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RESOURCES AND RECYCLING

# END OF LIFE TREATMENT OPTIONS FOR BIOPLASTICS; A COMPOSTING EFFICIENCY CASE STUDY

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# 1. Introduction

Plastics are widely used manufacturing materials, with applications in a variety of industries. Chemically, they are high molecular weight polymers conventionally made from petroleum, synthetic plastics are produced in a series of steps, staring with the distillation of crude oil, separating it into groups of lighter components, called segments. Each segment is a mixture of polymeric hydrocarbon chains, which differ in terms of size and structure. One of these segments, naphtha, is what generates monomers which can in turn form plastics through polyaddition and/or polycondensation.

This process already produces pollutants and greenhouse gases, but petroleum-based plastics are also nonbiodegradable, persisting in the environment as waste.

Because of this, the constant increase in plastic production creates many problems, from its oil-based production all the way to end-of-life (EOL) treatment, as the same proprieties that make plastic useful (its durability, low reactivity and the ease with which great amounts can be produced) make conventional plastic into long-lasting waste that’s quickly piling up.

Furthermore, conventional plastic’s low costs make it a perfect candidate for single use goods, especially in the food sector, where contamination and moisture need to be kept out. This packaging’s short lifespan means that tons of single-use plastic (SUP) are discarded after sometimes just days of use, but can persist in the environment for thousands of years.

To overcome some of these problems various alternatives have been suggested. One of these alternatives is a different kind of plastics, bioplastic. This means a polymeric compound that is both functionally like synthetic plastics and largely environmentally sustainable.

The substitution of conventional plastics with bio-based should reduce the dependency of plastics on fossil fuels and the pressure on landfills as bioplastic have alternative EOL treatments available.

Just like conventional plastic, bioplastics are not just one single material, instead they are comprised of a whole family of materials with different properties and applications. But unlike their conventional counterparts, there isn’t an universally accepted definition or terminology for bioplastics or bio-based plastic. For example the *Business-NGO Working Group for Safer Chemicals and Sustainable Materials* (a collaboration to promote the use of safer chemicals in consumer products) defines bio-based plastics as “plastics in which 100% of the carbon is derived from renewable agricultural and forestry resources such as corn starch, soybean protein and cellulose", meanwhile the US Department of Agriculture defines them as "commercial or industrial goods, (other than feed or food), composed in whole or in significant part of biological products, forestry material, or renewable domestic agricultural materials, including plant, animal or marine materials". ASTM instead defines a bio-based material as "an organic material in which carbon is derived from a renewable resource via biological processes".

According to European Bioplastics, a plastic material is defined as a bioplastic if it is either biobased, biodegradable, or features both properties.

## 1.1 Categories of bioplastics

Following the EU's definition we can study each part: the term 'biobased' means then that the material or product is (at least partly) derived from biomass, such as corn, sugarcane, cellulose, or even organic waste.

Biodegradable refers instead to a material's EOL. Biodegradation is a chemical process during which microorganisms that are available in the environment convert materials into natural substances such as water, carbon dioxide, and compost. The process of biodegradation depends on the surrounding environmental conditions, on the material and on the application. Since this property depends only on chemical structure, biobased plastics may be non-biodegradable, while some fossil-based plastics can biodegrade.

In particular, European law defines biodegradable plastic as a material that can physically decompose, ending up as just CO2, biomass, and water. European directives also state that bioplastic packaging must be recycled via composting or anaerobic digestion.

A biodegradable plastic is then only defined by its chemical structure and by the EN13432/EN14995 certification, obtained if the material passes the following tests:

- Chemical test
- Biodegradability test
- Disintegration test
- Real test
- Ecotoxicity test

We can then use this two part definition to classify different types of bioplastics, as depicted in Fig. 1.

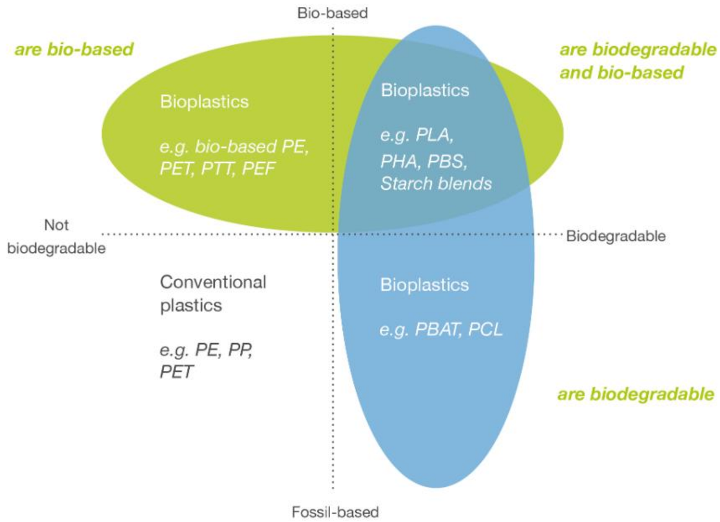



*Fig. 1: Plastic classification according to source and biodegradability criteria. (https://www.european-bioplastics.org/bioplastics/)*

A material which is both biobased and biodegradable not only saves emissions from the use of fossil fuels, but it can also be treated as organic waste, sent to a composting plant or to an anaerobic digester and then reintroduced as a new resource.

It’s worth noting tough, that most biodegradable plastic needs specific conditions, not present in a natural environment, to decompose. Because of this not all compostable plastic might not be compostable at home, but some only in controlled industrial plants.

# 2. Production

The first part of a material's life cycle is its raw material extraction and subsequent production. If we want to analyze bioplastics' behaviors and impact, we need to start from its creation, and how it compares to alternative materials.

## 2.1 Production and concerns

Bioplastic alternatives exist for almost every conventional plastic material and corresponding application, but currently only represent about 1% of the about 367 million tonnes of plastic produced annually, with a global production of 2.42 million tonnes in 2021, and only a slow rise of production capacity is predicted, increasing to approximately 6.3 million tonnes in 2027. But as demand is rising, and with more sophisticated materials, applications, and products emerging, the market is already growing very dynamically. It's also worth noting that even in this 1% only around 60% of the bioplastics produced are biodegradable. This distribution is highlighted in Fig. 2.

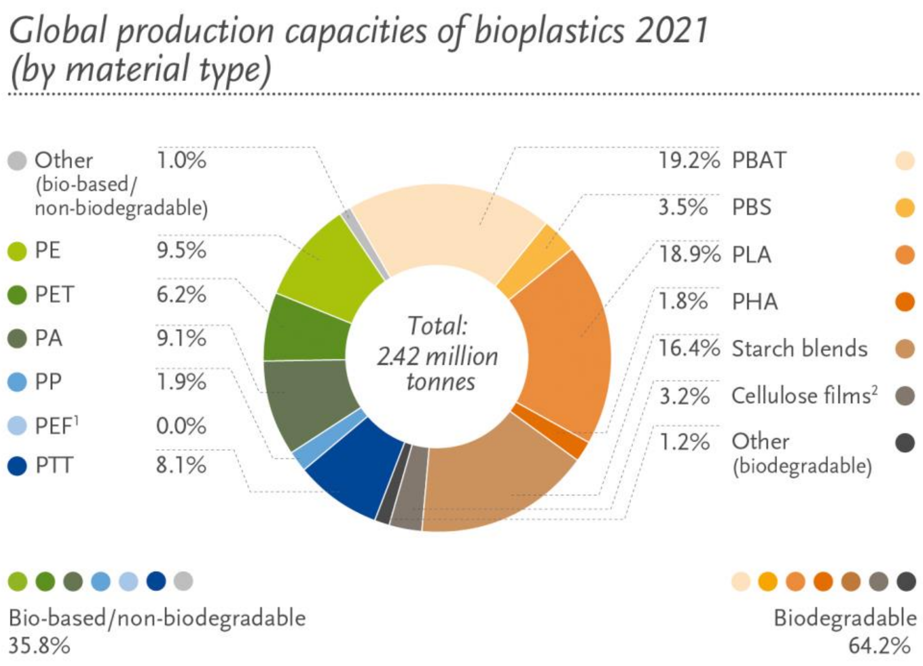



*Fig. 2: Global production capacities of bioplastics 2021 (by material type). (https://www.european-bioplastics.org/market)*

Since there are many types of bioplastics the production is not only technically different, but it also has varying impacts. A positive example is PLA, its production saves two-thirds of energy compared to traditional plastics in addition to having no net increase in carbon dioxide gas during biodegradation, because the plants from which they were produced absorbed the same amount of carbon dioxide when they were cultivated. Notably, PLA emits 70% less greenhouse gases when it degrades in landfills.

But there are also negatives, a recent study, which compared seven traditional plastics, four bioplastics, and one made from both fossil fuel and renewable sources, determined that bioplastic production resulted in greater amounts of pollutants, from both fertilizers and pesticides, and the chemical processing required. It was also found that bio-plastics contribute more to ozone depletion than traditional fossil fuel-derived plastics, and that bio-based PET is a potential carcinogen with pernicious toxic effects on earth ecosystems.

There are not only technical considerations but also concerns about repurposing of land for producing plastic instead of fulfilling food requirements, as a recent statistical study revealed that almost a quarter of the agricultural land producing grains is used to produce biofuels and bioplastics.

Even their strength, the ability to decompose, can be a concern if not well managed. For example, when a cornstarch-derived bioplastic is composted, the cornstarch molecules slowly absorb water and swell up when buried, in turn, this causes the bioplastic to break apart into small fragments more easily digested by bacteria. However, other kinds of bioplastics, low or non-degrading, only break-down at high temperatures or in industrial sites. Even when the bioplastic can fully degrade there can be issues, the process produces methane, a greenhouse gas, but it’s important to remember that while this by-product must be contained and treated, PLA still emits 70% less greenhouse gases when it degrades in landfills than traditional plastics, and substituting the latter with corn-based PLA can reduce greenhouse gas emissions by 25%.

### 2.1.1 Source types

Among the many types of sources, plant- and starch-based sources (as in wheat, rice, sweet potato, barley, sorghum, corn, cellulose derivatives primarily) account for around 80% of the overall bioplastic market. Their main drawback is the rise in specific crop production can affect the human food chain. In addition, they provide with lower amounts of biomass and require more time for production compared to other sources.

But starch is also cheap, renewable, and an easily modifiable biopolymer, it is made of two main polymers, amylose, and amylopectin. Starch chains bind together via strong hydrogen bonding, resulting in a rigid structure composed of highly ordered crystalline regions, an can then be formulated into suitable thermoplastic material.

Another one of the most well-known source type for the production of bioplastics are bacteria. Many bacteria can in fact produce Polyhydroxybutyrates (PHBs, their structure is shown in Fig. 3), macromolecules synthesized and accumulated as reserve materials when the bacteria grow under different stress conditions, often using agricultural residues as carbon sources. PHBs are completely biodegradable and have especially high production results (61%) when glucose is used as a carbon source. A drawback is the high production cost, the biggest contributor to this cost is the carbon feed, but sugarcane bagasse, an agricultural residue, can be used to reduce it, along with lowering the land requirement to produce feedstock. Furthermore, the yield of PHB can be boosted by optimization of the production parameters as well as the substrates.

PHBs are a part of one of a family of bioplastics: polyhydroxyalkanoates (PHAs), a class of bio-based plastics that are biocompatible, biodegradable, and non-toxic polyesters that can be synthesized by both specific bacteria or plants and from other renewable sources. For example, PHAs can be produced from methane released from feedstock in wastewater treatment facilities, landfills, composting or facilities; plastic compounders can be used as feedstock for successful, low-cost commercial production of PHA, along with wood biomass, grass, energy, and crop residues, instead of more

expensive biomass obtained from edible crops that can impact the human food chain.

One of the biggest positives of PHA bioplastics is that they can be digested naturally by marine microorganisms if decomposed into methane.

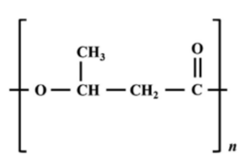


*Fig. 3: PHB plastic structure (Atiwesh et al. 2021).*

The most diffused starch or plant-based product is Polylactic acid (PLA), covering over 18% of all bioplastics. It is a thermoplastic aliphatic polyester obtained polymerizing lactic acid from renewable resources (corn starch, tapioca roots, chips or starch, and sugarcane). PLA is mostly used for sensitive food products, but it’s too fragile for other packaging manufacturing processes, often needing additives to make it more durable. Notably, PLA is the most biodegradable thermoplastic, typically degrading via hydrolysis. It can also be used for soil retention sheathings or waste shopping bags, and it can be converted into fibers by spinning and used to manufacture woven, disposable and biodegradable articles such as garments, feminine hygiene products, and diapers.

Algae can also be used similarly to produce bioplastics, seaweeds are cost-effective and easily cultivated throughout a wide range of environments and timeframes. Plus they can minimize the impact on the food chain.

The most commonly used seaweed types contain polysaccharides and are often negatively charged, allowing them to interact with cations, resulting in the formation of gels.

These gels have properties that cover a wide range of industrial applications required by all thermo-mechanical bioplastics. The seaweed’s polysaccharides are extracted from dried and ground seaweeds with a hot extraction method, followed by a two-step purification process. First, there’s the removal of dense cellulosic contaminants by centrifugation and filtration, and then the concentration of the purified mixture by water evaporation. Additives can be used to cause precipitation of the polysaccharides, which can be frozen and freeze-dried to be used in the manufacturing of bioplastics.

Another use for spirulina, a microalgae, is to help counteract the reliance of bioplastic production on feeding bacteria with large quantities of sugars, obtained from natural crops. This is because we can develop a cyanobacteria of the Spirulina strain which can constantly produce sugar, leaking it into the surrounding saltwater. The natural bacteria there present feed off the leaked sugar and convert it to into bioplastic.

To a smaller extent, mycelium, the vegetative fungal extension that gives rise to mushrooms, can be used to make plastic-like materials for biodegradable packaging. Like algae, mycelium is composed of polysaccharides, along with chitin, proteins, and lipids. It can create a fibrous biomaterial that can be combined with agricultural by-products (such as the peels from corn stalks and seeds) to make composite materials for industrial use.

