EIP-AGRI Focus Group

Reducing the plastic footprint of agriculture

STARTING PAPER – Nicolas Beriot

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1. Introduction

Plastic is a relatively cheap, light and resistant material that can provide many benefits to agriculture. For example, the long-term use of plastics for greenhouses enables to grow vegetables in a warmer and more controlled environment while the single-use of plastic as mulching films enables to reduce the need for water and herbicides (Espí et al. 2006). However, plastic use comes along with two major issues. First, plastic production relies mainly on petrochemicals from petroleum and natural gas, which are not sustainable resources. Moreover, only a third of agricultural plastics are recycled in EU, while most of them are sent to energy recovery facilities and to landfill. Secondly, weathering of plastic used in agriculture generates debris that accumulates in the environment (Gionfra 2018). More specifically, the use of biofertilizers (e.g. compost and sewage sludge) contaminated by microplastics (particles <5 mm) is an important source of plastic contamination (Corradini et al. 2019b). The accumulation of the plastic debris in agricultural lands rises concerns for soil health. Plastic debris in high concentrations reduces the crop growth(Gao et al. 2019). Moreover, micro and macro plastics in the terrestrial environment can be transported by water runoff and wind to the rivers and the seas, where they threaten the aquatic ecosystems. For instance plastic debris can be ingested by organisms, from plankton to mammals causing digestive problems (Galafassi et al. 2019). Different strategies can be applied to reduce the plastic footprint in agriculture. This starting paper provides the state of the art and knowledge gaps of plastic use in agriculture, its benefits and drawbacks and the strategies to make plastic use more sustainable. The Focus Group will reflect on and share practical experiences and expert views to reduce the negative effects of plastic use in agriculture.

The tasks of this Focus Group

EIP-AGRI Focus Groups are temporary groups of 20 selected experts focusing on a specific subject. Each group explores practical innovative solutions to problems or opportunities in the field, and draws on experience derived from related useful projects. Each EIP-AGRI Focus Group meets twice and produces recommendations and outcomes report.

The EIP-AGRI Focus Groups also discuss and document research results, best practices and identify the implications for further research activities that will help to solve practical problems in the sector.

This starting paper serves as background document to prepare the first meeting of the **EIP -AGRI Focus Group on "reducing plastic footprint of agriculture"** which is taking place in May 2020. For this purpose, the document aims to:

- establish a common understanding about the purpose and scope of the Focus Group.
- identify some preliminary issues and key questions for discussion at the first Focus Group meeting.
- present the available knowledge on how to reduce the plastic use and increase the recycling of plastics used in agriculture, which also serves as a preliminary basis for the Focus Group final report.

The overarching question of the focus group is:

How to reduce the plastic footprint in agriculture through recycling and introducing alternatives?

The main question will be addressed through these specific tasks:

- Identification of the main use and properties of plastics in farming activities, and their advantages or threats for the sustainability of agricultural production.
- Identification of the indirect sources of plastic contamination such as the use of contaminated biofertilizers or waste water.
- Review of existing knowledge about the impact of plastic on the agricultural environment.
- Discussion of the existing practices as well as limitations for the reduction of plastic use, its recycling and its degradability in the environment.
- Exploring opportunities and needs for innovations to reduce/replace the use of plastics while maintaining the economic and environmental performance of the farm.
- Presenting the existing monitoring methods and suggesting ideas for improvement in this area

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2. The plastic world

2.1. What do we call plastic?

A common definition of plastic is a material which is at least partly made of organic polymer and can be moulded into solid, non-soluble, objects (Hartmann et al. 2019). An organic polymer is a repetition of many monomers that contains carbon. For example polyethylene, a commonly used polymer, is composed of a chain of carbons atoms whereas polylactic acid, a polymer used in biodegradable plastics, is composed of a chain of lactic acid (Figure 1). This definition puts emphasis on the behaviour of plastics to be malleable while other definition may focus on the chemical composition.

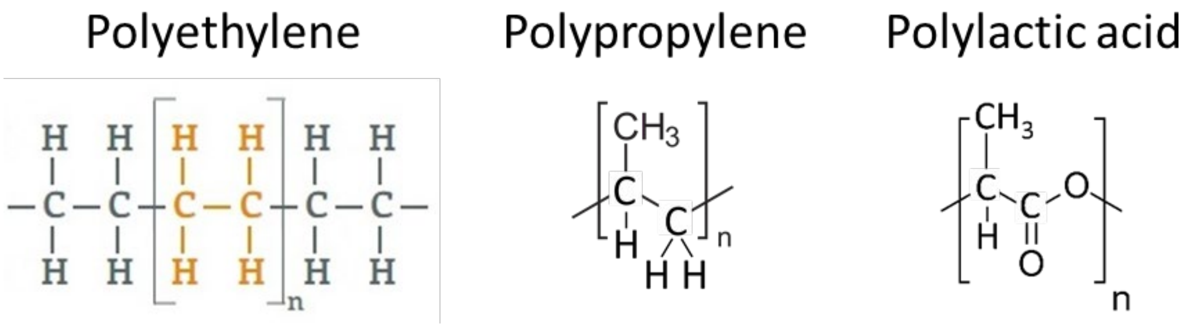

Figure 1. Chemical structure of polyethylene (PE), polypropylene (PP) and polylactic acid (PLA).

The two main polymers used in agriculture are polyethylene (PE) and polypropylene (PP). Other common polymers are Polyvinyl chloride (PVC) and Polyethylene terephthalate (PET). The structure of some plastic polymers is presented in Annex 1

2.2. What are plastics made of?

Conventional plastics are petroleum-based, meaning that they are made from fossil resources such as natural gas, oil or coal. In Europe plastic production account for 4% to 6% of all the oil and gas used, about 45% being used for transportation and 42% for electricity and heating. Plastic can also be produced from crops and are then called bio-based. Industrial fermentation and bio-catalysis of the plants lead to the production of plastic polymers. For example, sugar cane can be processed to produce ethylene, which can then be used to manufacture polyethylene. In Europe, 57 million tonnes of primary plastics were produced in 2016, the share of bio-based plastics being 1% of EU annual plastic consumption (European Commission 2018).

Plastic can be made of a single polymer or a blend of several types, associated in different manners. Additives are added to adjust the elasticity, the colour, the mechanical strength, the degradability of the plastic (examples can be found in Annex 2).

Bio-based plastics should not be confused with biodegradable plastics. In fact **bio-based polymers** such as bio-based PE, PET or PVC, possess identical properties to their conventional versions meaning they are very resistant to degradation. On the contrary, **biodegradable plastics** are made to be degraded in specific condition, on a short-term scale. Biodegradable polymers can be petroleum-based or bio-based.

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2.3. Plastic degradation processes

The degradability of the plastic polymers is a source of concern when plastic debris remains in the environment. In fact the low degradation rate of the plastic debris leads to accumulation in the environment (Rillig 2012). Degradation is as well a major issue when the plastic is intended to be composted. Plastic degradation relies on two main processes: weathering and biodegradation.

Weathering

Weathering refers to abiotic reactions such as thermal degradation, photo-degradation, oxidation, hydrolysis and to mechanical degradations (e.g. wind or ploughing). Weathering plays an important role in the degradation processes, as weathered plastic will undergo faster biodegradation (Restrepo-Flórez et al. 2014). For example, photo-degradation can change the chemical structure of plastic polymers making them easier to be degraded by microorganisms.

Biodegradation

Biodegradation of a polymer is a biological process leading to its complete or partial conversion to water, CO_2, methane, energy and new biomass by microorganisms (bacteria and fungi) (van Ginkel 2007). The biodegradation process can be divided in three different steps (Figure 2).

1. The organisms colonize the polymer and grow on its surface (Figure 3).

2. Then the organisms degrade the polymer. They mostly do it by secreting enzymes (e.g. hydrolases) that can depolymerise the polymer. **Depolymerisation** is the break of chemical bounds in the polymer that leads to smaller molecules. The main process of depolymerisation is the catalysis of hydrolyses with enzymes.

3. Finally, the hydrolysis products released from the polymer are used as an energy source or a carbon source for the microorganisms leading for example to emission of CO_2 or the increase of biomass.

