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# **Compostable Polymers and Nanocomposites — A Big Chance for Planet Earth**

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Additional information is available at the end of the chapter

<http://dx.doi.org/10.5772/59398>

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## **1. Introduction**

In this chapter, the significance of composting composites and nanocomposites based on bio-based polymers used in various applications to reduce the amount of solid waste in landfills is presented. Furthermore, composting methods to produce compostable materials and international standard test methods for evaluation of the above mentioned materials have been explained.

Our every action must have an impact on the well-being of our planet, and our everyday decisions can help create a better world for all. Reducing the amount of solid waste in landfills and the addition of nutrient-rich organic matter are the help that composting gives to the Earth because organic content in the soil encourages the passage of air and water. The introduction of various contaminants into natural environments that have resulted in instability, disorder, harm, or discomfort to an ecosystem is known as pollution and includes different forms such as air, soil, water, sound, etc.

Chemicals that are released into the ground deliberately, accidentally, or by underground leakage have resulted in soil pollution, and these can include hydrocarbons, herbicides, pesticides, chlorinated hydrocarbons, and heavy metals such as chromium and cadmium. Natural and man-made sources such as vehicle emissions and other principal sources including chemical plants, petrochemical plants, PVC factories, and other plastic factories have caused air pollution [1, 2].

Waste can result in the obstruction of storm water runoff which causes stagnant water bodies to form, hence becoming a means of disease. Furthermore, waste dumped near water sources results in contamination of the groundwater source as well as the water body.

Plastic pollution is also a serious threat to some of the world's oceans. Ocean currents cause plastic detritus to cumulate together to form large garbage patches. Therefore, polymer pollution is a serious threat that is presented as follows.

### 1.1. Polymer pollution: A serious threat

Polymers are materials that the earth cannot digest and cause serious damage to the environment during their production and disposal process. All polymers produced thus far still exist and could remain with us for more than hundreds of years. Polymers break down into smaller particles which attract toxic materials and are swallowed by wildlife in the ocean or land and then contaminate our food chain. The growth rate in polymer production is significantly fast. Figure 1 presents rates of past and future plastic growth during a 60-year time period (1960 to 2020) through a semilog graph. In order for any of these four plastic categories to slightly change their order of magnitude, a long time duration is necessary. In addition, among the different plastics, polycarbonate and some alloys might be ones that achieve the commodity plastics status by 2020. An average of 8.1 % annual growth rate brought solid polymers from seven million tons to 196 million tons between the years 1960 and 2005. This number will continue to escalate to over 365 and 540 million tons in 2015 and 2020, respectively, with a more conservative yearly rate of 6.5 %. The overall production/consumption of plastics worldwide at the turn of the century had an average yearly growth rate of 15 %. In other words, the growth rate doubled every five years, until around 1979, when the trend broke at the first oil shock. Such a high growth rate was seen only then, as the average annual growth rate of plastics went from 15 % between the years 1960 and 1974 to 8 % between the years 1974 and 2000 and 2005. The expanding and fast developing markets, with more than a 10–15 % growth rate per year, were similar to the times of great success for the plastics built up in Europe, the USA, and Japan, in the 1960–1975 era [2].

World plastics production includes thermoplastics, polyurethanes, thermosets, elastomers, adhesives, coatings and sealants, and PP fibers, not including PET-, PA- and Polyacryl fibers as shown in Fig. 2 that is reported by the PlasticsEurope Market Research Group (PEMRG) [3]. Once the polymer is produced, the harm introduced is almost permanent. This results in a serious waste disposal and pollution problem. Solid waste is significantly increasing within the world. Where municipal waste is concerned, from the year 1995 to 2003, the average European citizen's municipal waste generation has continually increased by about 2 % per year from 204 million tons (457 kg/person) in 1995 to 243 million tons (534 kg/person) in 2003 [5]. The proportion of postconsumer waste in EU-27, Norway, and Switzerland according to the function could be observed in Fig 3. It is extremely difficult to measure the state of plastic waste. Statistics show that in 2008, an average of 24.9 megatons of plastic waste [4, 5, 6] was produced in EU-27, Norway, and Switzerland; however, confirming this distribution is quite difficult. Conventional polymers which are made from a hydrocarbon base, such as polyethylene, polypropylene, polystyrene, polyethylene, terephthalate, etc., are virtually nonbiodegradable [6].

In addition to their extreme effects on the ecosystem, chemicals can cause a range of illnesses including birth defects, cancer, and damage to the nervous and immune system and also affect the blood and the kidneys. Many of these toxic substances are also given off during the

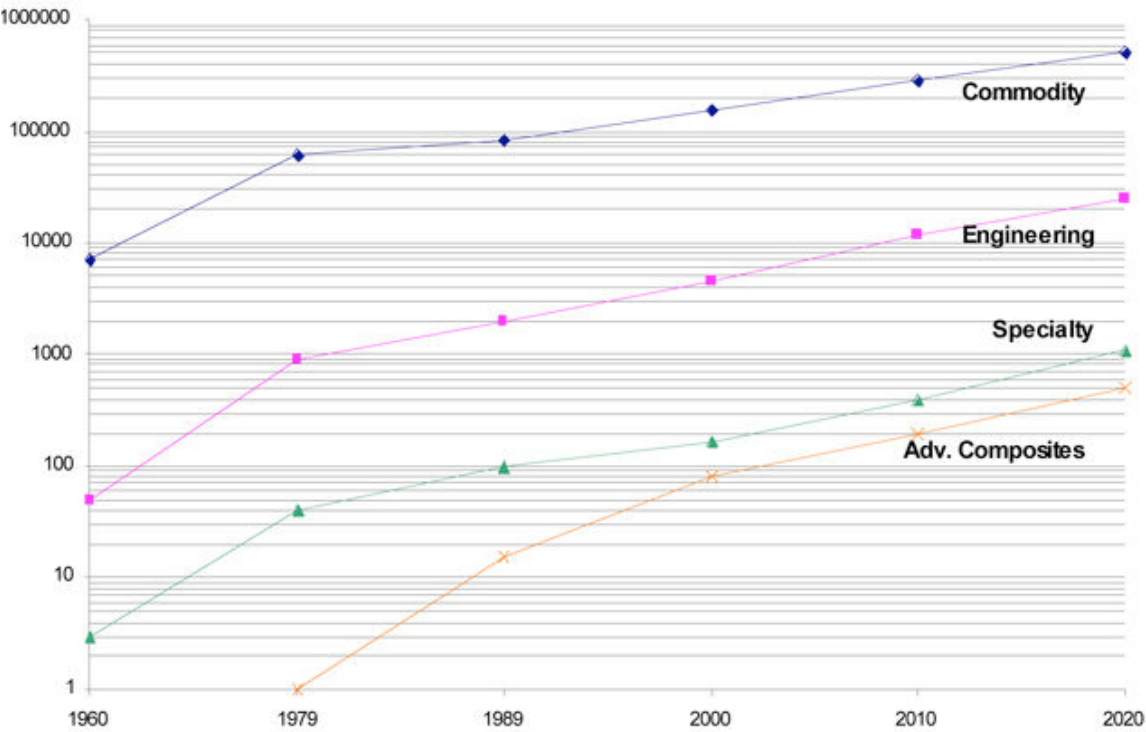


Figure 1. Rates of past and future plastics growth, over a 60-year time span [2]

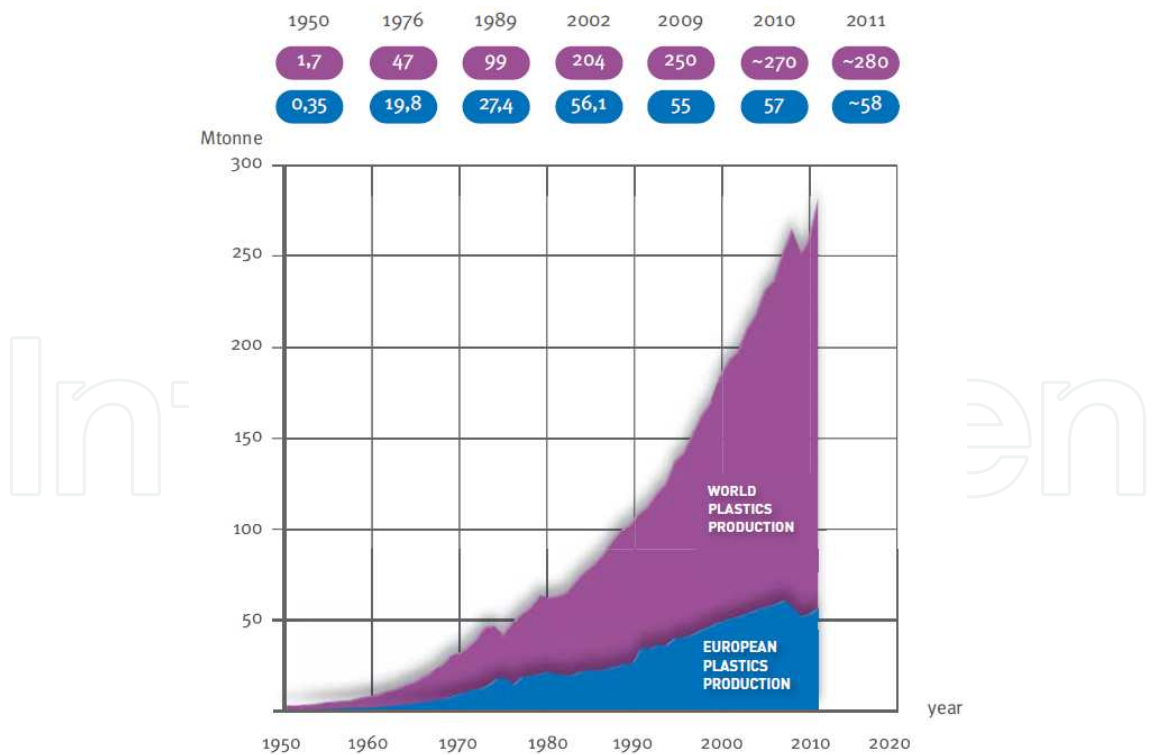


Figure 2. World plastics production 1950–2011 shows that the plastics industry continues to grow rapidly [3]

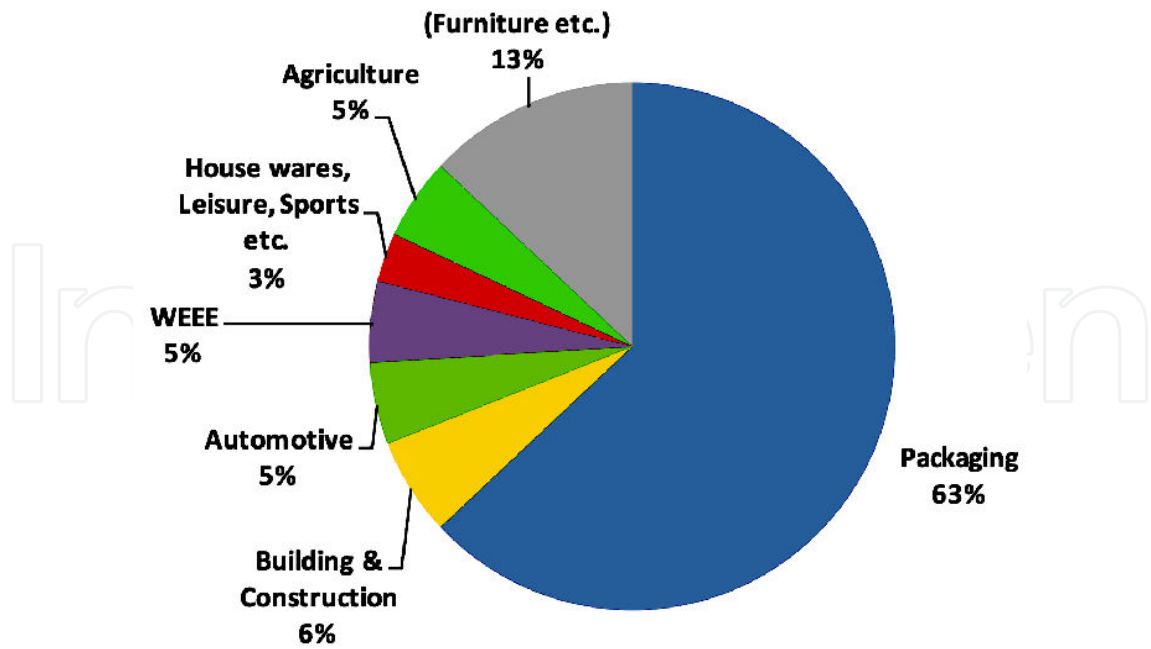


Figure 3. Proportion of postconsumer waste [5]