More recently, in 2014, a new source was found, crab shells and tree fibers. Multiple layers of crab-shell chitin and cellulose were sprayed to form a flexible film. It can be compared to polyethylene terephthalate (PET), the most common traditional transparent food packaging, but this novel bioplastic material showed a 73% reduction in oxygen permeability, thus an increase in shelf-life.

## 2.2 Resource and emission savings

Concerns on the production methods have to be weighed against conventional plastic impacts, to comprehensively compare the two, the most important tool is life cycle assessment (LCA), a process that can help determine the overall impact of a product on the environment during its entire life cycle.

This means that the whole life of the relevant product is evaluated, starting from its raw material extraction to the processing stages, manufacturing, distribution, use and disposal. We can assess this impact relation to various issues: global warming potential, human toxicity, abiotic resource depletion, eutrophication and acidification.

In addition, especially with the food chain concerns, it is essential to consider Land Use Change (LUC) related emissions, a tool to consider when land is converted to spaces for both composting, and biofuel feedstock production or other relevant uses.

This means we need to understand the LCA of different bioplastic types and for different composting, recycling, and disposal scenarios.

Because of its market relevancy many studies have focused on PLA, showing, for example, a significant reduction in green-house gases when bottles were made by subsisting 20% of  PET bottles with PLA ones. Another study, focusing on Global Warming Potential (GWP), showed that it was possible to reduce greenhouse gas emissions by 25% substituting traditional plastics with a corn-based PLA.

Such examples provide assurance on the future developments of bioplastics, especially when paired with hopeful forecasts of renewable energy use.

Additionally, the use of PLA and starch-based bioplastic over their traditional counterparts significantly reduces carbon dioxide emissions, in the case of PLA by 50–70%.

However, for a smart management of bioplastic wastes, it has been proposed that the reduction of greenhouse gas emissions must reach zero LUC emissions.

Conventional plastics tough are not the only alternative, for example, compostable waste might also be collected in paper bags.
Even in this case an LCA evaluating Mater-Bi bags showed that the production of paper bags, due to their higher weight, consumes much more energy than production of thinner materials. It was found that overall Mater-Bi bags have a significantly lower environmental impact than paper bags, and would have a similar impact to polyethylene bags if the latter were cleaned and incinerated. Often though, waste bags are sorted out at composting plants because polluted by the organic waste stuck on the film. With this taken into consideration, the Mater-Bi bags show a much better environmental profile than the alternatives.

## 2.3 Sustainability spectrums

Even before LCAs, studying the relationship between conventional and bioplastics and questioning which was actually more sustainable was wide-spread.
Already in 1998 the *plastics pyramid* (Fig. 4) was developed as an attempt to visually display the life cycle hazards of different plastics to assist in materials selection. The ranking took in consideration the material's toxicity, considering production hazards, use of harmful additives, hazards in use, and disposal hazards. From this limited considerations bio-based polymers are most preferable.

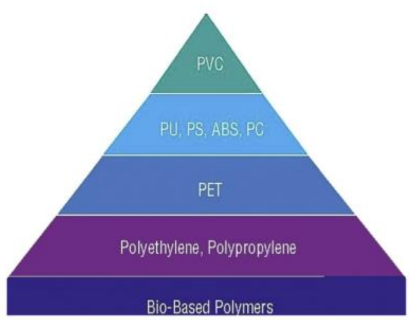



*Fig. 4: The plastics pyramid (Álvarez-Chávez et al. 2012).*

This first analysis didn't fully delve in how compostable these materials were, and was expanded upon in 2005 with the *Plastics Spectrum*, which displays the recyclability of various plastics alongside their life cycle hazards (Fig. 5). Followed by an *Environmental Preference Spectrum* in 2006 for the health-care industry (Fig. 6). This last spectrum was the first to try and provide criteria for what makes bio-based materials preferable. The preferred biobased plastics are those sustainably grown that can be recycled with already existing infrastructure, while suggesting avoiding those that are manufactured with, contain, or emit highly hazardous chemicals or those that are not easily recyclable. This report defines "sustainably produced bio-based materials as those that are: grown without genetically modified organisms (GMOs), hazardous pesticides, certified as sustainable for the soil and ecosystems, and compostable into healthy and safe nutrients for food crops".

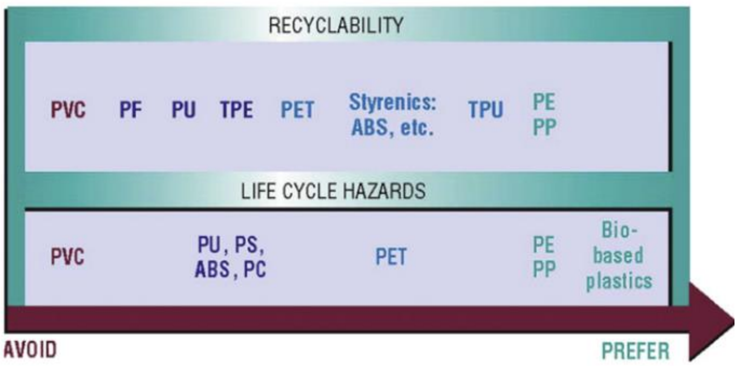



*Fig. 5: The plastics spectrum (Álvarez-Chávez et al. 2012).*

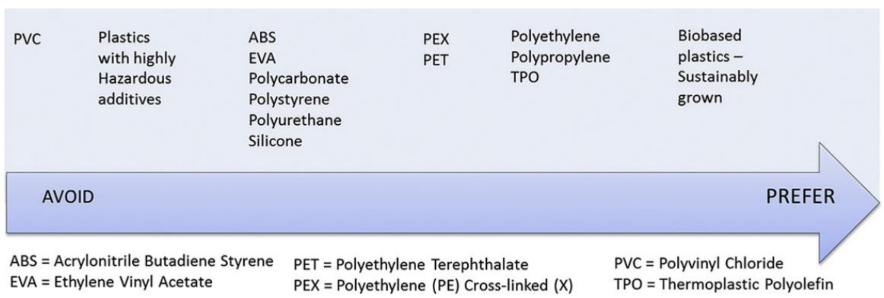



*Fig. 6: Environmental preference spectrum for the health-care industry (Álvarez-Chávez et al.2012).*

Following these principles, the *Plastics Scorecard* was created in 2009 to rate different types of plastics based on their life cycle impacts and hazards to both human health and environment. Its core elements are: sustainable feedstocks, green chemistry and closed loop systems.

Based on the core principal plastics receive a grade from F to A (good life cycle performance) (Fig. 7). For example, to obtain an A grade for PLA we need the base corn to have been grown without GMOs and atrazine pesticide, or the grade drops to C. Still, the difference with conventional plastics is huge, the maximum attainable grade for PVC is F because of its chemical releases and breakdown products (dioxins and furans that are persistent, bio-accumulative, toxic and carcinogenic chemicals).

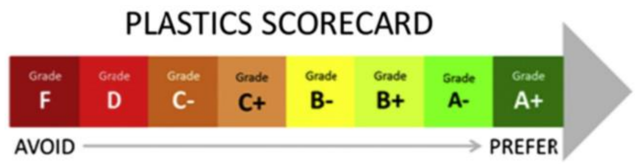



*Fig. 7: Plastic scorecard (Álvarez-Chávez et al. 2012).*

Adding to this last subdivision the principles of sustainability developed by the *Sustainable Biomaterials Collaborative*, a network of organizations formed to further the development and use of sustainable biomaterials. These principles include:

1. Reducing the amount of material, product and packaging used
2. Eliminating single-use products if they can't be recycled nor composted
3. Avoiding fossil fuel-based materials
4. Addressing sustainability across the entire life cycle of the material
5. Including in "sustainability" issues of environment, health, and social and economic justice
6. Designing products to be reusable, recyclable or compostable
7. Encouraging agricultural systems that are sustainable for farmers, the environment, farm workers and communities, including reducing transportation impacts.
8. Supporting family owned and operated farms
9. Avoiding GMOs
10. Using chemicals that meet the 12 Principles of Green Chemistry.
11. Avoiding materials that have not been tested for environmental and public health effects
12. Decentralize production and buy locally

Analyzing bio-based plastics according to sustainability criteria produced the Bioplastics Spectrums for Occupational Health and Environment (Figs. 8 and 9). From the health and safety impact comparative analysis (Fig. 8), emerges that PHAs, PLA, and starch are the preferred materials, since although there are some occupational hazards in their production, they were lower than for the others. The environmental analysis (Fig. 9), found that starch, urethanes, PHA, zein, and soy protein are preferred, even if GMOs and pesticides may be used in feedstock production.

In general feedstocks are grown according to industrial agricultural methods, with significant use of energy, water, land, GMOs, toxic pesticides and fertilizers.

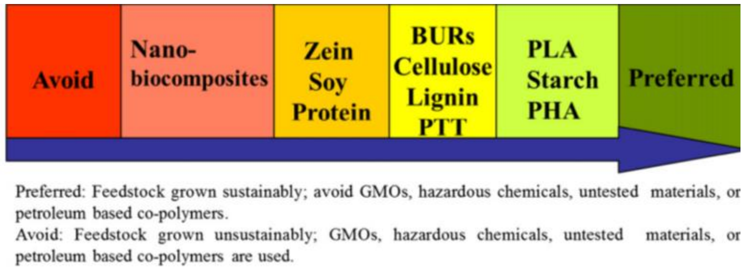



*Fig. 8: The Bioplastics Spectrum: comparative occupational health and safety impacts of bioplastics. BURs: bio-urethanes; PHAs: polyhydroxyalkanoates, isolated and purified by enzymatic methods; PTT: poly(trimethylene terephthalate). GMOs: genetically modified organisms (Álvarez-Chávez et al. 2012).*

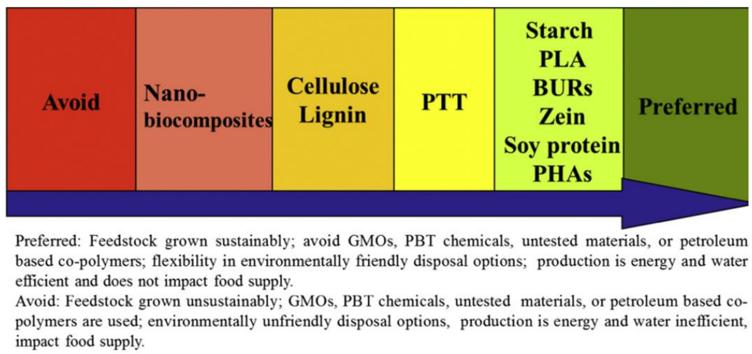



*Fig. 9: The Bioplastics Spectrum. Comparative environmental impacts of bioplastics. BURs: bio-urethanes; PHAs: polyhydroxyalkanoates, isolated and purified by enzymatic methods; PTT: poly(trimethylene terephthalate). GMOs: genetically modified organisms; PBT chemicals: persistent bioaccumulative and toxic chemicals (Álvarez-Chávez et al. 2012).*

# 3. EOL

Replacing traditional plastics with bioplastics is not necessarily enough to solve the plastic waste issue. To increase bioplastics' sustainability over their whole life cycle, the increasing in production must be paired with effective strategies to manage bioplastic products at their end of life, or they will simply substitute the traditional plastic waste.

We need to consider all the possible EOL treatments that bioplastics can go through, LCAs have shown that the eventual incineration or landfilling of bioplastic products is not a useful alternative. Bioplastics are instead suitable for a broad range of EOL treatments, including reuse, mechanical recycling, organic recycling, and energy recovery other than the classic composting. Most of the material produced can easily be recycled alongside their conventional counterparts, contributing to higher recycling quotas, they can also join conventional energy recovery streams. Just like with any other waste stream we can consider the waste hierarchy (Fig. 10), most bioplastics are produced with the goal to be disposable, so often re-use is not really applicable, while recovery can mean both energy recovery via incineration, and biomass recovery via composting. As the least preferred methos disposal, o landfilling, was already unattractive even without the rise in emissions found with LCAs.

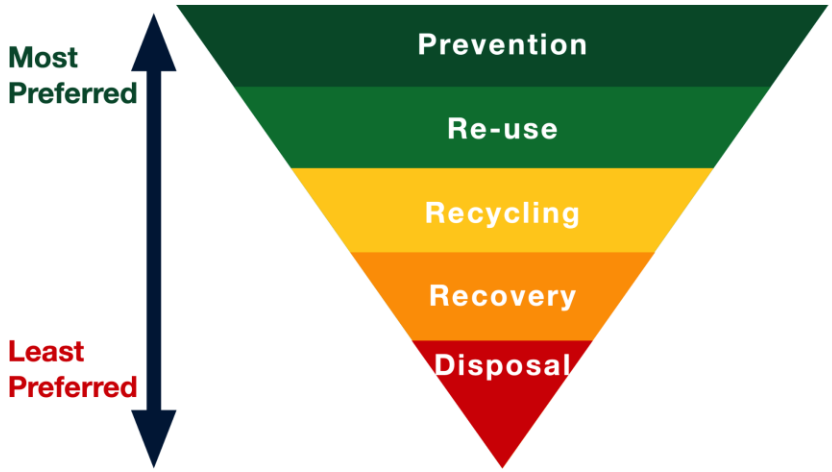



*Fig. 10: Waste hierarchy pyramid (https://ismwaste.co.uk/help/what-is-the-waste-hierarchy).*

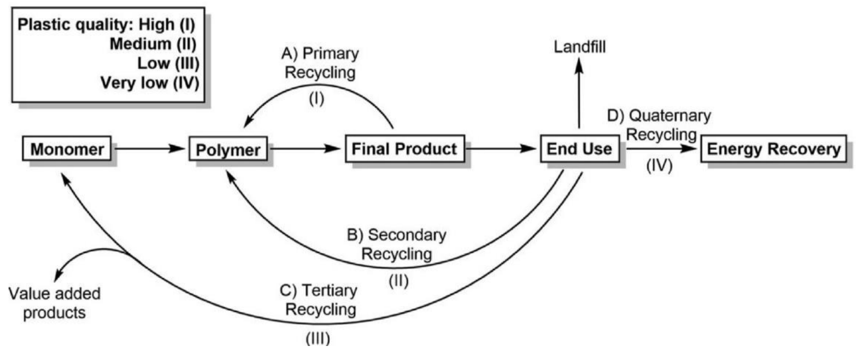
## 3.1 Recycling

Recycling, and mechanical recycling in particular, must play a prominent role, it's the most preferred disposal method because it allows a reduction in emissions, carbon footprint as well as raw material consumption.  While for non-biodegradable plastics recycling's importance is immediate, the same is not true for biodegradable plastics, as biodegradation is often seen as the only appropriate disposal option, even if they can degrade slowly under ambient conditions. Moreover, their biodegradation in the environment or landfills can lead to uncontrolled methane emissions, which is why it's preferred to degrade bioplastics in specific composting plants. It's a valid solution, but it should be seen as the very last life cycle step, after many steps of reuse and recycling, just like for their traditional counterparts. Disposal can result in even more losses for bioplastics, as it discards valuable bioderived molecules and raw materials (e.g., lactic acid for PLA), chemical recycling could instead transform waste bioplastics into alternative feedstocks for monomers and intermediate products, preserving primary renewable resources and further decreasing the bioplastics' environmental impact.

