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Review Article

Resource or waste? A perspective of plastics degradation in soil with a focus on end-of-life options



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Abstract

'Capable-of-being-shaped' synthetic compounds are prevailing today over horn, bone, leather, wood, stone, metal, glass, or ceramic in products that were previously left to natural materials. Plastic is, in fact, economical, simple, adaptable, and waterproof. Also, it is durable and resilient to natural degradation (although microbial species capable of degrading plastics do exist). In becoming a waste, plastic accumulation adversely affects ecosystems. The majority of plastic debris pollutes waters, accumulating in oceans. And, the behaviour and the quantity of plastic, which has become waste, are rather well documented in the water, in fact. This review collects existing information on plastics in the soil, paying particular attention to both their degradation and possible re-uses. The use of plastics in agriculture is also considered. The discussion is organised according to their resin type and the identification codes used in recycling programs. In addition, options for post-consumer plastics are considered. Acknowledged indicators do not exist, and future study they will have to identify viable and shared methods to measure the presence and the degradation of individual polymers in soils.

Abbreviations: ABS, acrylonitrile-butadiene-styrene; BPA, bisphenol A; DOM, dissolved organic matter; EPR, Extended Producers Responsibility; EPS, expandable

polystyrene; ETS, European Emissions Trading scheme; GPPS, Polystyrene (General Purpose); HBCD, hexabromocyclododecane; HDPE, high-density polyethylene; HMC, heat melt compactor technology; LCP, liquid crystal polymers; LDPE, low-density polyethylene; NHV, net habitable volume; PA, polyamide; PAC, pro-oxidant additive containing; PBT, polybutylene terephthalate; PC, polycarbonate; PEEK, polyaryletheretherketone; PET, polyethylene terephthalate; PHA, polyhydroxyalkanoate; PLA, polylactic acid; PMMA, polymethyl methacrylate; POM, polyoxymethylene; PP, polypropylene; PPA, polyphthalamide; PPS, polyphenylene sulphide; PS, polystyrene; PSU, polyarylsulfone; PTFE, polytetrafluoroethylene; PU or PUR, polyurethane; PVC, polyvinyl chloride; PVDF, polydifluoroethylene; RIC, resin identification code; TPE, thermoplastic polyester elastomer

Keywords: Environmental science, Biogeoscience, Industry, Microbiology

1. Introduction

The occurrence of plastics in soil, and hence their transfer to other environmental compartments, depends mainly on social trends and individual behaviour. An understanding of causes is essential for the design of measures against pollution. The main subject of this review is to describe the polymers degradation in soils; all this with the purpose of providing advice for the development of risk assessment tools in pollution and policies on plastics use. A special focus on plastics in agriculture, on its uses and on possible reuse, and on agronomic practices that influence the degradation of different polymers.

It is not possible to obtain reliable estimates of the amount of plastic debris that reaches the soil environment, but the quantities are nevertheless quite substantial. Compared to the hydrosphere, for which there are quantification methods, detailed and large-scale studies, and abundant studies on the degradation of these polymers in water (either freshwaters or seawaters) (Jambeck et al., 2015; Neu et al., 2018), on the pedosphere these information are rare, scattered and not homogeneous. The effort of this review is to collect and systematize existing knowledge on different plastic polymers and their behaviour in soils. The contemporary literature on the impacts of plastics on the soil environment is discussed by evaluating the significances of plastic use from the perspective of soil biogeochemistry, agronomy and the society.

2. Main text

2.1. Should plastics last or is it preferable them to self-degrade rapidly?

In the society of today, we have a tendency to take plastics for granted. However, the most widely used thermoplastic polymeric material, polypropylene, began to be

manufactured only sixty years ago (Andrady and Neal, 2009), when the Montecatini firm began large-scale commercial production of isotactic polypropylene. Plastics are robust by nature and tend to degrade minimally, nevertheless, their interaction with the natural environment does not exceed double the current global human median age: sixty years would be the maximum extension of the potential observation period, but studies on the behaviour of plastics in the total environment are much more recent (e.g., Sekine et al., 1966; Kinoshita et al., 1975). The progress of plastics manufacturing (Table 1) in the last few decades has significantly overtaken that of any other manufactured material. Following a global change in packaging from reusable to single-use containers, making containers has become the major market of plastics. The combination of single-use and low-cost containers has created an increase from less than 1% by mass in 1960 to more than 10% by 2005 in the share of plastics in municipal solid waste in middle- and high-income countries (Jambeck et al., 2015). Geyer et al. (2017) estimate that in 2015, 407 Mt of plastic manufactured from virgin materials (so-called primary plastics) was in the use phase, while 302 Mt became waste. The cumulative waste generation of primary and secondary (recycled) plastic waste totalled 6300 Mt; 600 Mt was recycled, only 10% of which was recycled more than once. While before 1980, recycling and incineration were almost insignificant.

Ten percent of the manufactured plastics enter the hydrosphere (Thompson et al., 2009; Ruiz-Orejón et al., 2016), 8–12.7 million metric tons of plastic (in prevalence polypropylene and polyethylene, Pietrelli et al., 2017) ended up in the marine environment (Jambeck et al., 2015), sometimes harmfully (MacAli et al., 2018; Lamb et al., 2018). When they are fragmented into small particles (normally less than 5 mm in diameter) they become microplastics. They come from multiple sources clothing, cosmetics industry, tires, and even wastewater treatment plants can be a point source of microplastics that pollute the water bodies (e.g., McCormick et al., 2014). However, similar estimates for other environmental sectors are not yet available globally (Bläsing and Amelung, 2018). But, at a continental level, 63,000–430,000 and 44,000–300,000 tonnes of microplastics could be being added

Table 1. Plastics from 1950 to 2015: global production, use, and fate. Unit is billion metric tons (MT).

	^a 10 ⁹ MT
primary production	8.3
in-use	2.6
recycled	0.6
discarded	4.9
incinerated	0.8

^aGeyer et al. (2017).

annually to agricultural soils in Europe and North America, respectively (Nizzetto et al., 2016a).

When introduced into the total environment, thermoplastics are not easily biodegradable, so they can last, almost intact, for prolonged periods of time. These polymers degrade by the effect of (sun)light, rain, wind and/or by biological breakdown. Their lifetime depends on both their chemical nature and the characteristics of the environment in which they are located. Compostable plastics, such as blended thermoplastic starches, can degrade within months (Pang et al., 2013) but will take significantly longer for other polymers (Andrady, 2003).

Plastics are rarely used by themselves: individual polymers are usually mixed with additives such as carbon or silica to strengthen the matter, thermal stabilizers, plasticizers, fire retardants, UV stabilizers, colorants, matting agents, opacifiers, or lustre additives. These additives can raise the possibility of adverse health issues, such as the case for plasticizers (e.g., Koch and Calafat, 2009; Oehlmann et al., 2009; Hahladakis et al., 2018) or in the case of black plastics (Turner, 2018).