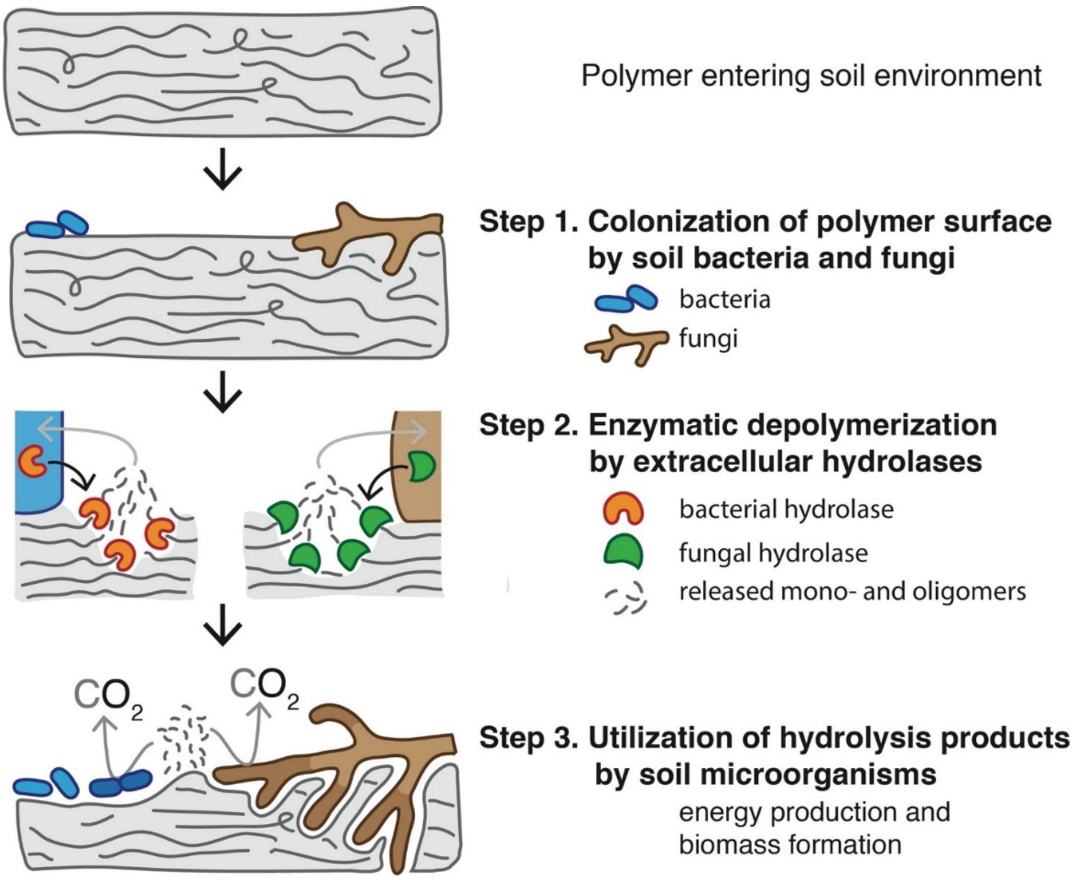


Figure 2. Three fundamental steps involved in polymer biodegradation in soils. (Sander 2019)

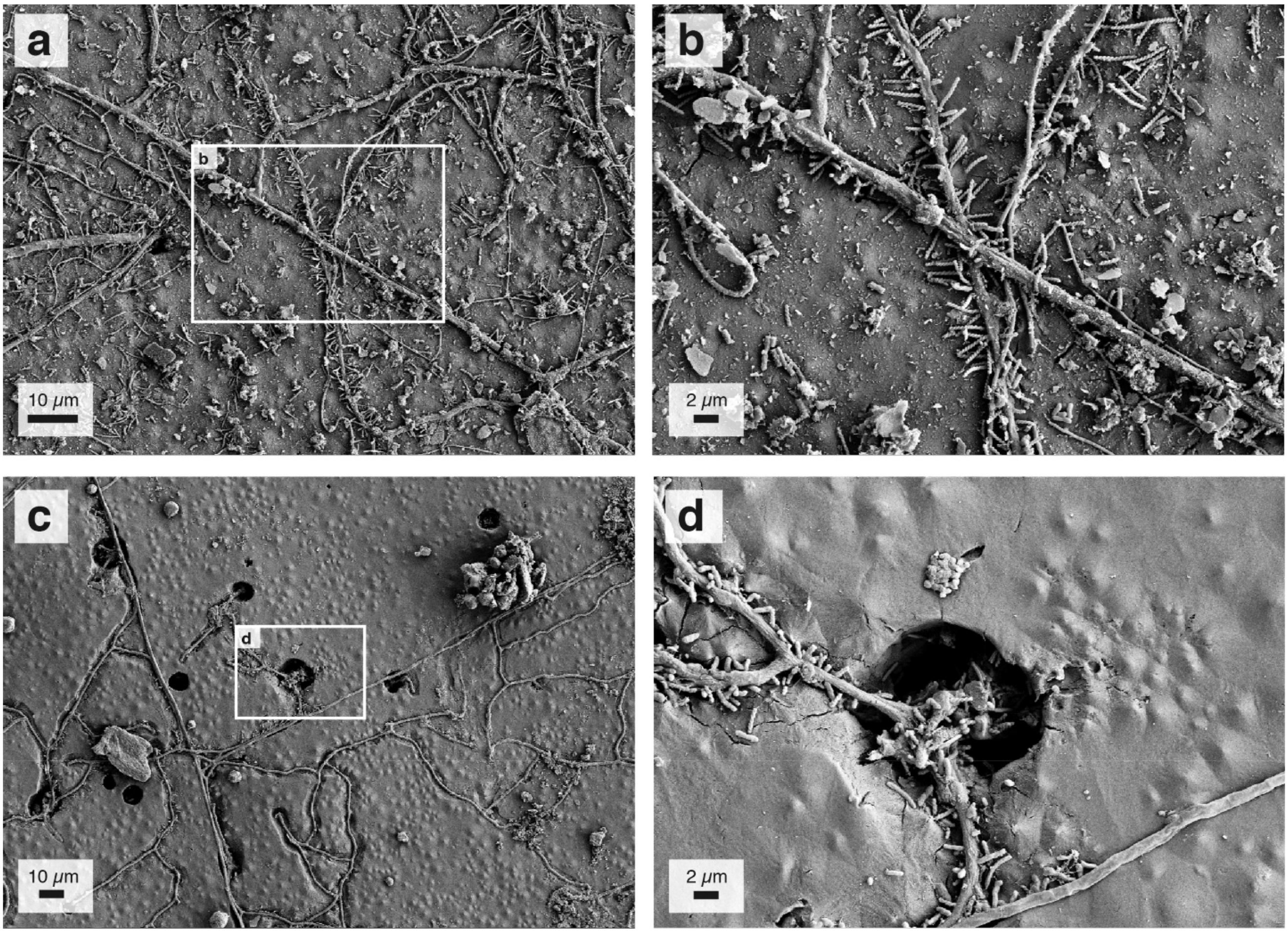


Figure 3. Scanning electron microscopy images of the surfaces of polybutylene adipate-co-terephthalate (PBAT) films that were incubated in an agricultural soil in the laboratory (6 weeks; temperature of 25 °C). The images illustrate colonization of PBAT films by both fungi and unicellular organisms. Images in panels a) and c) were collected at different spots on the PBAT film surface. Panels b) and d) show magnifications of areas highlighted in panels a) and c) (Sander 2019).

Biodegradation can be measured as a mass loss, a change of plastic properties or an increase emission of CO_2 (Lucas et al. 2008). The biodegradation depends on the time, the abiotic and biotic conditions and on the properties of the plastic.

- **Time**

The International Organization for Standardization (ISO) 17556, consider that biodegradable plastic should reach at least 90% biodegradation in the soil within two years (Carol et al. 2017).

- **Abiotic conditions**

Abiotic conditions are important for both the weathering and biodegradation. For instance, the microorganisms' activity will be maximal at optimum temperature, moisture level and oxygen content. The temperature can be critical because above a certain temperature (the glass transition temperature, specific to each plastic) the polymer structures changes and lead to a faster weight loss (Copinet et al. 2004). The glass transition temperature for polylactic acids (PLA) is about 55ºC and this temperature is often reached in industrial composting.

- **Biotic condition**

The biodegradation of plastic polymers requires microorganisms to secrete enzymes. Some microorganisms are able to secrete specific enzymes that will break specific compounds. In fact some bacteria and fungi are able to degrade PE, but they have been studied only in the lab so far (Huerta Lwanga et al. 2018). However, these organisms have to be present in the environment to degrade the plastic (Restrepo-Flórez et al. 2014). Moreover, the competition between microorganisms will determine which ones are growing. Therefore, the presence of microorganisms capable of plastic degradation in the initial microbial community determines the success of plastic degradation.

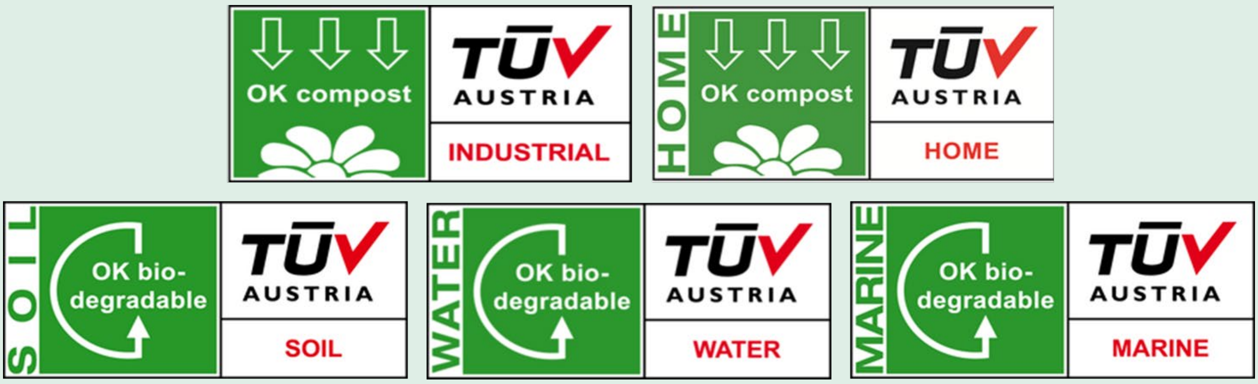
- **Properties of the plastic**

As shown before, the chemical structure of the plastic polymer determines its degradability but many other characteristics are important. First, plastics can contain a blend of polymers. This is often the case for biodegradable plastics, which combine properties from more resistant polymers with more degradable polymers to make applicable plastics. The type of polymers and the way the plastic is made will affect the degradability (Brodhagen et al. 2015). Moreover, molecules can be included in the blend as additives to enhance or decrease the degradability of the plastic. It is the case for pro-oxidant additive containing **(PAC)** plastics. They are polymers, mainly LDPE, which contain a pro-oxidant additive to enhance oxidation and photo-degradation (Selke et al. 2015). In the presence of light and under aerobic conditions, PAC plastics degrade quickly into small pieces. PAC plastic are also commercialized as oxo-plastics, photodegradable plastics, oxo-bioplastics. However, the degradation in the environment of PAC plastics is mostly incomplete. When all additives are consumed and the abiotic conditions are not favourable, degradation process stops (Selke et al. 2015). Finally, the thickness of the plastic is a determinant factor as the degradation occurs only on the contact area with the environment and thicker plastics have a lower surface to volume ratio.