For bio-based, non-biodegradable polymers (such as bioPET or bioPE, all indistinguishable from their traditional counterparts), they can be mixed with their traditional counterparts and recycled in the already existing recycling facilities, but this does not always apply to biodegradable ones. Biodegradable bioplastics, especially those used for packaging, are entering both the streams of plastics recycling and green-waste composting, which could result in increased sorting costs, yield loss, and decreased processability and quality of the recycled or composted output.

Since the bioplastics market is predicted to continue to grow, bioplastics and conventional plastics are expected to coexist, and if a critical mass of collected bioplastic waste can be reached it might lead the way to an independent recycling stream.

While some call "organic recycling", it's not exactly a method aimed to recover plastic materials or monomers to be recycled and reintroduced in the life cycle of plastic products. This is the aim of traditional recycling options, such as mechanical (primary or secondary) and chemical (tertiary) recycling. For example, as long as the material quality is high, biodegradable plastics could be mechanically recycled with a primary recycling, meaning the recycled plastic has the same purpose as virgin plastic, and then by secondary recycling, to be used for less demanding applications. With the material quality decreasing under a certain threshold, there is still the option to chemically recycle, recovering valuable monomers. All available recycling options (listed in relation to waste quality in Figs 11 and 12) should be explored, in order to maximize the environmental benefits reusing these materials.





*Quality of plastic material associated with the various end-of-life options for plastic waste (Fredi and Dorigato 2021).*

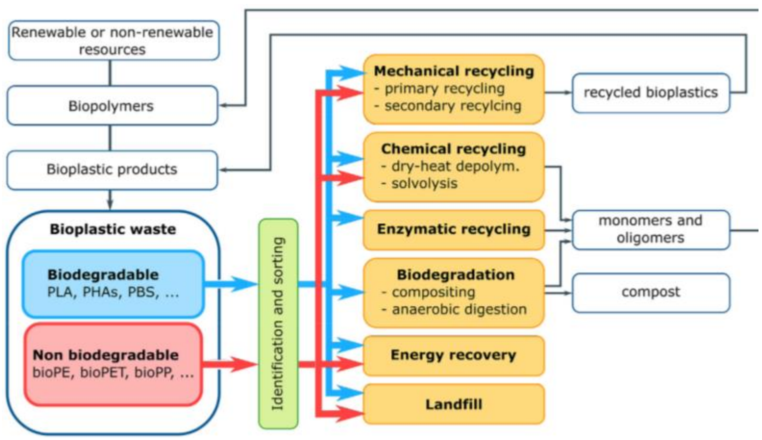



*Fig. 12: End-of-life routes for biodegradable and non-biodegradable bioplastic waste (Fredi and Dorigato 2021).*

### 3.1.1 Mechanical recycling

Mechanical recycling is the processing of waste by physical means, it is regarded as the main approach for plastic recovery, as it is generally less expensive, requires relatively simple technology, and has a lower environmental impact than chemical recycling.

As all recycling it starts with waste collection, screening, and manual and/or automatic sorting, and is composed of several steps such as grinding, washing, drying, compounding/extrusion, and granulation. These steps may occur different configurations according to size, shape, and composition of the feed, an example of the first steps can be seen in Fig. 13.

Mechanical recycling comprises both primary and secondary recycling. The first is a closed-loop technique that can only be performed on high quality waste of known history. In this case the recycled material is used for applications with requirements equivalent to those of virgin plastics. Because of these restrictions it's generally not related to post-consumer plastics, but to reconversion of uncontaminated plastic waste, and thus it does not require sorting and cleaning. Secondary recycling is instead a mechanical reprocessing of waste, the recycled material generally shows poorer mechanical properties, due to reduced material purity and degradation processes. It is only economically feasible when the waste doesn't need expensive separation and purification, which means that it should not be constituted by too many different materials or be contaminated.

Most biodegradable polymers, including PLA, PHAs, are aliphatic polyesters, which tend to be quite thermosensitive and susceptible to thermal degradation, leading to a decrease in mechanical properties. While mechanically reprocessing these materials, it is also fundamental keep the materials dry to not worsen the thermal degradation, which can be complicated by impurities containing humidity. For PLA, an additional issue is the low Tg (55-60 C), above which the material becomes sticky.

Similarly, thermoplastic starch is sensitive to hydrolysis and recycled material should be intended for downgraded applications.

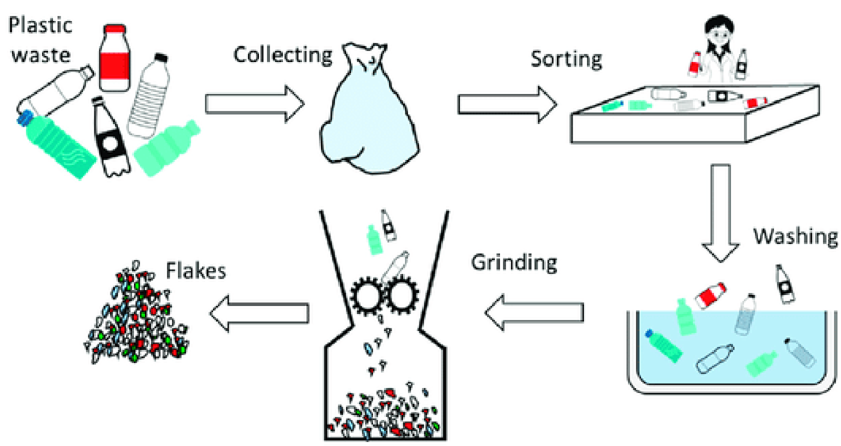



*Fig. 13: Mechanical recycling for plastic wastes (Kuzmanović et al. 2021)*

### 3.1.2 Chemical recycling

Chemical, or tertiary, recycling, is a steadily growing recycling stream consisting in the transformation of waste into useful chemicals, such as monomers and/or oligomers, which in tun are re-introducible in the polymer value chain and re-used for polymerization.

For biopolymers, tertiary recycling has been particularly successful with aliphatic polyesters. The main aim is saving primary resources, more than reducing waste. Unlike mechanical recycling, some of the chemical recycling techniques (e.g., pyrolysis) can be performed on low-quality, heterogeneous, degraded, or contaminated waste, which can then be converted into higher value chemicals. It also requires higher temperatures and is thus more energy-consuming. The two main techniques used are dry-heat depolymerization techniques (e.g., pyrolysis) and solvolysis methods (e.g., hydrolysis, alcoholysis).

Of these, pyrolysis is one of the most promising routes for waste that is difficult to mechanically recycle or depolymerize. It requires considerably lower temperatures than incineration and less pre-treatment steps than mechanical recycling.

Pyrolysis consists in the degradation of the material via heating, in an oxygen-free atmosphere and at moderate temperatures (300-700° C). Thermal degradation of the polymer chains can be accomplished with or without a catalyst (catalytic pyrolysis or thermal pyrolysis respectively), creating smaller and less complex molecules and producing solids (char), gases, and liquids that can be converted into chemicals. Since the volatile fraction of synthetic plastics is very high (97-99%) in respect to the ash content is low, plastics can yield a very high amount of oils (>90 wt%), but the yield can be decreased by additives such as fillers, flame retardants, plasticizers, and dyes, which increase the char fraction.

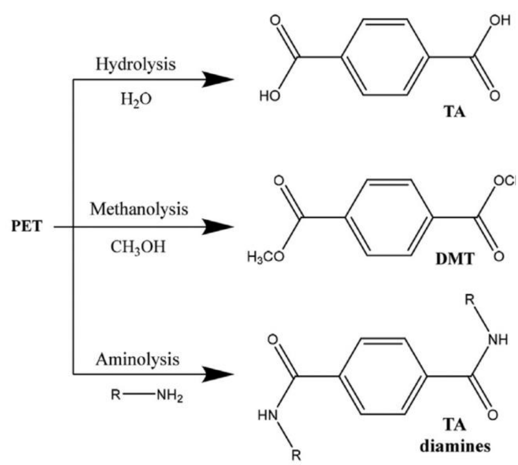
This is a well-established route for polyolefin, which yields small hydrocarbons, but also for polystyrene (PS), poly(methyl methacrylate) (PMMA), PET, and PA, yielding styrene, methyl methacrylate, terephthalic acid, and e-caprolactam, respectively. More interestingly biodegradable aliphatic polyesters can also be treated by pyrolysis, for example PLA can produce lactide, even if this reaction has a low yield and is very slow, and requires high temperatures (300-600° C) and a catalyst. The high temperature in particular may give way to undesired side reactions, such as lactide racemization, requiring special catalysts to lower the reaction temperature.

Solvolysis refers instead to all depolymerization and partial depolymerization techniques involving a solvent, which can but doesn’t have to be paired with heat. The most common techniques are hydrolysis, alcoholysis, and glycolysis.

These techniques are most suitable for step-growth polymers such as polyesters, polyamides, and polyurethanes, for which solvolysis can be thought as the reverse reaction to polycondensation. Of the main techniques:

- Hydrolysis: it has two steps, water diffusion into the bulk polymer and the hydrolysis reaction proper. There is a difference between low water diffusion rates, where polymer degradation occurs first on the surface, and high water diffusion rates, where the polymer is subjected to homogeneous erosion. To increase the degradation rate we can increase the temperature (above the polymer's melting point), or even the water pressure.
- Alcoholysis, an alcohol group cleaves ester bonds, promoting a transesterification reaction
- Glycolysis refers to the insertion of a glycol into the polymer chains, which replaces ester bonds with hydroxyl groups.

The difference between different solvolysis reactions are exemplified trough PET recycling, as we can see in Fig. 14 different solvents give different output products, and specifically the alcoholysis process in Fig. 15 and hydrolysis in Fig. 16.





*Hydrolysis, methanolysis, and aminolysis reactions of PET that yield terephthalic acid (TA), dimethyl terephthalate (DMT), and TA diamines, respectively (Fredi and Dorigato 2021).*

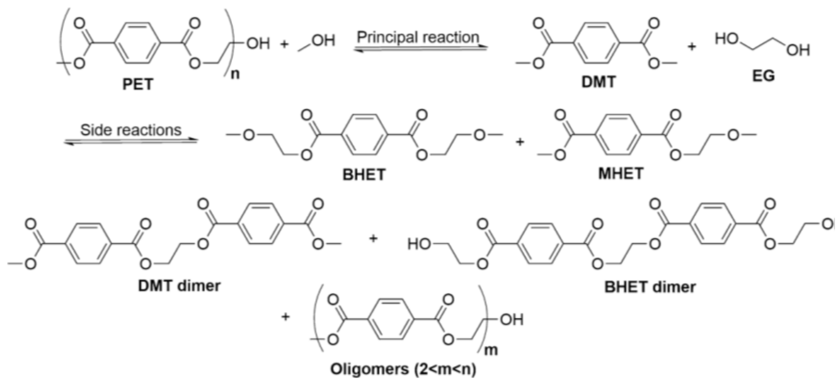



*Fig. 15: Overall reactions for PET alcoholysis using supercritical methanol (Lamberti et al. 2020).*

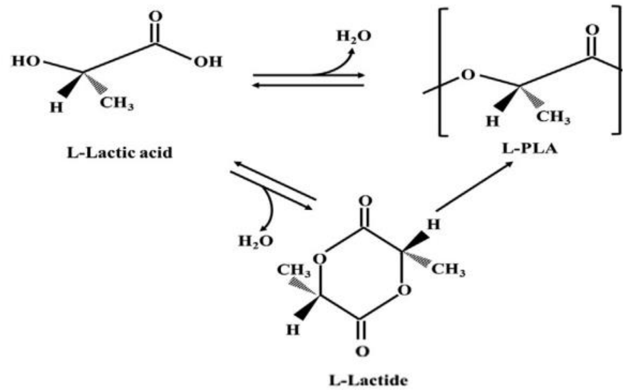



*Fig. 16: Polylactic acid (PLA) hydrolysis (Atiwesh et al. 2021)*

Until now chemical recycling of biodegradable plastics, and solvolysis in particular, has not been a very important EOL option, but it is promising from an economic and ecological point of view. For example, with PLA, obtaining lactic acid from hydrolytic degradation can require less energy than producing it from biomass fermentation

### 3.1.3 Enzymatic and microbial recycling

New promising techniques that focus on enzymes and microorganisms that degrade biodegradable bioplastics in a selective and controlled way, with the aim of recovering monomers and other valuable chemicals, unlike biodegradation and compositing, which are instead disposal methods. It could be considered a chemical recycling techniques, but they are relatively new methods and could branch out differently.
Several research works and patents have been published but the technology of enzymatic depolymerization is still at the early stages. This method is quite slow, especially when used on

highly crystalline polymers or polymers with high intermolecular forces, and the yield cannot be raised through higher temperatures, because the enzymes would degrade too.

