

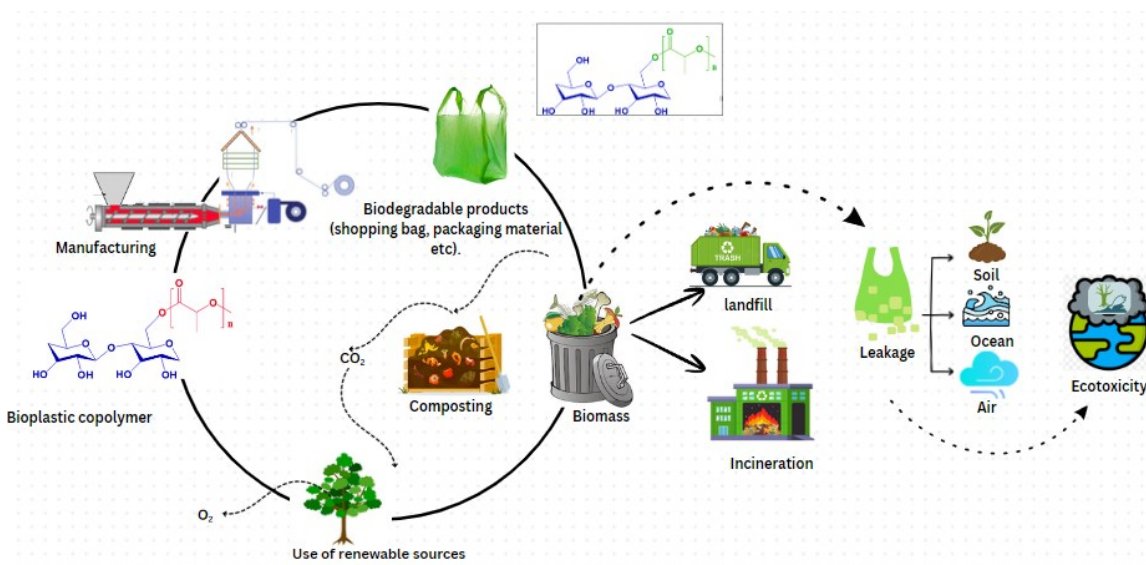
Environmental Fate and Ecotoxicological Impacts of Bioplastics: Degradation Pathways and Emerging Knowledge Gaps

Noshabah Tabassum ^{a,*} It Ee Lee ^{b,c,*} Iqra Safdar ^a Maria Qayyum,^a Amna Bashir ^d Tanzeela Tahir,^a Qamar Wali ^{b,c} and Hammad Khan^e

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GRAPHICAL ABSTRACT



Environmental Fate and Ecotoxicological Impacts of Bioplastics: Degradation Pathways and Emerging Knowledge Gaps

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Plastic waste is one of the most concerning issues for the environment in the world. Many researchers are seeking sustainable solutions by replacing petroleum-based plastic with bio-based plastic. Bioplastic is synthesized from natural resources, and it can degrade in different ecosystems. Therefore, it could serve as alternative to combat the harmful impacts of conventional plastic. This review explores different bio-based polymers such as polylactic acid (PLA), polyhydroxyalkanoates (PHA), polybutylene succinate (PBS), starch blends (SB), and cellulose-based bioplastics (CB). These polymers can be used for many industrial applications, including agriculture, automobiles, textiles, packaging, and medical. To give insight into the procedure of bioplastic manufacture, various processes are analyzed in this review, including the solvent casting technique, extrusion techniques, injection molding, and 3D printing. The products of bioplastics such as micro-nano plastic, monomers, and oligomers released after degradation are critically analyzed and the toxicity of bioplastic on different ecosystems has been discussed. A research gap was also identified, as most toxicological studies of bioplastic do not include the LC₅₀/LD₅₀ threshold.

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Keywords: Toxicity; Biodegradable material; Polymer categories; Applications of bioplastics; Environmental impact; Sustainable materials; Green polymers

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INTRODUCTION

Plastic, a manufactured material derived from polymers, is extensively used because of its strength, reasonable cost, and efficiency. There are two main categories of plastics: bio-based (obtained from biomass raw materials) and oil-based (obtained from petroleum-based substances). Oil-based plastics are one of the most common materials in the present-day world. However, their manufacturing is responsible for environmental problems (Tulamandi *et al.* 2016). Globally, cumulative plastic manufacturing has reached 8300 million tons, with annual growth of 415 million tons each year, while 6300 million tons of plastic build up as waste. Of these, ~883 million tons of plastic are recycled, ~883 million tons are sent for incineration, and ~4542 million tons are set free into the

environment or landfills (Adelaja and Daramola 2022). Based on historical trend analysis, the annual global use of plastic is predicted to rise from 464 million tons in 2020 to approximately 884 million tons by 2050 (Dokl *et al.* 2024).

Contamination from the growth of plastic waste in the environment causes escalating damage to both the ecosystem and human health (Hopewell *et al.* 2009) (Fig. 1).