To conclude, the degradability is not an intrinsic property of a plastic. It depends on the environmental conditions and the time considered. For example some polylactic acids (PLA) based plastics may degrade in few days in an industrial composter but undergo less than 2% mass loss after one year in the soil (Lv et al. 2017). Therefore, the term "biodegradable plastic" may be confusing. A clear regulatory framework for biodegradable plastics is still missing in EU. TÜV AUSTRIA propose some different labels for different degradation condition (Box.1)

Box.1: Certification of plastic degradability, example of TÜV AUSTRIA

TÜV AUSTRIA developed certifications for degradation in industrial and home compost and in marine, fresh water and terrestrial environments (Figure 4) (AUSTRIA 2020). For example, the "OK biodegradable SOIL" label applies to finished products used for horticultural and agricultural application. It is based on several European and international standards for biodegradability and ecotoxicity. The test demands at least 90% biodegradation in two years (according to standard EN 13432) at ambient temperature (between 20°C and 25°C) and no detectable toxicity effects when 10 % on wet mass basis of the material are added to a compost or 1% are added to a soil substrate (according to Standard ISO 16929).



2.4. Categorizing and identifying the plastic debris

When plastics are in the environment, the degradation processes always lead to plastic debris. A common way to characterise plastics debris is by the particle size, however, there are no fixed definition yet for the particle size limits for different plastic fragment sizes (Figure 4).

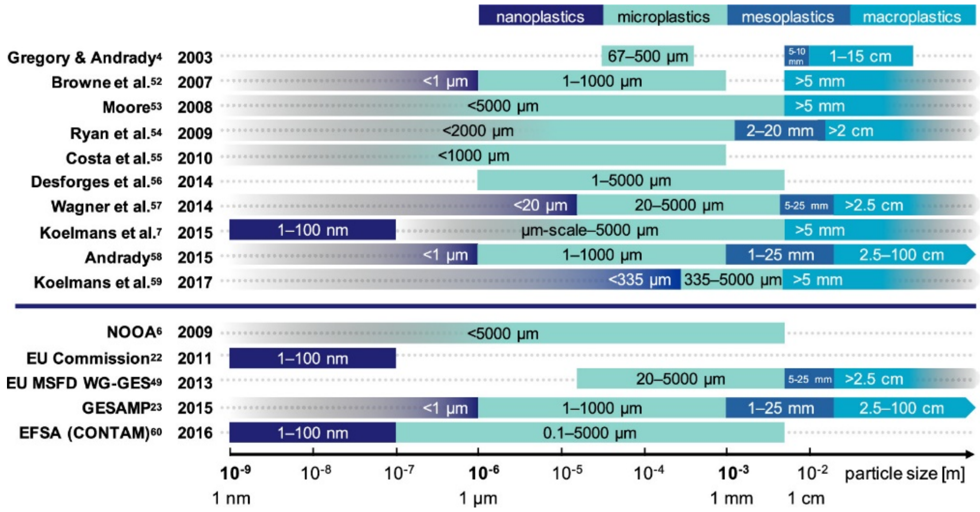


Figure 4. Categorization of plastic by size, there are no fixed boundaries for nanoplastics, microplastics, mesoplastics and macroplastics (Hartmann et al. 2019).

A recent work by Hartmann et al. (2019) proposes a framework consisting of seven criteria to define the particle as plastic (criteria 1 to 3) and to describe it (criteria 4 to 7, Figure 5.) The framework makes the difference between primary particles that did not undergo degradation and secondary particles that come from the degradation of plastic (Figure 6).

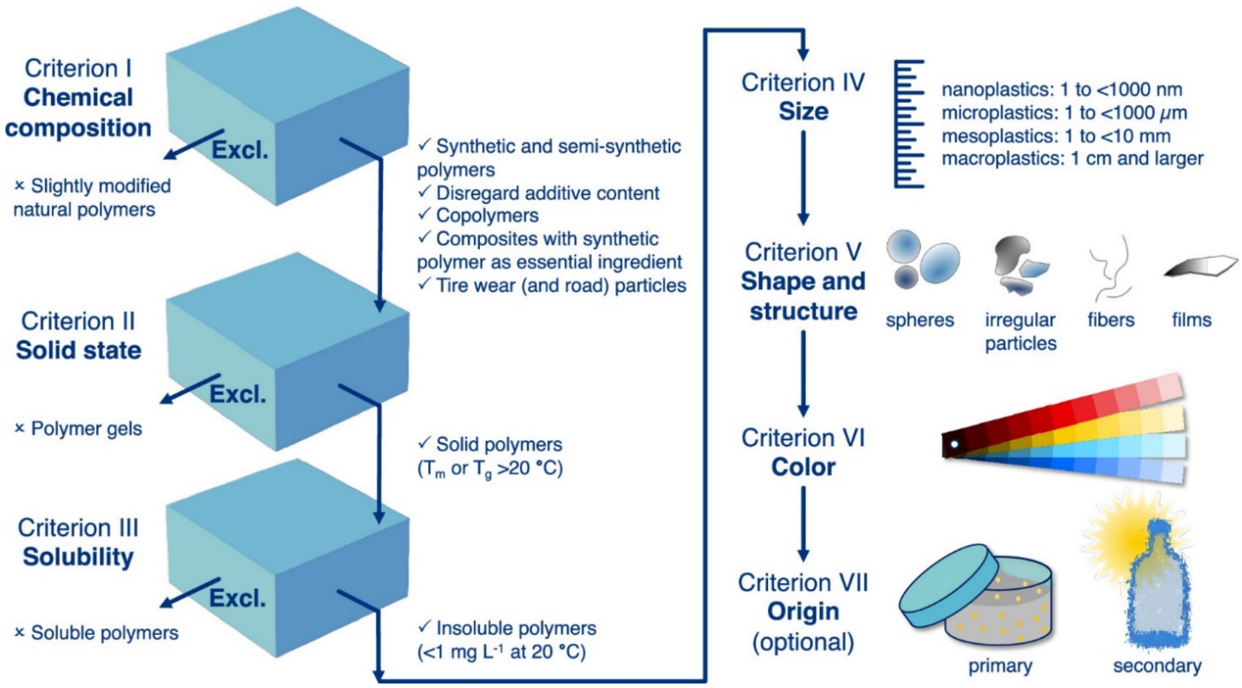


Figure 5. Proposed definition and categorization framework for plastic. Criteria 1 to 3 are used to define plastic and criteria 4 to 7 to describe it. (Hartmann et al. 2019)

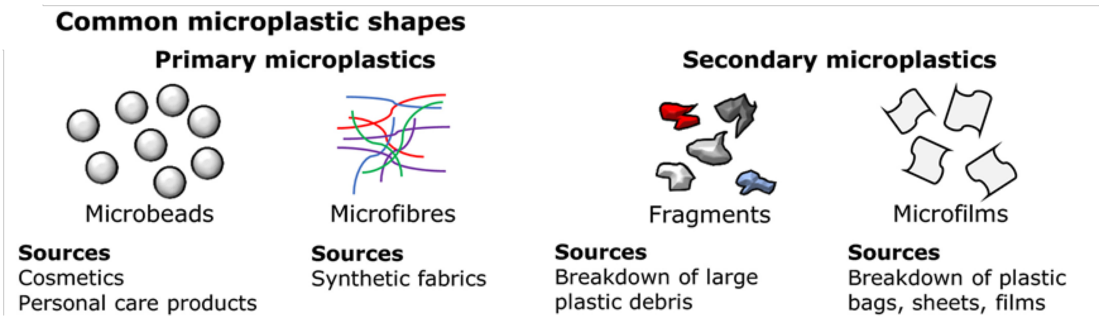


Figure 6. Common microplastic shapes and their main sources. (Helmberger et al. 2019)

The description of the particles depends on the technique used for their identification. Most of the identification methods require a preliminary step of extraction of plastics from the sample and a second step of identification (Figure 7). A study from Möller et al (2020) presents the latest technics for extraction and identification of plastic in soil. One technique is to separate the plastic particles from the soil by density (Möller et al. 2020), other promising methods are oil extraction (Crichton et al. 2017) or the electrostatic separation (Felsing et al. 2018).Extracted particles can then be identified.

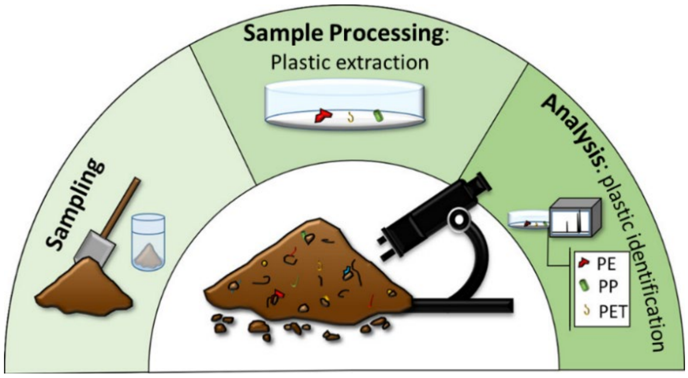


Figure 7. The three steps of plastic determination in the environmental samples: sampling, processing and analysis. (Möller et al. 2020)

Here we describe four developed methods for plastic identification and suggestions for field applicable methods (Box 2).