## 3.2 Energy recovery

Energy recovery via incineration, can be useful to dispose of all the non-recyclable and non-biodegradable plastic waste, which have a high calorific value, similar to traditional plastic. When biobased plastics are incinerated, they are considered to produce renewable energy
In incineration plants, or waste-to-energy (WTE) plants, the heat generated from the combustion produces superheated steam in a boiler, this steam drives turbogenerators and produces electricity (Fig. 17).
To prevent odors from escaping, the air in the refuse bunker is kept below atmospheric pressure. High-capacity rotary crushers break down bulky material, and the walls are protected with refractory material lining from both heat and corrosion. After the incineration, we are left with ash, about 10 per cent of the original waste volume.
Pollutants have to be removed from the flue gas before it can be released, for example via electrostatic precipitators, lime powder dosing equipment and catalytic bag filters.
Any ferrous scrap metal contained in the ash can be recovered and recycled, while the ash can be landfilled, of bigger bottom ash could even be used as aggregates.

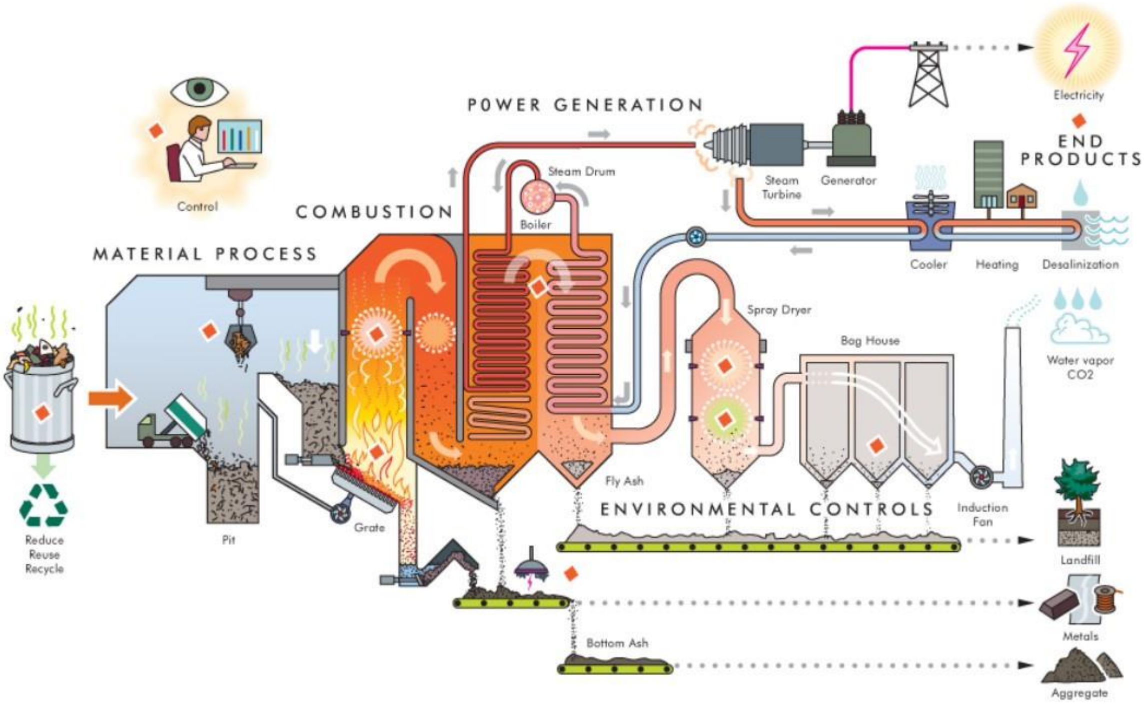



*Fig. 17: Waste to energy plant scheme ([https://www.cleanenergywire.org/factsheets/waste-energy-controversial-power-generation-incineration](https://www.cleanenergywire.org/factsheets/waste-energy-controversial-power-generation-incineration)).*

## 3.3 Composting

Composting is the controlled biological aerobic conversion of organic waste into CO2, H2O, heat, minerals, biomass, and humus useful for plant growth. This process is activated by microorganisms such as bacteria, yeasts, and fungi. In the European Union, composting follows the EU Council Directive on Landfill of Waste (1999/31/EC), urging to limit biodegradable waste that ending up in landfills. This is aided by the 2008/98/EC Directive on Waste, which encourages the separate collection and safe treatment of biodegradable waste.

Compostable plastics are a subcategory of biodegradable plastics. The first, such as PLA and TPS, decompose in a relatively short time under strict composting conditions, while the latter the process may be slower. This means that while all compostable plastics are biodegradable, not all biodegradable plastics are compostable.

Compostable bioplastic can thus be recovered along with organic waste and go through the industrial composting process, an established process for transforming biodegradable waste into stable, sanitized products to be used in agriculture. Different technologies are available but the general process of composting is the same, it can be divided into two distinct phases: active composting followed by curing.

The first phase lasts a minimum of 21 days. under strict conditions, microorganisms grow on organic waste, breaking it down to CO2 and water. Part of the energy is released into the surrounding environment as heat, since organic waste is amassed in piles the total production of heat can be high. When the temperature of the composting pile increases, the microbial populations shifts: microbes adapted to ambient temperature (mesophiles) stop their activity, or even die, and are replaced by thermophiles. In industrial composting facilities temperatures in the composting heaps range between 50°C and 60°C, for hygienisation purposes, temperatures need to remain above 60°C for at least one week, in order to eliminate pathogenic microorganisms.

During the curing phase, the rate of decomposition declines to a slow and steady pace, and the compost matures at temperatures in the lower mesophilic range (< 40°C) with the synthesis of humic substances.

The composting plants where all of this happens are large-scale professional facilities dealing with significant amounts of organic waste. They assure optimal process conditions, fast degradation, good emission control, and good compost quality. This is why the term "Industrial" (or municipal) composting is used, to distinguish it from "Home composting". In industrial plant important process parameters are controlled, such as material structure (size of particles), moisture content, aeration (availability of oxygen), temperature, pH, carbon/nitrogen ratio. In addition to the stable parameters, the final compost is subject to quality control analysis to verify if it meets the compost specifications.

Some of the most common technologies are windrow composting, aerated static piles, tunnel composting and in-vessel composting. These can also be integrated by anaerobic digestion, the methane produced in an anaerobic digester can be converted to biogas.

### 3.3.1 Anaerobic digestion and integrated plants

Anaerobic digestion converts organic waste into three main substances: biogas, rich in methane, biosolids (the microorganisms grown on the organic matter), and liquor (the dissolved organic matter), these last two can both be used as fertilizers.

It is composed of four main steps, happening in the absence of oxygen: first is hydrolysis, the extracellular enzymes of bacteria divide the complex biological macromolecules to produce simple sugars, fatty acids, and amino acids.

The second step is acidogenesis, these products are absorbed by acidogenic microorganisms, producing intermediates such as volatile fatty acids (VFAs). These intermediates are in the third step converted into acetate, hydrogen, and CO2 trough acetogenesis. Then, during the last step, methanogenesis, methanogenic organisms turn them into CH4.

The process takes place in a sealed vessel called a reactor, it contains the complex microbial communities that can break down (or digest) the waste, producing biogas and digestate.

Multiple organic materials and waste streams can be processed in one digester (some examples in Fig. 18), a practice called co-digestion. These co-digested materials can include manure, food waste, energy crops and residues, fats, oils, and greases (FOG) among others. Co-digestion can be useful in increasing biogas production from low-yielding or difficult-to-digest organic waste.

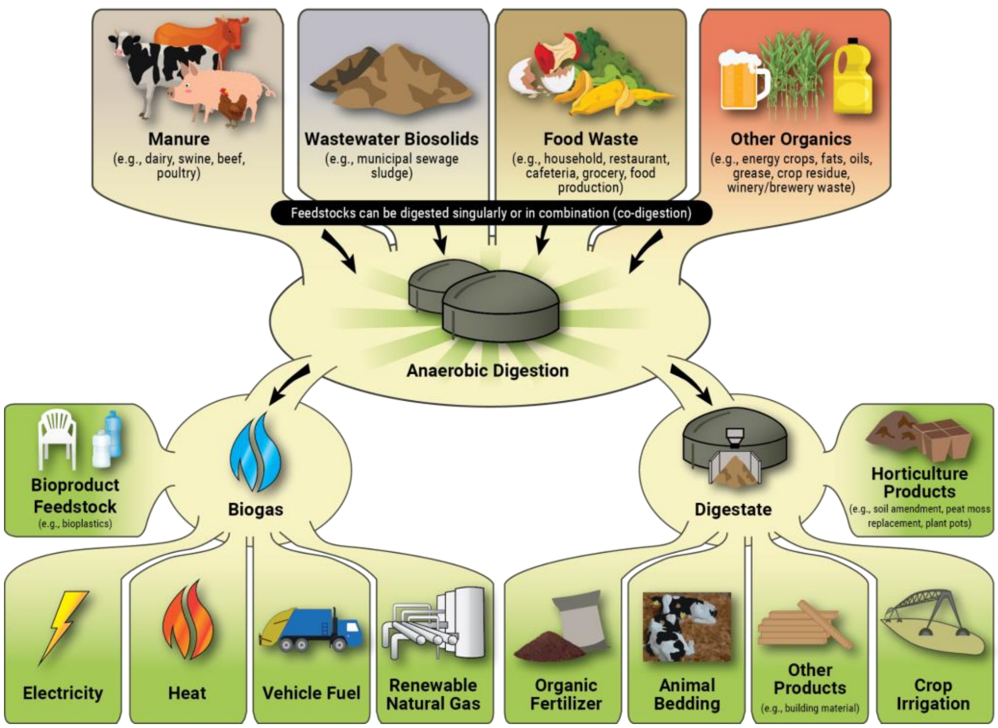



*Fig. 18: Anaerobic Digestion streams (https://www.epa.gov/agstar/how-does-anaerobic-digestion-work#:~:text=Anaerobic%20digestion%20is%20a%20process,in%20the%20absence%20of%20oxygen.).*

The produced biogas can then be used like natural gas to provide heat, generate electricity, and power cooling systems, or it can also be purified removing the inert or low-value constituents

($CO_2$, water, $H_2S$, etc.) creating renewable natural gas (RNG). RNG can enter into the natural gas distribution system, compressed and used as vehicle fuel, or processed further.

The other product is digestate: the residual material, composed of liquid and solid portions, which can be separated and handled independently. With various treatments, both parts of the digestate can be used in many applications, from animal bedding to nutrient-rich fertilizer to even a foundation material to create more bio-based products.

By following this process with an aerobic composting we get what is called an integrated plant, this has many favorable consequences, such as:

- a better energetic balance with a net production of energy,
- a better odor emissions control, and at a lower cost,
- A lower surface use compared to only aerobic solutions, which has an impact on food chain stability too,
- a reduction in $CO_2$ emission (up to zero emissions or even positive balance),
- an higher homogeneity for the flow entering the aerobic composting segment, which gives fertilizing elements (high nitrogen content with slow release) and composting times are reduced,
- a better sanitation thanks to the double thermal treatment,
- an high efficiency in recovering both material (compost) and energy (biogas), reducing the climate impact and closing the nutrient.
- This integration also helps to close the water balance of a single anaerobic digestion treatment, as the effluent treatment can disappear, if well balanced, the digester effluent water can supply the water required for composting (Fig. 19). But in case only the digestate from a dry digester is being composted, there could be a net water deficit,
- With mixed waste streams, relatively small amounts of food waste can still be handled in a plant designed for greater quantities of green waste. Plus during start-up and shutdown periods of the anaerobic sections, food waste can be diverted directly into to the composting system
- It can remove the phytotoxicity of the digested effluent.

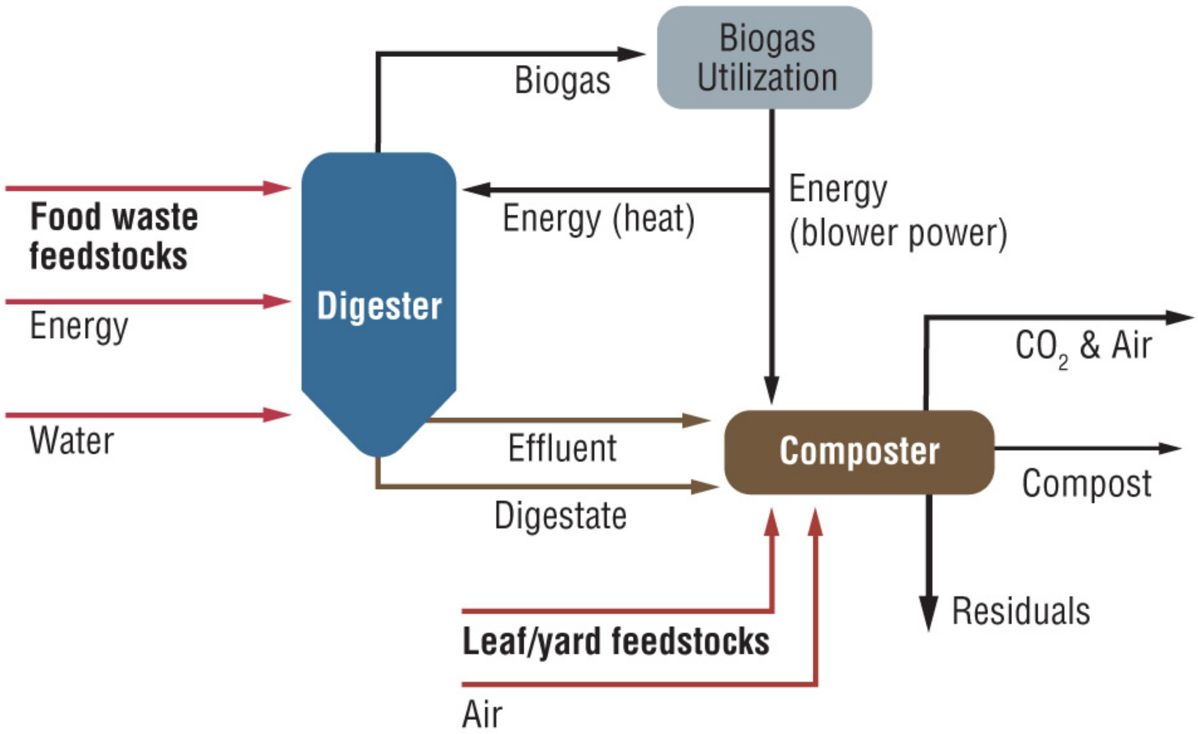



*Fig. 19: Inputs and outputs for an integrated AD and composting system (https://www.biocycle.net/integrating-anaerobic-digestion-with-composting).*

## 3.4 Comparison between EOL treatments

To assess the different impacts of the most widespread kinds of bioplastics, PLA and MAter-Bi, trough different EOL treatments a LCA study was conducted by Vincenzo Piemonte. The disposal scenarios considered are municipal solid waste incineration (MSWI), composting, anaerobic digestion and mechanical recycling.