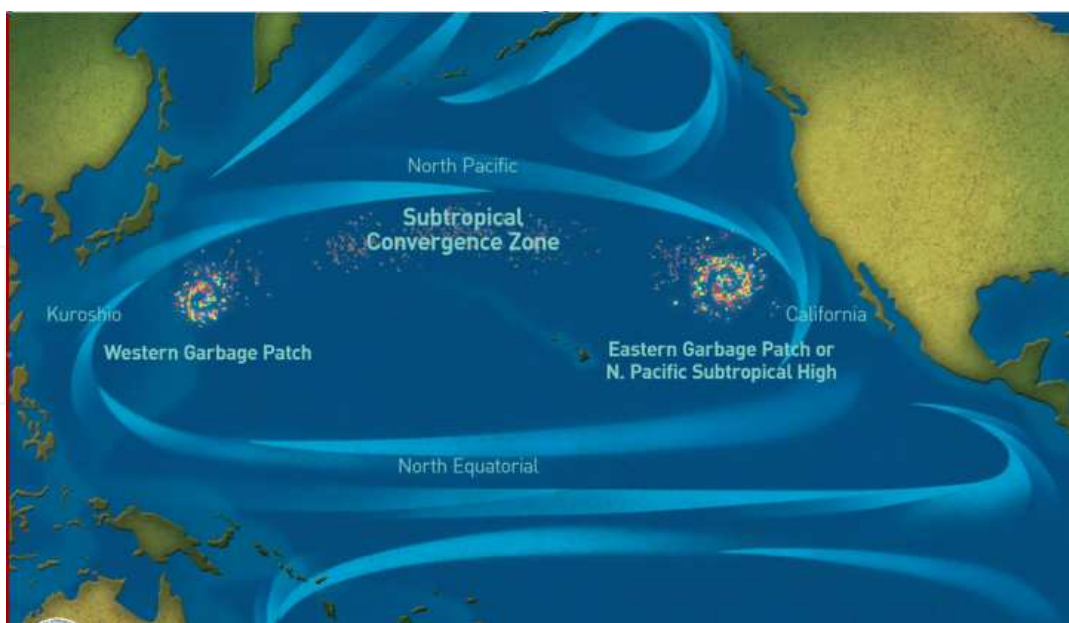
recycling of polymer. As is the case with all other chemical substances, the “disposal” of polymer seems to be a fallacy.

Polymeric wastes cause drain blockage and irreparable damages to the urban sewage systems. Plastic wastes that are constantly dumped into rivers, streams, and sea pollute the water, soil, marine life, and also the air we breathe. Clogged drains can create extremely bad conditions for mosquitoes to gather while also causing flooding during the monsoon.

Fig. 4 shows Pacific Garbage Patch, as a result of the mentioned condition [7]. Since plastic does not undergo bacterial decomposition, landfilling using plastic would mean preserving the poison forever. Stability of plastics to degradation, closing of landfill sites, and growing water and land pollution problems caused lots of concern about polymers. Waste problem and its serious impact on the environment lead to new interest in the area of degradable polymers. Waste plastic fills bird’s stomachs and slowly kills them (see Fig. 5). The interest in environmental issues is growing up; also there are increasing demands to develop materials that do not burden the environment. With the excessive use of plastics and increasing pressure being placed on available capacities for plastic waste disposal, the need for biodegradable plastics and biodegradation of plastic wastes has led to its increased importance in the past few years [8].

Polymers are made of major chemicals that are highly toxic and pose a serious threat to all living species on the planet Earth. Some of the polymer components such as benzene and vinyl chloride are proven to cause cancer, and other gases and liquid hydrocarbons bring about great damages to the earth and air. The toxic substances that are emitted during polymer production are synthetic chemicals like ethylene oxide, benzene, and xylene [9]. Figures 6a and 6b show acid rain production cycle and huge smoke that are produced by polymers production plants.





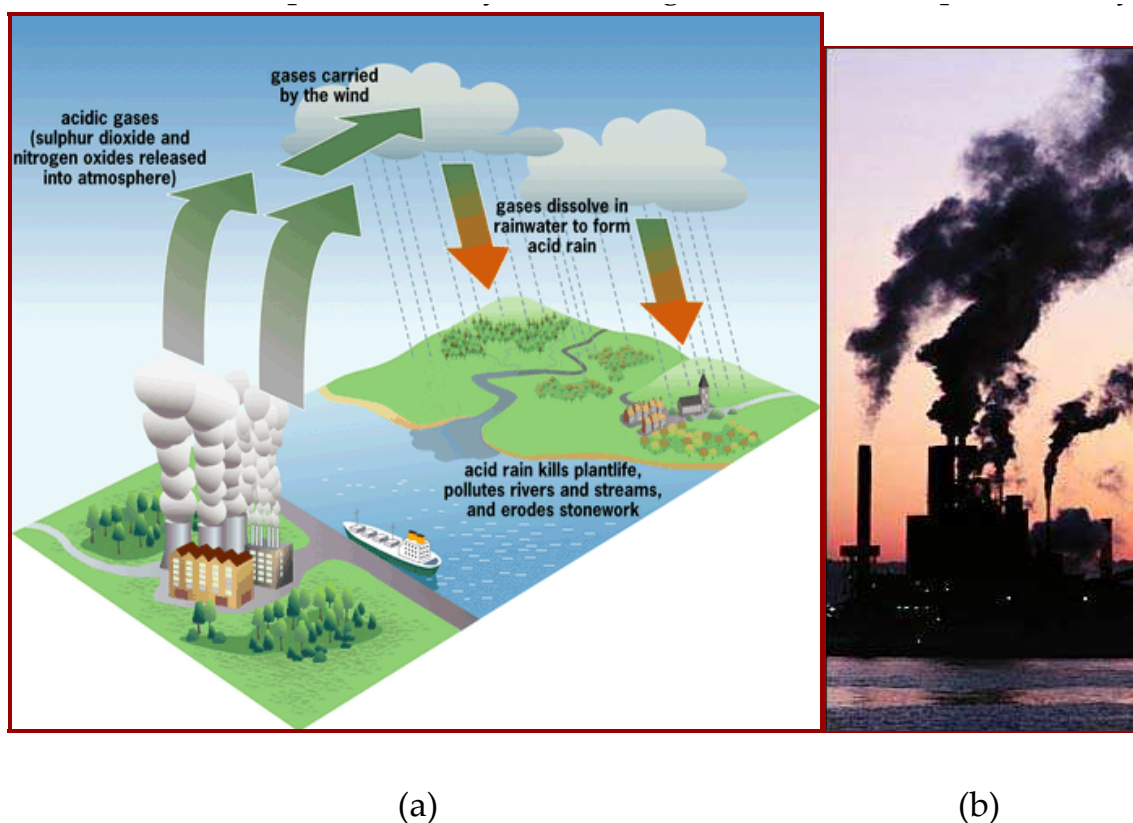
**Figure 4.** Pacific Garbage Patch [7]



**Figure 5.** Bird corpse, photo: Chris Jordan

Contaminants such as persistent organic pollutants (POPs) are also attracted by polymeric waste, especially in marine life. Many of these contaminants are hydrophobic; therefore, mixing or binding with water is not possible.

The role of plastics waste on the impact of the toxic chemicals is not evident. These chemicals could potentially move to clean environments by plastics, and when taken in by wildlife, the chemicals could transfer into the organism's system by plastics. However, in certain conditions, plastic could become less available to wildlife and act as a sink, particularly if they are



**Figure 6.** (a). Production cycle of acid rain in the Earth [10] (b). Huge dangerous smoke: A result of plastics production [10]

buried on the seafloor. Microplastics have a large surface area-to-volume ratio and are prone to make chemicals more available to wildlife and the environment compared to larger-sized plastics [11].

However, microplastics could pass through the digestive system faster than larger plastics once they have been ingested, potentially giving less chance for chemicals to be absorbed into the circulatory system [8]. A descriptive example is presented in the next section.

#### 1.1.1. Descriptive example

In 2002, the production of PET worldwide was 26 million tons which is expected to rise to 85 million tons in 2018. Numerous postconsumer PET products, especially bottles and containers, are not directly hazardous to the environment. You can see a photograph in Fig. 7 that shows the Caspian Sea beach captured by the author. However, its substantial volume fraction in solid waste streams, high resistance to the atmosphere, poor biodegradability, and photo degradability has caused serious problems. Each year, it is estimated that a billion plastic bottles are disposed, while recycling only one plastic bottle can conserve enough energy to light a 60 W light bulb for up to 6 h [12].

PET waste can be seen everywhere, so the world production rate of PET waste grows fast (Fig. 8). A greater necessity is felt for the recycling of this product.

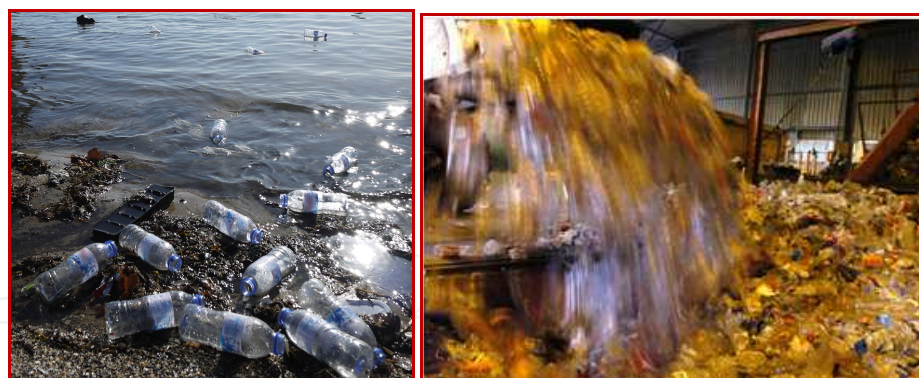




**Figure 7.** PET waste as a threat, serious cause of concern to the environmentalists

In Singapore, 684, 400 tons of plastic wastes were generated in 2008, and the recycling rate was 9 %. Even though PET has major advantages for use, such as its nontoxic nature, durability, and crystal-clear transparency, its nonbiodegradability seems to be the serious cause of concern to environmentalists [13].

Since it is not appropriate to dispose of waste PET by landfills, other recycling methods of waste PET products including physical and chemical recycling have been developed. Chemical recycling of PET includes chemolysis of the polyester with an excess of reactants such as water (hydrolysis), alcohols (alcoholysis), glycols (glycolysis), amines [14], and ammonia (ammonolysis) [15].



**Figure 8.** PET waste can be seen everywhere (left image), so the world production rate of PET waste grows fast (right image)

## 1.2. Which way must be chosen to save our planet? [7]

It is believed that any attempt to dispose of plastic through landfills is also harmful. In addition to the toxic seepage from the landfill which caused to contamination of precious water sources, the waste mass hinders the flow of groundwater. As landfills are also prone to leakages, the lead and cadmium in the wastes mix with rain water and then drip through the ground and drain into nearby streams and lakes and other water sources, poisoning the water we use.



Others believe that polymers refuse any attempt at disposal, whether through recycling, burning, or landfilling. When one hazard is done away with, it paves the way for another to come. One of the only ways to overcome the noxious danger of plastic pollution is to reduce the use of plastic and completely avoid it if possible.

Some people are of the belief that one of the ways to cut off the hazards of polymer pollution is to reduce the use of polymer and thereby force a reduction in its production. It is best to refrain from using plastic whenever and wherever you can. It is better to opt for the use of a cloth bag when carrying your groceries. Any attempt we make to end polymer pollution will have long-term benefits for the generations to come.



**Figure 9.** Burning a polymer caused releases of poisonous chemicals. Photo courtesy of Flickr

Waste strategies used across the globe are quite similar and are based upon the prevention and recycling of waste. For example, Japan has extensive rules and regulations pertaining to waste and other sustainable production and consumption policies under the “3Rs – reducing, reusing, and recycling” umbrella.

The European Union has its own strategy in dealing with waste, by preventing waste from the start, recycling waste, and optimizing the disposal of waste [5].

By recycling polymers, we are only returning them back into the marketplace and eventually into the environment, hence causing no reduction in its use. The recycled polymer is degraded in quality and requires the production of a newer polymer to make the original product. Burning a polymer has its own disadvantages. When burned, it could release a great number of poisonous chemicals into the air (Fig. 9). In addition to these dangers, recycling polymers is not very economical. Studies conducted by many “Public Interest Research Groups” have indicated that it is also a very dirty task, requiring hard physical work. Recycling of polymer

has been connected to skin and respiratory problems as a result of being exposed to toxic fumes, especially hydrocarbons and residues emitted during the process [7], [12].