Plastic materials have been invented to last. So, for the human interest, should plastics last when they enter the total environment, or is it preferable them to self-degrade? An action can certainly be addressed by employing those polymers which have demonstrated the greatest resistance to degradation as their use as recycled material is more competitive than waste-to-energy (e.g., Liu et al., 2006; Miao et al., 2013). In Austria, for instance, after sorting, one third of the total plastic waste from packaging is used by the cement industry, and one third re-granulates into raw materials (Van Eygen et al., 2018).

2.2. Similar but extremely different: polymers degrade differently, and can be recycled differently

Plastic materials are distinguished into different classes (Klein, 2011); they can be recycled but they must be mandatorily reprocessed separately (Hopewell et al., 2009). Therefore, rising the number of recycling programs, the Society of the Plastics Industry issued the Resin Identification Code (RIC) to make it easier to sort out objects according to their resin type (ASTM, 2013). The symbols used as part of the RIC consisted of arrows that cycle clockwise to form a triangle that encloses a number, where the individual number refers to the type of plastic (Table 2): (1) polyethylene terephthalate (PET) (beverage bottles, cups, other packaging), (2) high-density polyethylene (HDPE) (bottles, cups, milk jugs), (3) polyvinyl chloride (PVC) (pipes, siding, flooring), (4) low-density polyethylene (LDPE) (plastic bags, six-pack rings, tubing), (5) polypropylene (PP) (auto parts, industrial fibres, food containers), (6) polystyrene (PS) (plastic utensils, cafeteria trays), and (7) other plastics, such as

Table 2. Type of polymers and individual recycling characteristics.

RI ¹	Type	^a Mold _{max} °C	^b Melt _{max} °C	Recycling	Recovery ^{2,3}	Key Issues
1	PET	163	200	mostly	flakes, drying, crystallizing, plasticizing and filtering, then converting in polyester fiber, strapping, and non-food containers, or depolymerized to monomers	high capacity recycling lines
2	HDPE	65	140	⊖	cascading, downcycling	
3	PVC		215	⊖	mechanical recycling or feedstock recycling	
4	LDPE	65	135	⊖	heating, floating, and sinking	
5	PP	65	170	⊖	melting, extruding, pelletizing	
6	PS	65	240	⊖		compactors costs
	EPS			⊖⊖	reprocessed granulating and recompressing, extruded to GPPS ⁴ pellets	transport costs
7	ABS	85	220	⊖	shredding and blending with virgin ABS	
	LCP			(⊖)	energy only	
	Nylon 6	120	220			
	PA			(⊖)	energy preferentially	
	PBT		225	(⊖)	energy only	
	PC	93	220	⊖⊖		
	PEEK			(⊖)	energy preferentially	
	PLA			⊖⊖	hydrolyses back into its monomer lactic acid or biodegrades in presence of oxygen and humidity, and the relatively high temperatures	
	PMMA		160	⊖⊖	thermal process (400 °C) and distillation or by direct reprocessing (PLEXIGLAS [®])	
	POM	100	175	(⊖)	energy preferentially	
	PPA			(⊖)	energy preferentially	
	PPS			(⊖)	energy preferentially	
	PSU			(⊖)	energy preferentially	
	PTFE			⊖		
	PUR			⊖⊖	mechanical: reused in its polymer form, chemical: oligomers for new polyurthanes	
	PVDF			(⊖)	energy preferentially	
	TPE			⊖⊖	shaping, (scrap) and finishing	

¹ Resin Identification Code (ASTM, 2013).

² Totally ⊖⊖, mostly/partially⊖, not recyclable⊖

³ according to PlasticsEurope.

⁴ General Purpose Polystyrene.

^a Greene (2014).

^b Belofsky (1995).

acrylic, nylon, polycarbonate (PC), polyurethanes (PU), and polylactic acid (PLA) (ASTM, 2013).

Experimental data on degradation of plastics in soils are few and rather scattered (Table 3) (Nikolic et al., 2014; Osman et al., 2017; Tachibana et al., 2010). Biopolymer degradation trials prevail but PET, PP, and PS also have been included in some experiments. And, in the RIC category 7, several polymers experienced a forced degradation condition trial, as well. In general, periods of incubation of these experiments span from one week to two years at temperatures normally higher than room temperature. The majority of experiments were run under aerobic conditions (da Luz et al., 2013; Khan et al., 2017; Setua et al., 2000; Shah et al., 2016; Tomita et al., 2003; Urayama et al., 2002). If, otherwise under anaerobic conditions, the oxygen source was derived from the organic material itself, the degradation was, generally, more effective, arriving at final products such as alcohols, aldehydes, organic acids or, even, carbon dioxide or methane. All the other parameters are, mostly, quite poorly described, including soil type. Few papers (Liu et al., 2017)

Table 3. Some experimental data on degradation of plastics in soils.

Polymer Type	Soil type	Biota	Incubation (days)	Aerobic degrad. (%)	Ref. Nr.
PP	Hapludalf	-	660	†1	1
PS	Hapludalf	-	660	†1	1
PET	Hapludalf	-	660	†1	1
PLA	-	<i>Pleurotus ostreatus</i>	45	10	2
PLA	soil for pottery	-	600	75	3
PP	Calcaric Cambisol	-	30	-	4
PS-graft-starch	soil rich in humus	-	150	55	5
PS	soil for cactus growing	<i>Penicillium</i> spp.	70	83	5
PS-starch	-	-	150	6	6
Nylon 4	composted soil extract	<i>Fusarium</i> spp. [#]	*50	100	7
Nylon 12	various	<i>Bacillus pallidus</i> strain 26	**7	35	8
Nylon (coated)	various	various	***90	3	9
PU films	various	<i>Aspergillus fumigatus</i> strain S45	***25	23	10
PU polyester	-	<i>Aspergillus tubingensis</i> ^{##}	***30	40	11

Reference Number: 1 Gómez and Michel (2013), 2 da Luz et al. (2013), 3 Urayama et al. (2002), 4 Liu et al. (2017), 5 Nikolic et al. (2014), 6 Tachibana et al. (2010), 7 Tomita et al. (2003), 8 Setua et al. (2000), 9 Osman et al. (2017), 10 Khan et al. (2017), 11 Shah et al. (2016).

[#] also *Stenotrophomonas* spp. is included.

^{##} also *Bacillus subtilis* MZA-75, *Pseudomonas aeruginosa* MZA-85.

* temperature 25 °C, **60 °C, ***>30 °C.