The study covers all the main relevant process steps from raw material production to the final waste treatment or recycling of the used material, all the emissions (fertilizers, pesticides etc.) relative to the agricultural area allocated are taken into account.

Not included instead are the retail of the shells; production and transport of secondary and tertiary packaging; production and disposal of the infrastructure (machines, transport media, roads, etc.), and their maintenance, and the total cut-off was not to be more than 5% of input materials as referred to the functional unit.

For all materials it’s assumed that the transportation is carried out via railway over an average distance of 100 km.

For the MSWI, it was considered that the facility provides for the energy co-generative recovery, and that that the electric and thermal energy produced by the bioplastics incineration displace the grid electricity and the process heat used for the bioplastics granules production.

For the anaerobic digestion it’s assumed that both PLA and Mater-Bi have a biodegradation degree equal to 85% and that the biogenic gas produced is recovered with an efficiency of 95% and then burned in an industrial furnace to produce electricity with an efficiency of 36%. Again, this electricity displaces the grid electricity used for the production of polymer granules. Not included instead are the energetic burdens for biogas collection and purification.

For composting was assumed an aerobic degradation by 60% of PLA and Mater-Bi, while the remaining 40% is divided between biomass and residue, and it’s also assumed that 95% of the degraded carbon evolves into $CO_2$, the remainder, caught in small anaerobic pockets (due to not perfect mixing of the medium), is considered to evolve into $CH_4$. It’s also assumed that the 50% of the produced compost displaces the 20% of fertilizer used in the bioplastic feedstocks production.

Lastly, the mechanical recycling was divided in two option.

The first one (open loop LCA option, Fig. 20) assumes that only the 90% of the product will be reused

Becoming a product “B”, different from the starting one (“A”), it was thus assumed that all the environmental benefits and burdens can be split between the two products. Furthermore, the product ‘‘B’’ will then be disposed by MSWI.

The second option (closed loop LCA, Fig. 20) assumes instead that the 90% of product ‘‘A’’ will be recycled into the same starting product, and since food-grade applications require an absence of contaminants a subsequent combined vacuum and heat treatment is needed.

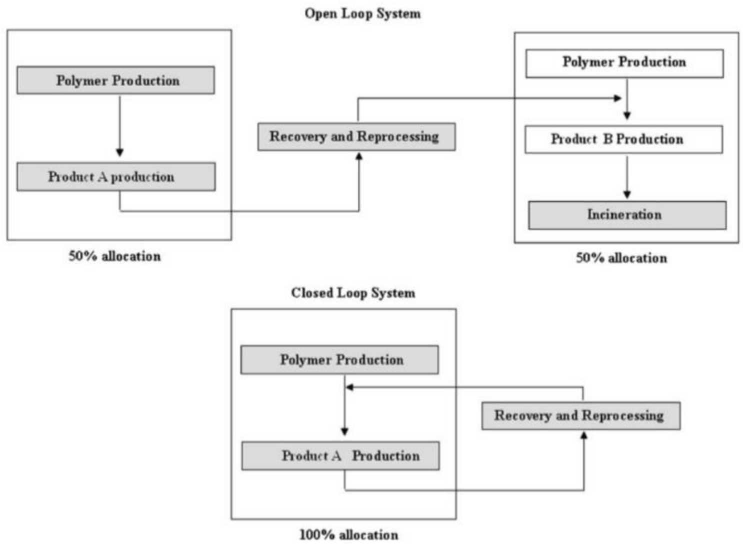



*Fig. 20: LCA Allocation procedure scheme (Piemonte 2011).*

Thus, PLA and Mater-Bi shells production was compared to two traditional plastics, PET and PE, both in terms of primary energy demand and GHGs emissions. The resulting GHGs savings obtained with bioplastics is reported in Fig. 21a, in terms of Global Warming Potential (time horizon 100 years), GWP100a, (measured as kg of CO2 equivalents). The same comparison is shown again in Fig. 21b in terms of primary energy consumption. In particular the substitution of PET with PLA leads to a GHG reduction of 60% and a primary energy demand reduction of about 40%.

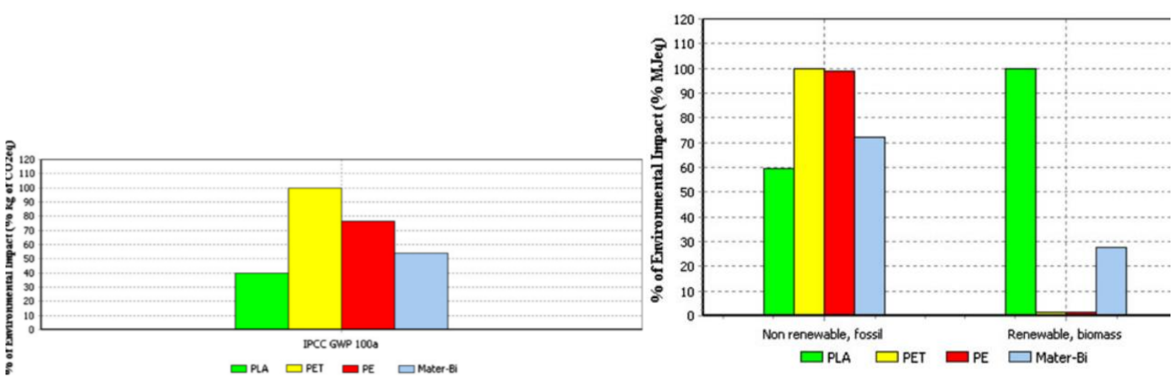



*Fig. 21: a) Global warming potential 100a; b) Cumulative energy demand; (LCA cradle to gate) (Piemonte 2011).*

To take into account the final disposal of the bio-based products, and aiming to avoid the depletion of the environmental benefits of the production phases an analysis of the primary energy demand can be seen in Fig. 22, considering as possible waste scenarios the mechanical recycling (open loop option), the incineration, the composting and the anaerobic digestion. Having considered the open loop mechanical recycling the results provided are very conservative.

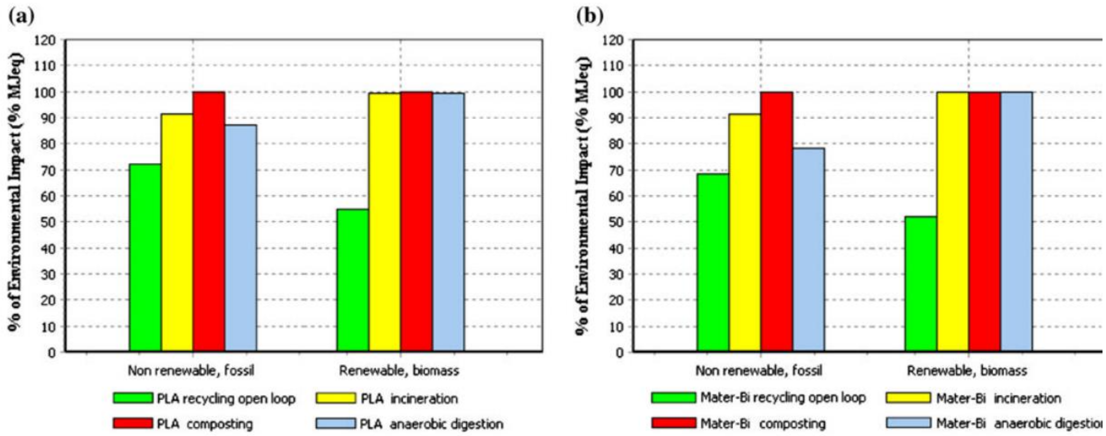



*Fig. 22: Energy savings by different disposal scenarios (LCA cradle to grave) for a) PLA and b) Mater-Bi (Piemonte 2011).*

Figure 23 reports then the comparison of the GWP for all the disposal processes considered in this work. An important note is that that if the recycled biopolymers are used as raw materials (as it has been assumed that 90% of cor-based biopolymer was displaced), the CO2 capture from the feedstock production, cannot be taken into account. Since the PLA production is 100% based on corn, while Mater-Bi only 34%, this is strongly evident.

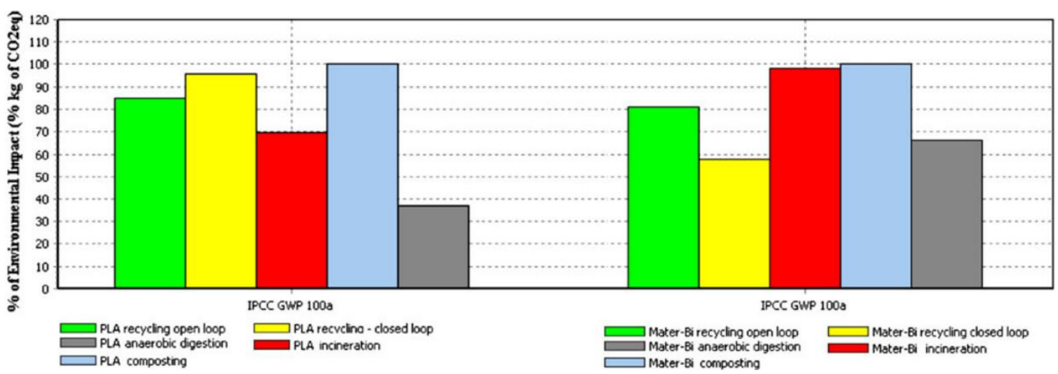



*Fig. 23: Global warming potential 100a for different disposal scenarios (LCA cradle to grave) (Piemonte 2011).*

To consider the overall environmental impact of the different avenues of bioplastics disposal, Fig. 24 reports the comparison obtained using the Ecoindicator 99 methodology. The environmental advantages of recycling are clear for ‘‘Ecosystem Quality’’ and ‘‘Resources’’ with a minimum reduction of about the 50% of the environmental impact with respect to all the other disposal processes.

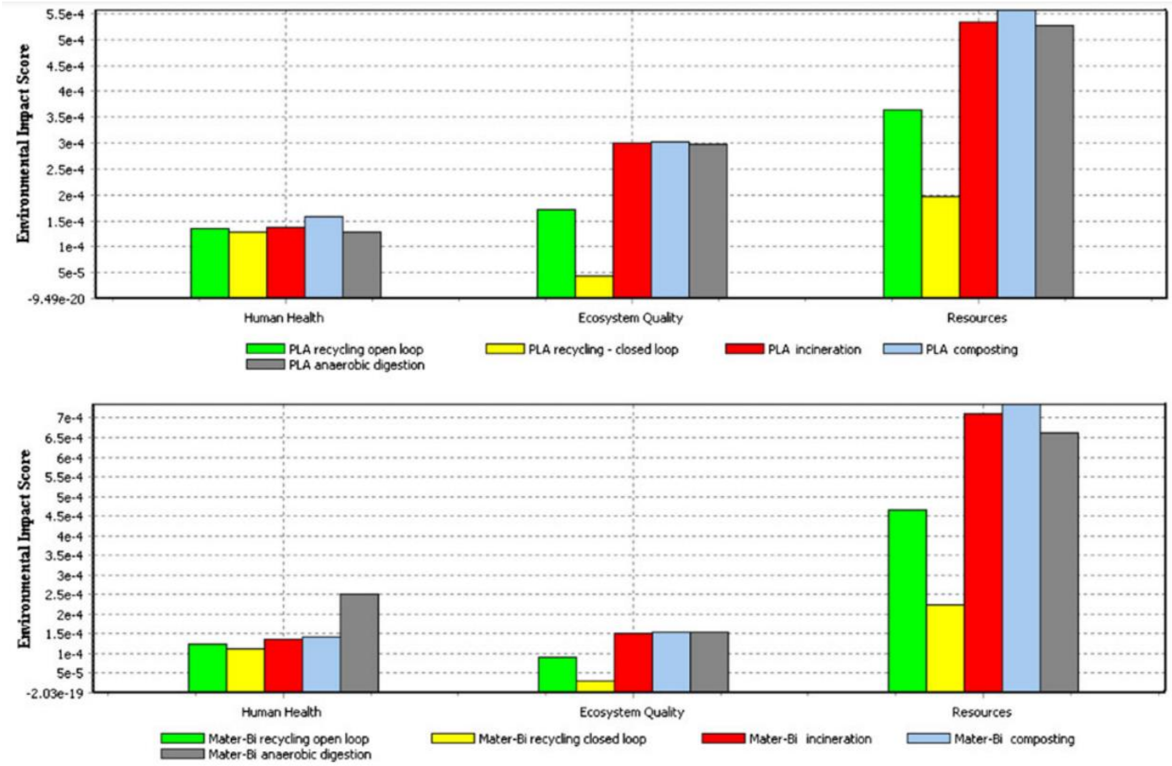



*Fig. 24: Overall environmental impact assessed by the Ecoindicator 99 methodology (Piemonte 2011)*

# 4. Efficiency case study

Even if composting is not the first choice for EOL treatment, it still serves an important purpose for recovery of nutrients from low-grade bioplastic waste. Furthermore, knowing that bioplastic is the most efficient material for organic waste collection, it means that here will always be a bioplastic fraction entering the biodegradation streams. It’s then important to know how efficient this processes actually are in bioplastic reduction.