#### *1.2.1. Serious response to polymer pollution*

As regards to the increasing challenges of waste production and its management, the European Parliament and the Council have fostered a number of official orders. These orders are critical to ensure that waste is recovered or disposed of without harming the environment and human health.

According to the European official order on packaging and packaging waste [13], the management of packaging and packaging waste's utmost priority should be the prevention of packaging waste. In addition, the reuse of packaging, recycling, and other forms of recovering packaging waste and, therefore the reduction of the final disposal of such waste should be considered fundamental.

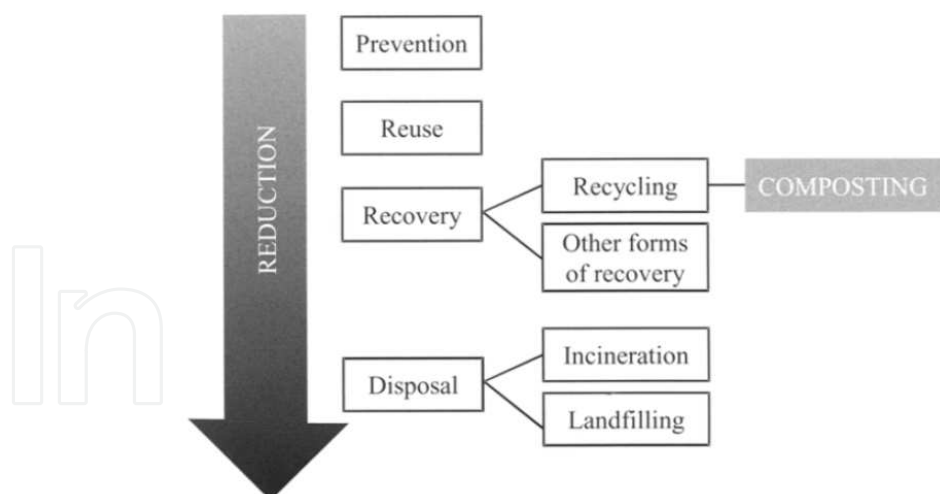
As observed in Fig. 10, some solutions are provided for reducing polymer pollution. Prevention refers to the reduction of the quantity of materials and substances that are included in packaging and packaging waste that can be harmful to the environment. It includes developing clean production methods and technology for packaging and packaging waste at the production process level for marketing, distribution, and utilization stages. Reuse is the process in which packaging is refilled or used once more for the same purpose which it was produced. Recovery includes operations such as using a fuel to generate energy, recycling of organic substances which are not used as solvents, etc. (including composting and other biological transformation processes). Energy recovery is defined as the use of combustible packaging waste in order to generate energy by completely burning the substance (incineration) with or without other wastes but with recovery of heat.

Recycling is a process in which waste materials are reprocessed for the original purpose or for other purposes including organic recycling but excluding energy recovery.

Disposal operations include deposit into or onto land (e.g., landfilling), incineration, etc. Compostable polymers, known as biological or organic recycling, are a valuable recovery option.

The EU official order on packaging and packaging waste defines organic recycling as the aerobic (composting) or anaerobic (bio methanization) treatment of the biodegradable parts of packaging waste under controlled conditions and using microorganisms. This process produces stabilized organic residues or methane. It is noteworthy to mention that landfills are not considered as a form of organic recycling.

Most developed countries have put the waste management hierarchy to use, i.e., minimization, recovery and transformation, and land disposal, using strategies that depend on factors such as population density, transportation infrastructure, and socioeconomic and environmental regulations. Let us also contribute our part, and save our environment from polymer pollution



**Figure 10.** Composting, as a solution to solve Earth problem

to make it a better environment for the future. To do so, one of the best ways to reduce the hazards of polymer pollution is changing them to compost.

## 2. Compost [11, 23]

Compost is a versatile product and obtained from composting, biodegradation of organic waste that is industrially, commercially, or domestically produced. Its fundamental use is in conditioning and fertilizing soil by the addition of humus, nutrients, and beneficial soil bacteria, with a wide range of specific applications.

Methane is an organic material produced via organic materials “anaerobically” without air in landfills and is a gas with 25 times the global warming impact of  $\text{CO}_2$ ! This same organic mulch helps to absorb carbon back into the soil if it is composted.

### Better Soil, Better Life, Better Future

It is interesting to note that about 60 % of the garbage Australians throw out could be put to better use as mulch to improve soil quality and in the garden as compost.

Composts improve soil quality, assist plant growth, increase water holding capacity, store carbon in the soil, and reduce the need for chemical fertilizer and pesticides.

Earthworms flourish in enriched soils. Activities of earthworms help release essential nutrients strengthen plants and also increase their resistance to various diseases.

Compost is an organic matter that has been decomposed and recycled as a fertilizer and soil strengthener. Compost is a very important component of organic farming. Simply put, composting process merely requires making a heap of wetted organic matter that is known as green waste (leaves, food waste) and waiting for the materials to decompose to humus after a period of weeks or months. Composting nowadays includes a multi-step monitored process

with exact inputs of air, water, and carbon-rich and nitrogen-rich materials. In order to assist the decomposition process, the plant matter is shredded, water is added, and proper aeration is ensured by regularly turning the mixture. Worms and fungi can also further decompose or break up the material. Aerobic bacteria and fungi manage a chemical process by converting the inputs into heat, carbon dioxide, and ammonium. Ammonium is a form of nitrogen ( $\text{NH}_4$ ) used by plants. When existing ammonium is not used by plants, it is converted by bacteria into nitrates ( $\text{NO}_3$ ) through a process known as nitrification. Compost production is shown in Fig. 11.



Figure 11. Compost

Compost is rich in nutrients that are used in gardens, landscaping, horticulture, and agriculture. Compost has itself advantages for the land in many ways, including as a soil conditioner, as a fertilizer, as an additive of vital humus or humic acids, and finally as a natural pesticide for soil. Compost is useful for erosion control, land and stream reclamation, wetland construction, and as a landfill cover in various ecosystems. Organic ingredients that are considered useful for composting can also be used to generate biogas through anaerobic digestion. Anaerobic digestion is quickly replacing composting in some parts of the world (especially central Europe) as a main means of downcycling waste organic matter.

<div><div></div><div>The soil structure, porosity, bulk density improves caused to create a better plant root environment</div></div> <div><div></div><div>Reduces runoff and erosion, Increases infiltration, increases permeability of heavy soils</div></div> <div><div></div><div>The capacity of water holding in sandy soils improves, reducing leaching and water losing</div></div> <div><div></div><div>Create a variety of macro and micronutrients</div></div> <div><div></div><div>Suppresses or controls or certain soil-borne plant pathogens as well as nematodes</div></div> <div><div></div><div>Supplies considerable quantities of organic matter</div></div> <div><div></div><div>Modifiescation exchange capacity (CEC) of soils, improve their ability to maintain nutrients for plant use</div></div> <div><div></div><div>Givesbeneficial microorganisms to soils</div></div> <div><div></div><div>Improving and stabilizing of soil pH</div></div> <div><div></div><div>Can attach and degrade special pollutants</div></div>
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Table 1. Benefits of Using Compost [15] (taken from [www.epa.gov](http://www.epa.gov))



### 3. Applications of compost [2]

Compost is used as an organic fertilizer, to improve and condition soil, to manufacture topsoil, as a growing medium and mulch for use in:

- Agriculture (intensive, organic)
- Growing fruit and producing wine
- Horticulture
- Potting
- Nurseries
- Greenhouses
- Private gardens
- Landscaping (e.g., parks)
- Ground rehabilitation
- Silviculture

There are a variety of benefits in using compost on roadside applications (Table 1). In the following section, these benefits are discussed in greater detail.

#### 3.1. Improved structure

Compost has a significant impact on the physical structure of soil. In fine-textured (clay, clay loam) soils, adding compost can reduce bulk density, improve workability and porosity, and enhance its gas and water permeability, thus reducing erosion. When an adequate amount is used, its addition can have both an immediate and long-term positive effect on soil structure. It opposes compaction in fine-textured soils and enhances water-holding capacity and enriches soil aggregation in coarse-textured (sandy) soils. The high degree of organic matter decomposition results in a stable residue known as humus. The components of humus act as a kind of soil adhesive and hold the particles together, making them more resistant to erosion and improving the soil's ability to hold moisture. With its humus content, compost has soil-binding properties.

#### 3.2. Moisture management

Drought resistance and efficient water utilization can be enhanced by adding compost. As a result, the intensity and frequency of irrigation may be decreased. Whereas compost can maintain many times its own weight in moisture, indeed its use can greatly contribute to establish roadside plantings. Furthermore, studies have suggested that adding compost in a sandy soil can facilitate moisture dispersion. Using of compost caused to allowing the movement of water laterally, more lightly from its point of application.

### **3.3. Modifies and stabilizes pH**

Adding compost to soil may modify the pH of the final mix. Depending on the pH of the compost and native soil, adding compost may increase or decrease the pH of the final mix. Therefore, adding neutral or slightly alkaline compost to acidic soil will increase the soil pH if sufficient amounts are added.

In certain conditions, where compost was applied at low amounts such as 10–20 tons per acre, it was found to have an effect on soil pH. Using compost also allows the ability to buffer or stabilize soil pH. This phenomenon could be more useful where it will effectively resist to pH change.

### **3.4. Increases cation exchange capacity**

Compost can also modify the cation exchange capacity of soils, making it possible to hold nutrients longer. It can also enable crops to utilize nutrients more efficiently while decreasing nutrient loss by leaching. Therefore, soils' fertility and their organic matter content are closely linked. In addition, adding compost can greatly improve the retention of plant nutrients in the root zone by enhancing the cation exchange capacity of sandy soils.

### **3.5. Provides nutrients**

Compost products include various kinds of macronutrients and micronutrients. While they are often good source of nitrogen, phosphorous, and potassium, composts also include micronutrients that are essential for plant growth. Since composts contain relatively stable sources of organic matter, the nutrients are supplied in a slow-release form. Large amounts of nutrients are normally not found in compost compared to most commercial fertilizers. However, compost is usually added at much greater rates. As a result, it can have a great effect on nutrient availability. By adding compost, significant effects can be observed in both the fertilizer and pH adjustment (lime/sulfur addition). Compost has benefits of both providing nutrition and making the common fertilizer programs more effective.

### **3.6. Provides soil biota**

Soil organism's activity is very significant in productive soils as well as healthy plants. Their activity depends mainly on the presence of organic matter. Bacteria, protozoa, actinomycetes, and fungi consist soil microorganisms. They are not only found in compost but spread in soil media quickly. Microorganisms have an essential role in organic matter decomposition. After that, humus formation and nutrient availability will occur. Furthermore, microorganisms have benefits for root activity as special fungi do symbiotically with plant roots which help them extract nutrients from soils.

### **3.7. Suppresses plant diseases**

The level and type of organic matter and microorganisms present in soils may have an influence on the disease rates of many plants. Previous studies have indicated that the

increased population of certain microorganisms may suppress specific plant diseases such as pythium and fusarium as well as nematodes. Numerous attempts are being made to optimize the composting process so that the population of these beneficial microbes might increase.

### **3.8. Binds contaminants**

Another capability of compost is binding heavy metals as well as other contaminants that caused to reduce both their absorption by various plants that is named bioavailability and leachability. As a result, sites that are contaminated with different pollutants could be improved via modifying the native soil with compost. Similar binding effect lets compost be used as a filter for storm water treatment. Furthermore, it has been reported that compost caused to minimize leaching of pesticides in soil systems.

### **3.9. Horticulture and agriculture**

Compost is used in horticulture in many different contexts. Compost can be mixed with sand, clay, aged sawdust, and other materials in raised-bed gardening in order to create an enriched mix for landscape beds or raised-bed gardens. In this case, compost should be about 30 % of the total mix. To avoid nutrient and oxygen competition with plants, high-quality compost should be used.

Similar to bedding mixes, using of compost up to 30 % based on total mix, depending on maturity and salinity, may be a useful ingredient in potting media in a container garden.

It could be used as a substitute for peat moss, but it must be used in limited amounts due to low porosity and water-holding capacity of peat. Compost has a nutrient content lower than the necessity for supplemental chemical fertilizers, although this must be determined in each case.

Areas that have been excavated areas around the foundation of new buildings are backfilled after construction has been completed, but these planting zones may contain rubble, residues of toxic chemicals, and other undesirable substances. In order to improve the soil in these zones and provide a healthier start for the foundation plantings, it is a good idea to remove the backfill and replace it with a mix of soil and compost.