† anaerobic degradation <3%.

indicate a soil taxa, using the World Reference Base for Soil Resource or the U.S. Soil Taxonomy, the main acknowledged systems for soil classification. However, describing quite modal soils, *i.e.* those soils with characteristics that are not distinctive, or otherwise useful to be extrapolated to similar situations. Degradation rates for traditional polymers incubated within soils are generally low. The exception is an incubation experiment involving microorganisms isolated from soils that were found to degrade nylon 4, a typical synthetic polyamide (Tomita et al., 2003) or a burying experiment of PS-graft-starch copolymers in indecipherable soils ‘rich in humus, for cactus growing, and for orchid growing’ (Nikolic et al., 2014), or PLA buried, in lab conditions, under commercially available soil for pottery (clayey, hypothetically) (Urayama et al., 2002). These highly qualitative descriptions do not allow these experiments to be replicated, or that the results can be extrapolated to real situations.

2.2.1. Polyethylene terephthalate (PET)

Selke et al. (2015) conclude that there is no reason to think that PET could experience substantial degradation when exposed for longer periods of time to the same pedo-environment. These conclusions come from buried PET sheets at a 45 cm depth within a sandy soil that do not fragment or degrade after 3 years. Shorter period trials evidenced, however, a changing in soil biological activity: an increase in enzymatic activities (lipase, protease, cellulase, and dehydrogenase) during the first week of laboratory-scale and full-scale composting conditions (Voběrková et al., 2017) or a physical translocation of microplastics operated by collembolans (Maaß et al., 2017).

As it is unmanageable to remove all plastic fragments from soils, a shared resolution can originate from two distinct needs; repairing paths and disposing of old containers. For instance, converting plastic waste into cement-like materials. Soft-drinks bottles and some other forms of packaging made with PET typically contain that one type of plastic only, which makes them easy to recycle. Mixing with crushed rock or recycled material from former roads and buildings can result in a material similar to concrete, asphalt, or mortar composites (Jacob-Vaillancourt and Sorelli, 2018). The resulting, more flexible and resistant to shocks, material might show remarkable acoustic insulation characteristics (Okoro et al., 2011; Badache et al., 2018).

2.2.2. High-density polyethylene (HDPE)

The cheapest and highest volume synthetic polymer is polyethylene, which worldwide is factory-made on a quantity of 100 million tons per year (Schneiderman and Hillmyer, 2017). HDPE, characterised by its large density to strength ratio and resistance to many different solvents, is frequently recycled. HDPE is chemically similar to LDPE but has stronger intermolecular forces and tensile strength (*i.e.* little branching). HDPE has benefited from rumours about potential

environmental issues associated to bisphenol A (BPA), a xenoestrogen used to produce other polymers, PVC and PC, and epoxy resins. HDPE degrades absorbing solar UV radiation, undergoing photolytic, photo-oxidative, and thermoxidative reactions (Andrady, 2011). This happens in the oceans (Lebreton et al., 2018; Romera-Castillo et al., 2018) but quite unlikely in soils where it is quite steady. However, its stability can be exploited rather than suffered. For instance, as in the case of PET, post-consumer plastic waste incorporated in concrete ameliorates the final product, on both a short- and long-term perspective, giving properties like creep, chemical resistance, drying shrinkage, or tensile strength (Jassim, 2017).

2.2.3. Polyvinyl chloride (PVC)

PVC is particularly stable in soil, but its weathering can cause surface embrittlement and microcracking, yielding microparticles and microplastics, stable as well (Rillig, 2012). These polymers are not degradable in soil but, apart microplastics, another risk is the release of ethers of the phthalic acid, commonly known as 'phthalates', plasticisers that are largely used in the production of PVC (Pivnenko et al., 2016; Zhang et al., 2018a). In soils, due to their high lipid affinity, phthalates are not normally retained by the mineral components, whereas they can accumulate where (alive or dead) organic matter is abundant (Haarstad and Borch, 2004; Šýkorová et al., 2011).

2.2.4. Low-density polyethylene (LDPE)

LDPE is resistant to acids, alcohols, bases, and esters but is made unstable by strong oxidizing agents, aliphatic and aromatic hydrocarbons, and particularly haloalkanes.

Medium term studies (10 years) conducted by Albertsson and Karlsson (1988) on 0.02–0.16 mm LDPE films have shown that without oxidation additives only evolved 0.2% wt. of CO₂, while irradiated with UV sensitizer they lose some percentage of weight in a few weeks. Similar results were obtained by Selke et al. (2015), who concluded that for films 3 years is a very short degradation time. Considering biota as an LDPE degrading agent, fungus *Fusarium* can adhere provoking surface damage (Shah et al., 2008) while *Lombricus terrestris* can transport it physically and selectively by size throughout soil (Huerta Lwanga et al., 2017). The oxidation of LDPE (and HDPE) by microorganisms was also shown by Chiellini et al. (2007).

2.2.5. Polypropylene (PP)

Polypropylene is analogous to polyethylene, with higher mechanical properties and thermal resistance (below 100 °C), but a lower chemical resistance to strong oxidants and nonpolar solvents. Nevertheless, PP resists the action of non-oxidizing acids and bases, to fats and organic solvents. In terms of biodegradation, microbial

communities can damage PP (Cacciari et al., 1993), but also stimulate soil enzymatic activity (Correia et al., 2015; Liu et al., 2017); for instance, in a Calcaric Cambisol, one-month accumulation of PP microplastic increases dissolved organic matter (DOM), including NO_3^- , and PO_4^{3-} in the soil solution.

From the point of view of reutilisation, PP fibres can efficiently increase the strength of cement treated clay (Chen et al., 2015). Soil reinforced by fibres is a geotechnical engineering technique that has gained consideration because the insertion of synthetic fibres has been demonstrated experimentally to increase the soil shearing behaviour, due to the mobilisation of the tensile strength of fibres at larger deformations (e.g., Li and Senetakis, 2017). This technique can improve the liquefaction resistance of soils (e.g., Liu et al., 2011).

2.2.6. Polystyrene (PS)

Polystyrene is resistant to both acids and bases, nevertheless, it can be affected by chlorinated and aromatic solvents. It is quite harmful to the soil environment as it can hinder the existence of earthworms (Cao et al., 2017) or contaminate with hexabromocyclododecanes (HBCDs), molecules used in extruded (XPS) and expanded (EPS) polystyrene foams (Gao et al., 2011; Li et al., 2012; Zhu et al., 2017). Particles with high specific surface areas are a good storage medium for them. The HBCDs isomers can be easily translocated from soil to plants and animals (Covaci et al., 2006; Zhu et al., 2017). Within the soil environment, polystyrene normally has a positive polarity (Fricker et al., 2017) but the retention of PS is unlikely and the transport of PS nanomaterial is observed under atypical conditions (pH 10, 0.4 mM ionic strength) (Hoggan et al., 2016). The retention increases in the presence of 10 mM Ca^{2+} (Quevedo and Tufenkji, 2012) and at a higher ionic strength (Nevius et al., 2012). In terms of biofilm formation, PS surfaces usually show hydrophobic properties but if coated with goethite, that can easily occur in the soil environment, they become hydrophilic (Pouran et al., 2014) and negatively-charged PS can be linked more toughly to biofilms (Chen et al., 2012; Nevius et al., 2012).