- The simplest method is to use a visual identification under a light microscope combined with a melting test (S. Zhang et al. 2018). The plastic particles are identified from soil organic matter by their change of shape, colour and brightness after melting. This method gives the number of plastic particles and their area but does not give indications about the type of polymer. Moreover, plastics that are denser than the extraction liquid and that do not melt at the used temperature (~140ºC) are not detected. It is a destructive method because the melted sample cannot be used for further analysis.
- Another destructive method is the thermal extraction desorption gas chromatography mass spectrometry (TED GC-MS) (Dümichen et al. 2017). The plastic particles are burned and the molecules emitted are analysed by gas chromatography. It is a sensitive and well-established method for the characterization and mass-quantification of many polymer types and their organic additives. However, TED GC-MS does not give information about the number and the area of the particles.
- Raman and Fourier transform infrared (FTIR) are two different spectroscopy methods commonly used in microplastic research (Möller et al. 2020). They measure the sample response after exposure to a beam and compare the obtain spectra with a reference library. Raman and FTIR complement each other and should be chosen in accordance with the research aim. The two methods give an estimation of the number and area of particles for all the type of polymers present in the reference library. Other methods are being developed for a faster, cheaper and more accurate determination of microplastics.

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Box 2 : What methods to assess plastic contamination at the farm levels?

There is a need to develop field applicable methods to measure the plastic content. Such method could rely on the following points:

1. **Visual identification** of the macro plastic debris and their sources:
   - Identifying the presence of plastic in the environment (plastic bags, plastic mulch, greenhouses)
   - Estimate the content in the soil using a visual comparative chart (e.g. Figure 8)

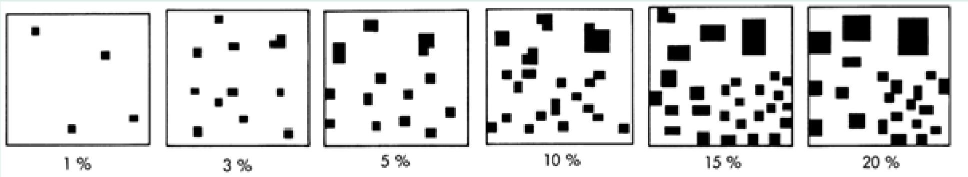

Figure 8. Example of visual comparative chart for the estimation of the area covered with plastic debris

2. **Microplastic assessment**:
   The method developed by Zhang et al (2018) only requires basic laboratory materials (glassware, filters and microscope). It could easily be implement by technicians or students. Innovative handheld FTIR devices could allow the assessment of microplastics in the field (Figure 9). However the technology developed so far is not accurate enough to detect plastic particles in the common environmental contents (Corradini et al. 2019a).

Figure 9. Handheld FTIR could enable the assessment of microplastics in the field.

3. Plastic use and sources of plastic contamination in agriculture

3.1. Direct use of plastic

Generally, plastics in agriculture can be divided into two categories, single-use plastics and long-term use plastics.

3.1.1 SINGLE USE PLASTIC

The main use of single use plastic in agriculture is **plastic mulching** (Figure 10). The European Commission estimated in 2016 that 100 000 tonnes of plastic mulch is used per year in European Union. Plastic mulch is generally used for one or all of the following three reasons:

- **Increasing soil temperature**
Plastic mulch was first noted for its ability to increase soil temperature in the 1950s . The increase of the temperature depends mostly on the plastic colour. Black is the predominant mulch colour since it can both absorb and re-emit solar radiation as heat. By contrast, transparent plastic films are poor absorbers of solar radiation but transmit 85% to 95% of radiation to the soil. This greenhouse effect makes transparent films profitable in colder regions or in hotter regions for soil solarisation. **Soil solarisation** is a soil sterilisation method to eradicate soil-borne pathogens and devitalise weed growth by reaching very high temperature (increase of ~15ºC of the soil temperature at 25 cm) (Tamietti and Valentino 2006). At night, the plastic mulch prevents heat loss by limiting the soil radiation. Higher soil temperatures increase nutrient availability, enhance nutrient uptake by roots, increase the number and activity of soil microorganisms, and speed up plant germination and growth leading to higher and earlier yields.

- **Increasing water use efficiency**
The water use efficiency (WUE) is estimated by dividing the yield per ha by the total amount of water applied. Plastic mulch is a barrier that prevents water evaporation from soil and therefore increases water availability for plants (Deng et al. 2006). Plastic mulch can also increase the rainwater harvesting when associated to a ridge-furrow tillage, the ridge being mulched by plastic and plants growing in the furrows (Figure 12) (Yang et al. 2020). An analysis of 266 studies showed that plastic mulching significantly increased crop yield by 24% and WUE by 28% on average (Figure 10 , a and b) (Gao et al. 2019).

- **Decreasing weed growth**
Opaque (often black) plastic mulch avoids weed growth by preventing light to reach the soil (William James 1993). Plastic mulch can reduce weed emergence by 64% to 98% during the growth season, depending on the surface covered with plastic (Kasirajan and Ngouajio 2012). With clear plastic mulch, an herbicide is needed to prevent weed growth beneath it.

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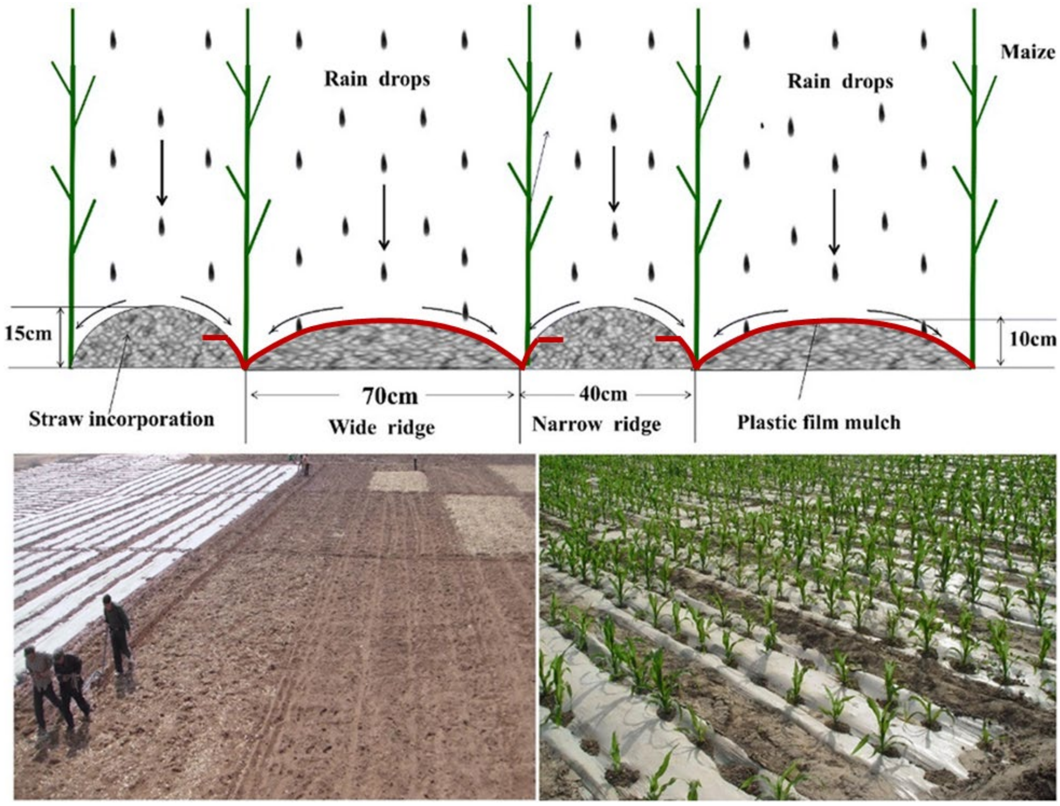

Figure 10: Film-mulched ridge-furrow tillage combined with straw incorporation to increase the water use efficiency and the soil quality, experimental case for maize growing in the Semiarid Loess Plateau, China (Yang et al. 2020)

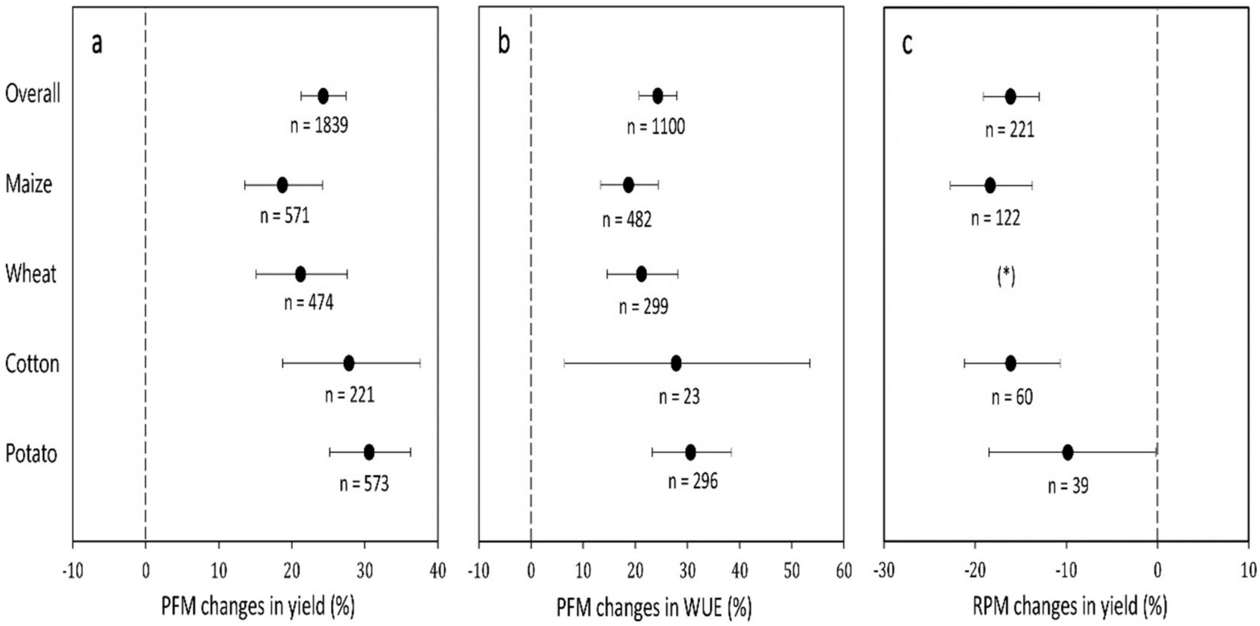

Figure 11. The effect of plastic film mulching on crop yield (a), water use efficiency (b), and the effect of plastic debris on crop yield (c). Error bars represent 95% confidence intervals. The letter "n" indicates the number of observations. It is visible that mulching increases both yield and WUE for all crops studied (Gao et al. 2019)

