacts" and "Conserve and sustainably use the oceans, seas and marine resources for sustainable development".
- SDG3&8: "Ensure healthy lives and promote well-being for all at all ages promoting a social and inclusive model, wealth of depressed people and geographical areas, inclusive and sustainable economic growth, full and productive employment, and decent work for all". Because of the development on innovative processes and products from different feedstocks with wide geographical availability and promoting the development of new jobs there are positive feedbacks inherent with SDG3&8.

- SDG 9: "Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation". For the plastic industry particular attention should be given to targets 9.5 on scientific research and technological capabilities of industrial sectors, and 9.1 on reliable infrastructure to support economic development and human well-being. Virtuous examples within SDGs adopted by the plastic industry have been reported in section 4.1.

In 2015 the EU also launched the EU's Circular Economy Action Plan (CEAP) a comprehensive body of legislative and non-legislative actions with the intent to shift EU economy from a linear to a circular model. The Action Plan mapped out 54 actions, as well as four legislative proposals on waste, included targets for landfill, reuse, and recycling, to be

Fig. 5. Sustainable development goals (SDGs) of ONU 2030agenda.

met by 2030, along with new obligations for separate collection of textiles and biowaste (European Commission, 2015).

In 2018, Europe gave one of the major spurs to self-responsibility on post-consumer waste disposal, approving both EU directive 2018/851 (European Parliament and the Council, 2018a) on wa ste, and EU directive 2018/852 (European Parliament and the Council, 2018b) on packaging and packaging waste. The former laid down the rules for waste management systems where the municipalities have the general responsibility for collecting municipal waste. The latter set the measures aiming to prevent the production of packaging waste, promoting packaging reuse and recycling together with other forms of waste packaging recovery to reduce their final disposal. EU directive 2018/852 has been further amended in 2022 (see above).

3.5. Monitoring tools and labelling

The need to make economy truly circular, adopting sustainable production and consumption models, leads to the introduction of new measuring tools focusing on the whole environmental impact of products and processes by life cycle assessment (LCA) from "cradle to grave", preserving resources, reducing GHGs emissions, and closing the loop (Van Fan et al., 2023; Mallick et al., 2023; Das et al., 2023).

In order to compare and quantify the sustainability of a new product or process compared to conventional industrial practices, the EU has implemented various tools and reference documents (BAT-BREF). Other than that, within the Legislative framework above described further important tools such as Life Cycle Assessment (LCA), Environmental Product Declaration (EPD), Product Environmental Footprint (PEF), ECOLABEL, Green Public Procurement (GPP), have been devised and regulated giving adequate means to the industry, the scientific community, and end users to compare and chose best products (Fig. 6).

More in detail, we can specify that.

- **BAT-BREF**: Best Available Techniques Reference Documents (BREFs) are a series of documents covering, as far as is practicable, the industrial activities listed in the European Directive 2010/75/EU (IED, see above, European Parliament and the Council, 2010).
- **LCA, LCI, LCIA, LCC sLCA:** Life Cycle Assessment (LCA) is an internationally standardised methodology (UNI EN ISO 14040:2021 and UNI EN ISO 14044:2018) introduced to assess the environmental impacts and resources depletion throughout the entire product's life cycle, considering the impact within pre-determined specific environmental issues (Finnveden et al., 2009). LCA originated in the 1960s and 1970s in the energy industry, but evolved in time, and is now commonly applied to products, processes, or services (McManus and Taylor, 2018). In order to carry out a comprehensive LCA, inputs (resources and energy consumption) and outputs (pollutants and wastes) must be accounted for to determine impacts on the environment, human health, or biodiversity (Banti et al., 2020; Muralikrishna and Manickam, 2017). Thus, LCA is a powerful tool to identify products and processes with least negative impact and is a means to achieve further environmental certifications (EPD, Eco label).

