Biodegradable Plastics: Promise, Pitfalls and the Road Ahead

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Introduction:

Plastic is one of the most useful inventions of the last century. It is light, cheap, strong and endlessly adaptable. It is also one of the most stubborn. A polythene bag discarded today may remain in the environment for hundreds of years, breaking into ever-smaller fragments called microplastics that now turn up in rivers, soil, drinking water, seafood and even human blood.

Globally, the world produces well over 350 million tonnes of plastic every year, and only a small fraction is recycled. The rest is landfilled, burned or leaks into the environment. Little wonder that people are looking for a material that does the job of plastic but disappears when the job is done. That search has led to **biodegradable plastics**.

The scale is easy to underestimate. One widely cited analysis estimates that humans had made about 8.3 billion tonnes of plastic by 2015. Of the roughly 6.3 billion tonnes that had become waste, only about 9 per cent was recycled and 12 per cent incinerated; the remaining 79 per cent sat in landfills or the natural environment (Geyer et al., 2017). A separate estimate put the plastic entering the oceans from land at 4.8 to 12.7 million tonnes in 2010 alone (Jambeck et al., 2015).

Bioplastics, biodegradable and bio-based together, are still a sliver of this picture. Industry data put their global production capacity at about 2.2 million tonnes in 2022, roughly half of one per cent of all plastic made (European Bioplastics, 2022). The promise is large; the present footprint is small.

Defining Biodegradable, Biobased and Compostable Plastics

A biodegradable plastic is one that microorganisms such as bacteria and fungi can break down into water, carbon dioxide (or methane) and biomass. Two terms are often confused:

- **Biobased plastic** is made from renewable raw materials such as corn, sugarcane, cassava or algae. Being biobased says nothing about whether it breaks down.

- **Biodegradable plastic** is defined by what happens at the end of its life, not by what it is made from. Some biodegradable plastics are made from petroleum, and some biobased plastics are not biodegradable at all.

Then there is **compostable plastic**, a stricter category. It must break down within a set time under defined composting conditions, leaving no toxic residue. Standards such as EN 13432 in Europe, ASTM D6400 in the United States and IS/ISO 17088 in India set these requirements.

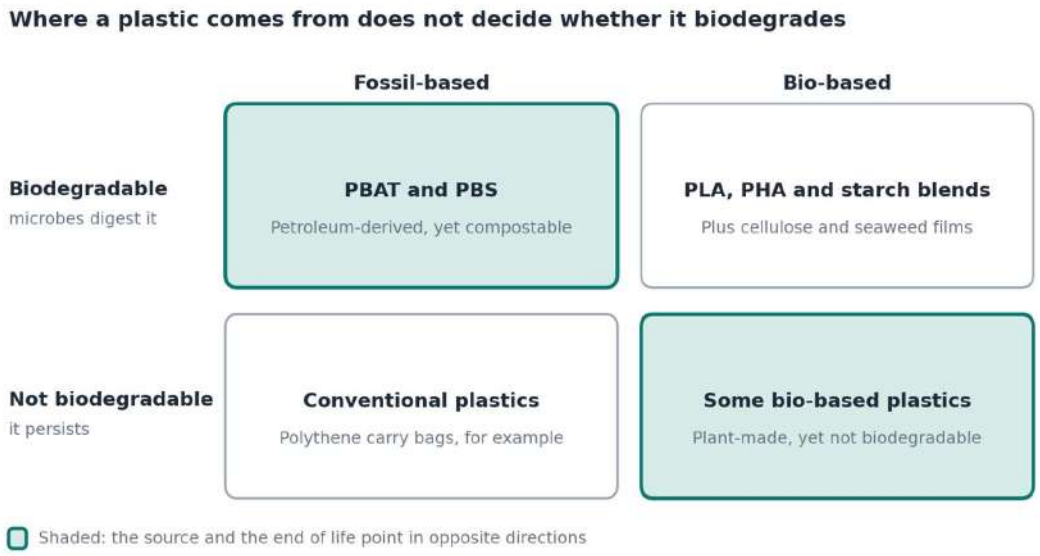


Figure 1. Source and fate are independent. PBAT and PBS are petroleum-derived yet biodegradable, while some bio-based plastics never biodegrade (Haider et al., 2019; Rujnić-Sokele and Pilipović, 2017).