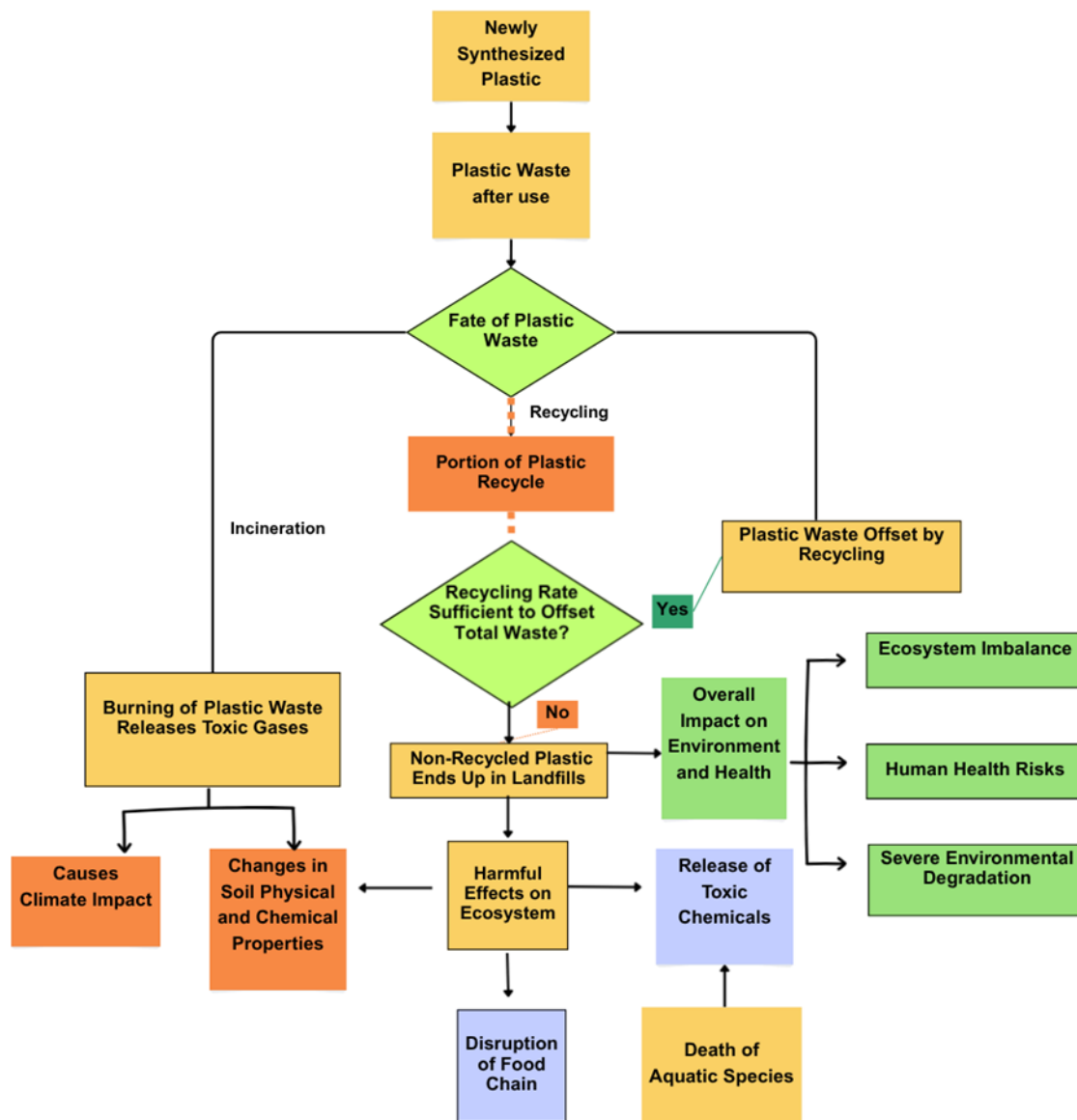


Fig. 1. The environmental impacts of plastic (adapted and modified from Ali *et al.* 2023a)

Recent advances in the research of next generation bioplastic produced from renewable resources have been reviewed by Ehman *et al.* 2026), who outlined the categories of biopolymers along with their potential industrial applications. These types of plastics are also a major source of carbon footprints and growing climate change. Additionally, they can be persistent and dwell in the surroundings for many years due to their non-biodegradable properties. This is the main reason for polluted oceans, landfills, and ecosystems (Wilson 2015). In recent years, bioplastics have risen as a viable option to tackle these environmental or ecological problems created by conventional plastics (Abbott

et al. 2012). Bioplastics are innovative materials, obtained from sources that are renewable materials, including biomass, plant starch, and microbes, with some other combinations. Wood and wood-derived bioresources such as saw dust, wood flour, and pulp industry byproducts also serve as a great biomass source because it contains high quantities of cellulose, hemicellulose, and lignin (Chinthapalli *et al.* 2019). The components are widely explored as raw material, reinforcing agents, and additives for bioplastic manufacturing. These lignocellulosic components help in enhancing the characteristics of bioplastics (Fig. 2).

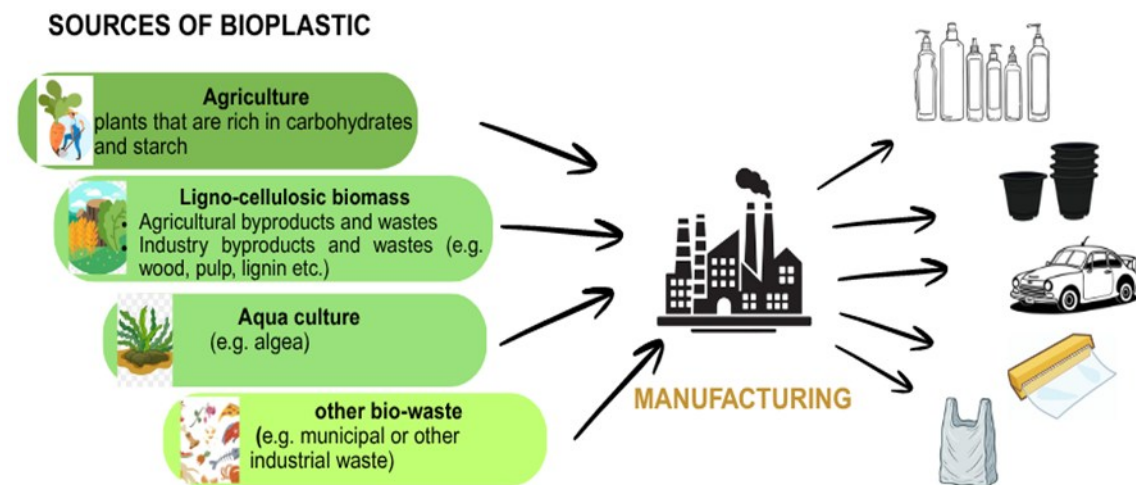


Fig. 2. Major sources of bioplastic production (Jabeen *et al.* 2024, CC BY-NC 4.0)

The growth of bioplastics has created a potential pathway to minimize the need for fossil fuels as well as reduce ecological problems (Rodríguez *et al.* 2020). Biodegradable plastics, with the help of microorganisms, heat, sunlight, and moisture, can break down or decompose naturally into simpler molecules (Chauhan *et al.* 2024). Biodegradable polymers can play a pivotal role in the prevention of plastic waste buildup. Main types of bioplastics are composed of cellulose-, starch-, aliphatic polyester-, lignin-, protein-, and chitin-based polymers. Several studies have assessed the effect of biodegradable and degradable plastics on the composting of green waste and compost quality (Emadian *et al.* 2017). Bio-based non-biodegradable plastics, such as bio-based polyethylene (bio-PE) and bio-based polyethylene terephthalate (bio-PET), are identical to their petroleum-based counterparts even though they are made from biogenic resources (Cui *et al.*, 2023).

Classification helps to clear up common misconceptions around terms such as “biobased” and “biodegradable.” Not all manufactured items with the term “bio” are necessarily sustainable. This significant divergence between biodegradable and non-biodegradable bioplastics accentuates the diversity of materials available and their alignment with specific industrial needs. It also emphasizes how crucial it is that users carefully select bioplastics according to their desired end-of-life (EOL) outcomes and environmental performance. Regardless of the application of single use packaging or long-term products, bioplastics play a progressively crucial role in the transition toward a circular, decarbonized bio-based economy because studies have confirmed that poor disposal of bioplastic can cause formation of microplastic and nano plastic.

The bioplastic production capacity increased from 1.9 million tonnes in 2022 to 2.3 million tonnes in 2025, showing an increasing amount of demand for environmentally friendly solutions. Various types of bioplastics contribute differently to global production.

PLA-based bioplastics hold the largest share, followed by PHA based bioplastics in global bioplastic production (European Bioplastics 2025) (Fig. 3). By observing current trends of the world, bioplastic production capacity by 2030 is forecasted to reach 4.69 million tonnes, expecting a considerable increase from the 2025 market share (Fig. 4).