PS is quite durable and, apparently, unaffected by biodegradation. However, some insects, which have commonly been seen as pests, are able to degrade it within their larval gut. In fact, the larvae of *Tenebrio molitor* L. eat Styrofoam, a trademarked brand PS item used for thermal insulation (Yang et al., 2015). This closed-cell extruded polystyrene foam is rapidly (24 h) degraded in the larval gut of the larvae that, fed with XPS as the sole diet, lived (30 days) as well as those fed with cellulose. One month is the time required by a larva to transform into an adult beetle, under normal conditions. This means an extreme adaptation to the new diet, taking into account that less than 1% of the XPS incorporated into living biomass, in fact approximately half of the ingested carbon is converted into CO_2 and the other half egested. Other organisms living in soils can colonise PS foam flakes inducing alterations like

holes, or corrosion, these are fungal species such as *Aspergillus*, *Penicillium*, or *Fusarium* (Umamaheswari et al., 2013).

In terms of reuse, bricks obtained by recycled XPS aggregate, instead of mineral sands, obtained good performances (Bosco Hernández-Zaragoza et al., 2013), and a permeability coefficient decrease with the increase in consolidation pressures and curing age (Zhu and Ma, 2015).

2.2.7. Other plastics

This category includes acrylic, nylon, polycarbonate, polyurethanes, polylactic acid, and other biodegradable plastics (a discussed list of polymers can be found in Siracusa et al., 2008), and multilayer combinations of different plastics.

Synthetic fibres for textiles uses exist since WWII period. Acrylic and nylon are particularly resistant polymers, they can release by-products in a particularly aggressive aqueous environment but they are definitely stable within the soil. However, within two months nylon 4 (polyamide 4) is degraded by bacterium *Stenotrophomonas* (KT-1 strain) and fungus *Fusarium* (KT-2 strain) (Tachibana et al., 2010). Nylon fibres containing fluorocarbon and fire-retardant additives are prone to biodegradation as well; their burial within soil has been found to be damaging when followed by aerial exposure (Setua et al., 2000). Considering the resistance to degradation of the material within the soil environment, the inclusion of nylon fibres within un cemented and cement-stabilized soil caused an increase in the unconfined compressive strength and axial strain at failure. They changed the brittle behaviour of the soil, giving a more ductile behaviour that increases shear strength and friction angle of the natural soil (Estabragh et al., 2011, 2012).

Polycarbonates are thermoplastic polymers that photodegraded when exposed to UVs, and hydrolyse to bisphenol A at temperatures below 80 °C and high humidity (Bair et al., 1981). Then, BPA leaching could occur at a lower temperature under not-extreme pH levels (Morin et al., 2015), but photosensitized transformation can occur in the presence of dissolved organic matter (Chin et al., 2004). When reused, PC waste added to ABS, together with compatibilizers, increases the final mechanical properties (Hamad et al., 2013) of the recycled material.

Polyurethanes are chemically inert, thermally stable, and flammable resistant. However, light stability is a critical aspect, UV radiation promotes harmful reactions (Newman and Forciniti, 2001). The fungus *Aspergillus tubingensis* can grow on the surface of PU film with biodegradation capabilities, such as surface cracking, pore formation, and loss in tensile strength (Khan et al., 2017). PU can bind light density soil imparting good slake durability, resistivity against impact effects, abrasion, and freeze-thaw resistance; an additional property is the low unit volume weight (Komurlu and Kesimal, 2015). In a short-term experiment, a PU elastic

gel with strong adhesion capabilities can reduce the erosion throughout the consolidation layer formed, providing the future vegetation seeds a chance to develop (Linag et al., 2017). The chemical PU recycling is normally precluded, but the synthesis of thermoplastic and PUs flexible foams can recover useful monomers (Schneiderman et al., 2016).

Bio-based plastics are produced from renewable resources (Iwata, 2015). Polylactic acid (PLA) is, in fact, a bio-based polymer from monomers of lactic acid derived from biomass. PLA buried in (unknown) soils at ~ 25 °C for 4 (Kamiya et al., 2007), 12 (Shogren et al., 2003), 20 (Tsuji et al., 1998), or 24 months (Calmon et al., 1999) shows no weight change and no significant physical changes. The results of the tests are very contradictory, in fact an open burial trial at ~ 20 °C in (mysterious) soil shows signs of degradation after 4 months (Weng et al., 2013a and 2013b). However, PLA is degraded within the soil environment within a couple of months, but it takes high temperatures (>50 °C) (Itavaara et al., 2002; Tokiwa and Calabia, 2006; Karamanlioglu et al., 2017a). A degradation between 20% and 75% can occur after 20 months of soil burial (Urayama et al., 2002). The current literature does not allow to understand which soils accelerate or slow down the phenomena of degradation. Instead, it appears that the properties of soils change, for example within the soil, PLA incorporation lowers pH dramatically (Karamanlioglu et al., 2017b).

Other polymers produced to be (bio)degradable (Roy et al., 2011; Iwata, 2015) are included in the same category. These polymers degrade in the soil. There are some examples, for instance a PS-graft-starch biomaterial exposed to 6 month biodegradation by burial method, in three different types of commercially available soils monitored by mass, achieved the highest degradation rate in 'soil for cactus growing' (>80 %) (Nikolic et al., 2014).

However, the first step in degradation is oxidation, but usually the materials contain stabilizers to avoid oxidation. So, one strategy is to make constituents more prone to oxidation: pro-oxidants added materials or pro-oxidant additive containing (PAC) plastics are being sold as oxo-degradable plastics (e.g., Patwary and Mittal, 2015). These oxo-biodegradable plastics can be degraded by white rot fungi *Pleurotus ostreatus* (da Luz et al., 2013).