If the product has course textures and is mature, then two or more inches of compost can be used alone or together with conventional mulch products to keep root zones cool, conserve moisture, and act as a slow-release fertilizer. For a weed barrier, compost can be used at double or triple the amount and be placed on top of a thick layer of newspapers, to replace geomembrane weed barriers. This, however, only holds true for composts that are free of weeds.

For trees and shrubs, mixes of old compost with the native soils can be used as backfill. Immature composts may cause settling and young root disturbance since they are deprived of oxygen. To create new turf areas such as lawns and recreation areas, compost can be applied before seeding or sodding and work into the soil. Compost can be used seasonally as covering and may also be raked into the soil. Some turf farms also use compost to prevent topsoil loss by growing grass in a couple of inches of the material.

Finally, for use in fields, in order to grow corn, wheat, soybeans, and some other crops, compost can be spread on top of the soil by using spreaders pulled behind a tractor or a spreader trucks. The obtained layer after spreading is very thin, about 6 mm which is worked usually into the soil before planting process. When attempting to rebuild poor soils or control erosion, application rates as 25 mm or more are usual.

### **3.10. Erosion control**

Topsoil loss is a serious ecological issue. A relatively new technology in this realm is the application of compost to control sediment runoff and fight erosion. It has recently been adopted by local authorities, developers, farmers, and other major disturbers of soil as another tool to reduce topsoil loss.

A compost blanket is a layer of compost spread over a disturbed area of soil. While having a high water-holding capacity, compost can remain on the surface to temper the impact of rainfall. Even insignificant amounts can be helpful, but typical recommendations require a 5 cm (2 in.) layer to insure adequate surface coverage. Direct planting into the blanket is also possible.

Compost berms and socks are used alone or together with compost blankets to alleviate the impact of high-volume water discharges. Compost berms are more aesthetically satisfactory than silt fences and remove the need to do away with the berm when the project is complete. After passing the time, compost biodegrades simply and returns to earth. A mesh tube that is stuffed with compost is named a compost sock. The compost socks show better response to heavy equipments and can be anchored, removed, and reused easily. When a sock based on biodegradable fiber is used, it may be left in place to biodegrade; however, since this is not in confidence with the idea of the sock, it is not common.

Other important applications of compost are as follows: Planting media for artificial or constructed wetlands, Cap for a landfill cell when used closely to encourage vegetation and erosion reduction, and erosion control of possibly alleviating damages and restore beauty and functionality to riparian zones in the future.

## **4. Biodegradation [1, 6, 16]**

Degradation is an irreversible process that leads to great changes of the material structure, usually characterized by a loss of properties and/or fragmentation. Degradation is under the effect of environmental conditions over a certain period of time and consists of one or more steps. Properties such as integrity, molecular weight or structure, and mechanical strength decreases during biodegradation.

According to Dr. Rolf-Joachim Muller's definition [25], biodegradable plastics refer to plastics and non-water-soluble polymer-based materials that degrade via an attack by microorganisms. It is believed that the biodegradation of plastics is usually a heterogeneous process.



Due to the size and the lack of water solubility of polymeric molecules, microorganisms cannot transport the polymeric material into the cells directly like in most biochemical processes; rather, they must first excrete extracellular enzymes that depolymerize the polymeric chains outside the cells (Fig. 12).

Therefore, if the molar mass of the polymers can be sufficiently reduced to generate water-soluble intermediates, these can be transported into the microorganisms and fed into the appropriate metabolic pathway(s). As a result, the end products of these metabolic processes include water, carbon dioxide, and methane (in the case of anaerobic degradation), together with a new biomass. The extracellular enzymes are too large to penetrate deeply into the polymer material and so act only on the polymer surface. Consequently, the biodegradation of plastics is usually a surface erosion process. Although the enzyme-catalyzed chain length reduction of polymers is in many cases the primary process of biodegradation, nonbiotic chemical and physical processes can also act on the polymer, either in parallel or as a first stage solely on the polymer. These nonbiotic effects include chemical hydrolysis, thermal polymer degradation, and oxidation or scission of the polymer chains by irradiation (photo degradation).

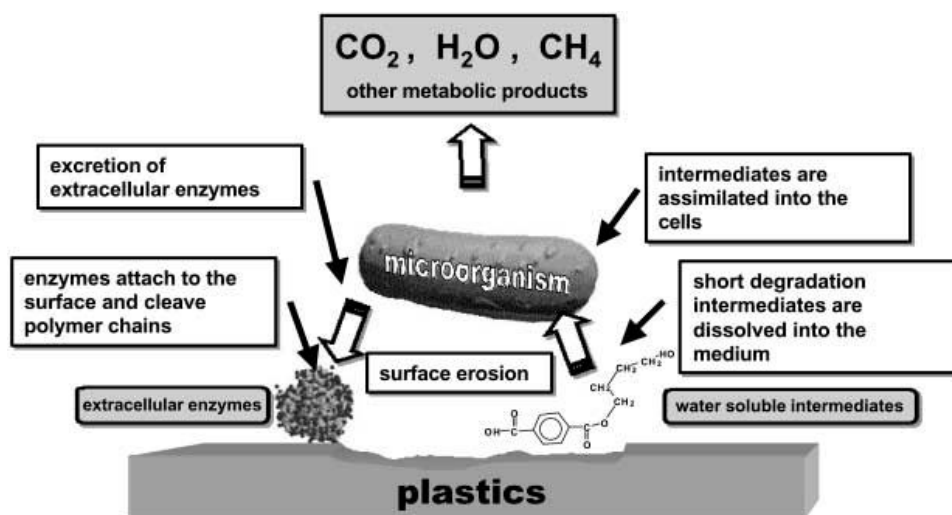


Figure 12. General mechanism of plastics biodegradation [28]

#### 4.1. Biodegradable

According to ASTM D883-99, degradation results from the action of naturally occurring microorganisms such as bacteria, fungi, and algae (according to ASTM D883-99). One of the necessary steps in the testing strategy for materials is testing the biodegradability to define ultimate compostability and a suitable indicator of final compostability. Of course, biodegradability is not the same as compatibility. For instance, a potato or a fruit is fully biodegradable but will not compost as such in a composting environment. In a particular context, even geographical or legal context may affect on the definition of compostable, to make fully a biodegradable product “non-compostable.”

## 4.2. Compostable

A number of standardization committees such as ISO, DIN, ASTM, CEN, and UNI have been working assiduously on compostability testing as well as acceptance criteria or rules for several years. Therefore, the general principles and guidelines regarding testing and basic characteristics have been defined which are universally accepted; however, discussion still continues for particular aspects.

According to ISO and ASTM standards, biological degradation during composting caused to produce CO<sub>2</sub>, water, inorganic compounds as well as biomass at a rate consistent with other known materials that are compostable and do not leave visually toxic or distinguishable residues.

To claim compostability, it should have been proved that packaging can be disintegrated and biodegraded in a composting system (can be shown by standard test methods). Also its biodegradation must complete during the end use of the compost.

The compost should be meeting the relevant quality criteria that include amount of heavy metal, no obviously distinguishable residues, and finally no ecotoxicity.

Environmentally degradable polymers or EDPs can be described as follows:

- Polymeric materials that maintain the same formulation during use as conventional polymers
- Polymeric materials that degrade to lower-molecular-weight compounds after use by a combination of the above biological, chemical, and physical incitement or other stimulations in the environment
- Polymeric materials that degrade ultimately to H<sub>2</sub>O and CO<sub>2</sub>

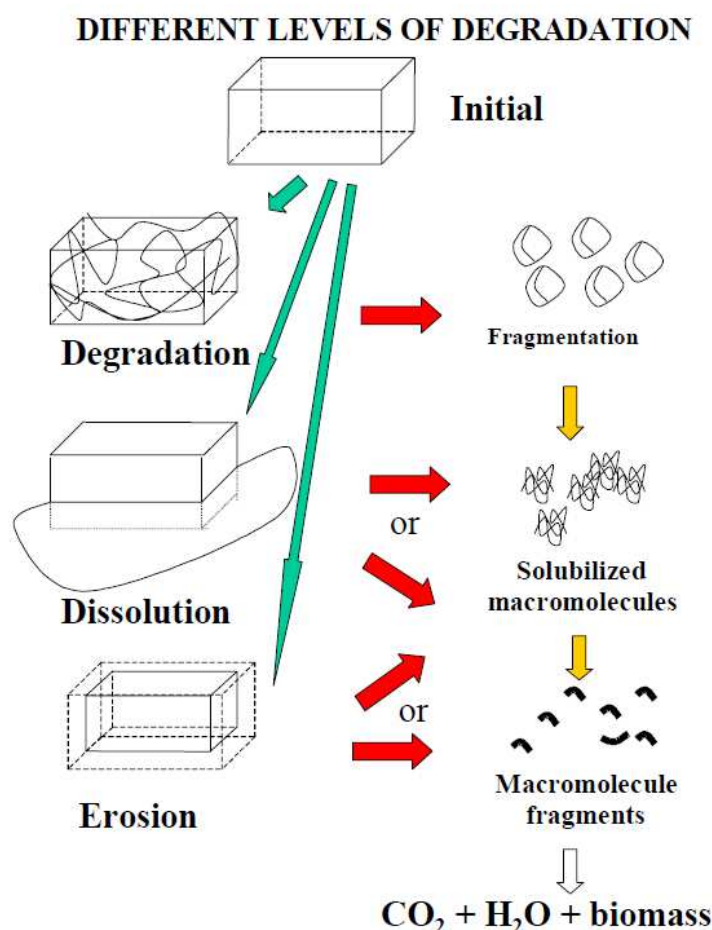
## 4.3. Different levels of degradation

When transferring from a polymeric device insertion to a living organism, regardless of the type, there are different levels of degradation. The various levels, such as isolated organism or the environment itself, are schematized in Fig. 13.

As shown in Fig. 13, it is observed that dissolution and fragmentation processes do not relate to macromolecule scission.

Actually, they show the disappearance of the visible device and hence leave biostable macromolecular compounds as residues. The fragments or the dissolved macromolecules will be retained in the human body, unless they are rejected through boils and abscess or by filtration if molar masses are less than the filtration threshold (10, 000 D to 40, 000 D, depending on the compound).

In the environmental conditions, dissolved macromolecules or the fragments can be stored as organic sand or reached to running or underground water after dissolution.



**Figure 13.** The various levels of degradation for a polymer device

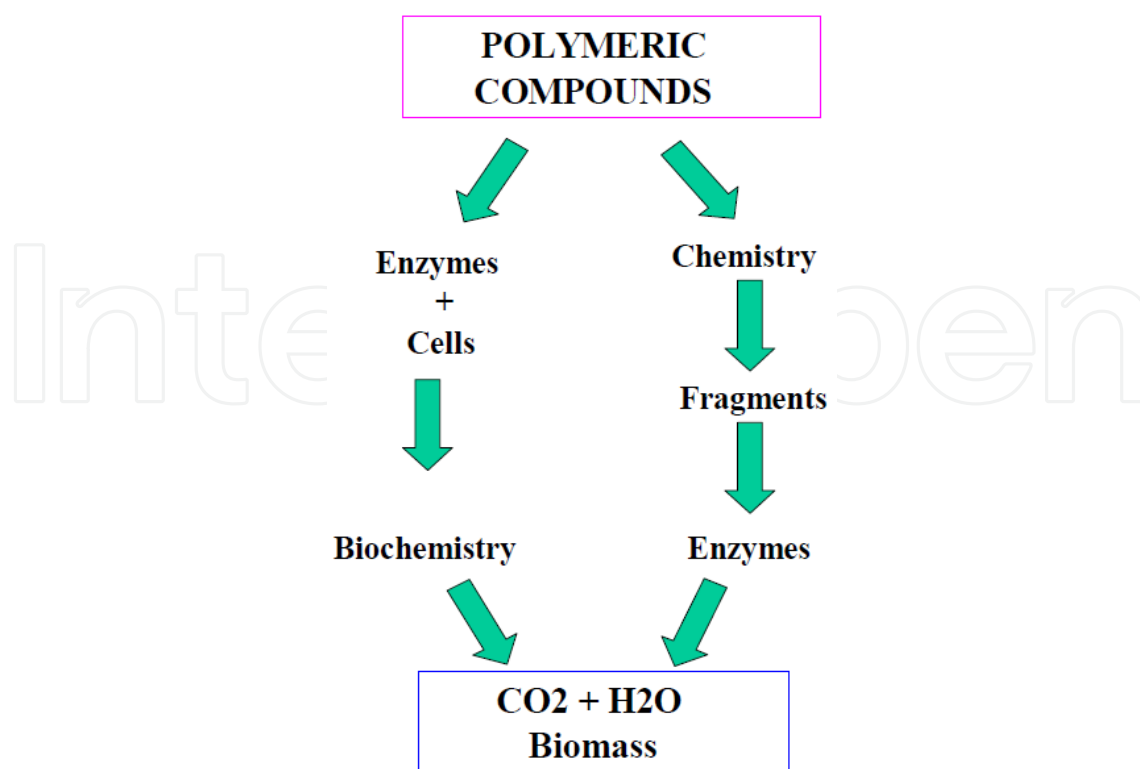
Another stage is the process of macromolecule breakdown to some biostable small molecules is achieved. In this stage, toxic compounds might be generated, and therefore only biostable biocompatible by-products are the acceptable degradation process products.