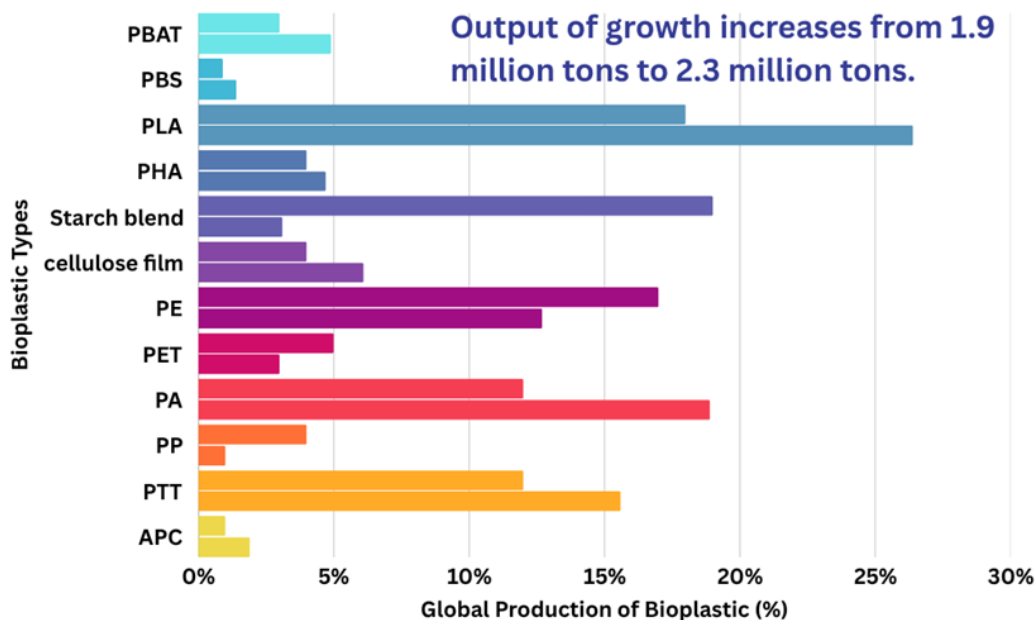


Fig. 3. Global bioplastic production capacity trends based on reported data estimated from 2022 and 2025 (European Bioplastics 2025)

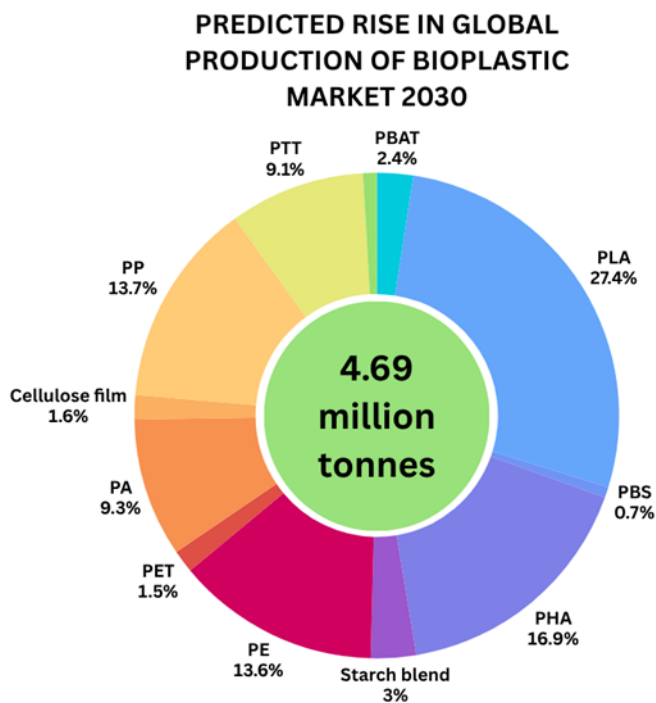


Fig. 4. Predicted global production capacity of bioplastic for 2030 (European Bioplastics 2025)

As global production of bioplastics continues to grow rapidly, it is becoming increasingly important to consider this development within a broader framework of sustainable material design (Arias *et al.* 2018). Merely replacing petroleum-based plastics with bio-based alternatives is not sufficient to achieve true environmental sustainability. A deeper transformation is needed one that reimagines how materials are extracted, used, and eventually returned to natural or industrial ecosystems (Udayakumar *et al.* 2021).

A recent review article gave comprehensive information of biopolymer classifications, bioplastic production method, industrial techniques and their application which give an insight knowledge about bioplastic industries (Ehman *et al.* 2026). In comparison, this research deeply analyzes the bioplastic production techniques its influence in biodegradation behavior, integrates degradation pathway with end-of-life pathway, environmental leakage (system failure of circular bioeconomy), environmental fate, exposure routes, and ecotoxicological impacts, thereby providing comprehensive environmental evaluation of bioplastics. Distinct attention is given to ecotoxicological impacts and potential formation of microplastics and nanoplastics. This research also emphasizes some critical research gaps which were not previously discussed in review articles.

BIOPLASTIC CATEGORIES AND THEIR APPLICATIONS

Bioplastics are categorized into three fundamental divisions based on their composition. However, it is important to emphasize that not all bio-based plastics are biodegradable. These categories include fossil resource-based but biodegradable plastics, biobased biodegradable plastics, and biobased but non-biodegradable plastics. The biodegradability property and source of raw materials are the foundation of categorizing bioplastics. Bioplastics include polysaccharide-based, protein-based, and polyester-based versions, all having different advantages in durability, flexibility, and decomposition, as shown in Table 1.

Table 1. Bioplastic Properties and Applications

Types of Bioplastics Used	Key Features	Application	Reference
Polylactic Acid (PLA)	Biobased, industrially compostable under specific conditions, high crystallinity, processable through traditional methods, and blending with other polymers.	Packaging, active packaging (antimicrobial properties with additives), 3D printing, and medical applications	(Babu <i>et al.</i> 2013)
Polyhydroxy-alkanoates (PHA)	Biodegradable, biobased, high flexibility, good water barrier properties, can replace conventional plastics including PP and PE.	Packaging (films, storage boxes), medical applications, biodegradable alternatives to synthetic plastics	(Samrot <i>et al.</i> 2021)
Bio-Polyethylene	Derived from renewable resources, chemically identical to conventional PE, recyclable but not biodegradable	Packaging films, shopping bags, bottles	(Siracusa & Blanco 2020)

Table 1. Bioplastic Properties and Applications

Types of Bioplastics Used	Key Features	Application	Reference
Bio-Polyethylene Terephthalate	Comparable properties to traditional PET, biobased, non-biodegradable	Soft drink bottles, food containers, textiles	(Siracusa & Blanco 2020)
Polybutylene Succinate (PBS)	Biodegradable, with good mechanical properties	Agricultural films, compostable packaging, and disposable tableware	(Mohamad <i>et al.</i> 2021)

Comparative Analysis of Biopolymer Categories

The radar chart (Fig. 5) describes the comparative performance evaluation of multiple biopolymer categories across seven key factors, each evaluated on a scale of 0 to 10. This illustration reveals the strengths, limitations, and compromises, which helps in determining the suitability of the material for specific applications. The figure demonstrates the diverse patterns of biopolymers (Clarke *et al.* 2024). Every polymer has limitations in performance, revealing that the selection of material depends on the specification of the application. The evaluation shows that the chemically synthesized biopolymers, such as PLA, PHA, PHBV, Bio-PE, and Bio-PET, display elevated scores in mechanical integrity, including thermal stability, tensile strength, barrier properties, as well as processability (García-Chumillas *et al.* 2024). As demonstrated, PLA shows notable mechanical properties, making it a great source for demanding applications. Such performance helps to explain why it is the most produced bioplastic in the world, *i.e.* 910,000 tons per year (Ehman *et al.* 2026). In contrast to natural polymers, its score for biodegradation is low, and its cost efficiency evaluation is between normal and low (Acharjee *et al.* 2024). It shows strong barrier properties and processability, approaching the performance of traditional plastics despite being generated from biobased materials (Liang *et al.* 2024).