Fig. 6. Environmental Product Declaration (EPD), Footprint (PEF), ECOLABEL, Green Public Procurement (GPP) labels. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Along with LCA, other two indicators are taken into account for a complete evaluation: Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA). Life Cycle Inventory is the collection and analysis of environmental interventions data such as primary resource consumption, air emissions and waste generation consumption, which are associated with a product from "cradle to grave" starting from extraction of raw materials, impact of production and use, up to final disposal, including recycling, reuse, and energy recovery.

The analysis of the costs of the environmental impacts associated with goods and services or externalities is an important phase for anyone wishing to implement the GPP policy in a structured and formalized way. Article 96 of the Procurement Code and subsequent amendments specifically refer to life cycle costing allowing to evaluate costs along the entire life cycle of the product. sLCA is a social and socio-economic Life Cycle Assessment aiming to evaluate the social and socio-economic aspects of products and their positive and negative impacts along the entire life cycle, including the extraction and processing of raw materials, production, use, reuse, maintenance, recycling and finally disposal.

- **EPD, PEF, ECOLABEL** are voluntary certifications, and are powerful tools to:

i) communicate sustainable product performance to customers/end-consumer through a recognized, systematic approach.

ii) Demonstrate leadership by performing a product environmental footprint to fulfil buyers' requirements. Only 10%–20% of the products currently on the market can meet the criteria required by Ecolabel (https://environment.ec.europa.eu/topics/circular-economy/eu-ecolabel-home_en) requirements in accordance with the ISO standard 14,024, one of the most reliable ways to communicate environmental information to consumers. Not all products can be certified ECOLABEL, and a specific product catalogue is available online (https://ec.europa.eu/environment/ecolabel/products-groups-and-criteria.html).

- **Green Public Procurement (GPP):** is a voluntary instrument, which helps stimulate demand for sustainable goods and services, otherwise difficult to market. The level of compliance with GPP criteria can be measured and evaluated in the qualification processes, monitoring of suppliers and the selection of services and products, with specific operating procedures for purchasing category or sub suppliers (LCA, carbon, water footprint) (https://ec.europa.eu/environment/gpp/index_en.htm).
- **Product Environmental Footprint (PEF):** project environmental impact is a recognized method for the calculation of a product environmental footprint. Since 2011, the European Commission has worked towards the development of a harmonized methodology for the calculation of the Products Environmental Footprint (PEF). 2013/179/EU guidelines provide requirements on how to calculate a PEF as well as on how to create product or sector-specific methodological rules. Environmental Footprint Category Rules will be used for comparisons between products or between organizations (European Commission, 2013).

As far as labelling is concerned, although identification of polymers was first mentioned in 97/129/EC (European Parliament, 1997), labelling became mandatory only with Directive 2018/852 (European Parliament and the Council, 2018b). F or what concern traditional plastic packaging, each material is identified by the numbering and abbreviations, enclosed in the Mobius symbol (see Fig. 7 a). Although, this symbol refers to recyclability, if paired with the number 7 without