## 4.1 Methodology

### 4.1.1 Statistical relevancy

To consider the efficiency of composting plants in biodegrading bioplastics we can focus on a single country, in this case Italy.

First, we need to figure out the national situation of present treatment plants. In Italy the waste stream feeding these plants comprehends both domestic/food waste, biodegradable green waste, and industrial/mud waste. There are three types of composting plants present in Italy: aerobic, anaerobic, and integrated. In regards to bioplastic assessment, we can consider humid (domestic) waste as the main vector of transport, as their presence in green (garden and plant) waste and muds should be irrelevant.

From 2021 ISPRA data, we know that across all three kinds there are 356 plants, and during the same year they have treated a total of 5,010,595 t of humid waste, producing 1,174,993 t of refuse, how these amounts are distributed between the three types can be seen in the following table, while the regional distribution of each type can be seen in Fig. 25.

| ISPRA Data 2021 | composting | integrated | anaerobic | TOT |
|---|---|---|---|---|
| Humid waste (t) | 1,864,997 | 2,824,222 | 321,376 | 5,010,595 |
| Refuse (t) | 481,718 | 654,835 | 38,440 | 1,174,993 |
| Plants | 293 | 42 | 21 | 356 |

*Tab. 1: Biodegradation flows in Italy for 2021*

*Fig. 25: Location of composting plants (light blue), anaerobic digestion (yellow) and integrated plants (green) (ISPRA 2021).*

To assess how much of this waste is comprised of bioplastic, and how much of it is actually degraded in the system we can take and analyze samples across the nation and through the year. Before carrying out the sampling campaign we need to define a minimum relevant value for the sampling size of both the plants and the number of samples themselves. To do this we can refer to the IAF Mandatory Document for the Audit and Certification of a Management System Operated by a Multi-Site Organization, which states that depending on whether we are referring to a first or control campaign, the minimum number of sites to sample is:

- First sampling: the sample size needs to be equal to the square root of the total site number, rounded up to the nearest larger integer.

$$n = \sqrt{T_i}$$

- Control campaign: the sample size needs to be equal to the square root of the total site number multiplied by 0.6, rounded up to the nearest larger integer.

$$n = 0.6\sqrt{T_i}$$

These formulas should only be applied to a homogeneous set of samples, we can obtain this homogeneity via plant size and geographic location, not only in Italy but dividing them also in smaller regions. For each of these smaller regions, in this case 10 have been identified, we can compute a minimum relevant number of plants, summing them in an overall national one that takes in consideration the regional density of plants.

To then identify which plants can be considered relevant, we also refer to the UNI/PdR 79:2020 "Metodo di prova per la verifica della disintegrazione dei manufatti in impianti di compostaggio industriali", which defines how to identify the minimum characteristics of a composting plant in terms of operations, process management, requirements in terms of quality management systems, and process representativeness. We honed in on plants where waste is subjected to a composting press of over 12 weeks for a minimum flow of 10000 t a year, we find that analyzing plants under this size is not relevant and we can group together all those over the 10000 t/y. We do not then differentiate treatment technology or turning methods.
Considering for each region plants with a yearly capacity over 10000 t/y we can determine first Ti, the total number of plants of this size, and then n, the minimum sample size, following the previous notion n = √Ti, since this is the first campaign.
We have the results in Tab.2:

| Regions: | Veneto FVG TAA | Lombardia | VdA Piemonte Liguria | Emilia Romagna | Toscana | Umbria Marche | Lazio Abruzzo Molise | Campania Calabria Puglia Basilicata | Sicilia | Sardegna | Tot |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Plants >10000 t/y | 20 | 19 | 13 | 13 | 9 | 7 | 14 | 20 | 12 | 11 | 138 |
| n | 5 | 5 | 4 | 4 | 3 | 3 | 4 | 5 | 4 | 4 | 41 |

*Tab. 2: Minimum plant sample size computed for each region and total.*

We can make the same considerations to define a minimum relevant number of samples to be taken, still considering plants with a processing time over 12 weeks and a capacity over 10000 t/a, but also considering waste aeration (forced or convective) and sanitation (following the D.M. 5/2/98 allegato 1, sub-allegato 1, cap. 16), while focusing on plants that have been in production for over 3 years, and, if the plant has more than one output flow, clear separation and traceability.
To have a representative analysis from ISPRA and regional guidelines we need a sample for every 200$m^3$ of material, assuming an average density of 0.4t/m3 we would need a sample for every 80 t of inflow material.
Following the previously stated guidelines on statistics relevance, we need N number of samples such as:

- For a first campaign, N = √(yearly capacity / 80) rounded up to the nearest larger integer.

- For a control campaign, N = 0.6 * √(yearly capacity / 80) rounded up to the nearest larger integer.

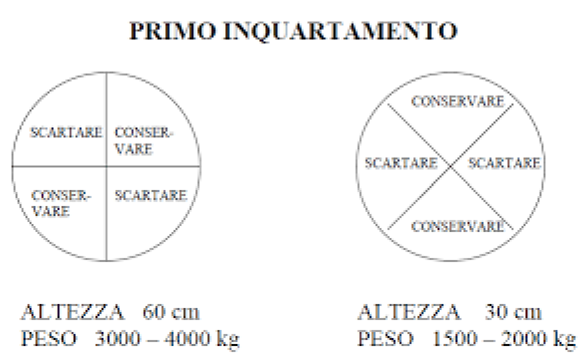
It's also important to note the variability of input flows over time, and the need to repeat the sampling campaign multiple times during a year in order to deal with this heterogeneity. Since we consider big-sized plants it's suggested to sample every 3 to 4 months.
This variability isn't very relevant for the refuse analysis, as it is the cumulative amount for the year.

| | Total (t/y) | n | Over 4 months | Quarterly |
|---|---|---|---|---|
| Authorized capacity | 4935749 | 249 | 747 | 996 |
| Refuse | 1234322 | 125 | 375 | 500 |

*Tab. 3: Minimum sample amount computed for yearly relevancy*

### 4.1.2 Sampling

Each sample should be around 3-4 t, the size of a truck load, as indicated by CNR. each sample should be weighted and handled in an specific zone, preferably cemented and kept clean. Here we can carry out the quartering, a sub-sampling procedure. First, the biggest pieces are taken out as they might hinder the analysis, then all the collection vessels (such as trash bags) are opened and emptied, they are then saved for a separate vessel analysis, as those can be made of bioplastics too.
All the waste is then mechanically mixed to have a uniform distribution, then spreaded in a circle with a thickness under 50-60 cm. We then divide this "cake" in 4 equal parts, the two diametrically opposing quarters are eliminated and the remaining half is mixed again, this procedure is then repeated again until we are left with a sample of around 200 kg to analyze.



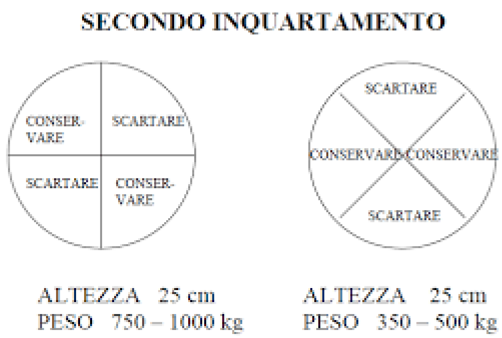



*Fig. 26: Quartering scheme ( DIVAPRA, IPLA, ARPA, 1998).*

After weighing the sample we can proceed to separating the material components. This is usually done passing first through a vibrating sieve with mesh size of around 20 mm, all passing waste is analyzed by hand, the fines can be subjected to a granulometric analysis and are usually the part most contaminated by metals.

Each product category is weighted, whenever a material is mixed it must be categorized along with what seems the major constituent from a visual analysis.

In this study two sets of categories have been used, one for the vessels:

1. Compostable bioplastic shopper
2. Compostable bioplastic waste bag
3. Compostable bioplastic produce bag
4. Oversize (>50l) compostable bioplastic waste bag
5. Paper bag
6. Traditional plastic bag
7. Traditional plastic bag, non-packaging

And one for the waste itself:

1. Compostable bioplastic bag, packaging
2. Compostable bioplastic bag, non-packaging
3. Compostable bioplastic internal and flexible, packaging
4. Compostable bioplastic internal and flexible, non-packaging
5. Compostable bioplastic rigid, packaging
6. Compostable bioplastic plates
7. Compostable bioplastic cups
8. Compostable bioplastic coffee pods

9. Compostable bioplastic rigid, non-packaging
10. Traditional plastic
11. Other non-compostable material

Where Compostable rigid bioplastic for non-packaging goods includes plates cups and coffee pods.

From each category we can compute the percentage of residual dry-weight (rdw%) percentages, residual weight after drying (no detectable humidity) and cleaned (no detectable organic material) in respect to the as-is weight (ai). Then we can obtain the dry weight (dw), for the internal and rigid categories this is done simply by multiplying the as-is weight by the rdw%.

For the bag categories we also need to consider the results of the vessel analysis, from which we obtain the number of each type of bag, which multiplied by their average weight can give us the total weight of each category.

We can then compute the ratio between both oversized (>50l) and normal compostable plastic waste bags and compostable shoppers and produce bags, important because the first two make up the macro-category “Compostable bioplastic bag, packaging” and the latter two the macro-category “Compostable bioplastic bag, non-packaging”, and we can compute their dry weight as the sum of their sub-categories’.

Usually the total sum of the categories’ weight is lower than the startig sample weight, difference caused by losses in both material and humidity.

For each category we can also compute the weighted average in relation to the total amount delivered by the same agent, starting from the analyzed amounts.

For each agent “i” the average bioplastic content is:

$$\mu_i = \frac{\sum_1^n \quad bioplastic\%_n}{n}$$

Where n is the number of samples analyzed for the agent “i”.

Assuming that each agent only delivers waste in one macro-region we can also compute the weighted average content of bioplastic in each region’s humid waste as:

$$\mu_{region} = \frac{\sum_1^i \quad (tot\ humid\ waste\ delivered_i \times \mu_i)}{\sum_1^i \quad tot\ humid\ waste\ delivered_i}$$

These considerations are relative to both waste delivered at the plants and the out-coming refuse, but for the latter, we can once again consider a different set of categories:

1. Flexible bioplastic
2. Rigid bioplastic
3. Plastic
4. Other non-compostable material
5. Organic material
6. Liquids, metals and inerts

Where liquids resulting from the biodegradation process, metals and inserts should not contain relevant aunts of bioplastics and can easily be separated before the analysis.
For each refuse sample we have information from:

- Category analysis on fragments over 20 mm (MS)
- Lab analysis on fragments over 20 mm, if necessary using chloroform (BD - D) to determine bioplastic content, obtaining also humidity % and plastic content
- Lab analysis on fragments under 20 mm (LS - E) which gives the same information as the BD along with glass and metal percentages.

In most instances it was assumed that the humidity of both plastic and bioplastic content was equal to the sample's average humidity.

## 4.2 Results

To assess both the actual material flow of bioplastics and the efficiency of composting processes in degrading them we first need to consider the total amount of waste treated in composting plants, then how much of it was humid waste and finally how much was bioplastic and what types.
From the 2021 ISPRA data we know that in total Italy's 356 composting plants processed 8,307,426 t of waste, of which 5,010,595 t, or around 60%, was humid waste.
The sampling campaign considered 30 plants and 1353 total samples on 1,778,187 t of delivered humid waste, or around 35% of the national total.
From the category analysis was found that the average composition of the delivered humid waste was:

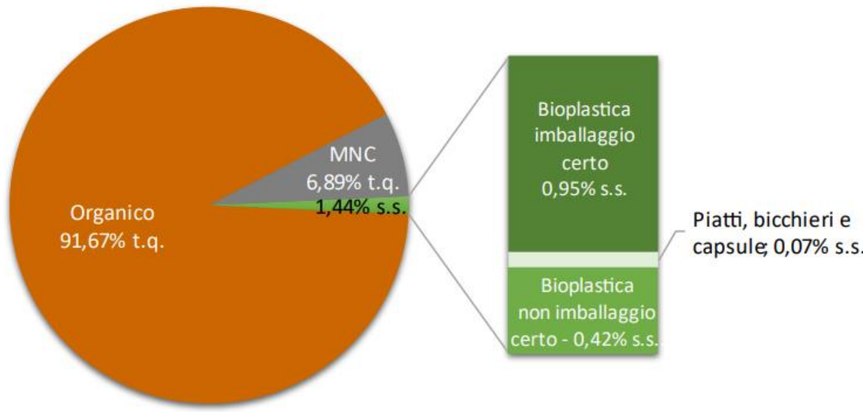



*Fig. 27: Average composition of the delivered humid waste (Report Finale Consorzio Italiano Compostatori).*

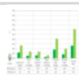
Which means that 93,11% of the waste treated was compostable organic material, of which 3,22% was bioplastics.

For the rigid bioplastic content, this was sampled differently through the year, in the first half it was divided in two sub-categories: rigid and flexible, while in the second half the amount of plates cups and coffee pods was specified. For the data analysis I favored this latter division, a the refuse samples have been categorized in the same way and it offers a better continuity and a more detailed look at the type of waste.