Natural polymers, such as starch-, cellulose-, protein-, and chitosan-based materials, score high in biodegradability and cost efficiency, but they are lower in thermal stability, tensile strength, and barrier properties. Starch-based polymers excel in biodegradability and affordability but have limitations in water absorption and barrier performance, while chitosan-based materials achieve better barrier scores with moderate biodegradability (Strnad and Zemljič 2023). Blends and composites, including hybrids and additive-enhanced materials, achieve higher overall scores, particularly in tensile strength and barrier performance (Yang *et al.* 2025). Trade-offs are evident: higher durability and barrier performance in synthetic polymers often come at the expense of biodegradability and cost efficiency, whereas natural polymers are more water sensitive. Optimizing these trade-offs is essential to maximizing performance across all criteria.

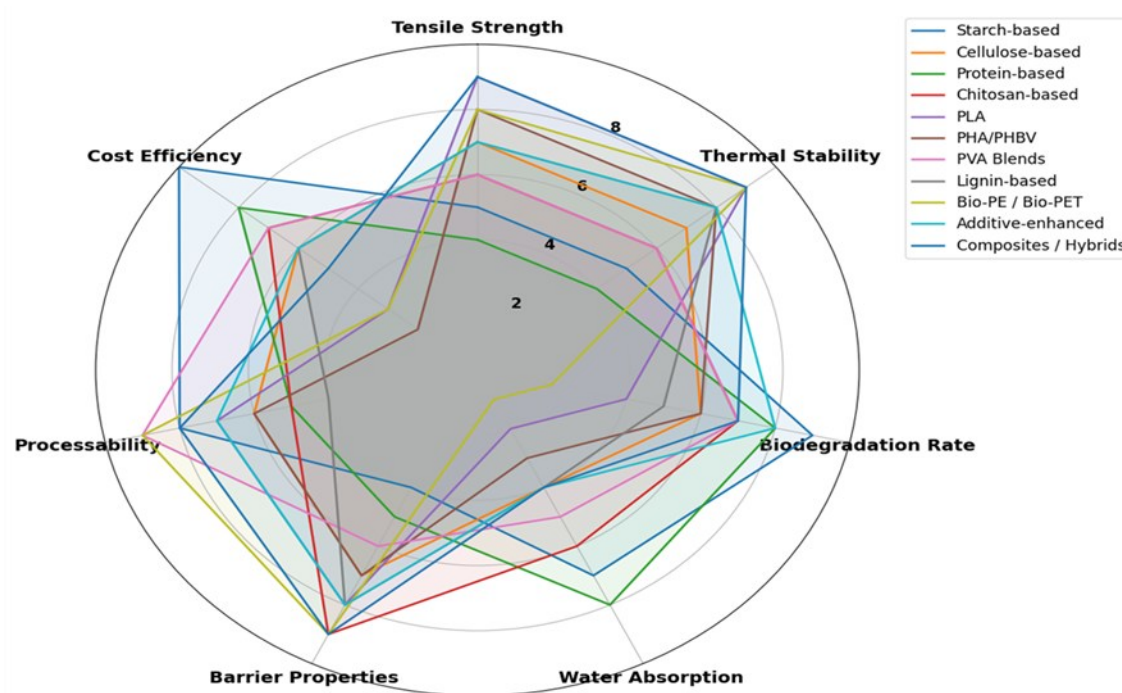


Fig. 5. Comparative properties of biopolymer categories (scale 0-10)

BIOPLASTIC AND CIRCULAR BIOECONMY DESIGN

Bioplastic materials are strongly linked with circular bioeconomy because of their renewable biomass and sustainable biological end of life pathway. The circular bioeconomy concept integrates the bioresources, new technologies, and sustainable consumption practices to reduce waste production and mitigate biodegradation patterns. According to the framework of circular bioeconomy products derived from natural resources are expected to circulate through manufacturing, usage, recycling and reintegration into natural environment. Bioplastic products can only be regarded as circular when their manufacturing, utilization, and end of life management simultaneously lower ecological impacts against traditional plastics. Achieving this need careful assessment of biomass sourcing, energy uptake during production, product longevity and biodegradation behavior (Sokra and Meta 2026).

This approach provides a reliable framework for determining design choices that are both environmentally responsible and functional. It does this by statistically assessing environmental effects at every step of a material's life, from the extraction of raw materials to end-of-life (Sivakanthan *et al.* 2020). However, the non-integrated infrastructure poses a significant challenge to circularity. Whereas some naturally derived polymers are engineered for industrial composting, several parts of the world lack the basic amenities to process them effectively. The environmental potential is undermined because of this disconnect between innovative sustainable materials and municipal waste management infrastructures (Sunil Badgujar *et al.* 2024). Therefore, it is critical in advance to work out matters of local infrastructure and consumer behavior through context-sensitive solutions.

BIOPLASTIC MANUFACTURING PATH AND BIODEGRADABLE BEHAVIOR

Bioplastics are sourced from renewable resources and can be produced from different processes, depending on the material, and biodegradation properties. The production phase involves specific extraction and drying methods to maximize efficiency and the quality of the product. They are mostly grouped into three principal categories: natural polymers (starch), polymers synthesis through microbes (PHA, PLA), and biobased synthetic biodegradable polymers (PBAT, PBS).

Bioplastics From Starch

Starch from plant sources is extracted through a process of wet milling, in which raw materials were submerged in water for a few hours. Then the material is crushed and separated into different components including starch, fibers, and protein (Abe *et al.* 2021). After the extraction of starch, it goes through the process of gelatinization, which involves the presence of heat and water so that the starch granules swell and are converted into a thick gel form. Plasticizer (glycerol or sorbitol) is added to reduce its brittleness, enhancing its elasticity and strength (Müller *et al.* 2012). Furthermore, the processed starch mixture is cast into different shapes and dried by using a hot air oven or vacuum drying. Vacuum drying is used when the material is sensitive to heating and/or to maintain the structural integrity of synthetic bioplastic (Geyer *et al.* 2017). The bioplastic product produced through this method also shows complete biodegradation (Fig. 6).

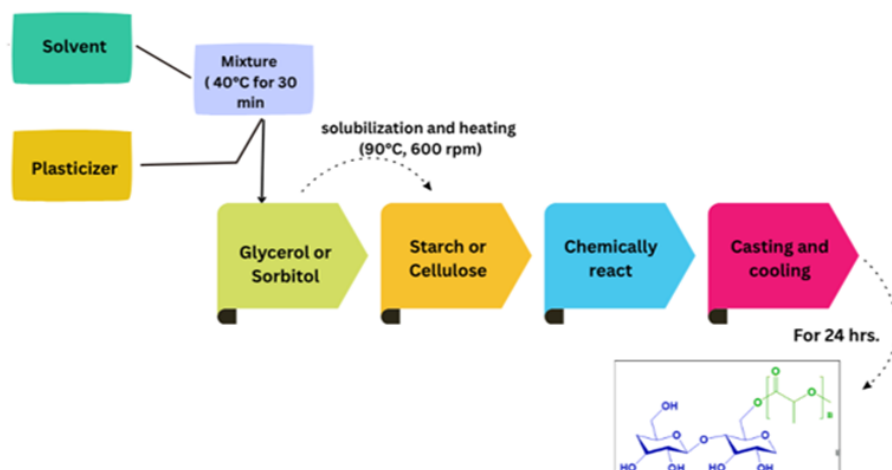


Fig. 6. Scheme for producing starch-based bioplastic and its impact (adapted from Ali *et al.* 2023a)