The concept of biocompatibility is very important and is acknowledged in medicine and pharmacology. As far as the outdoor environment is concerned, it is not defined in a similar way. The final stage of degradation is multiple, meaning that it consists of mineralization and also biomass formation with residual material.

As a result, the scheme describes the need for specific terms to distinguish these different stages and also distinguish the particularities of the different sections of human activity that are important. Another basic discussion has to be made to identify the possible routes leading from the device to the ultimate stage, which is named mineralization biomass formation.

The two main routes to degrade a polymeric device up to mineralization and biomass formation are possible that are shown in Fig. 14.

The left-handside route related the attack of the device or compound that is followed by an enzymatic process of the degradation products through biochemistry. In this route, the presence of proper enzymes and thus of specific cells under viable conditions (such as



**Figure 14.** The two general routes leading to ultimate degradation and bio-assimilation [27]

atmosphere, water, nutrients, etc.) is needed. No life-allowing conditions means that there is not any degradation happening.

The right-hand-side route has a different way in which breakdown of the device and macro-molecule depends on some chemical processes, and the elimination of the generated small molecules proceeds dominantly through biochemical pathways. In this type, the reagents (light, water, heat, etc.) are needed to trigger the degradation. In fact, no-triggering phenomenon means that there isn't any degradation happening [16].

## 5. The composting process and methods [26-29]

As nature's way of recycling, composting is the process of transforming organic material into solid-like product that is called humus. This process breaks down the organic materials by using microorganisms such as bacteria and fungi. Having a continuous supply of food (organics), water, and oxygen, the best gen is critical to obtain the best results. In addition, the other important factor to make the process work is managing the composting material's temperature.

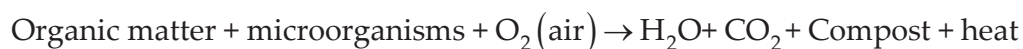
Making compost is viable from the most organic by-products [18]. Feedstocks such as poultry, hog, and cattle manures, food processing wastes, sewage sludge, municipal leaves, brush and grass clipping, and sawdust are the most common [19].



The main composted waste types are:

- Green waste: park and garden waste
- Biowaste: food waste
- Biodegradable waste stream from manufacturing (food processing wastes, wood wastes)
- Sewage sludge
- Municipal solid waste
- Slurries and manure from husbandry

During composting process, organic matter has broken down by microorganisms consequently carbon dioxide, heat, water and compost are produced:



Although nature compost is the end product of the stabilization stage, fresh compost is an intermediate product of the thermophilic stage.

The raw materials and the factors that affect the progress of the process are the main factors that affect compost characteristics.

Depending on the quality produced and product quality, composts have various applications. For instance, high-quality compost is being used in horticulture, agriculture, landscaping, and home gardening. The medium quality is used in erosion control and roadside landscaping.

Even low-quality compost in land reclamation projects can be used as a landfill coverer. There are three basic types of centralized composting processes:

1. **In-vessel method:** in this process, the organic material is composted inside a silo, a drum, an agitated bed in covered or open channel, in a batch container or other structure. The process conditions are clearly monitored and controlled; also the material is aerated and mechanically agitated.
2. **Aerated static pile method:** in this method compostable materials form into large piles, which are aerated by drawing the air through the pile or forcing air out through it. In this method, pile is not turned.
3. **Windrow method:** In this method, compostable material is formed into elongated piles, known as windrows. The windrows are turned on a regular basis mechanically. Therefore important composting systems are titles as follows [21]:
  - **Low-tech**
    - Windrow
  - **Mid-tech**
    - Aerated static pile

- Aerated compost bins
- **High-tech (in-vessel)**
  - Rotary drum composters
  - Box/tunnel composting systems
  - Mechanical compost bins

In high-tech “in-vessel” composting systems, enclosed rigid structures or vessels are used to contain the material undergoing biological processing [22]. For monitoring of the process, process control systems are used to evaluate biological activity by using probes that measure the air temperature and the concentration of O<sub>2</sub> and/or CO<sub>2</sub>. Precise determination of the status of the degradation process is possible via monitoring the concentration of evolved gases.

In most plants, an air treatment unit for limiting of the emission of particulate and gaseous pollutants into the atmosphere is also included.

In-vessel systems divide into two main categories: vertical and horizontal bioreactors. Vertical reactor has cylindrical structure or container and composed of concrete or steel, having a volume of about 100 to more than 2, 000 m<sup>3</sup> [30]. The material is loaded at the top and is extracted from the bottom continuously. Forcing air from the bottom of the reactor by means of a centrifugal blower is carried out, countercurrent to the flow of the composting material and caused to a suitable aeration. Vertical systems have been almost replaced by horizontal bioreactors. In horizontal systems, forced aeration is used to maintain the biomass at the necessary aerobic conditions, usually combined with mechanical turning. Continuous or discontinuous working cycle can be used. Composting needs special conditions, particularly of temperature, moisture, pH, aeration, and carbon-to-nitrogen (C/N) ratio, related to optimum biological activity in the various stages of the process [17].

Degradation of the waste in compost carried out in three phases [17, 23]:

1. Mesophilic phase
2. Thermophilic phase
3. Cooling and maturation phase

The mesophilic phase, according to the ASTM standard [3], is the phase of composting that occurs from 20 to 45; the thermophilic phase is the phase in the composting process that occurs from 45 to 75 which associated with certain colonies of microorganisms that have a high rate of decomposition.

### 5.1. The first mesophilic phase [23]

In the first stage of composting, mesophilic bacteria and fungi degrade degradable compounds of organic matter, such as monosaccharide, starch, and lipids easily due to their solubility. Organic acids are produced by bacteria, and the pH decreases to 5–5.5.

As heat is released from exothermal degradation reactions, the temperature starts to rise spontaneously. Also, the degradation of proteins leads to release of ammonia, and the pH rises from 8 to 9 rapidly. A few hours to a few days is needed to end this phase.

### 5.2. Thermophilic phase [23]

The thermophilic phase starts when the temperature reaches about 40 °C. The degradation rate of the waste increases as thermophilic bacteria and fungi take over. If the temperature reaches over 55–60 °C, microbial activity and diversity greatly decrease. The pH stabilizes to a neutral level after peak heating. This phase can last from a few days to several months.

### 5.3. Cooling and maturation phase [23]

When the easily degradable carbon sources have been consumed, the compost starts to cool. After cooling, stable compost is obtained. Then, mesophilic bacteria and fungi reappear, and finally the maturation phase follows. However, most of the species are different from the species of the first mesophilic phase. Actinomycetes often grow during this phase extensively, and a wide range of macroorganisms and some protists are usually present. The biological processes are now slow, but the compost is further converted to humus (humified) and becomes mature.

The required time for the phases depends on the composition of the organic matter as well as the efficiency of the process, which can be determined based on oxygen consumption during the process.

## 6. Compostable polymers

“Compostable polymers” were first introduced commercially in the 1980s and were also named “biodegradable polymers.” These materials that are the first-generation biodegradable products were made from a conventional polymer, usually polyolefin (e.g., polyethylene) mixed with starch or other organic substances. When starch was eaten by microorganisms, the products were broken down, leaving small fragments of polyolefins. In 1994, Narayan wrote: “The U.S. biodegradables industry fumbled at the beginning by introducing starch filled (6-15%) polyolefins as true biodegradable materials” [28].

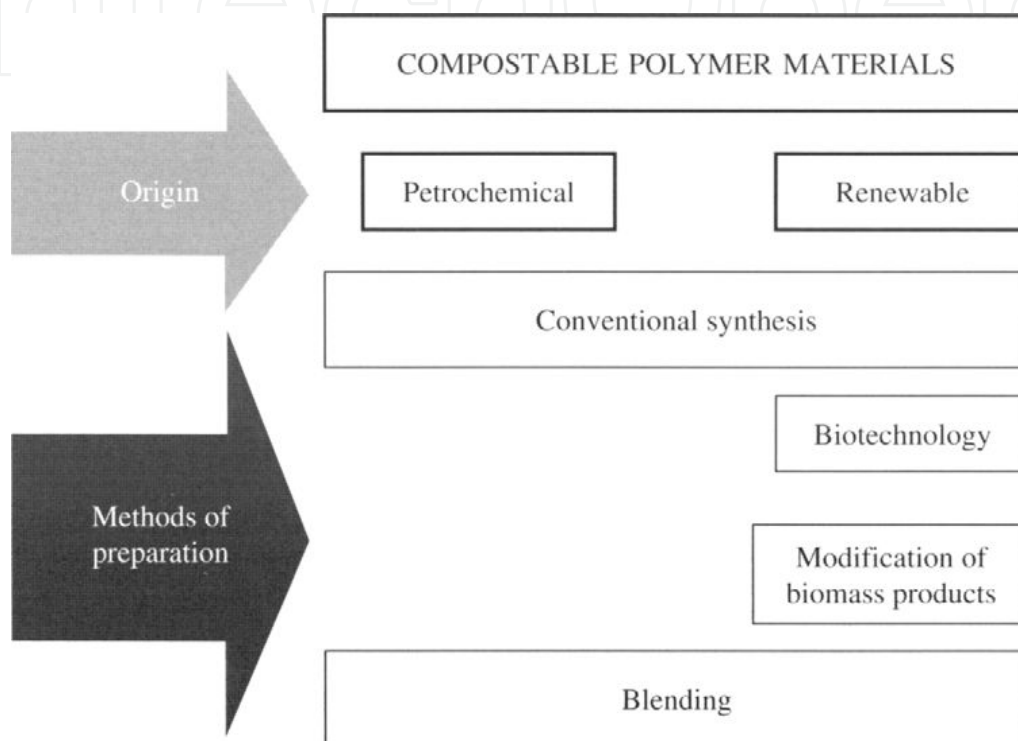
These were only biodisintegrable at the best conditions and not completely biodegradable.

According to ISO/DIS 17088 and ASTM D 6400 standards, definitions of compost and compostability are as follows:

**Compost:** Organic soil conditioner obtained by biodegradation of a mixture consisting principally of vegetable residues, occasionally with other organic material and having a limited mineral content

**Composting:** The autothermic and thermophilic biological decomposition of biowaste (organic waste) in the presence of oxygen and under controlled conditions by the action of microorganisms and microorganisms in order to produce compost

**Compostable polymer :** A polymer that undergoes degradation by biological processes during composting to yield CO<sub>2</sub>, water, inorganic compounds, and biomass at a rate consistent with other known compostable materials and leaves no visible, distinguishable, or toxic residue



**Figure 15.** Classification of compostable polymers

**Disintegration:** The physical breakdown of a material into very small fragments. Put briefly, the requirements a material must satisfy to be termed “compostable” include mineralization (i.e., biodegradation to carbon dioxide, water, and biomass), disintegration into a composting system, and completion of its biodegradation during the end use of the compost, which, moreover, must meet relevant quality criteria, e.g., no ecotoxicity. The satisfaction of requirements should be proven by standardized test methods. These requirements and test methods are described in Section 7.

## 6.1. Classification of compostable polymers

Compostable polymers can be divided according to the source of origin or preparation method (Fig. 15).

On the basis of origin, compostable polymers are derived from renewable and petrochemical resources.