2.3. Plastics in agriculture

If there is a sector in which the introduction into the environment of plastic polymers is inherent, this is the agricultural sector. In fact, some type of plastic products are manufactured specially to enter the total environment: films, crop shelters, mulching pellets, water hoses, drains, and PVC water pipes. Films for agriculture (Fig. 1), primarily developed for mulching application, are the most important one affecting yield, earliness of cropping, product quality, weed and microclimatic control, and



Fig. 1. Wormwoods (*Artemisia genipi* Weber, 1775) are cultivated for producing a traditional herbal liqueur popularized in the European Alpine regions (EU, 2008). This niche native crop, typically, enhances the local specificities calling attention to local products and to the maintenance of cultural landscapes (Carubba and Scalenghe, 2012). But, also this type of regionalisation, so linked to the naturalness of the mountain territories, it does not prescind from the use of plastic polymers. More recycling of plastics used in agriculture, such as these mulching films, can contribute to reduce impacts to the total environment. A way to achieve this could be Extended Producer Responsibility (e.g. OECD, 2001) schemes, which have already demonstrated their effectiveness (EC, 2018).

solarisation (Kyrikou and Briassoulis, 2007; Kasirajan and Ngouajio, 2012; Liu et al., 2014; Steinmetz et al., 2016). In some areas, their use is so massive that methods for mapping agricultural plastic waste has been developed using Landsat 8 images (Lanorte et al., 2017). Martín-Closas et al. (2017) summarise pros and cons for the adoption of (bio)degradable films for cultivating crops (Martín-Closas et al., 2016). In general, the increasing usage of LDPE films causes substantial costs to both farmers and broader society if once used, mulch fragments are often incorporated or left within soils (Jambeck et al., 2015; Brodhagen et al., 2017). However, this pattern is not mandatory, this material remains a resource until it is considered waste. Degradable polymers play a key function in mulching films or compostable waste bags, where degradability is a share of the main function (Ignatyev et al., 2014). Though, degradation of polyolefins used for mulch film and packaging, for instance, is a difficult task to get as no natural enzyme can directly cut polyolefins, consisting of a carbon chain with covalent carbon-carbon bonds (Nikolić et al., 2017). However, “it is much easier to start the oxidation and fragmentation of a material than it is to control the oxidation rate and degradation products and to ensure and convincingly prove that the material will be completely mineralized or degraded to acceptable degradation products” (Albertsson and Hakkarainen, 2017).

Seeing plastics as a resource instead of a problem, examples are microgreens, visual and flavour ingredients used to enhance the appeal of fine dining dishes (Xiao et al., 2012; Kyriacou et al., 2016). For the production of these young vegetable greens,

from an agronomical perspective, both peat-based mixes and synthetic mats are very expensive substrates. Recycled textile-fibres made of polyester, cotton, and PU or PET represent low-cost alternative substrates for the production of rapini micro-greens (*Brassica rapa* L.) ensuring competitive yield, low nitrate content, and a higher microbiological quality (Di Gioia et al., 2017). Other examples are the use of recycled plastic materials with anti-erosion functions, e.g. sands reinforced with PET or PP fibres (Malidarreh et al., 2017) or micronized PET as an additive for asphalts (Silva et al., 2017).

Plastic is not the only durable material that degrades slightly in the soil (Kibblewhite et al., 2015). Burial in soil preserves almost all objects for at least a limited time and in many cases beyond thousands of years. One million years is roughly needed for a glass fragment to fully decay, but within a soil this time might be even more protracted (Palomar, 2016). It is not a casualty, in fact, that glass artefacts from very early glassmaking's beginnings were exposed in our museums. Obsidian artefacts older than 30,000 ya BP buried in archaeological remains have changed not much, chemically and in appearance, since its burying (Hughes, 1998). Glass can be brittle or strong, but this does not affect its decomposition rate in soils, being less exposed to weathering. In general, soil pH is the key property that affects the extent of glass weathering (Palomar, 2016). The preservation capacities of different soils for different materials are variable, but apart from glass some materials, such as gold, ceramics, metals, and stones can survive virtually forever within the soil environment, although their surfaces could be altered (Kibblewhite et al., 2015). In thermodynamically very active environments, what can happen to these materials is a comminution, and cumulation of solid by-products producing sand-sized anthropogenic microparticles (Howard et al., 2013). Plastic has been added to these materials.

2.4. Resource or waste? A paradigmatical example

Like the non-natural plastic materials, even the stones, although natural, are not very alterable. A material that is poorly alterable in the soil can be limiting for its agronomic use (Nyssen et al., 2001), but this statement cannot be generalized. An analogy are the stones within the soil. The fine fraction of the soil performs fundamental functions for the nutrition of plants, for this reason the coarse fraction (>2mm in diameter) is currently defined as the 'skeleton'. The skeleton of the soil, often, is considered limiting for which it is eliminated (Ng Cheong et al., 2009). There are cases in which the skeleton, carrying out a peculiar and improving function for the growth of the vine plant, is added (Fig. 2). And there are many ways to have more soil in the mountains, for example, by increasing the amount of fine earth available for the roots. Stone clearance and riddling are a millennium old agronomic mountain practices (Fig. 2a). Smashing the soil skeleton: a different way to get the same result is using a crusher (Fig. 2b) with different consequences. Here, an example of

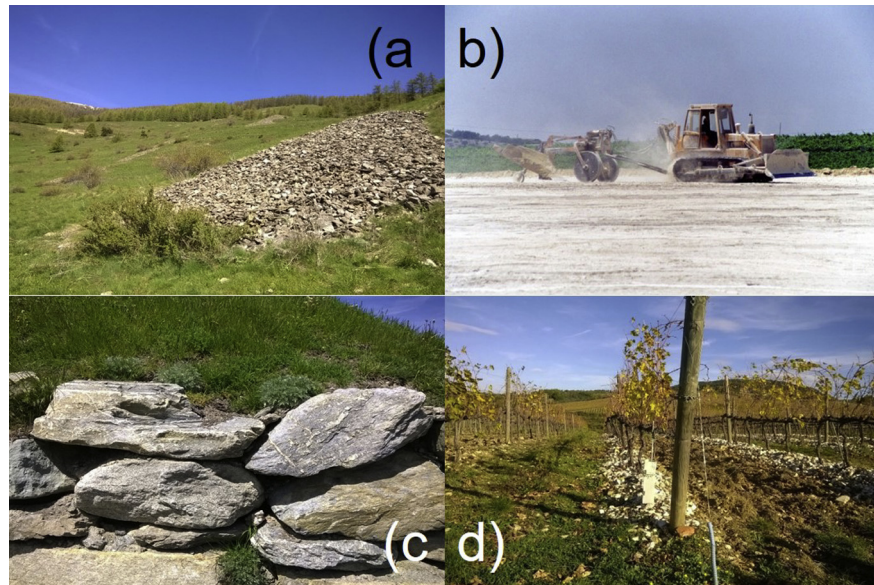


Fig. 2. Soil skeleton, different approaches to presence of an unwanted material within the soil: (a) the collection of stones in mountain soils, (b) crushing and mixing of limestone in vineyards, (c) the defence against erosion, an ancient use of stones, and (d) top quality wines, a modern use of stones.