Microbial Fermentation-Based Bioplastics (PLA and PHA)

PLA and PHA are produced starting with microbial fermentation of sugars derived from crops such as corn or cassava (Bugnicourt *et al.* 2014). For the synthesis of PHA polymers during the fermentation, bacteria are provided with unbalanced nutrients (less nitrogen and phosphorus), which triggers the accumulation of intracellular PHA granules. These are extracted from the cells through methods such as solvent extraction, chemical disruption, enzymatic digestion and (high-pressure homogenization. By contrast, PLA cannot be directly produced from the bacteria. Rather, the sugar is converted into lactic acid monomers, which are afterward polymerized into PLA (Yoon and Oh 2022) (Fig. 7). As it can be composted in an industrial setting, it has become increasingly prevalent in

applications like food packaging, textile packaging, 3D printing, disposable cutlery, wound dressings and surgical sutures. Its limitations include slow disintegration in natural conditions and brittleness (Ilyas *et al.* 2021; Mukherjee *et al.* 2023)

What makes PHAs attractive is their capacity to biodegrade in a variety of situations, including marine conditions. This makes them well suited for products that are susceptible to littering. However, their high cost of manufacturing and limited availability still prevent extensive usage (Li *et al.* 2016; Sharma *et al.* 2021). Their degradation depends on specific conditions such as enzymatic microbial actions and temperature. In natural environments, partial degradation may facilitate the synthesis of micro and nano plastics, regulating movement and ecological interactions.

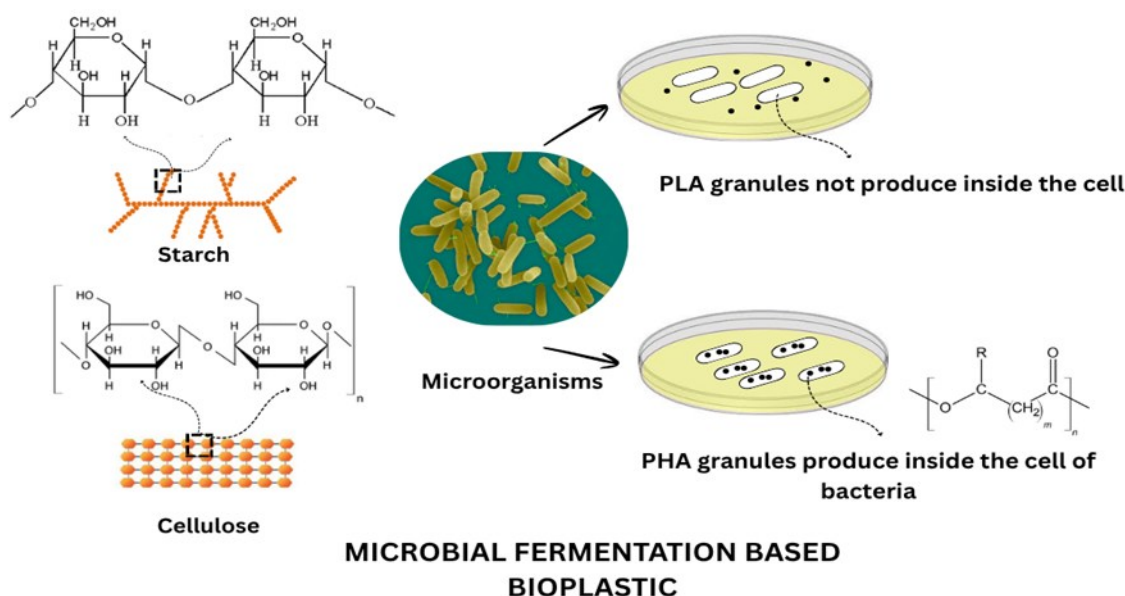


Fig. 7. Schematic diagram showing bio-based bioplastic production modified (Martins and Gupta 2024, CC BY-NC-ND 4.0)

Bio-Based Polyesters (PBAT)

PBAT is manufactured through the polycondensation method of 1,4-butanediol, adipic acid, and terephthalic acid using metallic catalysts to polymerize aliphatic and aromatic monomers into a flexible polymer chain. Its environmental degradation depends on enzymatic hydrolysis, where edaphic bacteria esterases enzyme to degrade polymer chain into carbon dioxide, water, and biomass. Although complete mineralization of PBAT is certified as an industrial composting system, its biodegradation under natural conditions is markedly slower and mostly dependent on microbial abundance and temperature. If incomplete biodegradation occurs, it can generate residual terephthalic acid or microplastic fragments that temporarily remain in the ecosystem before complete mineralization occurs (Kim *et al.* 2024).

Bio-Based Polyesters (PBS)

PBS (polybutylene succinate) can be made through the step-growth polymerization of succinic acid and 1,4-butanediol, using titanium-based catalysts to link the monomers into a highly crystalline polyester (Xu and Guo 2010). The breakdown of PBS is mainly through surface erosion facilitated by microbial enzymes such as lipases and esterases, which mineralize it into water and carbon dioxide. Although it is more thermally stable

than other bioplastics, its high crystallinity results in slower degradation in soil or marine environments compared to PBAT. Industrial composting is preferred to achieve rapid mineralization. In natural conditions, its fate is largely affiliated by moisture and temperature, as moisture is required to start hydrolysis that helps microbes to colonize and break the polymer chains.

Industrial Manufacturing Techniques for Bioplastics

Numerous techniques are used to synthesize bioplastics, each contributing unique benefits depending on the raw material and proposed applications, as shown in the Table. 2. Below are some of the most common techniques used in the manufacturing of bioplastics (Fig. 8).

Table 2. Sources and Applications of Bioplastics

S. no	Types of bioplastics based on	Material used	Method	Applications	Reference
1.	Rice straw-based bioplastic	Cellulose, rice straw, acetic acid	Solution casting	Packaging, agricultural features	Acquavia <i>et al.</i> 2021
2.	Keratin-based bioplastic	Poultry feathers, acetic acid, methanol, sulphuric acid, gelatin, 3-glycidyloxypropyl trimethoxy silane (GPTMS)	Electro-spinning	Packaging	Kumar <i>et al.</i> 2021
3.	Potato peel waste-based bioplastic	Potato peel, glycerin	Film casting	Packaging	Bano <i>et al.</i> 2024
4.	PBAT and thermoplastic cassava starch (TPS) blended TiO ₂ nanocomposite	Acetylated cassava starch, glycerol, titanium dioxide powder, poly (Butylene adipate-co-terephthalate	Blown film extrusion	Food packaging	Mushtaq <i>et al.</i> 2018
5.	Banana peel-based bioplastic	Banana peel, citric acid, acetic acid, chitosan, glycerol, aquadest	Film casting	Packaging	Yu & Chen 2008
6.	Cellulose-based bioplastic	Trifluoroacetic acid, trifluoroacetic anhydride, ethyl acetate, chloroform, naringin, carboxymethyl cellulose, cellulose acetate, ethyl cellulose, pectin	Solution casting	Food packaging	Saharan & Kharb 2022
7.	Polyhydroxybutyrate natural fiber-based bioplastic composite	Polyhydroxybutyrate (PHB), stearamide, lyocell	Extrusion injection	Textiles and apparel	Balavairavan & Saravanakumar 2021