The most common polymer used for plastic films is Low Density Polyethylene **(LDPE)** (Kasirajan and Ngouajio 2012). LDPE is a fully saturated polymer of hydrocarbons, which makes it highly resistant (Crawford et al. 2017). Consequently, LDPE debris accumulates in the environment (Figure 12). Some farmers try to improve the degradation of plastic to avoid plastic films removal and plastic debris accumulation by using PAC or biodegradable mulches. Alternatively, the conception of new biodegradable plastic films or paper-based films are a promising alternative for single use films.

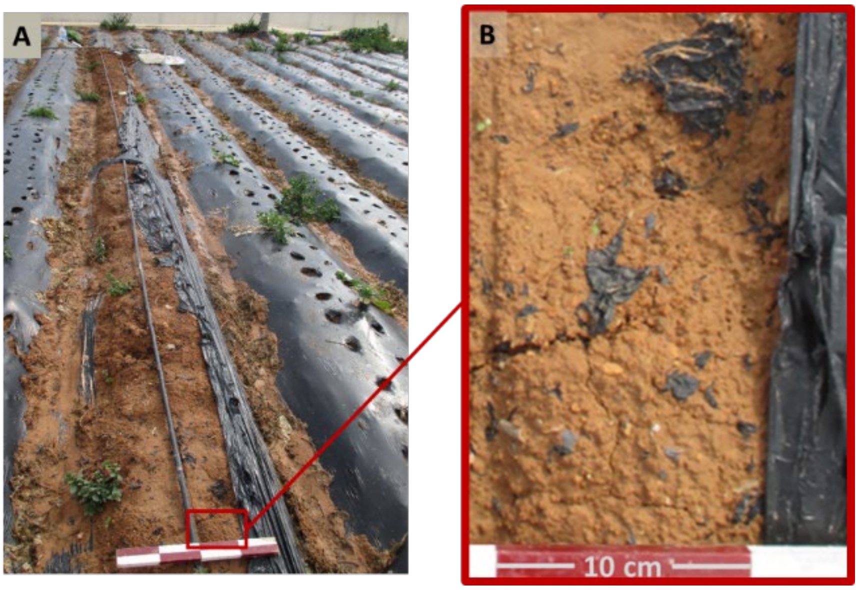

Figure 12. Light density polyethylene plastic mulch after harvest of Kohlrabi. The sides of the mulch film are buried into the soil making complete removal impossible and leading to debris accumulation over time. The plastic debris represents about 5% of the soil surface when compared to the visual estimation chart (Fig. 8)

Plastic packaging offers a cheap, easy and light solution to improve the conservation of agricultural products and therefore reduces waste. For example, plastic films are used to protect vegetables and fruits after harvest during their transport, and to wrap bales for silage preparation (Figure 13). Packaging is responsible of about 60% of plastic waste but at the same time it is comparatively more recycled than other plastic waste (Europe 2017).

Figure 13. Lettuces being wrapped in plastic in a harvesting mobile station (A). and bale being wrapped in plastic for silage preparation (B)

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Plastic is also used as a coating for some **controlled-release fertilizers** (CRF). In fact CRF's coatings are made of polymers such as polyethylene and polyurethane (Heuchan et al. 2019). The plastic coating allows a slower release of nutrients to prevent leaching and volatilization and therefore allows a better nutrient use. However, only some of them are made from biodegradable polymers, others accumulate in the soil (Han et al. 2009).

3.1.2 LONG TERM USE PLASTIC

Thicker and stronger plastics are used to build greenhouses, tunnels, crop protection nets and irrigation systems. These plastics will undergo slow degradation in the environment due to weathering mainly. For example the plastic cover of a greenhouse may last between 3 to 5 years and then be replaced. **Greenhouses** are the main activity requiring long term use plastics in Europe with an estimation of 111 000 ha used in Europe in 2006 (Figure 14). As comparison it was estimated that 427 000 ha of plastic where used for mulching in Europe the same year.

Figure 4. Intense use of plastic in agriculture in the "sea of plastic". This region of south east Spain concentrates greenhouses for vegetables production.

3.2. Secondary sources of plastic debris: fertilisers and irrigation

In this case plastic debris, mostly microplastics, comes from upstream activities.

- **Compost**

Applying compost to the fields is a common practice in agriculture to increase the soil organic matter and to help closing the nutrient cycle. Composts may contain plastic debris depending on its origins and on the process used for composting (Weithmann et al. 2018). For example a high-quality compost ("quality seal" label) from a biowaste composting plant contained about 20 microplastic particles per kilogram dry weight whereas the composts from a biowaste digester was nearly an order of magnitude higher (Weithmann et al. 2018). The difference could be explained by an accumulation of plastic through the digestion process because the organic matter of the compost decomposes while the plastic debris persist. Sources of plastic could be: missorting, the use in plastic bags in case of domestic compost or from agricultural use of plastic in case of compost from crop residues. In Germany alone, about 5 million tons of compost is used in the fields each year, leading to a potential microplastic input of 3 to 200 tonnes. There is no European regulation concerning the microplastic content in compost.

- **Sewage sludge and irrigation water**

Water treatment plants receive microplastic particles from the washing of synthetic clothes, the abrasion of tyres and roads and from microplastics for cosmetics and industrial use. When water from treatment plants is used to irrigate the fields or when sewage sludge is applied as a biofertilizer, microplastics can be introduced in the fields (Corradini et al. 2019b; van den Berg et al. 2020). Nizzetto et al estimated in 2016 that 63 000 to 430 000 tonnes of microplastics particles are introduced into agricultural soils trough sludge application each year in the European Union (Nizzetto et al. 2016).

4. Effects of plastic debris on the environment.

4.1. Transport and sorption of other contaminants

Figure 15 summarizes the diversity of sources of plastic contamination. In fact, plastic is found in all environments (Annex 4)

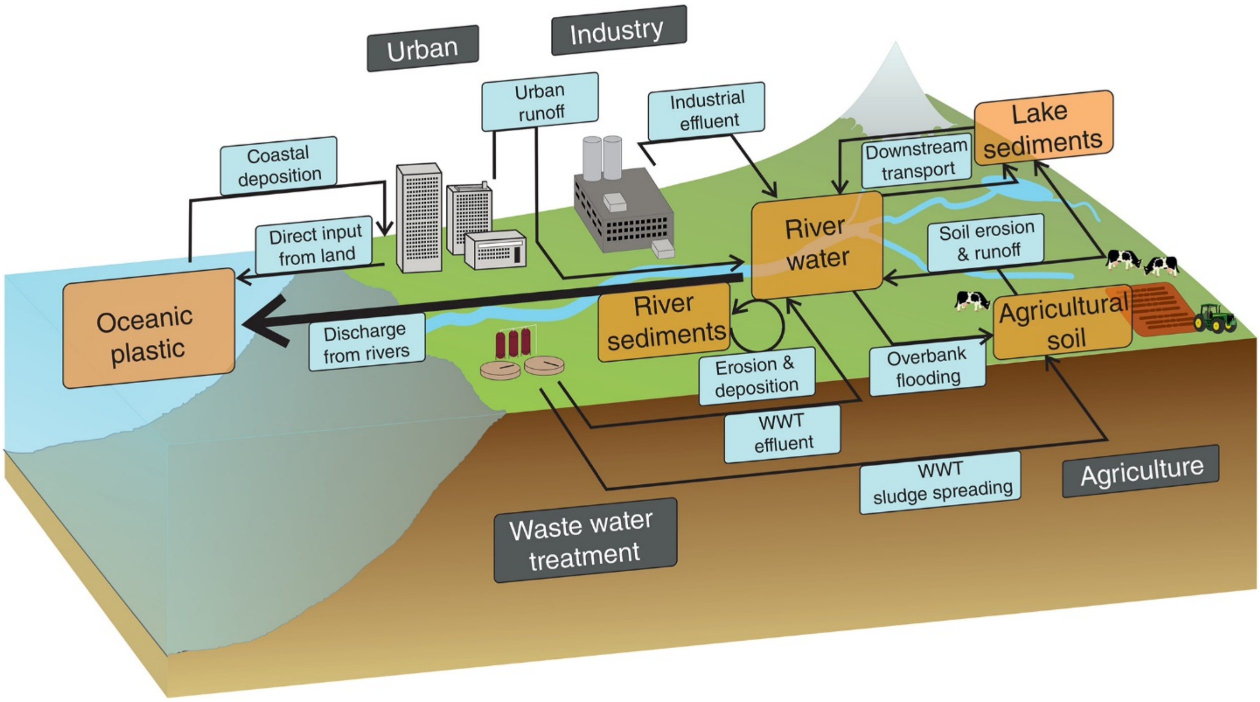

Figure 15. Conceptual model of plastic transport. Orange boxes represent sinks, blue boxes represent transport mechanisms and arrows represent transport pathways. Atmospheric microplastics are not included within the model as they cannot be attributed to a specific compartment or route of transport (Horton and Dixon 2018)

- **Plastic transport in the soil**

Plastic can be transported from the surface to deeper soil by bioturbation of the soil. It happens for example with the earthworms activity (Huerta Lwanga et al. 2017a) and during ploughing (Rillig et al. 2017). Drainage can also transport plastics in the soil, along preferential infiltration paths (Zubris and Richards 2005).