In detail the bioplastic content is as written in Tab. 4, and visualized in Fig. 27 and Fig. 28:

| Average weight | dw% | ai% |
|---|---|---|
| Packaging bag (flexible) | 0.60 | 1.35 |
| Non-packaging bag (flexible) | 0.27 | 0.70 |
| Internal packaging (flexible) | 0.31 | 0.70 |
| Internal non-packaging (flexible) | 0.14 | 0.32 |
| TOT flexible bioplastic | 1.34 | 3.07 |
| Packaging (rigid) | 0.0296 | 0.0407 |
| Non-packaging (rigid) | 0.0000 | 0.0000 |
| Plates | 0.0631 | 0.0082 |
| Cups | 0.0057 | 0.0082 |

| | | |
|---|---|---|
| Coffee pods | 0.0031 | 0.0045 |
| Cutlery | 0.0029 | 0.0043 |
| TOT rigid bioplastic | 0.1043 | 0.1459 |
| | | |
| TOT packaging | 0.95 | 2.1 |
| TOT non-packaging | 0.53 | 1.12 |

*Tab. 4: Average bioplastic content in the*  *(Report Finale Consorzio Italiano Compostatori).*

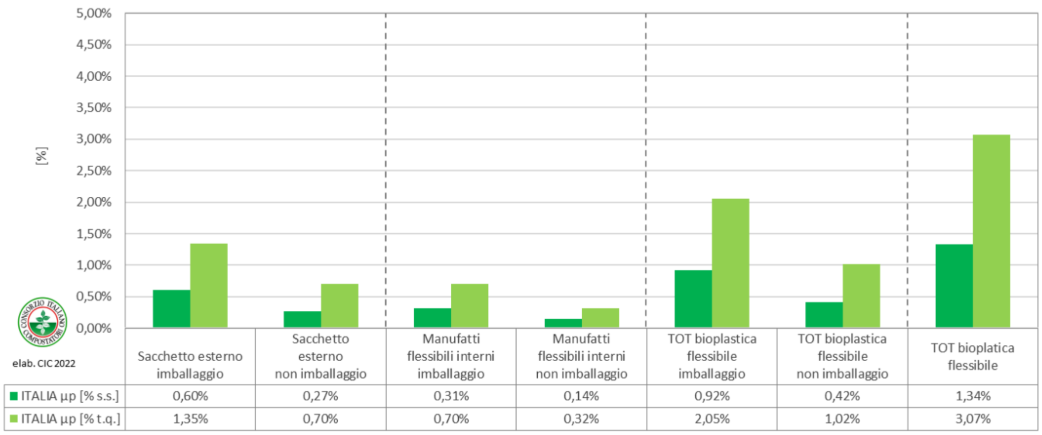



*Fig. 27: Flexible bioplastic content in the delivered humid waste (Report Finale Consorzio Italiano Compostatori).*

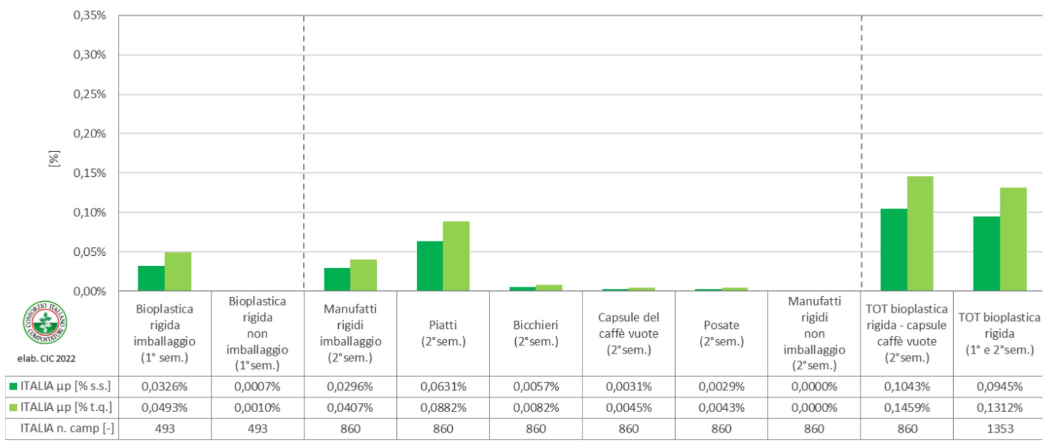



*Fig. 28: Rigid bioplastic content in the delivered humid waste (Report Finale Consorzio Italiano Compostatori).*

The same considerations can be made for the refuse analysis.

The national total refuse produced, as for ISPRA 2021 data, was 1,174,993 t,  and again around 35%, or 409.715 t, of these where produced by the 30 plants considered. Not all the refuse was analyzed, as 77,453 t were identified as liquids, metals and inerts and separated.
From the 161 samples then taken on the remaining 332,262 t we obtain the average contents:

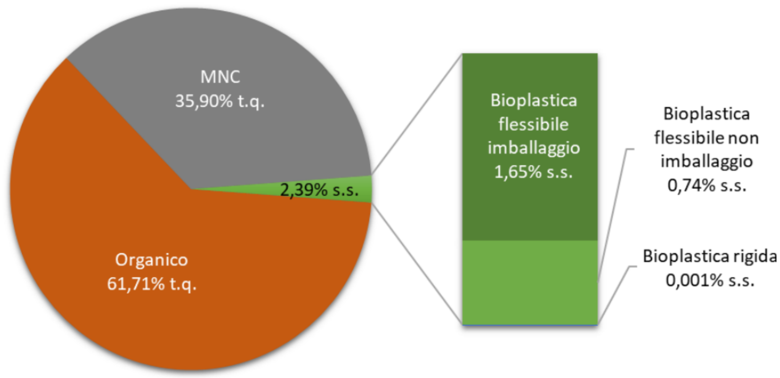



*Fig. 29: Average composition of the refuse (Report Finale Consorzio Italiano Compostatori).*

There is still a 35,90% of other non-compostable materials, while 64% is compostable material, of which 2.39% is bioplastic.
Again, in detail the composition is shown in Tab. 5 and Fig. 30.

| Weighted average | dw% | ai% |
|---|---|---|
| Flexible bioplastic | 2.3901 | 3.7795 |
| packaging | 1.6453 | 2.6017 |
| non-packaging | 0.7448 | 1.1778 |
| Rigid bioplastic | 0.0011 | 0.0012 |
| packaging | 0.0003 | 0.0003 |
| Plates, cups and pods | 0.0008 | 0.0008 |
| TOT bioplastic | 2.3912 | 3.7807 |

*Tab. 5: Average bioplastic content in the refuse (Report Finale Consorzio Italiano Compostatori).*


| elab. CIC 2022 | Bioplastica flessibile | Bioplastica flessibile imballaggio | Bioplastica flessibile non imballaggio | Bioplastica rigida | Bioplastica rigida imballaggio certo | Piatti, bicchieri e capsule | Bioplastica rigida non imballaggio certo | Bioplastica imballaggio certo | Bioplastica non imballaggio certo | Bioplastica |
|---|---|---|---|---|---|---|---|---|---|---|
| ITALIA µp [% s.s.] | 2,3901% | 1,6453% | 0,7448% | 0,0011% | 0,0003% | 0,0008% | 0,0000% | 1,6456% | 0,7449% | 2,3912% |
| ITALIA µp [% t.q.] | 3,7795% | 2,6017% | 1,1778% | 0,0012% | 0,0003% | 0,0008% | 0,0000% | 2,6020% | 1,1778% | 3,7807% |

*Fig. 30: Bioplastic content in the refuse (Report Finale Consorzio Italiano Compostatori).*

These percentages, put in relation to the known total flow entering and exiting the plants can give us a balance of the situation. In the following graph (Fig. 31), the humid waste processed in the 30 plants analyzed can be visualized, ignoring green waste as it can be assumed to be only relevantly converted in compost:

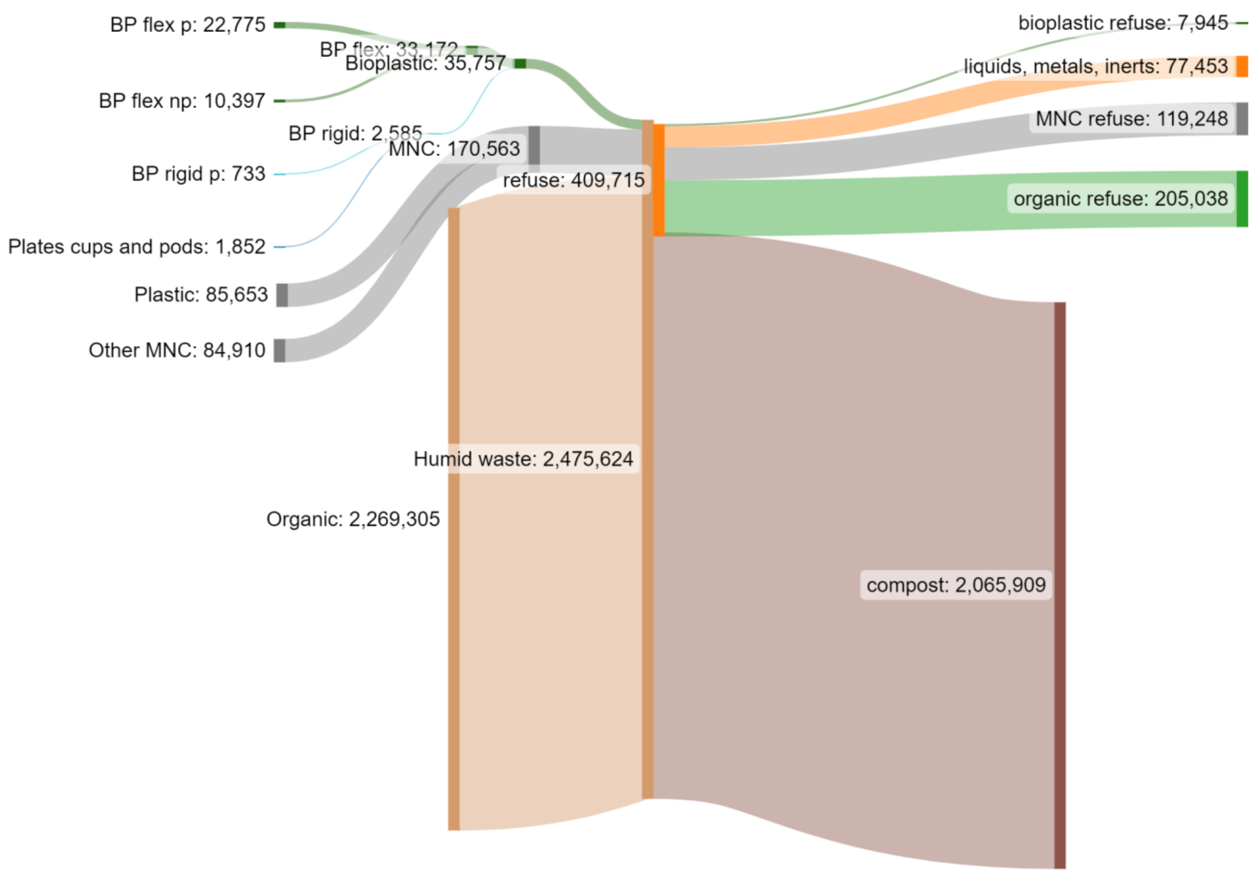



*Fig. 31: Material flow analysis on the 30 sampled plants,*

Since these averages have been computed as to have national statistical relevancy, we can also apply them to the total national flows, to obtain a clearer picture of the composting efficiency. In this case, for the refuse analysis I had to adapt the percentages to be relevant on the totality of refuse, and not just on the relevant fraction, since the sampling disregarded liquid, metallic and inert waste, I did this by proportionally relating the percentages from the relevant fraction to the total weight, and using this new percentage to compute the total national amounts, these can be seen in the following graph:

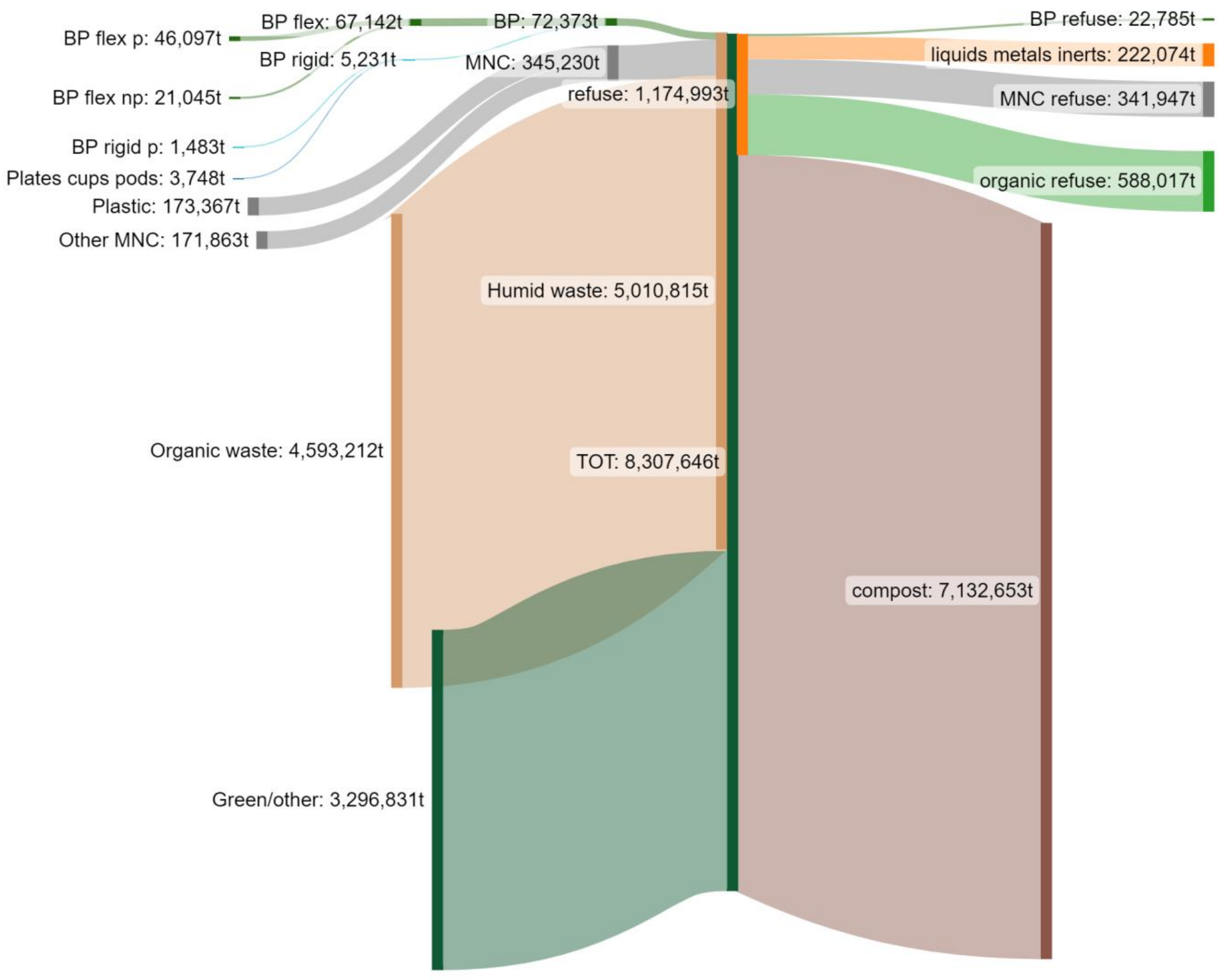



*Fig. 32: Material flow analysis on Italy's biodegradation plants.*

To focus on the bioplastic reduction we can observe the amounts involved in the total flow, both for each category, flexible and rigid (Fig. 33), and the total weight reduction (Fig. 34):