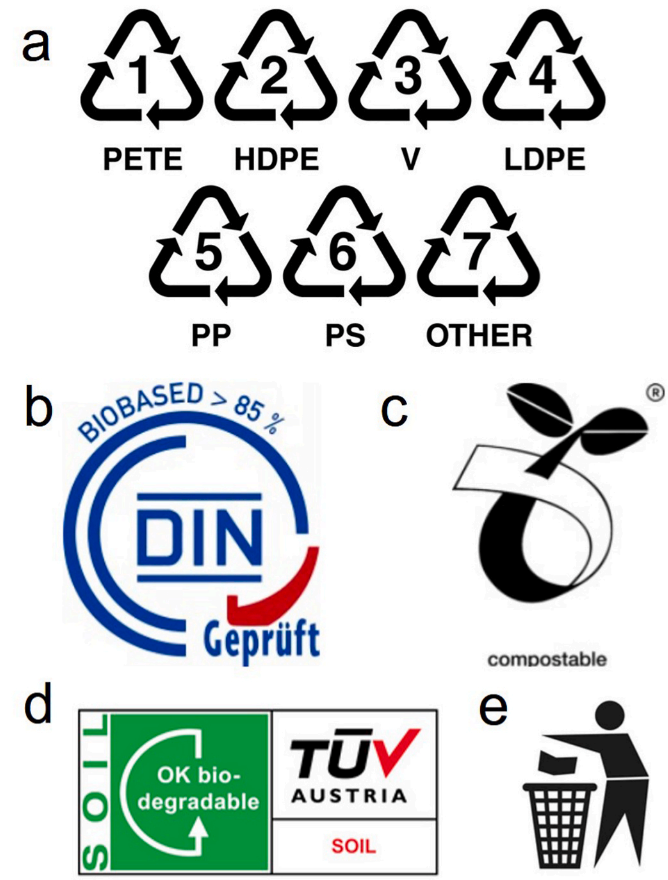

Fig. 7. The biobased label by a) Mobius symbols for polymer identification, b) DIN CERTCO, c) EUBP Seedling, d) OK biodegradable SOIL by TUV Austria Belgium and e) Avoid release into the environment.

any specification of the polymer, it means that the product/component is not recyclable.

On the contrary, the EU is lacking a directive for biobased plastics labelling and producers have no obligation to disclose the exact amount of bio-based materials with consequent unharmonized labelling. Nevertheless, European Bioplastics has compiled a comprehensive Environmental Communications Guide (European bioplastics report, 2023) providing general recommendations and specific guidelines communicating environmental claims for bioplastics. The Seedling is a reliable label for compostability (Fig. 7). The certification process is offered by Belgian certifier TÜV Austria Belgium and German certifier DIN CERTCO. Biodegradable and compostable products should be certified according to EN 13432/14,995 standards (European standard EN 13432, 2002, European standard UNI EN 14995: 2006).

In this direction, further steps have been made by the Italian Ministry of Environment and Energy Security by Legislative Decree 152/2006 art. 219 paragraph 5 Italian Legislative Decree 2022(https://www.gop.it/doc_pubblicazioni/1017_q3780zbgs8_cn.pdf), which entered into force from January 1, 2023, for the adoption of "Technical guidelines for the environmental labelling of packaging", to help Italian companies provide the environmental characteristics of their packaging in a clear and correct manner, while at the same time increasing consumer awareness of the final fate of packaging waste.

The guidelines implement the indications of the European Commission on the matter of strengthening the use of digitization of labels, facilitating the updating of the information, and avoiding market barriers. It is a unique technical support tool in the European panorama that can be presented as a virtuous example, for the method used and for the technical contents. The indications in question do not apply to drugs and medical devices for which sector legislations already establish specific obligations.

4. Socio, economic and environmental impact of EU directives and laws

According to COP 26 and COP 27 (Climate Change Conference, 2021,Climate Change Conference, 2022) ONU and EU reaffirmed the long-term goal of restraining global average temperature within 1.5 °C of pre-industrial levels, reaching carbon neutrality by 2050, in line with the 2030 Sustainable Development Goals and the Paris Climate Agreement objectives (ONU Agenda, 2030, Climate Change Conference, 2015).

In consideration of the conclusions of COP 27, the EC is setting higher limits to contain global warming and in January 2023 proposed to make packaging fully recyclable by 2030 (https://www.eea.europa.eu/about-us/climate-advisory-board/setting-climate-targets-based-on). If these goals have to be achieved, eco-design of new packaging, together with mandatory deposit return systems and reusable packaging for plastic bottles and aluminium cans must be implemented, removing unnecessary packaging, limiting over-packaging, and providing clear labels to support correct consumers disposal. In principle, recycled materials should decrease the need for virgin materials, boosting Europe's recycling capacity as well as making Europe less dependent on primary resources and external suppliers. Development of recycling facilities will also foster local growth by re-internalizing employment within a territory. Typically, a plant producing about 50,000 metric tons of recycled plastic will employ around 30 people. This is significantly more jobs than those generated by sending an equivalent amount of waste to landfill or incineration, or by the petrochemical industry synthesizing an equivalent quantity of virgin polymer. However, because plastic waste recycling systems are more complex than traditional waste processing systems, this leads to higher waste management costs. This additional cost has to be covered by producers and consumers of plastic goods through extended producer responsibility (EPR) (https://ec.europa.eu/commission/presscorner/detail/en/ip_22_7155, D'Ambrières, 2019).