8.	(PBAT), corn starch, Oil palm empty fruit bunch-based bioplastics	fiber, hemp fiber, jute fiber Palm empty fruit bunch, NaOH, H ₂ O ₂ , glacial acetic acid, Sulfuric acid, anhydrous acetic acid.	Electro-spinning	Textiles and apparel	Kim <i>et al.</i> 2018
9.	Cellulose acetate butyrate-based bioplastic	Cellulose acetate butyrate, maleic anhydride, acetone	Solvent-free technique	Medical devices	Mostafa <i>et al.</i> 2018
10.	Lignin-based bioplastic	Hydrolyzed lignin, cellulose, xylan, trifluoroacetic acid (TFA), trifluoroacetic acid (TFAA)	Solution casting	Food packaging	Gross 2002
11.	Corn starch and PBAT blended biofilm.	Poly (butylene adipate-co-terephthalate) (PBAT), corn starch, chlorella pyrenoidosa (CP) biomass, and disrupted CP biomass	Blown film extrusion	Food packaging	Jafarzadeh <i>et al.</i> 2020

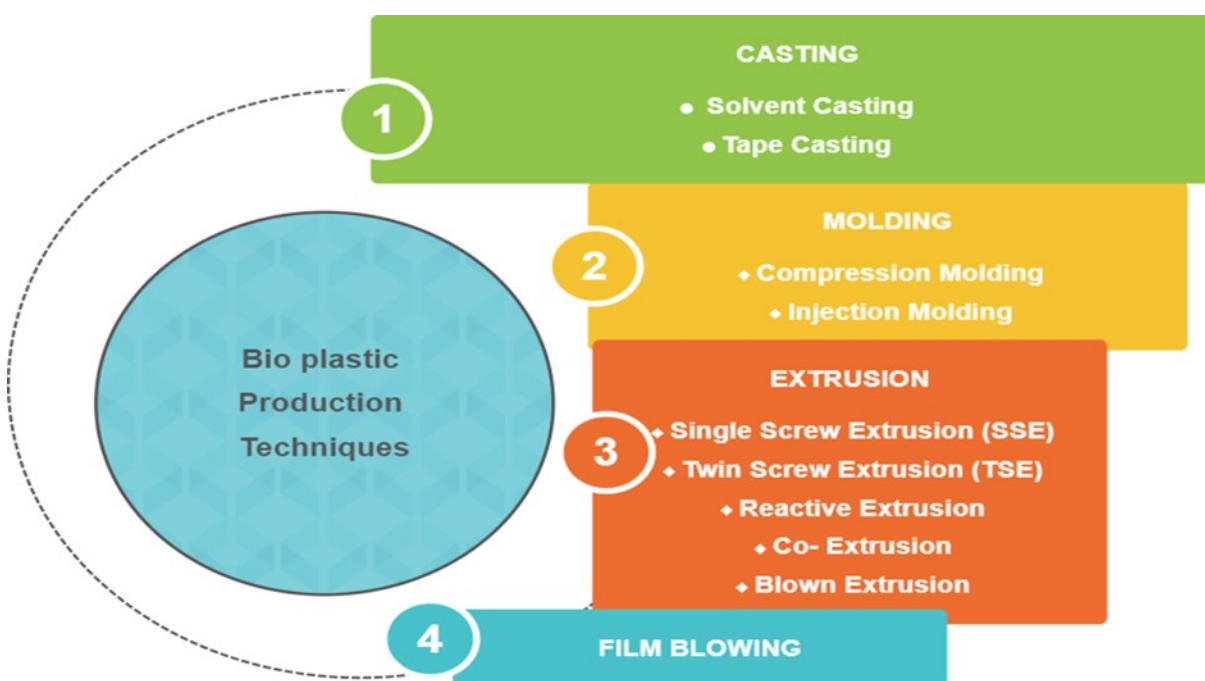


Fig. 8. Bioplastic production techniques

Solution Casting

The solvent casting technique is the most common technique used at the laboratory scale. This method involves the process of dissolution of polymer in volatile solvent with some other additives in a homogenous solution which is then poured onto the plates (petri plate, Teflon plates, *etc.*). The drying process can be done at room temperature or at a

controlled temperature up to 40 °C (de Moraes *et al.* 2013) (Fig. 9). The major environmental footprint can be attributed to the large surface area of film and toxicity of evaporated solvent used during formation. Compared to traditional molding techniques to achieve even spreading of bioplastic mixture across a large area, the polymer must be highly diluted with large volume of solvent (Cheerarot and Saikrasun 2023). This large surface to volume ratio creates a vast exposed reactive area which facilitates the rapid evaporation of toxic solvents acting as a wide “escape route” for chemical leakage with simultaneously enhances the adsorption of toxic pollutants from the surrounding environment (Saleem *et al.* 2025). This results in a high concentration of volatile organic compounds (VOC) in the atmosphere, which must be managed safely by using energy intensive ventilation systems (Islam *et al.* 2024).

Starch-based films synthesized in this manner can be mineralized completely in soil or water within 28 to 40 days. In contrast, industrial bioplastics such as PLA may take 90 to 120 days even under controlled conditions (Ghasemlou *et al.* 2024). Their tendency to fragment easily can promote the faster release of biodegradable microplastics (BMPs) into the environment. Although BMPs eventually mineralize, their short-term presence can still pose risk to aquatic and soil ecosystems. Solution casting facilitates incorporation of additives such as glycerol or sorbitol. However, if these plasticizers or additives are not fully bound to the polymer matrix, they may leach into soil or water, potentially altering pH or toxicity (Costa and Lackner 2025).