*6.1.1. Biodegradable polymers from renewable resources include:*

1. Polylactide (PLA)
2. Polyhydroxyalkanoates: poly(3-hydroxybutyrate) (PHB)
3. Thermoplastic starch (TPS)
4. Cellulose
5. Chitosan
6. Proteins

There are three principal ways to produce polymers from renewable resources, i.e., bio-based polymers:

1. To make use of natural polymers which may be modified but remain intact to a large extent (e.g., starch polymers)
2. To produce bio-based monomers by fermentation which are then polymerized (e.g., polylactic acid)
3. To produce bio-based polymers directly in microorganisms or in genetically modified crops (polyhydroxyalkanoates)

In general, on the basis of methods of preparation, compostable polymer materials can be prepared via:

1. Conventional synthesis:

Examples: PCL, poly (ε-caprolactone) – copolyesters

- Polymerization from renewable monomer feedstocks:

Examples: polylactic acid

2. Biotechnological route (extraction, fermentation)

Examples: poly(hydroxybutyrate-co-hydroxyvalerate) – PHBV

3. Preparation directly from biomass

Examples: plants – starch

4. Blending

Examples: Starch-polycaprolactone blends

A method based on blending of biodegradable polymers is very often used in order to improve the properties of compostable polymer materials or to decrease their cost. The various polymers used are both renewable polymers in an extruder in the presence of water or plasticizer [31].

### 6.1.2. Biodegradable polymers from petrochemical sources include:

1. Aliphatic polyesters and copolyesters (e.g., polybutylene succinate, PBS; polybutylene succinate adipate, PBSA).
2. Aromatic copolyesters (e.g., polybutylene adipate, PBAT)
3. Poly  $\epsilon$ -caprolactone – PCL
4. Polyesteramides – PEA
5. Polyvinyl alcohol – PVA

### 6.1.3. Blends

The blending of biodegradable polymers is one of the strategies adopted in producing compostable polymer materials. Blending is a common practice in polymer science to improve unsatisfactory physical properties of the existing polymer or to decrease cost. By varying the composition and processing of blends, it is possible to manipulate properties. The leading compostable blends are starch-based materials. The aim is to combine the low cost of starch with higher-cost polymers having better physical properties. An example of such material is Mater-Bi manufactured by Novamont [46]. Mater-Bi is prepared by blending starch with other biodegradable polymers in an extruder in the presence of water or plasticizer. Some of Commercially available blends are presented in Table 2.

Tradename	Supplier	Origin	Website
Mater-Bi	Novamont	Italy	<a href="http://www.materbi.com">www.materbi.com</a>
Ecostar	National Starch	USA	<a href="http://www.nationalstarch.com">www.nationalstarch.com</a>
Ecofoam	National Starch	USA	<a href="http://www.nationalstarch.com">www.nationalstarch.com</a>
Biograde (cellulose blends)	FKuR	Germany	<a href="http://www.fkur.de">www.fkur.de</a>
Bioflex (PLA blends)	FKuR	Germany	<a href="http://www.fkur.de">www.fkur.de</a>
Fasal (cellulose based)	Austel + IFA	Austria	<a href="http://www.austel.at">www.austel.at</a>
Cereplast	Cereplast, Inc.	USA	<a href="http://www.cereplast.com">www.cereplast.com</a>

**Table 2.** Commercially available blends

## 7. Biocompostables

Compared to other available options, biocompostable products are an eco-friendly alternative, which can help reduce social and economic inequalities, decrease the impact of our consumption on the environment, and provide opportunities for creating a better and sustainable planet. In line with this goal, many technical attempts have been made to find a substitute plastic for packaging, compostable polymers, tissue engineering, etc. Several biopolymers have been exploited to develop materials for eco-friendly food packaging. However, there is

a limitation on the use of biopolymers due to its usually poor mechanical and barrier properties, which may be improved by adding reinforcing compounds or fillers in order to form composites.

Most reinforced materials result in poor matrix–filler interactions, which usually improve with decreasing filler dimensions. The use of fillers with at least one nanoscale dimension (nanoparticles) produces nanocomposites. By using a variety of building blocks with dimensions in the nanosize region, designing and creating new materials with unprecedented flexibility and improvements in their physical properties is possible.

The ideal biopolymer is of renewable biological origin and biodegradable at the end of its life. Biopolymers include polysaccharides such as cellulose and starch, carbohydrate polymers produced by bacteria and fungi, and animal protein-based biopolymers such as wool, silk, gelatin, and collagen. On the other hand, poly(vinyl alcohol) (PVA), poly(caprolactone) (PCL), and poly(butylene succinate) (PBS) are examples of polymers that have synthetic origin but are biodegradable. Recently, natural renewable products made from starches extracted from corn, potato, tapioca, or other plants and vegetable matter are combined with biodegradable polymers to create products that are compostable or biodegradable and can assist in reducing the carbon footprint impact on the environment. Some product sources can come from recycled fiber from sugarcane, bamboo, wheat, rice, and even switch-grass to be formed into everyday used compostable.

### 7.1. Nanocomposites for food packaging applications

Most materials that are being used for food packaging are nondegradable and therefore create environmental problems. Several biopolymers have been taken advantage of to develop materials for eco-friendly food packaging. There have been limitations on the use of biopolymers due to their poor mechanical and barrier properties. This may be modified by adding some reinforcing compounds, forming composites.

Most reinforced materials present poor matrix–filler interactions, which usually improve with decreasing filler dimensions. To produce nanocomposites, the use of fillers with at least one nanoscale dimension (nanoparticles) is a common method.

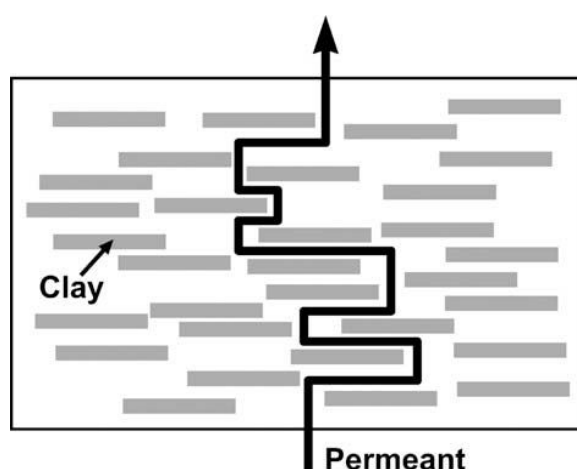
Nanoparticles have proportionally larger surface area than their microscale counterparts, which favors the filler–matrix interactions and the performance of the resulting material. Furthermore, nanoparticles can have other functions when added to a polymer, such as increasing of tensile modulus, antimicrobial activity, enzyme immobilization, biosensing, etc. An outline of the main kinds of nanoparticles which have been studied for use in food packaging systems is given, as well as their effects and application. Besides nanoreinforcements, nanoparticles can have other functions when added to a polymer, such as enzyme immobilization, antimicrobial activity, biosensing, etc.

Some of the nanoparticles are:

- Clays and silicates
- Cellulose-based nanoreinforcements

- Carbon nanotubes
- Silica ( $\text{SiO}_2$ )
- Starch nanocrystals
- Chitin/chitosan nanoparticles

The layered silicates which are commonly used in nanocomposites consist of two-dimensional layers that are 1 nm thick and several microns long depending on the used particular silicate. The presence of these types of reinforcing agents in polymer formulations increases the tortuosity of the diffusive path for a permeant molecule (Fig. 16) and provides good barrier properties [24].



**Figure 16.** Tortuous path of a permeant in a clay nanocomposite [32]

Biodegradable all-cellulosic composite nonwoven materials composed of cotton and kenaf or cotton and bagasse have been developed by Zhang [33].

Composting causes significant reduction in the use of chemical fertilizer, plant diseases, water consumption, erosion, etc. It also increases soil quality, production yield, and product quality. Some technologies exist, but investment cost may be a problem and preselecting is necessary. The composting method depends on waste composition.

## 8. Testing methods for evaluation of biodegradation

To determine biological action on man-made materials for various classes, test methods have been available for many years. Recently, the evaluation of the degradability of chemicals in the environment, specifically in wastewater, as one important aspect of the ecological impact of a compound has become significant when attempting to bring new chemical products to the marketplace. For this means, many standardized tests have been prepared for different environments, using different analytical methods [34]. An overview of existing international

standards in this area is provided in Table 3. In principle, tests can be subdivided into three categories: field tests, simulation tests, and laboratory tests. Fossil fuels will finish; therefore we require new resources for energy and polymers and effective waste management strategies (according to AS ISO 14855).

Table 3. Standard test methods for biocorrosion phenomena on plastics

ASTM G21-96	Standard practice for determining resistance of synthetic polymer materials to fungi
ASTM G29-96	Standard practice for determining algal resistance of plastic films
DIN IEC 60068–2-10-1991	Elektrotechnik; Grundlegende Umweltprüfverfahren; Prüfung J und Leitfaden: Schimmelwachstum; (Identisch mit IEC 60068–2-10: 1988)
EN ISO 846–1997	Plastics – Evaluation of the action of microorganisms
IEC 60068–2-10-1988	Elektrotechnik; Grundlegende Umweltprüfverfahren; Prüfung J: Schimmelwachstum
ISO 846–1997	Plastics: Determination of behaviour under the action of fungi and bacteria. Evaluation by visual examination or measurement of changes in mass or physical properties

Table 3. Standard test methods for biocorrosion phenomena on plastics

8.1. General principles in testing biodegradable plastics

Testing degradation phenomena of plastics in the environment has an overall problem regarding the type of tests to be implemented and the results that can be obtained. The guiding principle is that tests can be subdivided into three categories: field tests, simulation tests, and laboratory tests (Fig. 17).

While field tests, such as burying plastics samples in soil, placing them in lakes or rivers, or performing a full-scale composting process with the biodegradable plastic, represent the ideal practical environmental conditions, several serious disadvantages exist regarding these types of tests.

Environmental conditions such as temperature, pH, or humidity cannot be controlled very well. Also, the analytical opportunities to monitor the degradation process are limited. In most cases, evaluating visible changes on the polymer specimen or perhaps determining disintegration by measuring weight loss is the only solution.

However, if the material breaks into small fragments that must be quantitatively recovered from the compost, soil, or water, the latter approach can lead to a problem. The analysis of residues and intermediates is complicated by the unspecified and complex environment. The pure physical disintegration of a plastic is not known as biodegradation; therefore, these tests alone can never prove whether a material is biodegradable or not. Various simulation tests, as an alternative to field tests, have been used to measure the biodegradation of plastics in the laboratory.