- **Plastic transport in water bodies**

Agricultural soils may be an important source for microplastics to rivers, although it is likely that a high proportion will also be retained in the soil (Horton and Dixon 2018). When particles do enter rivers, they will be subject to the same transport processes which mobilize sediments, except that plastic will be transported further than most sediments because of their lighter weight. It is likely that on their journey throughout the freshwater environment, many particles will also be retained within sediments where river energy drops, in lakes for example (Nizzetto et al. 2016).

- **Plastic transport in the air**

Transport of microplastics within the air is another possibility for the lightest particles (Dris et al. 2016). This transport mechanism is likely to lead to the widest dispersal as it is the least limited by environmental boundaries, influenced mainly by the directions of air movement rather than the unidirectional flows that are generally the case on land and within waterbodies. Due to the limited data currently available, further research will be needed to better understand the processes involved in atmospheric microplastic transport (J. Wang et al. 2019).

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- **Sorption of other contaminants on plastic**

Recent studies have demonstrated that plastic debris can act as vectors for other environmental contaminants and spread them in the environment (Hartmann et al. 2017). This is the case for heavy metals and persistent organic pollutants such as polycyclic aromatic hydrocarbons and most pesticides (Wang et al. 2019). Adsorbed contaminants may be realised in the different organisms when ingested and cause damages (Teuten, et al. 2007). Contaminated plastics may also release contaminants in the soil solution and contribute to plastic toxicity (Machado et al. 2018) (Qi et al. 2018). In a similar way, contaminants adsorbed on plastic may decrease the plastic's biodegradation by reducing the activity of soil organisms.

4.2. Effects on the terrestrial environment

- **Soil physicochemical properties**

Only a few studies have examined the effects of plastic residues on soil properties (Dong et al., 2015; Jiang et al., 2017; Machado et al., 2018b). These studies showed that microplastics tend to increase soil bulk density, decrease porosity, water holding capacity, hydraulic conductivity and water stable aggregates in different extends depending on the type of debris and the type of soil. Because of these variations, the consequences for the agronomical performance of the soil are uncertain. Additionally, macro plastic debris may get stuck in agricultural engines when preparing the soil, adding a physical constrain (Liu et al. 2014).

- **Soil micro-organisms**

The interaction of microplastics with soil microbiota remains largely unexplored. Polypropylene (PP) particles in the soil (7% and 28%) were reported to have a positive effect on the overall soil microbial activity (Liu et al. 2017), while polyacrylic (0.05–0.4%), polyester (0.05–0.4%) and PS particles (1 mg kg^{-1}) showed a negative effect (Awet et al. 2018; de Souza Machado et al. 2018). More specifically, Qian et al 2018 showed that residual plastic film pollution changed the structure of the soil biological community; further, the plastic debris decreased soil organic matter and inorganic nitrogen content by downregulating microbial genes related to soil carbon and nitrogen cycles (Qian et al. 2018).

- **Plants and crops**

Plastic debris have been shown to negatively affect plant growth, especially root growth (Bosker et al. 2019; Chae and An 2020; de Souza Machado et al. 2019; Jiang et al. 2019; Qi et al. 2018; van Weert et al. 2019). More specifically, nanoplastics can enter the plant body from the soil and accumulate in tissues and cells (Bosker et al. 2019; Chae and An 2020; Jiang et al. 2019; T.-R. Zhang et al. 2019).
On a larger scale, Gao et al showed a yield decrease with increasing amount of plastic residue; when the plastic was >240 kg/ha (~0.15 g/kg) in fields using plastic mulch in China (Figure 11.C) (Gao et al. 2019).
Apart from risk for the crop production, macro plastics may be a threat to the quality of the product. Indeed, in leaf vegetable agriculture macro plastics may get stuck in the leaves. These products are less appealing to the consumer and need an extra cleaning step to remove all plastic debris.

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- **Macro-organisms**

Study of exposure of soil animals to microplastics showed that many organisms do ingest plastics. However, ecotoxicological effects at environmental concentrations are still uncertain (Chae and An 2018; Ng et al. 2018). Moreover microplastic ingested by organisms can travel in the food chain. For example microplastic concentrations increased from soil (0.87 ± 1.9 particles g^{-1}), to earthworm casts (14.8 ± 28.8 particles g^{-1}), to chicken faces (129.8 ± 82.3 particles g^{-1}) in home gardens in Southeast Mexico (Huerta Lwanga et al. 2017b). An increase in earthworms' mortality has been recorded, when exposed to 28%, 45%, and 60% of microplastics in the litter (Huerta Lwanga et al. 2016) but these plastic contents are higher than average contents in the environment (Annexe 4). Nanoplastics decreased the growth, locomotor activity, and intestinal microbiota viability of snails that were feeding on plants grown in soil with 10 mg kg^{-1} and 100 mg kg^{-1} nanoplastics (Chae and An 2020).
The effects of microplastics on terrestrial organisms are caused also by plastic additives and other contaminants that may be leak from the microplastics (Mai et al. 2018). Many plastic additives are suspected to be endocrine disruptors. It means that they may interfere with animal hormones and therefore impact the entire organism (Hermabessiere et al. 2017). Though it is still hard to draw definitive conclusions from the scientific literature, early studies about microplastic in soil concur with the wider base of marine microplastic toxicology in that microplastic are a threat to soil biota (Helmberger et al.).
Plastic debris are also ingested by bigger organisms (Zhao et al. 2016) resulting in various negative effects (Figure 16). The effects include blockage of the intestinal tract, inhibition of gastric enzyme secretion, reduced feeding stimuli, decreased steroid hormone levels, delays in ovulation and even failure to reproduce (Li et al. 2016)

Figure 16. Photographer Chris Jordan took pictures of albatrosses that died because of ingesting plastic debris http://chrisjordan.com/gallery/midway/

4.3. Effects on human health

Ingestion is considered the major route of human exposure to microplastics (Galloway 2015). Microplastics have been reported in many food items (Cox et al. 2019) (Table 1). The estimated intake of microplastics is 39,000–52,000 particles person^{-1} year^{-1} (Cox et al. 2019). A prospective study from Schwabl et al 2019 found a medium of 200 microplastics per 100g of stool in 8 samples (Schwabl et al. 2019). Microplastics may cause inflammatory lesions and induce an immune response (Figure 17). Chemical toxicity could occur due to the localized leaching of plastic components and adsorbed pollutants (Wright and Kelly 2017). As it is the case in soils, ingested plastic could lead to modifications of the gut microbiome. More studies are needed to fully understand the risk of microplastics to human health.

Table 1: Example of average microplastic concentrations measured in food items (Cox et al. 2019)

Food	Plastic particle content
Seafood	1.48 particles g^{-1}
Sugar	0.44 particles g^{-1}
Honey	0.10 particles g^{-1}
Salt	0.11 particles g^{-1}
Beer	32.27 particles L^{-1}
Bottled water	94.37 particles L^{-1}
Tap water	4.23 particles L^{-1}

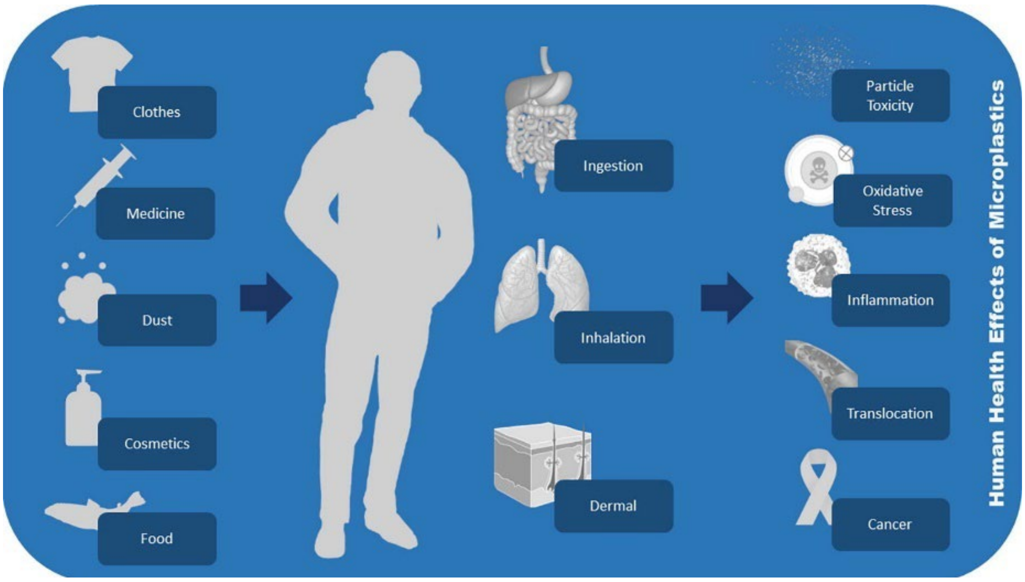

Figure 17. Sources, pathways and possible effects of microplastics on human health.(Prata et al. 2020)

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5. Strategies to reduce the plastic footprint in agriculture

5.1. Reducing

The first lever to reduce the consumption of plastic in agriculture and consequently reduce the plastic contamination is to reduce the need of plastic. Reducing the need for plastic is complex due to multiple services provided by plastic use. For example, to tackle the water supply deficiency, plastic mulch could be avoided if less water demanding crops could be grown. Subsurface drip irrigation or straw mulching could be other options. Additionally, some agricultural management like agroforestry or intercropping may also have a better water use efficiency than conventional agriculture under specific conditions. Currently no comparison between practices with plastic and alternatives without plastic in the same system exist. Alternative agricultural management may require changes of the complete crop production system.