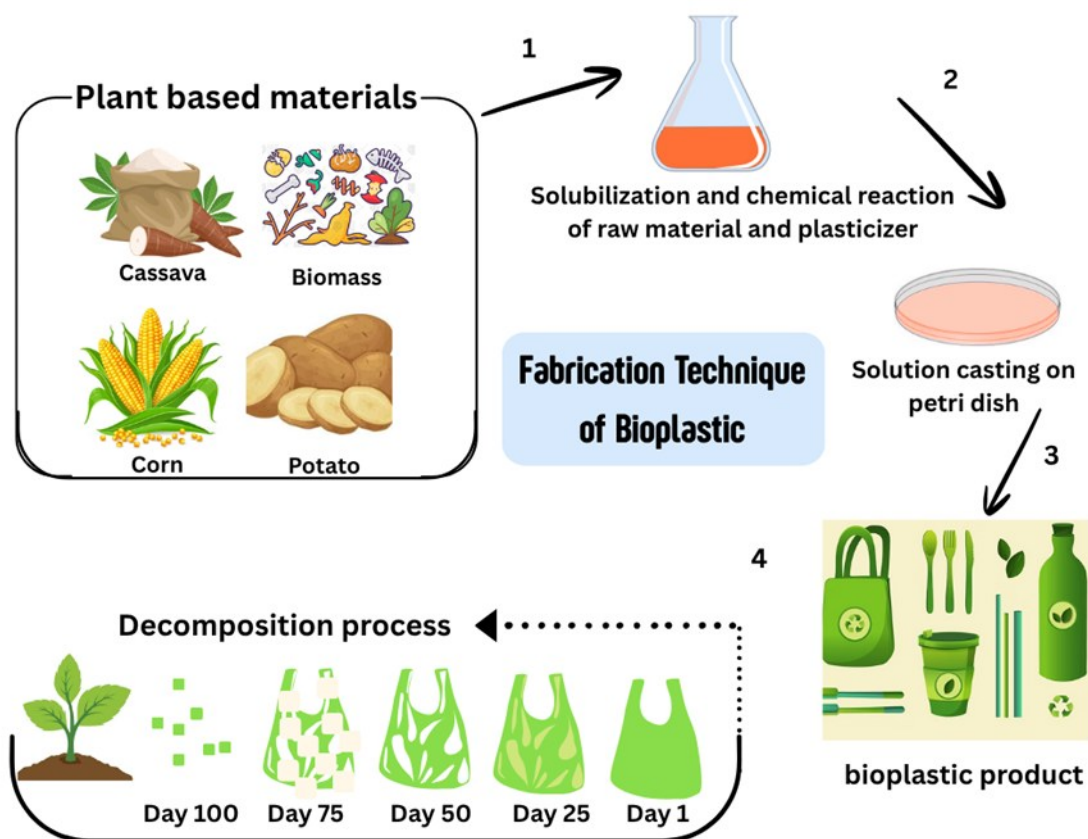


Fig. 9. Schematic diagram of bioplastic production through the solution casting technique (modified from Ilyas *et al.* 2022)

Injection Molding

When this technique is used for polymer processing, the bioplastic material is injected into mold under controlled conditions, such as high pressure, temperature, and filling amount. The mold is specifically designed for the desired shape product (Yin *et al.* 2020) (Fig. 10). Injection molded bioplastics exhibit slow surface erosion due to their low surface-to-volume ratio and compact structural density. High crystallinity serves as a physical barrier against moisture and microbes, resulting in long term persistence in natural soil or marine environments for years full mineralization of such dense materials generally requires industrial composting. These materials are reported to degrade into microplastics in natural environments, resulting in long-term ecological risks before complete mineralization (Dotson *et al.* 2024).

Extrusion

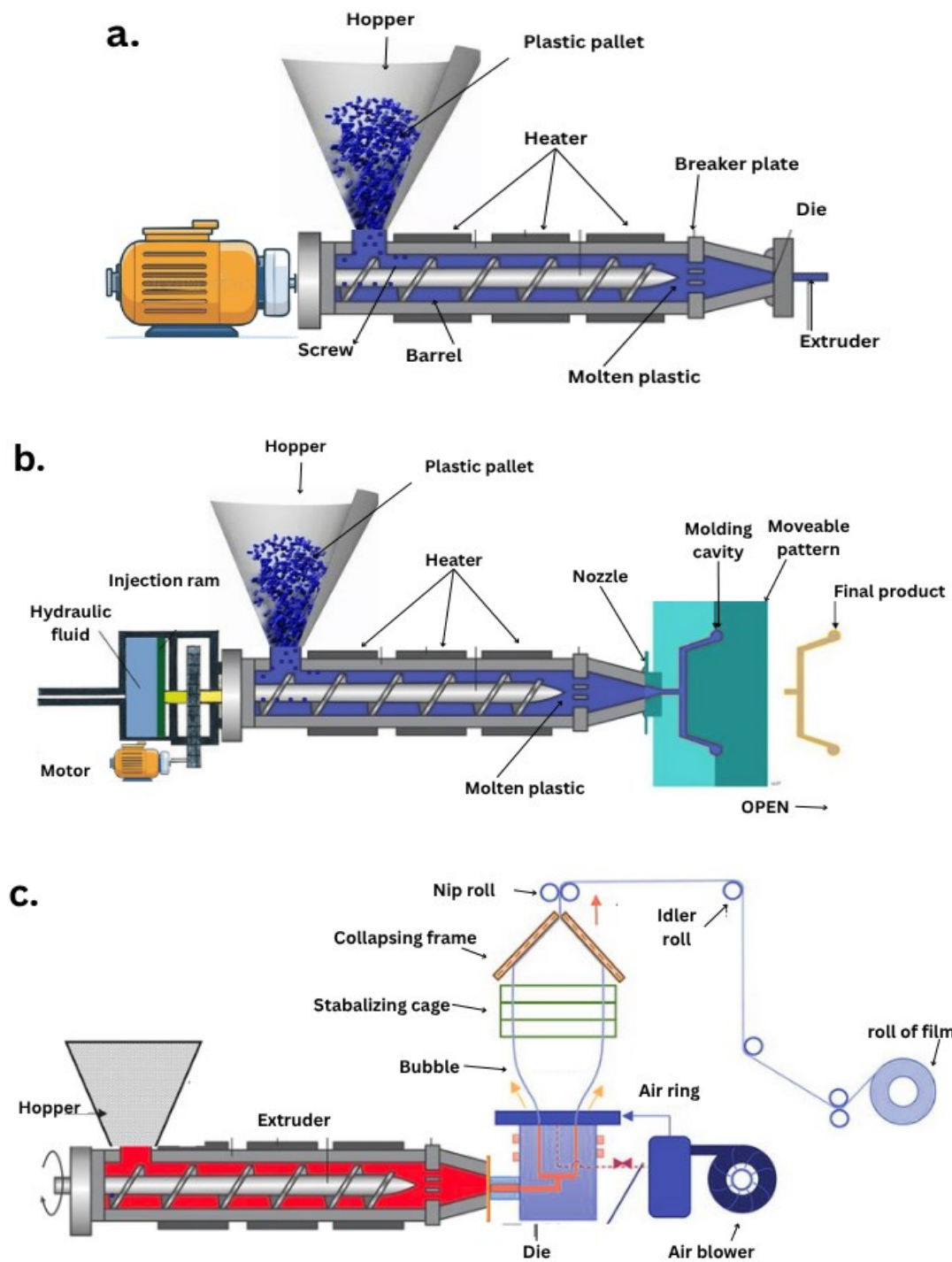
Extrusion is the most used method to manufacture plastic on an industrial scale. It is a continuous process in which the material, usually in pellet form, is introduced into a fixed barrel where it moves from different units, such as mixing of material, heating, compression, and pressure drop (Emin and Schuchmann 2017). The material undergoes both physical and chemical modification. The material is softened by heating, and it is transported to the end of the die through the rotating screw, which changes the shape of the material as it passes through the die (Bouvier and Campanella 2014). After extrusion, the bioplastic is cooled and hardened. Bioplastic based on gluten from wheat was manufactured by using this technique (Fig.10).

The polymer industry depends greatly on the extrusion process. It is a flexible method with an extensive range of extruder designs such as single screw extrusion, twin screw extrusion, and blown film extrusion. Since the screws in the extruder machines are separated, an array of configurations is achievable as well, and screws can be designed based on the nature of the material (Logié *et al.* 2017).

Extrusion produces bioplastic materials with a slightly lower density and thinner profile compared to injection molding. This results in a more homogeneous structure, which facilitates faster degradation in natural environments. In contrast, injection-molded bioplastics tend to exhibit minimal degradation under natural conditions. However, due to variations in bioplastic composition across different products, industrial composting or incineration is often considered a more effective end-of-life management option (Cheng *et al.* 2024).

3D Printing

3D printing creates bioplastics with a unique environmental fate characterized by porous, layered structures that speed up degradation compared to injection molding (Fig. 10). Because the process builds objects layer-by-layer, it leaves microscopic gaps and a high surface area that allow moisture and microbes to penetrate the “bulk” of the item more easily (Andanje *et al.* 2023).