vineyards that replaced arable land, almond orchards, olive groves, and natural grazing leading to the creation of new anthropogenic soils (Lo Papa et al., 2011). An ancient strategy of managing stones in soils is terracing (Fig. 2c): sloped planes cut into a series of consecutively receding flat surfaces for the purposes of farming, decreasing erosion, and surface runoff. A modern strategy of managing calcareous stones in top quality vineyards is growing vine directly in them. Natural soils in the rhizospheric zone have been replaced by ‘Alberese’ marly limestones in the 20 hectare ‘Solaia’ vineyard at the Tignanello estate (Marchesi Antinori, 2018), situated at some 400 meters above sea level with a southwestern exposure (Fig. 2d). The Marchesi Antinori firm, since 1978, produces the Solaia wine, a Cabernet Sauvignon, Cabernet Franc, and Sangiovese blend only produced in high quality vintages (average price 200 EUR per bottle; source www.winespectator.com). The stones in the soil have existed long before us, the plastic only for a few decades, but the analogies are many. The theme is to consider the residual value of the material or consider it simply a waste. And considering that plastics, as other materials, left on or in the soil will follow inevitably the broken windows theory (Weaver, 2015; Bateson et al., 2015): “consider a pavement. Some litter accumulates. Soon, more litter accumulates. Eventually, people even start leaving bags of refuse from take-out restaurants there or even break into cars” (Wilson and Kelling, 1982).

2.5. End-of-life options

Even if worldwide incentives for plastics recycling do exist, end-of-life options for plastic (solid) waste are in practice only partial (Garcia and Robertson, 2017).

Suitable options for post-consumer plastics, summarising, are: mechanical recycling, chemical recycling, composting, energy recovery, and dumping in landfills (Greene, 2014) (Table 4). All begins with sorting, and this applies to all options, with the exception of dumping (even if, currently, excavated plastic from landfill mining are seen as suitable recycling routes; Canopoli et al., 2018) (Fig. 3). Only developing polymer compatibilizer design strategies (e.g., Creton, 2017; Eagan et al., 2017) could permit recycling without pre-sorting. The costs of collecting, sorting, and re-processing and the low market value of the recycled plastics explain the low recycling rates globally (OECD, 2018).

2.5.1. Mechanical recycling

Considering that globally only 14% of plastic packaging is collected for recycling (World Economic Forum et al., 2016) and the volume of traded waste plastics globally is less than 5% of the annual new plastics production (Veilis, 2014), recycling of polymers is at the beginning of its journey. Plastics even originating from mixed wastes can be valuable raw materials; an assessment made in a virtuous country

Table 4. Type of disposal/recycling methods for plastics.

Process	Advantage	Weakness	Ref.
re-using	****	-	EC (2015), al-Salem et al. (2009)
composting	**	biodegradability	Kale et al. (2007), Gómez and Michel (2013)
re-extrusion	*	clean scraps	al-Salem (2009)
mechanical recycling	**	sorting costs, single-polymer	Zia et al. (2007), Gu et al. (2017)
co-gasification	**	air quality	Aznar et al. (2006)
coke ovens	**	air quality	Kato et al. (2004)
liquefaction	**	volume treated	al-Salem et al. (2009)
supercritical fluids	**	sorting costs, single-polymer	Goto (2009)
pyrolysis	**	costs, air quality	Mastellone et al. (2002), Achilias et al. (2007)
co-gasification	**	air quality	Aznar et al. (2006), Pinto et al. (2003)
hydrocracking	*	costs	Tukker et al. (1999)
degradative extrusion	*	costs	al-Salem et al. (2009)
catalytic cracking	*	costs	Brandrup et al. (1996)
energy recovery	*	air quality	EC (2015), EC (2018)
dumping	+	no advantages	EC (2018)

Few limitations that restrict their choice.

**** disadvantages not evident.

** some limitations that reduce their choice or require moderate ancillary practices.

* several limitations that reduce their choice or require special practices.

+ banned in several countries.

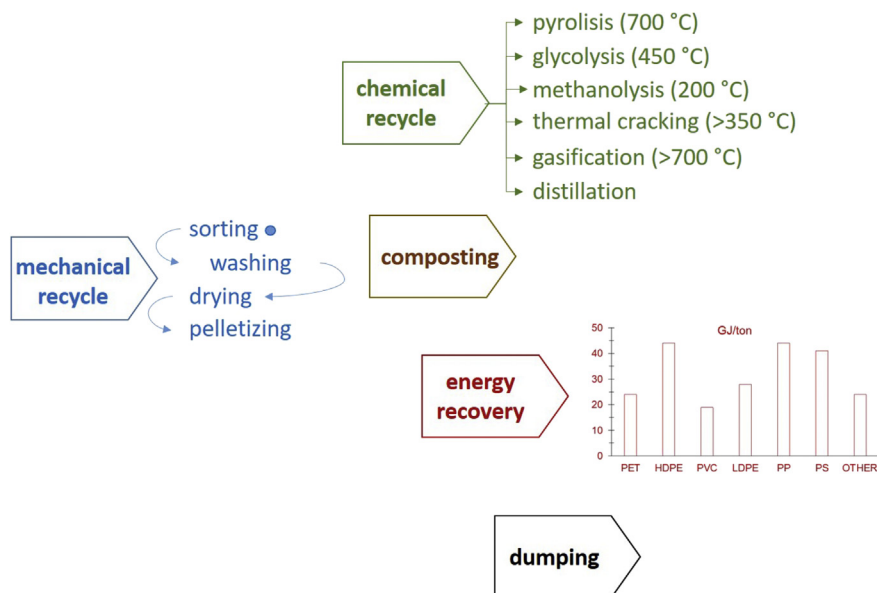


Fig. 3. End-of-life plastics.

starting from a hundred thousand tons of post-consumer plastic packaging waste (18 kg person⁻¹ yr⁻¹ Finnish wastes) shows that the maximum recyclable, and then available on the local market, could be 25,000 tons of rPP and 8000 tons of rHDPE (Dahlbo et al., 2018).

For mechanical recycling, in general, monotype polymers are more appropriate than multilayer plastics but temperature-sensitive polymers, composites, and thermosets cannot be handled mechanically.

The environmental benefits resulting from centralised recycling practices are much higher than those of distributed recycling practices (Gu et al., 2017).

2.5.2. Chemical recycling

It aims at the fabrication of valued products, such as monomers or petrochemical feedstocks, particularly from mixed PE/PP/PS, multilayer packaging, fibre-reinforced composites, or PU (Ragaert et al., 2017). Existing expertise largely relies on access to pure waste polymer feedstocks, which necessitate sorting of waste that is costly and time-intensive. Thermolysis makes available lower-molecular-weight products throughout a recycling strategy that decomposes polymers (e.g., Jia et al., 2016); monomers from depolymerisation need selective and effective catalysts that meet cost and energy metrics (Garcia and Robertson, 2017). Comparing with the chemical recycling method, mechanical recycling is, however, a favoured method that avoids problematic treatments: in fact, small impurities of one polymer type could alter the properties of the recycled plastic. A difficulty that can be fixed with compatibilizers that control the performance of mixtures (Hamad et al., 2013). The incorporation of

minor amounts of virgin polymers in the presence of suitable compatibilizers, a third component, which is added within the blend, dropping the interfacial tension so helping the interfacial adhesion between two polymers, which were before immiscible (Ragaert et al., 2017). Basing on findings from mechanical recycling, can result in good properties compared to those of the original waste: for example, the blending of PLA with PET produces a better thermal stability (Hamad et al., 2013).