EU interventions on packaging reuse and recycling are estimated to reduce packaging waste of about 37% by 2040 compared to 2018. Additionally, GHG emissions are bound to decrease to 43 Mton compared to 66 million and environmental damages from human actions are estimated to be reduced by €6.4 billion by 2030 (https://ec.europa.eu/commission/presscorner/detail/en/qanda_22_7157).

The EU commission is aware that the packaging industries will have to invest into a transition, but the overall economic and job creation impact in the EU is considered to be, on the whole, positive. Boosting reuse alone is expected to lead to more than 600,000 jobs by 2030.

On the other hand, according to European Plastics (2022)report and K 2022, the biggest international trade fair of the global plastics and rubber industry, the plastic industry is facing "increased instability, higher prices, and lower growth" (K, 2022, IPCC report, 2022). The EU plastics industry is struggling against increasing limitations especially concerning packaging, which is by far its biggest market.

On the October 30, 2022, Sole 24 ore, wrote (Sole24ore, 2022): "In Italy there are over 700 thousand companies that risk being overwhelmed by the proposal for a European regulation on the management of packaging that the Commission will have to present soon. A new regulation, …. Which freezes the packaging recycling strategy to focus on reuse. In fact, the change of strategy affects the country system which has a European primacy in the recycling industry. Among producers, industrial users and traders, the European turnaround has in fact a possible impact on 6.3 million employees and on a productive world that has a turnover of 1850 billion euros …. The Commission's proposal focuses on the short supply chain, on the reduction and elimination of packaging, on bulk, on containers to be reused. All aspects that are not said to be more sustainable and effective than the already operational

Italian model".

Adversely, according to the Ellen MacArthur Foundation reuse is a four business-to-consumer models which are summarised as i) refill at home; ii) refill on the go; iii) return from home; iv) return on the go (https://ellenmacarthurfoundation.org/upstream-innovation/reuse). If the at-home models (for example cleaning products to be refilled) and reuse can be implemented with relatively modest behaviour change from consumers, other strategies such as on the go models (for example returnable beverage cups) require new infrastructures at large scale (The World Economic Forum's Platform, 2021).

Moreover, packaging reuse in alternative to recycling is well known to pose difficulties especially for food packaging. In a paper recently published by Nahar and co-workers (Nahar et al., 2022), the authors report that cleaning of rPET using current industrial protocols was inadequate for food packaging due to scarce reproducibility, high costs and packaging suffering significant deformation.

Today there are still different, often opposite, opinions on whether packaging contributes to reduce food waste or not. According to plastics Europe "plastic packaging, offers an ideal solution to help combat food waste, providing numerous resource-efficient options to deliver food of the highest quality and with maximum shelf-life … significantly reducing food waste, energy consumption and the resources used" (IPCC report, 2022). Of opposite opinion is the plastic soup foundation which reports that five different food-packaging were tested and showed no significant improvement in shelf life enhancement. Moreover, they consider the food industry responsible for over 40% of plastic production, impacting on costs and GHG emissions (Plastic Soup Foundation, 2022).

In this complicated and chaotic panorama, further implications come from the recycling of packaging. In fact, especially for food packaging applications, recycled plastics are not always adequate as they may have different physical characteristics, odour, or colour (Geueke et al., 2018). It is important to include these constraints during product development, implying that replicability of industrial processes using recycled plastics is not guaranteed. Plastic manufacturers are facing the task of including recycled plastics in products and at the same time need to meet technical and specific food-contact requirements necessary for the market.