- **What practices can reduce the need of plastic while maintaining the productivity?**
- **What innovations and supports are required to implement these practices?**
- **How to make relevant comparisons between conventional plastic use and reduced plastic use in agriculture?**

5.2. Reusing

While keeping the same agricultural practices the need of plastic in agriculture could be reduced by extending the duration of currently used plastics. For example, in case of plastic mulch use, some farmers apply a thicker version of normal light density polyethylene and use it for several crops in a row. In a similar way, stronger plastic films for greenhouses and tunnels cover would have a longer life span. Another example would be to reduce plastic packaging by transporting harvest in reusable crates instead of individual plastic wrapping. The management of the empty crates, traveling through different country's should be organized at the European level to limit waste. The use of stronger plastic may require higher investment cost but if they indeed reduce the replacement of the plastic may be economically profitable.

- **How to make the reuse of agricultural plastic feasible and practical?**

5.3. Recycling

Agricultural plastics have a high potential for recycling due to the large quantities produced and their relatively homogeneous composition. On the other hand, agricultural plastics are often dusty or muddy, can be heavily weathered and are potentially contaminated with pathogens and pesticides. The collecting and sorting of the agricultural plastic is another issue for their proper recycling. In the absence of an EU wide obligation to set a collection scheme for agricultural plastics, only five Member States have established collection systems in other countries, there is a limited infrastructure in place that enables farmers and growers to easily recycle their plastics (European_Commission 2018). The recycling approach is promising because it does not imply to change the agricultural management (reducing) and does not need a lot of innovation to adapt the plastic polymers (improving degradability). However, it does require the organisation of a plastic circular economy. An ideal circular economy would combine **plastic industries** that produce plastic from standardised blends to facilitate the sorting and recycling, **local infrastructures** that collect the used plastics and **recycling plants** that can make raw materials for the plastic industry.

- **How to support the implementation of a plastic circular economy?**

Box 3: Examples of existing collection and recycling schemes for agricultural plastics in Europe (European_Commission 2018)

Ireland - IFFPG

In 1997, Ireland introduced legislation designed to assist and promote the recycling of agricultural plastics. Consequently, all producers are members of the IFFPG (Irish Farm Film Producers Group). The IFFPG is funded through a recycling levy charged to producers; and a weight based collection fee charged to farmers. The IFFPG arranges the collection and recycling of farm plastics across Ireland, either through bookable farmyard collections or a number of local one-day bring-centres (it ran 237 in 2016). The scheme is operating successfully. In 2016, the IFFPG collected 27,193 tonnes of farm plastics waste leading to 74% recycling of what producers placed on the market in the previous year. Of the plastics collected, over 60% was supplied to Irish recyclers.

France - ADIVALOR

Under French regulation there are no specific take back obligations for agricultural plastics, rather it is stipulated that producers, importers and distributors of waste generating products may, in accordance with the principle of extended producer responsibility, be required to manage their disposal. The French agri-plastics industry has created a national voluntary EPR initiative, managed by a private not-for-profit organisation called ADIVALOR, created in 2001. ADIVALOR is largely funded by manufacturers and suppliers. They are charged an 'eco-fee' when they place product on the French market. Farmers return any uncontaminated waste to one of 6000 collections points across France. Farmers are not charged for this service. ADIVALOR's statistics indicate that the scheme is successful. As of 2015, there were 385 producers, 1200 distributors and 280000 farmers participating across all materials. The collection rate of agricultural film increased from 42% in 2009 (the first year) to 71% in 2014, with almost 50,000 tonnes collected.

Germany - RIGK

In 2013, the German industry association for plastic packaging in partnership with waste disposal specialist RIGK, created a national recovery system for agricultural film. The scheme, called ERDE, started to collect a variety of film types in 2014. Its activities are funded by member companies i.e. manufacturers and importers. ERDE's success is reliant on voluntary participation; currently there are 7 participating manufacturers and over 20 collection partners. Farmers are incentivised to return their used plastics to collection points by a bonus, which can be redeemed against a future purchase. According to RIGK, ERDE collected 5412 tonnes of agricultural film in 2016, a 16.6% increase in comparison to 2015

5.4. Improving degradability, need for certified products

The degradability of the plastic polymers is a major issue when plastic debris are emitted in the environment, as low degradation rate leads to accumulation (Rillig 2012). With improving recycling, improving degradability is the most investigated way to reduce plastic footprint in agriculture. New plastic blends, adapted to the environmental conditions of each specific area, are needed for the agricultural practices requiring single use plastic. Preliminary tests of the new biodegradable blends should prove the degradability of the plastic in the targeting conditions before commercialisation. Regulation should implement certification in that sense. TÜV AUSTRIA proposes different certification for different matrices (soil, fresh water, sea, Box.1) but not for different climates. The development of biodegradable plastic competes with the reuse and recycling of plastics. Economic and environmental assessments are needed to decide which solution is the best for a specific case.

Another alternative to plastic mulching could be cellulose materials such as straw bark or paper films (Jabran 2019). Cellulose materials may have better biodegradability. It seems that paper mulch may lead to lower water use efficiency than conventional mulch and may be less efficient to reduce the growth of weed (Saglam et al. 2017). However, few comparative studies are available so far. The main aspect is that the deterioration of paper mulch caused enhanced evaporation. Treatments, with oil and sulphur for example are used to improve the paper resistance (Anderson et al. 1996). Straw, bark or other organic materials such as ramial chipped wood

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(woodchips from branches) or compost could also be used to reduce evaporation and control weeds and may be a source of organic matter and nutrients to the soil. These materials may be a cheaper alternative to mulch films when easily available in big of quantitates near the farm. New mulch films, paper based or biodegradable blends, are more expensive than conventional plastic films. The increase of the demand and innovation could reduce the cost of production. Additionally biodegradable mulches spare the removal, sorting and collecting of the plastic which are labour demanding and costly steps.

- **What innovative plastic alternatives are available to accommodate the variety of agricultural practices and environments?**

5.5 Remediation of plastic contamination

The plastic contamination could be reduced at two levels: in the biofertilizers and irrigation water used in agriculture and in the contaminated fields. Firstly, better sorting of organic waste, better filtering and degradation processes in composting plants, biowaste digesters and water treatment plants would decrease the plastic contamination. Secondly, the possible use of microorganisms to degrade plastic particles in the soil could reduce the plastic contamination in the fields. Both ways would rely on a better understanding of the biodegradation of plastic and on the use of suitable microorganisms. Some bacteria and fungi have been found to be able to degrade PE and other conventional plastics but no field applications have been done so far (Huerta Lwanga et al. 2018). Engineering a microbiome inoculum that could degrade plastic in industrial or environmental conditions is challenge of the current research. Enhance biodegradation is a promising solutions especially in the controlled processes in composting plants, biowaste digesters and water treatment plants.

6. Monitoring the plastic footprint reduction

The implemented strategies should be monitored to make sure aimed objectives are reached. Three different aspects can be identified:

- **Use of natural resources and energy**

Even though conventional plastics are petroleum based, their production is quite energy efficient compared to other materials. For example, in the current state of production bio-based plastic require more energy to produce the crops and transform them than the production of conventional plastic. Scaling up the production of bio-based plastics may balance this difference. The transport required at the different life-stages of the plastic should be included in the energy assessment. When deciding to change an agricultural practice at the farm level, the use of natural resources and energy could be taken into account to compare with the original practice. The use of natural resources and energy is often related to the cost of the product, which will affect the crop profitability.

- **Profitability of the crop production**

Implementing a new agricultural management should keep or increase the crop profitability. If additional costs are needed to reduce the environmental contamination it should be defined who will be covering the costs. For example, most countries ask the plastic producers to finance the collecting and recycling scheme.

- **Contamination to the environment**

In some cases, reducing the plastic footprint while conserving the crop profitability could mean increase the overall soil contamination. For example, in the case of plastic mulch used for weed control, stopping the plastic mulch use could mean an increase of herbicides use that may leave toxic residues in the soil and have other impacts on the environment. In another way, switching from LDPE plastic mulch to biodegradable plastic mulch will affect the soil microbial community because some microorganisms will benefit from the degradation of the biodegradable plastic. It is unknown if these changes will affect the presence of soil pathogens or beneficial microorganisms. Moreover, a well-developed method to monitor the plastic content in environmental samples is especially critical to assess the biodegradability of plastics directly applied to the soil (e.g. plastic mulching). More innovation is needed to provide a faster, cheaper and more accurate method

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Conclusions

Plastics are widely used in agriculture and provide many services. However, it creates new challenges for the management of the plastic waste and limiting the contamination of the environment with plastic debris. Agriculture plays a major role in plastic contamination because of the direct use of plastic and because of the use of biofertilizers contaminated with secondary plastic debris,. The long term effects of plastic contamination are still unclear and need further research. Innovative practices are needed to reduce the plastic footprint of agriculture. As a conclusion we highlight the main questions rising from this starting that will be addressed by the Focus group:

Knowledge gaps:

- What are the effect of plastic contamination, for the soil physicochemical properties, for soil organisms, for plants, for farm productivity, for the environment, for human health, for the toxicity of other contaminants?
- What agricultural practices can achieve good productivity with lower plastic use and plastic contamination?