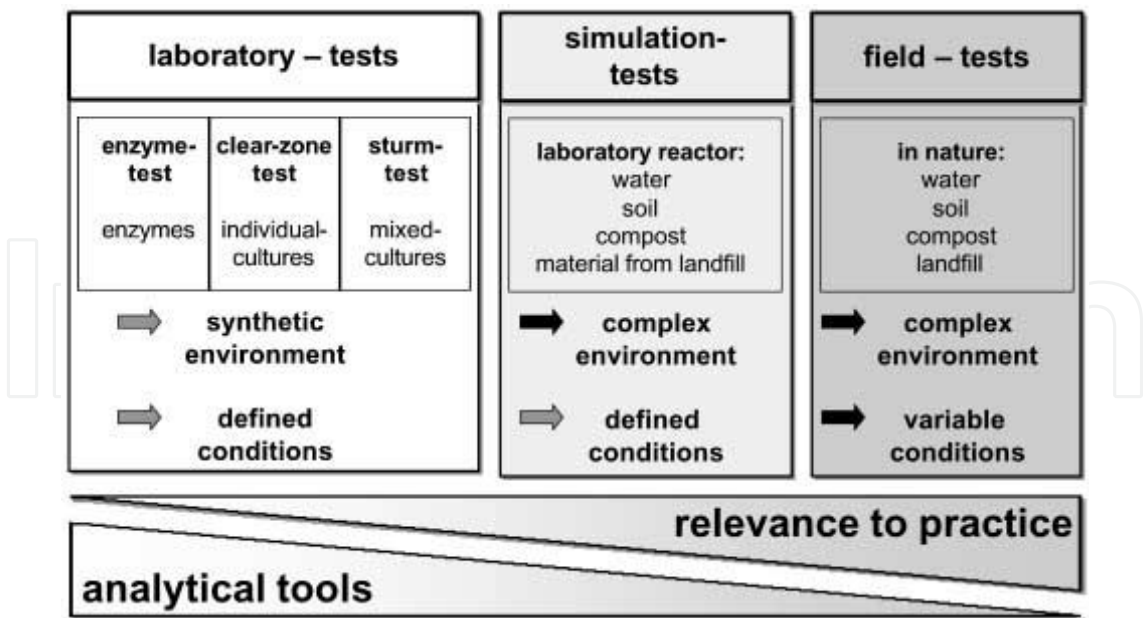


Figure 17. Schematic overview on tests for biodegradable plastics

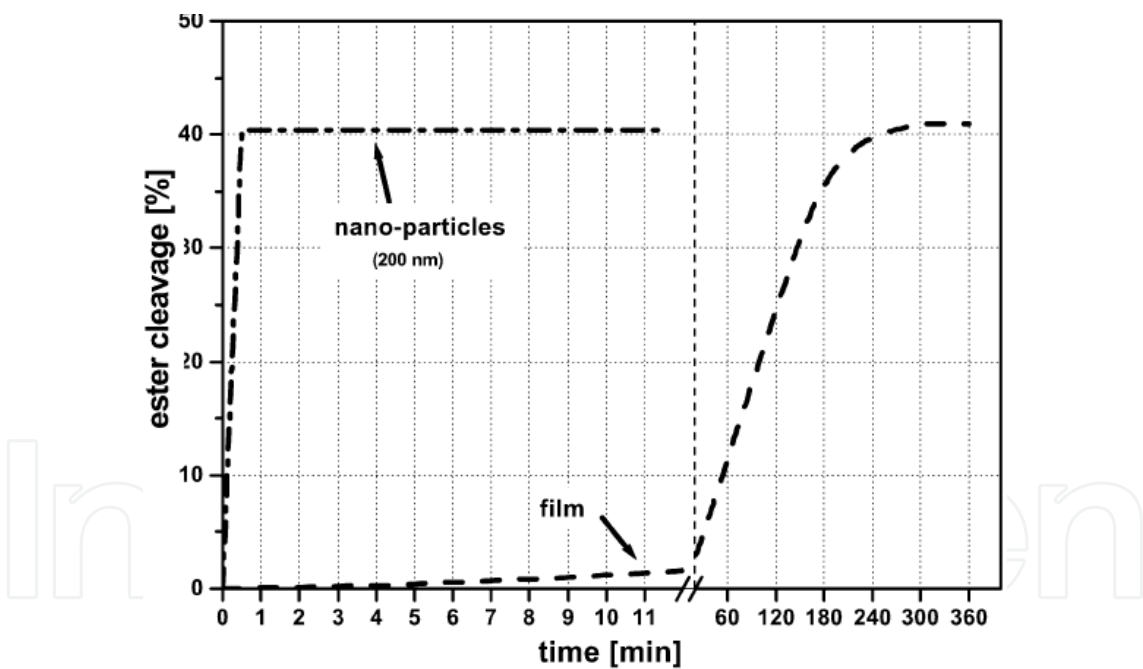


Figure 18. Comparison of the enzymatic degradation of the polyester poly(tetramethylene adipate). With a lipase from *pseudomonas* sp.

In this case, the degradation might take place in compost, seawater, or soil placed in a controlled reactor in a laboratory. However, the environment is still close to the field test situation; the external parameters such as temperature or pH or humidity, etc., can be controlled and adjusted; also the analytical tools available are better than would be used for some

important tests such as field tests, for example, for analysis of residues and intermediates and determination of  $O_2$  consumption or  $CO_2$  evolution.

Important tests include the soil burial test [35], controlled composting test [36-38], test simulating landfills [25, 39], and aqueous aquarium tests [40].

Occasionally, nutrients are added to increase the microbial activity and accelerate degradation that results in reduction of the time taken to conduct the tests.

Tests which are the most reproducible biodegradation tests are the laboratory tests, in which defined media are used and immunized with a mixed microbial population (from waste water) or individual microbial strains that may have been screened especially for a special polymer.

In the abovementioned tests, which may be optimized for the particularly used microorganisms' activity, polymers often show higher degradation rate than natural conditions.

During studying the basic mechanisms of polymer biodegradation, higher degradation rate can be considered as an advantage itself, but in laboratory tests, it is only possible to obtain limited conclusions on the absolute degradation rate of plastics in a natural environment. However, these tests are used to a great extent for many systematic investigations. Attempting to use more controlled and reproducible degradation tests involves using of systems where only those extracellular enzymes are present. These enzymes are used to depolymerize a particular group of polymers. This method, compared to weight loss measurements, cannot be used to prove biodegradation in terms of metabolism by a microorganism, but the system is valuable when used a lipase from *Pseudomonas* sp. for a polymer film and polymer nanoparticles at 40 °C and pH 7. Figure 18 shows an enzymatic degradation of a polyester poly(tetramethylene adipate) with a lipase. In the mentioned test, degradation is expressed as percentage of cleaved ester bonds. The highest ester cleavage of about 40 % results from the dissolution of low-molecular-weight ester groups that are not accessible to attack by the lipase [16, 41].

## 8.2. Aerobic biodegradation testing

This test method estimates the compostability of a plastic sample by measuring the amount of carbon dioxide developed over time and the degree of disintegration of the plastic at the outcome.

Samples and mature compost are mixed and tested for a period of six months (according to AS ISO 14855).

According to test method, the compost-sample mix is contained in 3 L glass jars that are called bioreactors and heated up to  $58 \pm 2$  °C inside a water bath. The mentioned bioreactors which are aerated continuously and have their contents mixed routinely are hydrated to maintain a favorable composting environment. All samples are assessed in triplicate against cellulose powder. For passing the biodegradation test, the sample must produce enough  $CO_2$  to theoretically degrade by more than 90 % w/w in total (or percentage degradation normalized relative to the degradation of the positive reference) in a period of six months. Figure 19 shows apparatus for aerobic biodegradation testing.



**Figure 19.** Aerobic biodegradation testing

#### *8.2.1. Disintegration testing*

The disintegration test is a pilot-scale aerobic composting test. In this test, an industrial composting process is simulated in a 200 Liter insulated composting bin. The compost is consisted of organic waste that should cause self-heating during its juvenile stages which is similar to full-scale composting process. Temperature of the compost, composition of exhaust gas, and pH and moisture are monitored routinely until the test is terminated at the end of 12 weeks. The obtained results must satisfy the validation requirements mentioned in a standard test method. Plastic fragmentation in an aerobic composting environment according to AS ISO is shown in Figure 20.

The bin's contents are turned manually at certain time intervals to maintain a uniform test environment. The test specimens can be visually evaluated during the test. At the end of 12 weeks, the remaining specimen fragments are retrieved, sized, and weighed, relative to the initial sample weight. By the test, degree of disintegration achieved can be determined. To pass disintegration testing, the sample must disintegrate or physically break down to a fragment size less than 2 mm, more than 90 % w/w after 12 weeks. All samples are tested in duplicate.



**Figure 20.** Disintegration barrels used to assess plastic fragmentation in an aerobic composting environment according to AS ISO



**Figure 21.** Typical growth seen in radish, seedlings bean during 14-day higher plant





**Figure 22.** Photo of an earthworm ecotoxicity test setup ecotoxicity testing mung

## 9. Regulation and voluntary standards

In the USA, two guidelines named EPA Class A and B were developed to manage the processing and beneficial reuse of sludge or mud, also called biosolids, following the US EPA ban of ocean dumping. Now, in 26 American states, composts are required to be processed to control for vector and pathogen according to these federal protocols, even though the application to non-sludge materials has not been tested scientifically. As an example, green waste composts at higher rates than sludge compost were used. UK guidelines regarding compost quality also exist which is common in Canadian, Australian, and the various European states. Some compost manufacturers participate in a testing program in the USA called the US Composting Council (USCC) that is offered by a private lobbying organization. In order to promote composting of disposable diapers, the USCC was established in 1991 by Procter & Gamble, following state forces to ban diapers in landfills, which caused a national uproar. Since composting diapers was not proven scientifically to be possible, ultimately the idea was not considered as a good idea. Therefore, composting emphasized to recycle organic wastes that were previously destined for landfills. In America, there are no legal quality standards, but a seal called “Seal of Testing Assurance” (also called “STA”) has been sold by the USCC. By paying a high cost, the applicant may use the USCC logo on products, agreeing to volunteer to customers a current laboratory analysis that includes parameters such as respiration rate, nutrients, pH, salt content, and limited other indicators. However that the STA program is not ISO approved, and STA is a financially beneficial activity for the private USCC, which is an organization that discloses its books earned and benefits \$65, 000 from STA fees in 2009. Existence some argue about the STA program means that EPA or USDA does not regulate composts. Tables 4 and 5 show titles of some important standards and definitions used in correlation with biodegradable plastics, respectively.

Coexistence of both biotic and nonbiotic processes, polymer degradation mechanism could also be referred to environmental degradation not only to environmental factors influence the polymer to be degraded, but they also have a influence on the activity of the different micro-organisms and microbial population. Factors such as humidity, temperature, salinity, pH, the



absence or presence of oxygen, and supply of different nutrients are important effects on the microbial degradation of polymers and should be kept in mind when the biodegradability of plastics is tested. A standard evaluation of biodegradable polymers should always be based on definitions and what biodegradation with regard to polymers actually means. International and national standardization organizations have published several different definitions.

Organization	Number	Title of the standard
ASTM	<b>D5209-92</b>	Standard test method for determining the aerobic biodegradation of plastic materials in the presence of municipal sewage sludge
ASTM	<b>D5210-92</b>	Standard test method for determining the anaerobic biodegradation of plastic materials in the presence of municipal sewage sludge
ASTM	<b>D5247-92</b>	Standard test method for determining the aerobic biodegradability of degradable plastics by specific microorganisms
ASTM	<b>D5271-93</b>	Standard test method for determining the aerobic biodegradation of plastic materials in an activated-sludge-wastewater-treatment system
ASTM	<b>D5338-98e1</b>	Standard test method for determining aerobic biodegradation of plastic materials under controlled composting conditions
ASTM	<b>D5511-94</b>	Standard test method for determining anaerobic biodegradation of plastic materials under high solids anaerobic-digestion conditions
ASTM	<b>D5525-94a</b>	Standard practice for exposing plastics to a simulated active landfill environment
ASTM	<b>D5526-94</b>	Standard test method for determining anaerobic biodegradation of plastic materials under accelerated landfill conditions
ASTM	<b>D5951-96</b>	Standard practice for preparing residual solids obtained after biodegradability standard methods for plastics in solid waste for toxicity and compost quality testing
ASTM	<b>D6002-96</b>	Standard guide for assessing the compostability of environmentally degradable plastics
ASTM	<b>D6003-96</b>	Standard test method for determining weight loss from plastic materials exposed to simulated municipal solid waste (MSW) aerobic compost environment
ASTM	<b>D6094-97</b>	Standard guide to assess the compostability of environmentally degradable non woven fabrics
ASTM	<b>D6340-98</b>	Standard test method for determining aerobic biodegradation of radiolabeled plastic materials in a aqueous or compost environment
ASTM	<b>D6400-99</b>	Standard specification for compostable plastics
ISO	<b>14851:1999</b>	Determination of the Ultimate Aerobic Biodegradability of Plastic Materials in an Aqueous Medium - Method by measuring the Oxygen Demand in a Closed Respirometer
ISO	<b>14852:1999</b>	Determination of the Ultimate Aerobic Biodegradability of plastic materials in an Aqueous Medium - Method by Analysis of evolved Carbon Dioxide
ISO	<b>14855:1999</b>	Determination of the Ultimate Aerobic Biodegradability and Disintegration of plastic materials Under Controlled Composting Conditions - Method by Analysis of evolved Carbon Dioxide
CEN	<b>EN 13432</b>	Requirements for packaging recoverable through composting and biodegradation -Test scheme and evaluation criteria for the final acceptance of packaging

**Table 4.** Titles of some important standards

DIN FNK 103.2	<p><u>Biodegradable plastics</u><sup>1)</sup></p> <p>A plastic material is called biodegradable if all its organic compounds undergo a complete biodegradation process. Environmental conditions and rates of biodegradation are to be determined by standardized test methods.</p> <p><u>Biodegradation</u><sup>3)</sup></p> <p>Biodegradation is a process, caused by biological activity, which leads under change of the chemical structure to naturally occurring metabolic products.</p>
ASTM sub-committee D20-96	<p><u>Biodegradable plastics</u><sup>1)</sup></p> <p>A degradable plastic in which the degradation results from the action of naturally occurring microorganisms such as bacteria, fungi and algae.</p>
Japanese Bio-degradable Plastics Society	<p><u>Biodegradable plastics</u><sup>1)</sup></p> <p>Polymeric materials which are changed into lower molecular weight compounds where at least one step in the degradation process is through metabolism in the presence of naturally occurring organisms.</p>
ISO 472	<p><u>Biodegradable plastics</u><sup>1)</sup></p> <p>A plastic designed to undergo a significant change in its chemical structure under specific environmental conditions resulting in a loss of some properties that may vary as measured by standard test methods appropriate to the plastic and the application in a period of time that determines its classification. The change in the chemical structure results from the action of naturally occurring microorganisms.</p>
CEN	<p><u>Biodegradable plastics</u><sup>1)</sup></p> <p>A degradable material in which the degradation results from the action of microorganisms and ultimately the material is converted to water, carbon dioxide and/or methane and a new cell biomass.</p> <p><u>Biodegradation</u><sup>2)</sup></p> <p>Biodegradation is a degradation caused by biological activity, especially by enzymatic action, leading to a significant change in the chemical structure of a material</p> <p><u>Inherent biodegradability</u><sup>2)</sup></p> <p>The potential of a material to be biodegraded, established under laboratory conditions.</p> <p><u>Ultimate biodegradability</u><sup>2)</sup></p> <p>The breakdown of an organic chemical compound by microorganisms in the presence of oxygen to biodegradability carbon dioxide, water and mineral salts of any other elements present (mineralization) and new biomass or in the absence of oxygen to carbon dioxide, methane, mineral salts and new biomass.</p> <p><u>Compostability</u><sup>2)</sup></p> <p>Compostability is a property of a packaging to be biodegraded in a composting process. To claim compostability it must have been demonstrated that a packaging can be</p> <p>biodegraded in a composting system as can be shown by standard methods. The end-product must meet the relevant compost quality criteria.</p>