On this delicate matter in December 2018, the European Commission launched the Circular Plastics Alliance (CPA) (Circular Plastics Alliance, 2018), mobilizing all players in the plastic value chain, from plastic producers and designers, through brands, retailers, and recyclers. Further, in August 2022 the EC notified to the European Committee for Standardization (CEN) and the European Committee for Electrotechnical Standardization (CENELEC, 2022) the need to develop a new standardization on plastics recycling and recycled plastics, to facilitate use of recycled plastics. To reach this goal, a series of actions have been undertaken, promoting design-for-recycling, and setting standards on the quality of recycled plastics.

In order to protect the recycling sector from crude oil price volatility, measures were adopted by the European Parliament making, for example mandatory for beverage containers to contain at least 35% recycled plastic by 2025 (European Parliament and the Council, 2018c; European Parliament and the Council, 2018dd), generating a market for recycled plastic. Unionplast, representing Italian plastics processing companies, in 2021 reported "the crisis in energy prices is seriously affecting a sector that has over 5000 companies, and more than 100,000 employees" and concluded "the uncontrolled increase in energy costs and the growing difficulty in finding raw materials is a deadly mix for our sector and creates the real risk of not being able to meet the demands of our customers. This situation has inevitable consequences also on the prices of our products" (Plastics Business, 2022). Thus, in many respects the recovery and reuse of packaging together with the reduction of unnecessary packaging offers many opportunities both from an economic and an environmental point of view.

However, the contraction of the plastics market, as a consequence for example of the SUPD, entails major economic and social problems for some industrial sectors and Member states. The biggest controversy of the SUPD lies in paragraph 11 of the Directive, more specifically in the definition of "chemically modified bio-based polymers". The Directive, in fact, poses equivalent limitations to plastics manufactured from fossil, or bio-based feedstock if the final product has been obtained by chemical modification. This implies that bio-based biodegradable plastics are prohibited similarly to fossil-based plastics regardless of the fact that they are derived from biomass or are biodegradable.

Although the intent of the Legislator was to reduce marine littering, the decision to assimilate fossil-based plastics and "chemically modified biobased polymers" has in fact brought the packaging industry in panic. The reason is that all best performing bio-based polymers such as polybutylene succinate (PBS), polylactic acid (PLA), polyhydroxyalkanoate (PHA) among others are all chemically modified (Beghetto et al., 2021a; Visco et al., 2022). It could be that the legislator intent was to accelerate the transition from fossil-based to bio-based polymers, but it may also be possible that alternative products to fossil-based manufacts banned by the SUP directive (EU) 2019/904 will not be available for some time. Some member states have transposed the SUPD even before the draft finalization, with a resulting unharmonized implementation across the EU. Still today there is confusion and concern among consumers, policy makers and within the industry on this argument (European Parliament and the Council, 2019a).

Another outstanding example of conflicts among Member States is the PPWD Regulation, in which the European Commission sets targets, regardless of strategies and investments developed in the years by Member states regarding packaging management and recycling (mechanical, chemical, and organic). With this measure, in fact, the Commission specifies actions to be adopted at National level for the achievement of new objectives, both in the management of packaging waste, and in packaging design. The final draft proposal of PPWD identifies the Deposit Return System (DRS, Art 43, 44 and Annex III, European Parliament and the Council, 2022b) as the only return system that countries should implement by January 1, 2028 for single use plastic packaging and metal beverages containers, with the only exception of countries reaching 90% of recycling. To date, DRS remain to be implemented throughout the EU.

4.1. Plastic industry actions towards net zero emissions by 2050

Within the EU framework directives, the plastic industry is trying to implement present and future strategies aiming to achieve climate neutrality by 2050. From an industrial point of view, the problem of achieving carbon neutrality by 2050 has both socio-economic and business implications which are generally being addressed with two different and complementary macro strategies: i) development or implementation of sustainable products and processes; ii) conscious and informed communication of the socio-economic environmental strategies adopted.