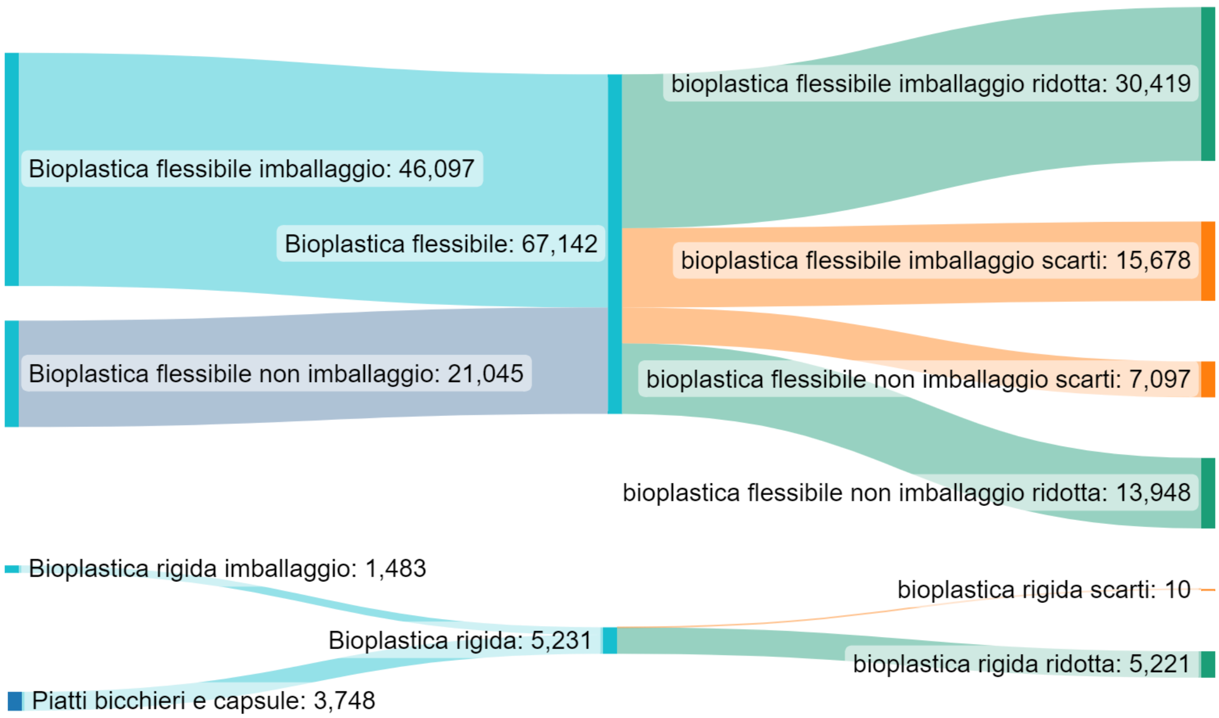



*Fig. 33: Bioplastic flow analysis on Italy's biodegradation plants.*

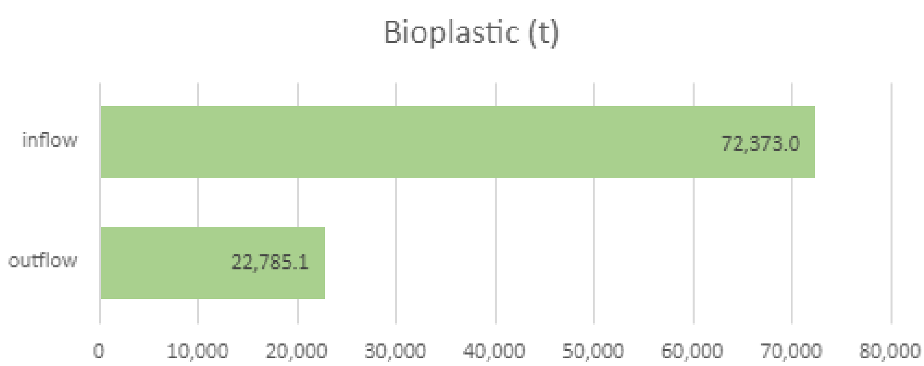



*Fig. 34: Bioplastic inflow and outflow on Italy's biodegradation plants.*

We can see that there's a significant reduction in bioplastic content, around 78%, especially in regards to the rigid fraction, where the reduction rate can be assumed to be near perfect.
In detail, each category's weight reduction by percentage can be seen in Tab. 6.

| TOT national flows | Delivered (t) | Refuse (t) | Reduction |
|---|---|---|---|
| TOT flexible bioplastic (packaging) | 46097.47 | 15677.59 | 65.99% |

| | | | |
|---|---|---|---|
| TOT flexible bioplastic (non-packaging) | 21044.50 | 7096.98 | 66.28% |
| TOT flexible bioplastic | 67141.97 | 22774.57 | 66.08% |
| TOT rigid bioplastic (packaging) | 1483.14 | 2.86 | 99.81% |
| Plates, cups and pods | 3747.93 | 7.62 | 99.80% |
| TOT rigid bioplastic | 5226.05 | 10.48 | 99.80% |
| TOT BIOPLASTIC | 72368.02 | 22785.05 | 68.52% |
| Packaging | 47580.61 | 15677.59 | 67.05% |
| Non-Packaging | 21044.50 | 7096.98 | 66.28% |

*Tab. 6: Material inflow, outflow and relative reduction on Italy's biodegradation plants.*

### 4.2.1 Vessel analysis

It is worth noting that a part of the flexible bioplastic, which is the most resilient, does not come from the waste itself, but from the necessary collection vessels. In the study conducted a vessel analysis took place on all but 4 samples, which had been delivered loose.

Of all vessels analyzed 63.49% was made of bioplastic, while 36.39% of conventional non biodegradable plastic, and the remainder paper.

The most used kind of bioplastic vessel was shoppers, which, weighing around 40 g (as-is weight) each can amount to a significant part of the flexible bioplastics treated.

### 4.2.2 Validation

To confirm the statistical relevancy of the acquired data I confronted the campaign results with the initial requirements. For the number of plants included, since the 30 tested are less than the 41 needed, I confronted each region's computed n with the amount of sites actually tested in the area, to see which areas were the most under-represented.

This discrepancy between the amount of tested plants and the required minimum was probably caused by a change in the area subdivisions, it was initially planned to have 5 macro-areas before doubling this number to 10. Due to the nature of the formula, specifically summing the regional minimums, the rise in regions meant a higher definition and a higher minimum relevant number, if the macro-areas had remained the 5 initially planned the national n would have been 28.

I also computed an ideal proportional distribution of 30 plants among the areas, to check also which regions were relatively under-represented (Tab. 7).

| | Veneto - FVG TAA | Lombardia | VdA Piemonte Liguria | Emilia Romagna | Toscana | Umbria Marche | Lazio Abruzzo Molise | Campania Calabria Puglia Basilicata | Sicilia | Sardegna | Tot |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Plants >10000 t/y | 20 | 19 | 13 | 13 | 9 | 7 | 14 | 20 | 12 | 11 | 138 |
| n | 4.5 | 4.4 | 3.6 | 3.6 | 3.0 | 2.6 | 3.7 | 4.5 | 3.5 | 3.3 | 37 |
| 2021 samples | 3 | 6 | 3 | 5 | 2 | 2 | 2 | 3 | 2 | 2 | 30 |
| proportional | 4 | 4 | 3 | 3 | 2 | 1 | 3 | 4 | 3 | 2 | 30 |

*Tab. 7: For each region considered the number of plants over 10000 t/y, the minimum relevant plant sample size, the number of plants sampled in the region and an idea distribution of a 30-plant sample size. Numbers in yellow represent a higher required sample size than the one used in the 2021 campaign, while green ones a respected minimum.*

While in absolute terms only Lombardia and Emilia Romagna were over the requirement, the proportional distribution is a bit closer to the regional plant density, with a concentration in the regions where the waste flow is higher. The regions with the most waste treated, both in total amounts and just humid waste, are in fact Lombardia, Veneto and Emilia Romagna, as we can see in the following table (Tab. 8), which feature more heavily in the samplings. This means that while the regional sampling plant distribution is not perfect it does cover most of the national flows, as it's obvious if we consider that the 30 plants have treated almost 3 million t of waste, over a third of all waste treated, and half of the humid waste.

| | Piemonte | Lombardia | Liguria | Emilia Romagna | Toscana | Marche | Umbria | Lazio | Abruzzo | Molise | Campania | Sardegna | Puglia | Calabria | Sicilia | Veneto | TAA | FVG |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| TOT waste treated | 6.31 E+0 | 2.14 E+0 | 6.75 E+0 | 1.04 E+0 | 3.73 E+0 | 1.13 E+0 | 1.75 E+0 | 2.91 E+0 | 1.79 E+0 | 7.28 E+0 | 1.64 E+0 | 2.49 E+0 | 3.46 E+0 | 2.13 E+0 | 4.54 E+0 | 1.32 E+0 | 1.13 E+0 | 3.77 E+0 |
| Humid waste treated | 3.60 E+0 | 1.16 E+0 | 4.21 E+0 | 4.85 E+0 | 2.27 E+0 | 7.42 E+0 | 9.57 E+0 | 1.46 E+0 | 1.45 E+0 | 7.01 E+0 | 1.29 E+0 | 2.01 E+0 | 2.55 E+0 | 1.84 E+0 | 2.52 E+0 | 8.18 E+0 | 7.09 E+0 | 3.00 E+0 |

*Tab. 8: Amounts of treated waste for each region*

For the number of samples, the initial minimum on the delivered waste was computed from the authorized capacity of the plants involved, but we now know that the plants actually treated

2,475,635 t of humid waste, from which we an compute a new n between 528 and 704 samples in a year, depending if the samples are taken every 3 or 4 months. This is well below, almost half actually, the actual number of samples taken, which can then be considered relevant.

For the refuse we had obtained an n of 125, meaning that the 161 samples actually taken wouldn't cover a re-sampling over 3 or 4 months, but for the refuse this is much less relevant as the seasonal variation is minor and refuse can often be stored for longer times.

Addressing the refuse streams, it might seem that the initial delivered non-compostable materials (345,230 t between plastic and other materials) increase to 564,023 t, but this includes not only the previous categories but also liquid refuse, which is a by-product of the composting process. The other categories withheld from the sampling campaign, metals and inserts, were instead already present in the "other non-compostable material" delivered.

## 5. Conclusions

The need for plastic will only keep rising, and with huge amount of waste still waiting for retrieval and treatment we need to keep focusing on alternatives. As one of such alternative bioplastics may seem a simple solution, and while some are preferable from a health and safety perspective and others from an environmental perspective, there is still much that can be improved. In general, the most widely used kinds are also some of those preferable, such as starch-based, PLA, and PHA polymers, but they also require more land for feedstock production. The risk of competing with food production for human consumption needs to be addressed, and more research on rising bioplastic yields to need less feedstock is needed.

Bioplastic production has also some of its traditional counterpart production issues, even if at a lesser extent, such as energy and water requirements, and use of hazardous chemicals/additives. Still, biodegradable plastics have the potential to reduce the use of fossil fuels and related environmental and health impacts, as well as to avoid non-degradable plastic wastes. Furthermore, if bioplastic waste is not disposed of correctly, all savings obtained with its production can be lost, it’s very important then to manage waste streams correctly, and identify the best EOL treatment for each kind of waste.

The ideal way to lower impacts during a material entire life cycle is to follow the waste hierarchy. This means that as long as bioplastic waste has a high quality and a low contamination rate it can be recycled and put back into use, passing through primary and secondary mechanical recycling. When the waste quality doesn’t permit it anymore, bioplastics have various option, chemical recycling, incineration or biodegradation, depending on how the waste was collected and the infrastructure available. Only the refuse that cannot be processed again should be landfilled, as it not only loses valuable nutrients, but bioplastic presence in landfills can create methane.

### 5.1 What’s next

A proposed solution to the interference with food production, one of the most pressing issues, especially considering the current global food crisis, is to keep researching. The objective is to develop a second generation of bio-based plastics, using instead of especially produced feedstock, sources that do not compete with food production, such as agricultural byproducts (like for the proposed production of PHBs) and wood. Along with research for other technological advances, especially focusing on trying to substitute harmful or damaging additives, pesticides and production catalysts.

It’s also important to keep consumers informed on best practices, such as product reuse and choosing the right materials for different needs, as well as best practices in dealing with bioplastics and the correct way to dispose of for each kind. This along with the enhancement of necessary infrastructure should help in sorting and collecting waste, and thus in following the ideal waste hierarchy. Also, at an infrastructural level, a rise in renewable electricity share in the grid could off-set the impacts of the energy requirements of both production and EOL processes. Meanwhile the water requirements could be lowered, changing from feedstock to byproducts would have a good impact, as would the rise in integrated biodegradation plants, where wastewater from a process can be reused in the other.

Another proposed idea is to create synergy, and prefer materials that generate useful byproducts. For example, when producing PLA, calcium hydroxide is used, creating calcium sulfate (gypsum), a byproduct of low value. Using instead ammonium salts, it would produce ammonium sulfate, which can be used as a fertilizer, providing both economic and environmental benefits

Of course, all these options have to be methodically researched, to check both the effects on the environmental impact and worker safety, ensuring that there isn’t a simple problem shift.

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