Main Types of Biodegradable Plastics

PLA (polylactic acid) is made by fermenting sugars from corn, sugarcane or tapioca into lactic acid, which is then linked into long chains. It is clear, rigid and widely used for cups, cutlery, food containers and 3D-printing filament.

PHA (polyhydroxyalkanoates) are produced directly by bacteria, which store them as energy reserves, much like plants store starch. PHAs are among the few plastics that degrade even in soil and seawater, but they remain expensive to make.

Starch blends combine thermoplastic starch with other biodegradable polymers. They are common in carry bags, mulch films and packaging.

PBAT and PBS are flexible, petroleum-derived but biodegradable polyesters, often blended with PLA or starch to make soft films and bags.

Cellulose, chitosan and seaweed-based films are newer entrants. Made from wood pulp, crustacean shells and algae, they are edible or highly degradable and are being tested as wrappers and coatings.

Table 1. The main biodegradable plastics compared (compiled from Haider et al., 2019; Rosenboom et al., 2022; Narancic et al., 2018).

Plastic	Made from	Main strengths	Where it degrades	Common uses
PLA	Fermented sugars from corn, sugarcane or tapioca	Clear, rigid, easy to process	Mainly industrial composting; slow in soil and sea	Cups, cutlery, food containers
PHA	Bacterial fermentation	Among the few that degrade in soil and water	Compost, soil, fresh water and sea	Films, packaging, medical items
Starch blends	Thermoplastic starch plus other biodegradable polymers	Low cost, soft	Compost and soil; varies with the blend	Carry bags, mulch films
PBAT and PBS	Petroleum-derived monomers	Flexible, forms thin films	Compost; slower in soil	Soft films and bags, blends with PLA or starch
Cellulose films	Wood pulp	Renewable, easily degraded	Compost and soil	Wrappers, coatings

How Biodegradation Works

Biodegradation is a relay. First, heat, moisture and sometimes light make the polymer chains react with water (hydrolysis) or oxygen, so long chains split into shorter pieces. Next, enzymes released by bacteria and fungi cut these fragments into small molecules the microbes can absorb. Finally, the microbes use those molecules as food, a step called mineralisation. With oxygen, the carbon ends up as carbon dioxide, water and new microbial biomass; without oxygen, as in a sealed landfill or digester, part of it becomes methane (Haider et al., 2019; Rosenboom et al., 2022).

Temperature, moisture, oxygen and the local microbial community decide how fast the relay runs, together with the plastic's own chemistry, such as how crystalline it is and how long its chains are. PLA is the textbook case. It stays glassy and slow to hydrolyse until it is warmed above roughly 55 to 60 °C, which is why an industrial composter can finish it within months while a garden heap or the sea barely touches it (Rosenboom et al., 2022; Narancic et al., 2018). A plastic that vanishes in one environment can persist in another, so a label that does not name the environment says little.

Current Applications

Biodegradable plastics are not a distant dream. You can find them in:

- **Compostable bags** for kitchen waste, which make collection of food scraps cleaner and easier.

- **Agricultural mulch films**, which can be ploughed into the soil after the season instead of being pulled up and discarded, saving labour and reducing plastic left in fields.
- **Food-service items** such as cups, plates and straws, particularly where the packaging is soiled by food and hard to recycle.
- **Medical uses** such as dissolving stitches and controlled-release capsules.

In many countries, including India, bans on identified single-use plastic items have pushed manufacturers and consumers to look for alternatives, giving the sector a strong push.

India's Plastic Waste Management (Amendment) Rules, 2021 prohibited a list of identified single-use plastic items from 1 July 2022 (MoEFCC, 2021), and under the country's plastic waste rules a product sold as compostable needs certification from the Central Pollution Control Board. That combination of bans and certification is a strong signal to the packaging industry.