<sup>1)</sup> Pagga (1998); <sup>2)</sup> Calmon-Decriaud et al. (1998); <sup>3)</sup> DIN V 94900 (1998)

**Table 5.** Definitions used in correlation with biodegradable plastics



9.1. Testing methods

In order to determine biological action on man-made materials, test methods have been available for quite a long time for different classes of materials. Recently, the evaluation of the degradability of chemicals in the environment, specifically in waste water, as an important aspect of the ecological impact of a compound has become very significant when efforts are being made to present to the marketplace a new chemical product. As a result, numerous standard tests for different environments have been developed using various analytical methods [34]. Table 6 shows an overview of some international standards in this area. In order to evaluate the influence of microorganisms on polymer, test methods have been initiated even before biodegradable plastics were first developed. While conventional plastics are relatively resistant against environmental influences, at some point, microorganisms can attack the plastics to a certain extent and create unwanted changes in the material properties, e.g., in the color or in mechanical properties such as flexibility or mechanical strength [35].

ASTM G21-96	Standard practice for determining resistance of synthetic polymer materials to fungi
ASTM G29-96	Standard practice for determining algal resistance of plastic films
DIN IEC 60068–2-10-1991	Elektrotechnik; Grundlegende Umweltprüfverfahren; Prüfung J und Leitfaden: Schimmelwachstum; (Identisch mit IEC 60068–2-10: 1988)
EN ISO 846–1997	Plastics – Evaluation of the action of microorganisms
IEC 60068–2-10-1988	Elektrotechnik; Grundlegende Umweltprüfverfahren; Prüfung J: Schimmelwachstum
ISO 846–1997	Plastics: Determination of behaviour under the action of fungi and bacteria. Evaluation by visual examination or measurement of changes in mass or physical properties

Table 6. Standard test methods for biocorrosion phenomena on plastics

While this wide range of degradation tests was already available, it was necessary to develop special test methods when working with biodegradable plastics.

As it could be understood from the listed standards in Table 6, special aspects of plastics materials could not be considered. Regarding the biocorrosion phenomena, the subject of whether or not that a plastic is degraded is not the concern, but it is important that whether minor chemical changes in the polymers (e.g., extraction of plasticizer, oxidation, etc.) caused to changes in the material properties. Evaluation of low-molecular-weight substances was developed specifically for biodegradable plastics during the past decade or so (Itvaara and Vikman, 1996). However, they have been tried to adapt to specific environments in which biodegradable plastics might be degraded. Furthermore, these methods consider the fact that plastics have a complex structure and are degraded by a heterogeneous surface mechanism mainly. Table 7 shows standard test methods used in evaluation of chemicals biodegradability.

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OECD Guidelines (OECD, 1993)

<u>301</u>	<u>Ready Biodegradability</u>
301 A-1992	DOC Die-Away Test
301 B-1992	CO <sub>2</sub> Evolution Test
301 C-1992	Modified MITI Test
301 D-1992	Closed Bottle Test
301 E-1992	Modified OECD Screening Test
301 F-1992	Manometric Respirometry Test
<u>302</u>	<u>Inherent Biodegradability</u>
302 A-1981	Modified SCAS Test
302 B-1992	Zahn-Wellens Test
302 C-1981	Modified MITI Test
302 D B draft (2002)	Inherent biodegradability-concave test
<u>303</u>	<u>Simulation Test</u>
303 A-2001	Aerobic Sewage Treatment: Activated Sludge Units
<u>304</u>	<u>Biodegradation in Soil</u>
304 A-1981	Inherent Biodegradability in Soil
306-1992	Biodegradability in Seawater
307 B draft (2000)	Aerobic and anaerobic transformation in soil
308 B draft (2000)	Aerobic and anaerobic transformation in aquatic sediment systems
309 B draft (2001)	Aerobic mineralisation in surface water-simulation biodegradation test
301 B draft (2002)	Ready biodegradability B CO <sub>2</sub> in sealed vessels (Headspace test)
311 B draft (2002)	Ready anaerobic biodegradability: Gas production from diluted anaerobic sewage sludge
ISO 7827-1994	Water quality – Evaluation in an aqueous medium of the “ultimate” aerobic biodegradability of organic compounds – Method by analysis of dissolved organic carbon (DOC)
ISO 9439-1999	Water quality – Evaluation in an aqueous medium of the “ultimate” aerobic biodegradability of organic compounds – Method by analysis of released carbon dioxide
ISO 9408-1999	Water quality – Evaluation in an aqueous medium of the “ultimate” aerobic biodegradability of organic compounds – Method by determining the oxygen demand in a closed respirometer
ISO 9887-1992	Water quality – Evaluation of the aerobic biodegradability of organic compounds in an aqueous medium – Semi-continuous activated sludge method (SCAS)
ISO 9888 B 1999	Water quality – Evaluation of the aerobic biodegradability of organic compounds in an aqueous medium – Static test (Zahn-Wellens method)
ISO 10634-1995	Water quality – Guidance for the preparation and treatment of poorly water-soluble organic compounds for the subsequent evaluation of their biodegradability in an aqueous medium -Static test (Zahn- Wellens method)
ISO 10707-1994	Water quality – Evaluation in an aqueous medium of the ultimate aerobic biodegradability of organic compounds – Method by analysis of biochemical oxygen demand (closed bottle test)
ISO 10708-1997	Water quality – Evaluation in an aqueous medium of the ultimate aerobic biodegradability of organic compounds – Method by determining the biochemical oxygen demand in a two-phase closed – bottle test
ISO 11733-1995	Water quality – Evaluation of the elimination and the biodegradability of organic compounds in an aqueous medium. Activated sludge simulation test
ISO 11734-1995	Water quality – Evaluation of the ultimate anaerobic biodegradability of organic compounds in digested sludge. Method by measurement of the biogas production



ISO/FDIS 14592–1	Water quality – Evaluation of the aerobic biodegradability of organic compounds at low concentrations – Part 1: Shake-flask batch test with surface water or surface water/sediment suspension
ISO/DIS 14592–2	Water quality – Evaluation of the aerobic biodegradability of organic compounds at low concentrations – Part 2: Continuous flow river model with attached biomass
ISO 14593–1999	Water quality – Evaluation of ultimate aerobic biodegradability of organic compounds in aqueous medium – Method by analysis of inorganic carbon in sealed vessels (CO <sub>2</sub> headspace test)
ISO/TR 15462–1997	Water quality – Selection of tests for biodegradability
ISO 16221 B 2001	Water quality – Guidance for determination of biodegradability in the marine environment
EN ISO 7827–1995	Water quality – Evaluation in an aqueous medium of the “ultimate” aerobic biodegradability of organic compounds – Method by analysis of dissolved organic carbon (DOC)
EN ISO 9439–2000	Water quality – Evaluation of ultimate aerobic biodegradability of organic compounds in aqueous medium – Carbon dioxide evolution test
EN ISO 9408–1999	Water quality – Evaluation of ultimate aerobic biodegradability of organic compounds in aqueous medium by determination of oxygen demand in a closed respirometer
EN ISO 9887–1994	Water quality – Evaluation of the aerobic biodegradability of organic compounds in an aqueous medium – Semi-continuous activated sludge method (SCAS)
EN ISO 9888–1999	Water quality – Evaluation of ultimate aerobic biodegradability of organic compounds in aqueous medium – Static test (Zahn-Wellens method)
EN ISO 10634–1995	Water quality – Guidance for the preparation and treatment of poorly water-soluble organic compounds for the subsequent evaluation of their biodegradability in an aqueous medium
EN ISO 10707–1997	Water quality – Evaluation in an aqueous medium of the “ultimate” aerobic biodegradability of organic compounds – Method by analysis of biochemical oxygen demand (closed bottle test)
EN ISO 11733–1998	Water quality – Evaluation of the elimination and biodegradability of organic compounds in an aqueous medium – Activated sludge simulation test
EN ISO 11734–1998	Water quality – Evaluation of the “ultimate”; anaerobic biodegradability of organic compounds in digested sludge – Method by measurement of the biogas production
<b>Inhibition tests</b>	
ISO 8192 B 1986	Water quality – Test for inhibition of oxygen consumption by activated sludge
ISO 9509 B 1989	Water quality – Method for assessing the inhibition of nitrification of activated sludge microorganisms by chemicals and waste waters
ISO 10712 B 1995	Water quality – <i>Pseudomonas putida</i> growth inhibition test ( <i>Pseudomonas</i> cell multiplication inhibition test)
ISO 11348 Part 1, 2, 3 – 1998	Water quality – Determination of the inhibitory effect of water samples and the light emission of <i>Vibrio fischeri</i> (Luminescent bacteria test)
EN ISO 8192 – 1995	Water quality – Test for inhibition of oxygen consumption by activated sludge
EN ISO 9509 – 1995	Water quality – Method for assessing the inhibition of nitrification of activated sludge microorganisms by chemicals and waste water
EN ISO 10712 – 1996	Water quality – <i>Pseudomonas putida</i> growth inhibition test ( <i>Pseudomonas</i> cell multiplication inhibition test)
EN ISO 11348 Teil 1, 2, 3 – 1998	Water quality – Determination of the inhibitory effect of water samples on the light emission of <i>Vibrio fischeri</i> (Luminescent bacteria test)

Table 7. Standard test methods for biodegradability of chemicals

## 10. Conclusion

Various contaminants into natural environments that have resulted in instability, disorder, harm, or discomfort to an ecosystem is known as pollution and includes different forms such



as air, soil, water, sound, etc. Reducing the amount of solid waste in landfills and the addition of nutrient-rich organic matter are the help that composting gives to the Earth. Polymers, composites and nanocomposites made of major chemicals that are highly toxic and pose a serious threat to all living species on the planet Earth. The earth cannot digest these materials and leads to serious damage to the environment during their production and disposal process.

Composting of composites and nanocomposites based on bio-based polymers used in various applications is an important solution to reduce the amount of solid waste in landfills or any other polluted area.

Which way must be chosen to save our planet: the management of packaging and packaging waste's, use of combustible packaging waste in order to generate energy by completely burning the substance or changing them to compost?

Composts improve soil quality, assist plant growth, increase water holding capacity, store carbon in the soil, and reduce the need for chemical fertilizer and pesticides. "Compostable polymer" undergoes degradation by biological processes during composting to yield CO<sub>2</sub>, water, inorganic compounds, and biomass at a rate consistent with other known compostable materials and leaves no visible, distinguishable, or toxic residue.

Nanoparticles can have other functions when added to a polymer, such as increasing of tensile modulus, antimicrobial activity, enzyme immobilization, biosensing, etc. An outline of the main kinds of nanoparticles which have been studied for use in food packaging systems is given, as well as their effects and application.

Testing degradation phenomena of compostable polymers and nanocomposites in the environment has an overall problem regarding the type of tests to be implemented and the results that can be obtained. The guiding principle is that tests can be subdivided into three categories: field tests, simulation tests, and laboratory tests. Important tests include the soil burial test, controlled composting test, test simulating landfills, and aqueous aquarium tests.

There are some regulation and voluntary standards such as EPA Class A and B tests in USA, UK guidelines regarding compost quality also exist which is common in European Union, Canadian, Australian in the world.

"Let us save our environment from polymer pollution to make it a better environment for the future" To do so, compostable polymers and nanocomposites are a big chance for planet Earth.

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