2.5.3. Composting

Composting, in general, is a practice adopted for resource recovery by reprocessing a surplus by-product from another process into a valuable new material. Several methods have been industrialised to handle different molecules, quantities and applications. Industrial scale composting can be carried out in various form, among other methods there are in-vessel composting (bioreactors, i.e. air flow- and temperature-controlled tanks), aerated static pile composting (aeration controlled perforated piping), or windrow composting (piling wastes in long rows) (e.g. de Bertoldi et al., 1983; Gajalakshmi and Abbasi, 2008; Unmar and Mohee, 2008). However, bio-based does not mean biodegradable as degradability does not depend on the origin of the raw material but depends on the chemical and physical structure of the polymer and its exchanges with the total environment in which it is located (Albertsson and Hakkarainen, 2017). However, creating supplementary end-of-life options such as composting is positive as it aims to decrease our global ecological footprint. However, following this option, it is important to remember that natural environments are more biodiverse and more variable in terms of humidity, oxygen, sunlight, and temperature (Briassoulis et al., 2010; Kale et al., 2007; Ray and Bousmina, 2005). It makes it tremendously problematic to control potentially degradable plastic materials, guaranteeing their whole degradation.

In a compost, complete mineralization is normally not the main goal, instead it is degradation to suitable degradation products. Particular conditions are a pre-requisite depending on the type of plastic (Albertsson and Hakkarainen, 2017). To let compostable plastics to be effectively degraded, controlled conditions of composting must be generated in (specialised) plants. One of the main complications connected to the disposal of partially degraded materials is that not one is altered everywhere in nature.

2.5.4. Incineration and energy recovery

Incineration reduces the need for landfill of plastics waste, however, there are concerns with hazardous substances being released into the environment: for instance, dioxins, other polychlorinated biphenyls and furans from PVC and halogenated additives (Gilpin et al., 2003). In any case, not all polymers have the same energy yield (Fig. 3), considering that individual calorific values for PS is approximately 41 MJ

kg⁻¹ (similar to heavy oil) 44 for PE or 46 for PP (similar to kerosene). The thermal and catalytic processes of converting waste plastics into fuels are other techniques to eliminate the refuse (Kunwar et al., 2016; Wong et al., 2015).

When dealing with the risks of emissions that are harmful to health, we must take into account that polymers have different market values, for example PVC is worth 60% of the PU, and different energy yields. The highest energy yields are intrinsically contained in HDPE and PP polymers, while the lowest are those of PVC.

The choices between the different options are not obvious, at all. For instance, Gradus et al. (2017) consider incineration alternatives in the Netherland and found that the market price for a reduction of 1 t of CO₂ would be 30 times lower than the indirect price when recycling rather than recuperating energy, (with 178 € as the shadow price of one tonne of CO₂ reduction by means of plastic waste recycling (during early 2018, the market price for CO₂ emissions in the European Emissions Trading scheme (ETS) is approximately 9 € per tonne): the net costs of plastic waste recycling are higher than for energy recovery, but the CO₂ emissions from the energy recovery option are higher than for the recycling option.

2.5.5. Dumping in landfills

End-of-life plastics are amassing in landfills resulting in both management issues and environmental harm (Barnes et al., 2009) (Table 4). An effective graphical abstract in Hahladakis et al. (2018) summarises options and concerned impacts. Plastics represent 5–25 wt% of the total waste in landfills (Canopoli et al., 2018). In fact, for instance, under reducing conditions, biodegradable plastics made from petroleum, may have more adverse environmental impacts than conventional plastics if their ultimate fate is landfilling and anaerobic conversion to methane (Gómez and Michel, 2013). Considering that this is the same as for glass, ceramics, earthenware debris, metals, etc., annually half of the production of solid plastics is wasted globally, of the one fifth generated by the United States (EPA, 2015). This signifies missed economic opportunities (Garcia and Robertson, 2017), more than 8 billion USD in the only United States (As You Sow, 2012). This is the last option, for example, according to European legislation (2008/98/EC Waste Framework Directive). Where action on plastics is identified as a priority, and the strategy part of Europe's transition towards a circular economy with key actions as separate collection of plastic waste, mainly by issuing new guidelines on separate collection and sorting of waste, and curbing plastic waste and littering, mainly by reducing single-use plastics (EC, 2018).

2.6. Lessons learnt from space mission planners

The amount of waste in space, and reducing the amount of plastic and the final volume of the end-of-life materials is strategic (Fig. 4). Forthcoming human missions to



Fig. 4. Plastics in space: Commander Jack R. Lousma, gathering three free-floating plastic wastes during the third mission for the Space Shuttle Columbia on March 1982. The astronaut will preserve them in a designated stowage volume. Credit: NASA (photo STS003-25-231).

Mars will be (probably) much more mass-limited than volume-limited, however the net habitable volume (NHV), the functional volume available to the crew, its maximization, will however be a goal to be achieved (Monje et al., 2003). The strategies to achieve this goal are comparable, to the future management strategies of an increasingly crowded planet Earth of beings that will produce more and more wastes. On space missions, waste is hand-compressed, wrapped, and placed in a stowage bag (so-called trash ‘football’) until to what the final destiny is not clarified; just generated immediately, it must take up little space, and not be dangerous over time (Burattini et al., 2014; MacElroy et al., 1992). Previous experience with the shuttle and ISS shows that water can leak out of a football even after it is wrapped tightly in tape. So, to avoid liquid droplets on the inside surface of the footballs, Heat Melt Compactor Technology (HMC) is used for trash handling. Trash that contains at least 20% plastic and 25% water (Linne et al., 2014). The HMC technology provides a 7:1 decrease in final volume via compression and heat yielding a dry, microbially stable, trash tile football containing more than one tenth of polyethylene, which, during heating caramelizes organic residuals as well, becoming softer, getting a dimensionally firm tile in the compressed state during cooling; these tiles will function as a last disposal object or as a storage form until repurposing/processing into convenient further items (Broyan et al., 2014). In space missions: volume reduction producing temporary recyclable mixed plastics items to substitute, for instance, radiation shielding, although obtained by specific materials, is a win-win strategy as it reduces the items being launched. On Earth, this strategy could be mimicked producing, in field, gravity defences (walls), crop shelters, ...