In farming, biodegradable mulch film can spare growers the labour of lifting and disposing of plastic after harvest, although its performance depends on the film type, soil temperature and moisture, and the fate of the fragments left in soil is still being studied (Haider et al., 2019).

Field evidence shows why the label alone is not enough. In a three-year experiment, researchers left several types of carrier bag in open air, buried in soil and immersed in the sea. The compostable bag had disappeared from the marine setting within three months, but the bag sold as biodegradable could still carry a full load of shopping after 27 months in soil, and the conventional and oxo-degradable bags were still present after three years (Napper and Thompson, 2019).

Limitations and Common Misconceptions

Here is where the story gets complicated.

1. Conditions matter. Many biodegradable plastics, PLA especially, need the sustained heat of an industrial composting facility, typically around 55 to 60 degrees Celsius. In a backyard compost heap, a landfill or the open sea, they may degrade very slowly or hardly at all.

2. Infrastructure is thin. A compostable cup is only useful if it reaches a facility that can compost it. Without separate collection and composting systems, it ends up in landfill or mixed with ordinary plastic, where it can even contaminate recycling streams.

3. "Oxo-degradable" is not the same thing. Some plastics are marketed as degradable because additives make them crumble faster. They fragment into microplastics rather than truly

biodegrading, which is why the European Union banned them and why scientists regard them with suspicion.

4. Greenwashing is real. Labels such as "eco-friendly" or "green" without a recognised certification can mislead shoppers. Always look for a standard and a certifying body, not just a leaf logo.

5. Production has a footprint too. Growing crops for bioplastics uses land, water and fertiliser. If the demand grows very large, it could compete with food production, which is why researchers are looking at agricultural residues, food waste and non-food crops as feedstock.

6. They can still become litter. A biodegradable bag thrown on the roadside is still litter, and it may take much longer to vanish than the label suggests. Biodegradability should never become an excuse to be careless.

Life-Cycle Considerations

Biodegradable does not automatically mean low impact. Life-cycle assessments count the energy, water, land and emissions of a product from raw material to disposal, and they show a mixed picture. Bio-based plastics can lower greenhouse-gas emissions compared with fossil plastics, but growing the feedstock may raise fertiliser use, water demand, acidification and land use. Which option wins depends on the product and on which impact is being counted (Lambert and Wagner, 2017).

How a plastic is discarded matters as much as how it is made. A comparison of a range of biodegradable plastics across industrial composting, home composting, soil, anaerobic digestion and seawater found that results differed widely between environments. The authors concluded that these plastics widen the end-of-life options without being a cure-all for plastic pollution (Narancic et al., 2018). The sensible reading is to use them where they replace items that are hard to collect or clean, such as food-soiled packaging, and not as a licence to use more.

Future Directions

Science is working on these weaknesses. Researchers are engineering bacteria to produce cheaper PHAs, designing enzymes that can chew through plastics in hours rather than years, and making bioplastics from banana peels, rice husk, sugarcane bagasse, seaweed and even fish waste. Others are building plastics with built-in "time-release" enzymes that begin degrading only after disposal. Meanwhile, better labelling rules and investment in composting infrastructure are starting to close the gap between promise and practice.

Enzymes are another active frontier. Engineered enzymes have broken down PET, a durable plastic used in drink bottles, into its building blocks in about ten hours, pointing to a future where degradation is a controlled recycling step rather than an accident of the environment (Tournier et al., 2020).

Conclusion

Biodegradable plastics are a valuable tool, not a magic wand. Used for the right applications, such as food-soiled packaging, mulch films and short-life items, and paired with proper collection and composting, they can meaningfully cut plastic pollution. But they work best as part of a bigger approach built on reducing waste, reusing materials and recycling what we can.

The real goal is not a world where plastic disappears by itself. It is a world where we stop treating materials as disposable in the first place.

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