Needs for innovation:

- How to limit plastic contamination in soil?
- How to improve the degradability of plastics while maintaining its properties for agriculture?
- How to eliminate plastic debris from organic fertilizers?
- How to remediate soil contaminated with plastic debris?
- How to identify and quantify plastic debris in soil (fast, cheap and accurate method)?

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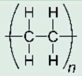
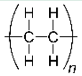
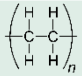
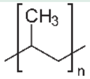
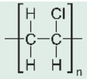
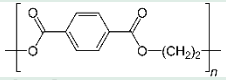
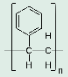
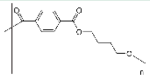
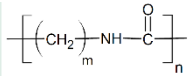
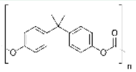
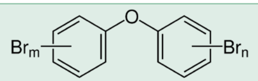
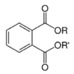
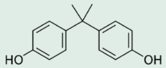
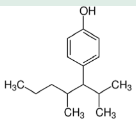
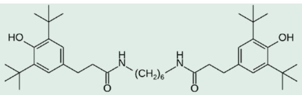
Annexes

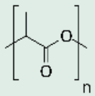
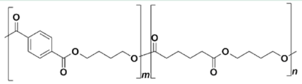
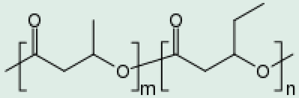
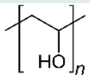
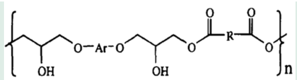
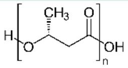
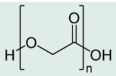
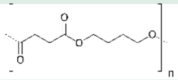
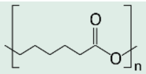
Annex 1 : Name, abreviation, description and share of the EU plastic demand for most comnly used conventinal plastic polymers

Name	Abb.	Chemical structure	Description	Example of use	% of the EU tot. plastic demand	% for agriculture use of the EU tot. plastic demand
Polyethylene	PE		low cost, good workability, excellent chemical resistance and electrical insulation	With high branching (2% of the Carbons) it produces LDPE, with low branching it produces HDPE	29.7%	1.1%
Low-density polyethylene	LDPE		Low tensile strength	Reusable bags, trays and containers, agricultural film, food packaging film	7.5%	0.1%
High-density polyethylene	HDPE		High tensile strength	Toys, milk bottles, shampoo bottles, pipes, houseware,	12.2%	1%
Polypropylene	PP		properties are similar to polyethylene, but it is slightly harder and more heat resistant	Food packaging, microwave containers, pipes, automotive parts,	19.3%	1%
Polyvinyl chloride	PVC		Can be rigid and flexible depending on the production process and additives used	Window frames, floor and wall covering, pipes, garden hoses,	10%	
Polyethylene terephthalate	PET		PET can be semi-rigid to rigid, and it is very lightweight	synthetic fibres (often referred as polyester), Water bottles	7.7%	
Polystyrene	PS		Polystyrene can be solid or foamed to produce expanded polystyrene (EPS)	Food packaging, insulation,	6.4%	0.5%
Polybutylene terephthalate	PBT		PBT has slightly lower strength and rigidity, slightly better impact resistance than PET	household electrical, insulator		
Polyamides	PA		Polyamides are a group of polymers that differs by the composition of their main chain. Most common polyamide is Nylon	synthetic fibres, automotive industry,		
Polycarbonates	PC		strong, tough materials, can be optically transparent	Plastic containers, transparent sheeting		

Annexe 2 : Different families of additives

Name	Chemical structure	Example of use	Potential adverse effect
Polybrominated diphenyl ether (PBDEs)		Family of additives for different use, including flame retardants	Endocrine disruptors
Phthalates		Family of additives for different use, including increase plastic flexibility, transparency	Endocrine disruptors
Bisphenol A		Precursor for plastic polymerisation, Antioxidant (reduce degradation)	Endocrine disruptors
Octylphenol and Nonylphenol		Family of additives for different use, including Antioxidants (reduce degradation)	Endocrine disruptors
Irganox		Antioxidant (reduce degradation)	Endocrine disruptors

Annexe 3 : Name, abreviation, description and degradability of the biodegrable polymers

Name	Abb.	Chemical structure	Description	Example of use	Degradation	Soil burial test
Polylactic acid	PLA		Bio-based from fermented plant starch such as corn, cassava, sugarcane or sugar beet pulp.	Packaging, agricultural films, synthetic fibres, nonwoven fabrics,	Biodegradable under industrial composting. Very slow to no degradation at ambient temperature in soil	(Shogren et al. 2003) (Lv et al. 2017) (Rudnik and Briassoulis 2011b) (Rudnik and Briassoulis 2011a) (Calmon et al. 1999) (Siakeng, Jawaid et al. 2020)
Polybutylene adipate terephthalate	PBAT		high flexibility and toughness, low stiffness	plastic bags, agricultural films and wraps	Biodegradable under industrial composting conditions. Slow degradation at ambient temperature in soil	(Palsikowski et al. 2018) (H. Wang et al. 2015) (Weng et al. 2013)
Poly(3-hydroxybutyrate-co-3-hydroxyvalerate)	PHBV		low elongation and low impact resistance	CRF, packaging	Biodegradable under industrial composting conditions. Slow degradation at ambient temperature in soil	(Calmon et al. 1999) (Sang et al. 2001) (S. Wang et al. 2005) (Gonçalves et al. 2009) (Tao et al. 2009) (Batista et al. 2010) (Gonçalves and Martins-Franchetti 2010) (Arcos-Hernandez et al. 2012) (Baidurah, Murugan et al. 2019)
Polyvinyl alcohol	PVA		high tensile strength and flexibility	Use as a moisture barrier in plastic films	Very limited degradation at ambient temperature in soil	(Corti et al. 2002)
Poly(hydroxyester-ethers)	PHEE		high thermal and chemical resistance.	improve the mechanical and water resistance of a blend	Slow degradation at ambient temperature in soil	(Shogren et al. 2003)
Polyhydroxyalkanoates	PHA		Similar to PP	packaging	Slow degradation at ambient temperature in soil	(Rudnik and Briassoulis 2011b) (Chan, Vandi et al. 2019) (Umesh and Thazeem, 2019)
Polyglycolide	PGA		high strength and stiffness	packaging	?	
Polybutylene succinate	PBS		Similar to PP	packaging	Slow degradation at ambient temperature in soil	(Kim et al. 2006) (Wang, Liu et al. 2020)
Polycaprolactone	PCL		good resistance to water, oil, solvent and chlorine	improve processing characteristics and impact strength of a blend	Almost full soil degradation	(Calmon et al. 1999) (Al Hosni, Pittman et al. 2019)

Annexe 4 : Abundance of microplastics in environmental samples

Matrix	Description	Abundance [g kg^{-1}]	Abundance [particles kg^{-1}]	References
Soil	horticultural soil in Argentina	0.02±0.014		Ramos et al. (2015)
Soil	Near the industrial area in Australia	0.3–67		Fuller and Gautam (2016)
Soil	Floodplain soils in Switzerland	0.055	≤ 593	Scheurer and Bigalke (2018)
Soil	Rice-fish co-culture ecosystems in China (Shanghai)		10.3 ± 2.2	Liu et al. (2018) b
Soil	Vegetable fields in China (Shanghai)		78.0 ± 12.9 (top layer) 62.5 ± 13.0 (deep layer)	Liu et al. (2018) b
Soil	Agricultural field in China (Shanghai)	≤ 0.00054	40 ± 126 (top layer) 100 ± 141 (deep layer)	Zhang et al. (2018) b
Soil	Greenhouse field in China (Shanghai)	≤ 0.00054	100 ± 254 (top layer) 80 ± 193 (deep layer)	Zhang et al. (2018) b
Soil	Fruit field in China (Shanghai)	≤ 0.00054	320 ± 329 (top layer) 120 ± 129 (deep layer)	Zhang et al. (2018) b
Soil	Greenhouse vegetable soils in China (Shanghai)		7100–42,960	Zhang and Liu (2018)
Soil	Forest buffer zone in China (Shanghai)		8180–18,100	Zhang and Liu (2018)
Soil	Sewage sludge application in Chile		600- 10400	Corradini (2018)
Soil	Soils amended with sewage sludge and compost in citrus orchard, China		545.9 ± 45.7 (after 30 t/ha/y sludge) 87.6 ± 9.3 (after 15 t/ha/y sludge)	Zhang et al. (2020)
Soil	Mulching in cropped soils in China (Hangzhou Bay)		263	Zhou et al. (2020)
Soil	Soils amended with sewage sludge in east of Spain		18,000 ± 15,940 light density plastic 32,070 ± 19,080 heavy density plastic	van den Berg et al. (2020)
Wetland	Urban tidal freshwater wetland in USA (Washington, DC)		1,270 ± 150	Helcoski et al. (2020)
Biota	earthworm, Lumbricus terrestris, exposed to microplastics in petri dishes	4.5 ± 2.5		Huerta Lwanga et al. (2016)
Biota	Terrestrial birds China (Shanghai)		22.8 ± 33.4 per bird, 0-116 per bird	Zhao et al. (2016)
Sludge	municipal treatment plant in New York		0 - 2000	Zubris and Richards (2005)
Sludge	municipal treatment plant in California		5000	Carr et al. (2016)
Sludge	municipal treatment plant in Ireland		4200 – 15000	Mahon et al. (2017)
Sludge	municipal treatment plant in Chile		34000	Corradini (2018)
Air	Urban and sub urban sites in Paris		2–355 particles/m^2/day	Dris et al. (2016)

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