Regarding the first macro strategy, the plastic and polymer industry is taking different actions to reach carbon neutrality within 2050. It is important to underline that there is not one right solution but many different strategies, which should network and collaborate. An important document recently released by SYSTEMIQ (SistemIQ, 2022) identified up to five drivers that could help industry, decision makers and civil society find an effective pathway towards a highly circular, low-carbon emission plastics system. This in mind some of the most relevant actions undertaken by the plastic industry today to achieve carbon neutrality are listed and discussed below.

- Implementation of plastic recycling: In agreement with the Alliance to End of Plastic Waste (AEPW), setting as mandatory 30 wt% recycled content for plastic packaging by 2030(Plastic Europe, 2021b), different plastic producers are supporting the reduction of plastic waste through the use of recycled content, achieving lower carbon footprint through the use of recyclable and renewable plastics, as compared to feedstock from virgin fossil-based sources (https://endplasticwaste.org/). In the section "changing plastics for good" of Plastics Europe an increasing number of virtuous industrial case studies are reported, that span from circularity, climate, sustainable use, innovation, plastics and health (Plastic Europe, Changing Plastics for Good). For example, Borealis is replacing traditional feedstock with a sustainable alternative (Bornewables™) for the production of a portfolio of circular polyolefin products, manufactured with second-generation renewable feedstock derived solely from waste and residue streams. As part of the measures of REset Plastic, the Schwarz Group (Lidl and Kaufland) has committed to reducing by 20% plastic consumption by 2025. Many other solutions have been proposed by big companies such as Yoplait, Ineos, Covestro, Corbion, LyondellBasell, Samsonite, Loreal testifying the great effort which the industry is devoting to achieve sustainable products and processes for a better future for generations to come (Plastic Europe, Changing Plastics for Good).

- Eco-design, within the boundaries of circular economy, is another powerful tool to boost recyclability of products which today are incinerated. In this context, within the plastic and polymers value chain, different initiatives have been undertaken by the manufacturing industry to mitigate the impact of End of Waste products. For example, two important sportswear and footwear companies recently announced the development of innovative fully recyclable running shoes and sky boots (Adidas, Tecnica Group). The textile and apparel industry, sadly known for the tremendous environmental impact (European Parliament News, 2022), is pushing to improve products circularity by different undertakings, such as collection and recycling of end of waste clothes, and eco-design, in agreement with the EU Strategy for Sustainable and Circular Textiles ((European Commission, 2022)). In this panorama, new NIR (Near-Infrared) detectors are playing an important part in developing new optical methods for the separation and recovery of different natural, synthetic and mixed textiles (Fibersort,) Spectral Engines Bolg, 2020). Further, an increasing number of companies offer to the textile and apparel companies the possibility to collect and recycle their production waste with an important reduction in net GHG emissions (see for example Nazena). Alternatively, marketplaces are available on the web where different plastic and polymer wastes may be put for sale and find a new life as secondary materials for different industries (Cyrklwaste market)
- Chemical recycling: Plastics Europe announced a significant increase in planned chemical recycling investment from 2.6 billion Euros in 2025 to 7.2 billion Euros in 2030. Chemical recycling is capable of processing plastic waste which would otherwise end up in incineration or landfill, producing recycled material with virgin plastic properties (see also section 3.1). This technology is essential to achieve 30% recycled plastics in packaging by 2030. In September 2020 LyondellBasell started up at Ferrara (Italy) one of the first semi-industrial prototypes for molecular recycling (MoReTec, molecular recycling technology), aiming to return post-consumer plastic waste to its molecular form to be used as feedstock to produce 2 Mt/year of recycled and renewable polymers by 2030.

These strategies should also be flanked by other strategies (Renewable Energy, process optimization), as Lucrèce Foufopoulos, Executive Vice President of Polyolefins and Circular Economy and CTO of Borealis stated "Based on a unique approach to the circular economy, we believe that embracing and investing in a hierarchy of technologies, ranging from mechanical to chemical recycling, delivers the optimum circular solution for the value chain with less impact on the environment. This approach will enable the plastics industry to achieve its ambitious recycling targets and will contribute to more sustainable living." (Plastic Europe, 2021a).