2.7. Plastics today: key challenges

Any material at the end of its life (glass, plastic, metals, ...) inserted in the soil in bulk may not be economically recoverable (e.g. Geyer et al., 2017). If we also consider ecosystem services potentially lost from the soil, it becomes so.

2.7.1. Microplastics in soils: a motive of concern?

Whereas plastic objects are fragmenting, smaller pieces enter the total environment (Barnes et al., 2009; Fahrenkamp-Uppenbrink, 2014; Ivar Do Sul and Costa, 2014; Lavender Law and Thompson, 2014; Vigneri, 2016): smaller than 5 mm microplastics (e.g., Duis and Coors, 2016) are released in the size of small nanometric (da Costa et al., 2016), micrometric (Gregory, 1996; Fendall and Sewell, 2009) or millimetric pellets (Thompson et al., 2009). The security of these micro- and nanoparticles is quite ambiguous, but rather unoptimistic (Nel et al., 2006; Ruan et al., 2018). But, although in the aquatic environments there were many descriptions, the presence of microplastics in terrestrial ecosystems were quite rarer in the literature of the past (de Souza Machado et al., 2018; Gallo et al., 2018; Horton et al., 2017; Ng et al., 2018; Nizzetto et al., 2016b; Rochman, 2018; Scheurer and Bigalke, 2018; Weithmann et al., 2018; Zhang and Liu, 2018). This depends, first of all, on the relative simplicity with which microplastics can be extracted from water and, then, quantified. In addition, there are patterns of accumulation, which has no equivalent in terrestrial ecosystems (Rillig, 2012). However, awareness is increasing that these microplastics might pose a risk to the health of soils. The extent of such risk, however, still remains equivocal due to controversial findings on the effects on soil biota (Cao et al., 2017; Rillig et al., 2017a, 2017b; van Gestel and Selonen, 2018; Hodson et al., 2017; Huerta Lwanga et al., 2018; Rillig and Bonkowski, 2018).

2.7.2. Curbing plastic waste and littering

Durability and resistance to degradation, characteristics that make plastics extremely useful, make these polymers difficult for Nature to digest. So, are bioplastics healthier for the total environment due to 'ecological' feedstocks and production impacts? The answer is perhaps, that it mandatorily depends on how product claims and performance follow accepted standards, and how consumers are educated on disposal options of bio-based plastics (CORC, 2011). A tailor-made management strategy for end-of-life plastics is absolutely mandatory: dematerialization, substitution, reuse, recycling, waste-to-energy, or conversion technologies must be judiciously weighed to select the right answers to the, essentially inevitable, global progression in production and use of these polymers (Geyer et al., 2017).

A serious concern with bio-based plastics, perceived as degradable, is the deleterious effect they may have on the final quality of recycled plastic products, in fact if not properly sorted, their massive production could lead to significant difficulties for recycling (Albertsson and Hakkarainen, 2017). Sociologically, and pessimistically, they could induce an increase in waste production if consumers consider that it is harmless to toss them into the soil. A modern production of plastic polymers must take these risks into account, and getting tuned to the rigor and frugality of the approach with time (Rao, 2017).

2.7.3. Methods for the study of plastics within the soil

When a piece of plastic degrades because of weathering it, however, breaks down into pieces of debris, of course smaller, but normally it does not mean a degradation. In the case of soil, in fact, the correct scientific question is: what is measured when the degradation of a polymer is estimated? The total disappearance being unrealistic for most polymers. In the case of films, the extent of the covered area, instead of the weight of the polymer, is certainly a more consistent indicator of the degradation of mulches (Moreno et al., 2017), but in most cases an acknowledged indicator does not exist, although some enzymes produced by microorganisms could be tested (Tokiwa et al., 2009). Extremely rare are the existing techniques for the study of plastic polymers in the soil (Bläsing and Amelung, 2018). Among the few, some of them estimate their presence within the soils, while others rely on proxies. Among the techniques of the first type, hyperspectral imaging to visualize the microplastics on soil surface (Shan et al., 2018), or floatation methods to extract the PE or PP microplastics from soils (Zhang et al., 2018b), or either laser-induced breakdown spectroscopy to sort the type of polymers (Tang et al., 2018). Among the techniques of the second type, portable X-ray fluorescence could infer the presence of brominated flame retardants additive in EPS, XPS, PU, and ABS (Sharkey et al., 2018). In particular, in agriculture there is a lack of standard methodologies for identifying the types, the quantities, and the flows of plastic polymers (Blanco et al., 2018).

2.7.4. Turning challenges into opportunities

The dream is to create a circular plastic economy where products are mostly recyclable, and their waste minimised (Geyer et al., 2017). To move towards that vision, for instance, Europe is foreseeing an economy where products containing plastics are designed to get better robustness, usual reuse and easy recycling. A key issue is that all plastics packaging placed on the EU market is either reusable or could be recycled in a cost-effective way by 2030 (EC, 2018). In this context, ways of maximising the impact of new rules on Extended Producers Responsibility (EPR) (OECD, 2018) are envisioned as well (EC, 2018). Furthermore, EPR schemes can support finance action to curb (plastic) littering, with positive returns on the

behavioural plan. Challenges connected to the production, and end-of-life of plastics can be turned into opportunities, covering a value chain of growth, jobs, and innovation (EC, 2018).

3. Conclusions

The main shortcoming of the current study relate to the fact that despite the presence of plastic mixtures in the soil, the individual polymer behaves in extremely different ways. In general, plastic polymers designed to last, even within the soil environment, remain for long periods. Polymers designed to biodegrade in the soil do not disappear neither quickly nor completely, but gradually degrade. In general, stepping up the reuse and the recycling of plastics can bring significant environmental and economic benefits. A key message is raising public awareness guaranteeing high-quality separate collection. Bläsing and Amelung (2018) close their paper on the analytical methods of plastics in soil saying that “*Nearly nothing is known about plastic pollution of soil; presumably, because awareness is either not existent or because no standardized methods are available for plastic quantification in soil*”. A small, but not trivial, thing that we all can do for the soil is to understand that the polymers of the unknown pieces of plastic we find mixed in it they are not made of a homogeneous material but are extremely different from each other. We, as citizen, can do it now, easily, using some water, fire, an alcohol, and the simplest ketonic solvent that is habitually in our houses as nail polish remover (Harris and Walker, 2010). At the same time, scientists must develop and standardise methods for quantifying and characterizing plastics in soil. This is the first urgent need for research in this field to proceed. What is measured when the degradation of a polymer is estimated? Acknowledged indicators do not exist and future study they will have to identify viable and shared methods to measure the degradation of individual polymers in soils. Furthermore, further research is needed to progress our understanding of the impacts of microplastics, including their effects on the total environment, soil in particular.

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