Regarding the second macro strategy, sustainability reporting is one of the most common tools used to communicate non-financial data concerning environmental, social, economic and governance issues in the broadest sense, referred to as Environmental, social and corporate governance (ESG, Wikipedia portal), which is regulated by the Corporate Sustainability Reporting Directive (CSRD) (European Parliament and the Council, 2014). An increasing number of organizations are providing frameworks for sustainability reporting and are issuing standards to guide companies in this practice. In 2021 the EU commission opened a consultation to gain better insight on the functioning of ESG rating and contribute to achieve the European green deal goals by improving the quality of information on which industry, investors, and other stakeholders take decisions impacting the transition to a sustainable economy (https://finance.ec.europa.eu/regulation-and-supervision/consultations/finance-2022-esg-ratings_en).

In the EU, ESG and sustainability reporting is compulsory for listed companies, but during the years it has become a widely accepted methodology so that many companies are delivering sustainability reports on a voluntary basis (an example is CALZATURIFICIO S.C.A.R.P.A. spa). The use of EU monitoring tools such as LCA, Carbon Footprint, Ecolabel, EPD, PEF and other certifications constitute the framework to measure socio economic and environmental impact and achieve ESG certification.

At EU level these measures promote communication of "accountable, transparent and responsible business behaviour and sustainable growth, promoting society's interests and a route to sustainable and inclusive recovery" (European Parliament and of the Council, 2014), thus ESG and Corporate Social Responsibility are powerful tools, rewarding virtuous companies, generating market competitiveness. The commitment of different companies all along the plastics and polymers value chain clearly emerged from the 2023 Top-Rated ESG Companies List (Sustainanalytics, 2023), where companies dealing with containers and plastics (Billerud,(Klöckner Pentaplast Group,Adapa group www.kpfilmscm/), consumers durables (Thuele group), building products (BOAL group,), chemica(ls ()Covestro, food products (Heineken holding,), textiles & apparel (Kering group,), were among the top 50 best ESG rated companies of the year.

ESG has also become a crucial document to access financial tools, used by socially conscious investors to screen potential investments and companies adopting ESG rating are more likely to attract and retain talents thanks to their greater social credibility, stimulating employees' motivation (The World Bank Group, 2023). Additionally, OECD reported that adoption of ESG criteria has been found to have a positive impact on companies' financial performance and value (Baron, 2014; OECD, 2012).

5. Conclusions

In 2021 the IPCC reported that global warming is a consequence of human activities. In 2022 UN secretary-general António Guterres opened his speech at COP27 stating that humanity is "on a highway to climate hell with the foot on the accelerator" and continued "Humanity has a choice: cooperate or perish. It is a climate solidarity pact or a collective suicide pact".

Ultimately the scope of this paper is to give an overall idea of the complexity of the challenge we are facing today: whichever choice the legislator will make, it will inevitably generate consent and disagreement. Based on a practical example (polymers production, plastics manufacturing), a comprehensive review has been given, analysing how policies and regulations put in place to limit or restrain plastic pollution, generate many different socio-economic and environmental impacts and conflicts. If humanity wants to guarantee a future for generations to come, a clear dialog between the industry, scientists, policy makers, NGOs, citizens, and different stakeholders is required in order to work together to achieve the Agenda 2030targets by 2050.

As reported in this paper, the EU legislative framework, together with best practices adopted by industry and society bode well and a circular, net zero plastics system in Europe may be within reach.

Credit author statement

Valentina Beghetto: Conceptualization, Investigation, Writing – original draft, Writing - review & editing, **Manuela Facchin**, **Vanessa Gatto**: Data curation, Writing - review & editing, **Annamaria Visco**, **Riccardo Samiolo**: Data curation, Formal analysis, **Salim Brahimi**: Reviewing, Formal analysis, **Cristina Scolaro**: Supervision, Formal analysis.

Declaration of competing interest

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Data availability

Data will be made available on request.

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