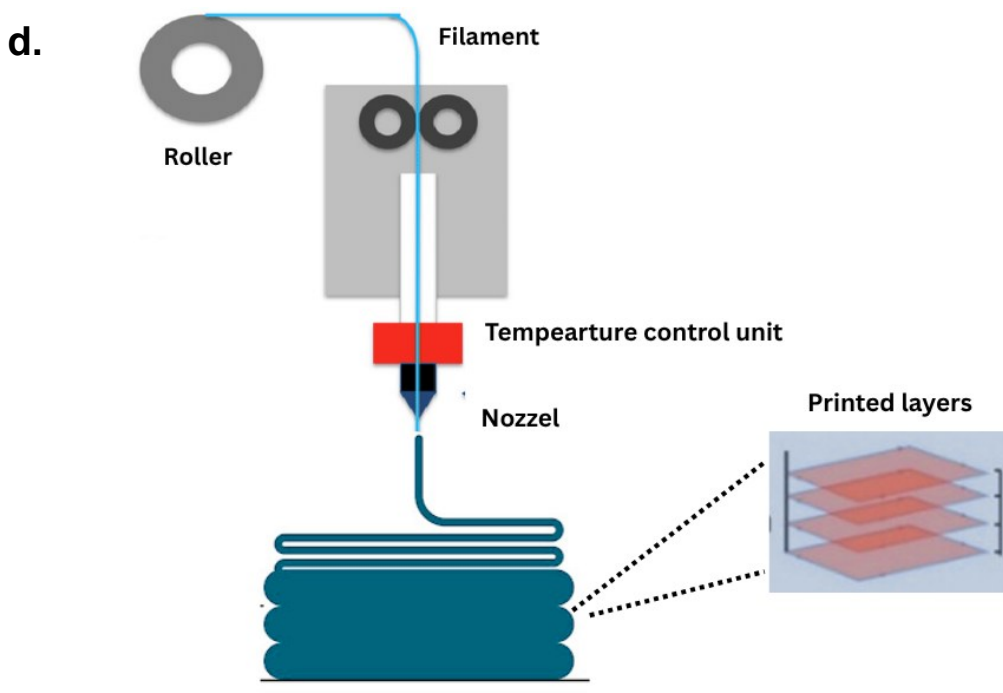


Fig. 10. Visual representation of industrial techniques used for bioplastic manufacturing, adapted and modified from Britti Bacalhau *et al.* (2017) and Ma *et al.* (2024). **a.** Extrusion technique **b.** Injection molding technique **c.** Blown film extrusion technique **d.** 3D printing

BIODEGRADABILITY AND ITS IMPACT ON THE ENVIRONMENT

Biodegradation of bioplastics is a fundamental aspect of life cycle evaluation and is increasingly recognized by the world's industrial sectors. Biodegradable polymers usually undergo degradation through two main stages fragmentation and microbial adsorption. Fragmentation is the breakdown of polymers into small pieces, which provide a large surface area for microbial colonialization. Microbial adsorption is the attachment of microorganisms on the polymer surface. It is an important step to start enzymatic degradation of polymer chain into monomer or oligomers ultimately resulting in complete mineralization (Bátori *et al.* 2018). The time of biodegradation is determined by factors such as its functional groups, structure, crystalline nature, size of polymer chain, *etc.* Over 90 different types of microbial actions cause the breakdown of polymers in distinct ecosystems. However, plants or bio-based plastics are considered more beneficial than conventional plastic, but their long-term environmental impacts are still under research (Laface *et al.* 2023).

ENVIRONMENTAL IMPACTS: BIOPLASTICS VS. FOSSIL-BASED PLASTICS

This section reviews the findings of research on the impact of bioplastics and compares them with conventional plastics, as shown in Table 3. Greenhouse gas emission result indicates that the bioplastic PEF releases less emission compared to the petrochemical PET (Eerhart *et al.* 2015). In addition, eutrophication potential data indicates that bioplastics have higher potential than traditional plastics. Bioplastics' contribution toward the stratospheric ozone layer has been found to be lower than that of conventional plastic (Weiss *et al.* 2012).

Table 3. Environmental Impact of Bioplastic Compared to Conventional Plastic

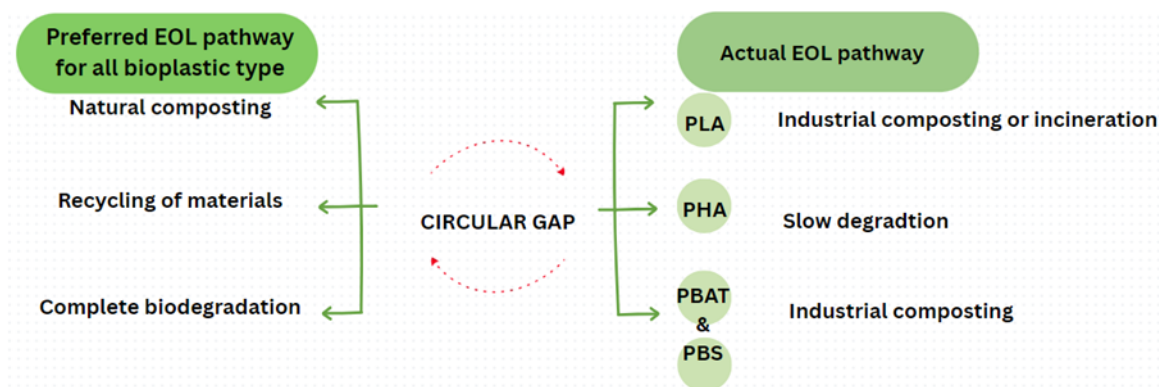
Impact	Conventional Plastics	Bioplastics	Reference
Greenhouse gas	Petrochemical PLA and PHA emit 3.1-ton CO ₂ eq. per ton and 3.5-ton CO ₂ eq. per ton	PEF emits 2.1-ton CO ₂ eq. per ton	(Sinan 2020)
Eutrophication	6 + -11 kg PO ₄ - eq/(ha*a)	5 +- 7 kg PO ₄ - eq/t	(Bio leader 2025)
Stratospheric ozone depletion	2.4 + -1.3 kg N ₂ O ~ eq/(ha*a) r	1.9 +- 1.8 kg N ₂ O ~ eq/t a	(Bio leader 2025)

END-OF-LIFE (EOL) PATHWAYS

Biodegradability and recyclability are usually considered as the primary advantages of the bioplastics, but their true end-of-life (EOL) performance is far more complicated. The labelling of an item as “biodegradable” or “compostable” cannot guarantee environmental safety unless the methods or procedures of their disposals are adequately supported by local infrastructure. The critical EOL pathway for bioplastics includes industrial composting, aerobic digestion, anerobic digestion, physical recycling, chemical recycling, energy from waste incineration, and controlled disposal in landfills (Briassoulis *et al.* 2019; Spierling *et al.* 2020).

The actual waste management systems and the theoretical biodegradation capacity of bioplastics are very different (Fig. 11). For instance, a considerable proportion of these materials continue to enter uncontrolled landfill due to littering, inefficient segregation practices, limiting industrial composting capacity, high cost of processing, and confusion with traditional plastic during sorting. Common polymers such as PLA, PBAT, and PBS degrade well under certified industrial composting but do not break down well in unmanaged landfills or home compost bins (Von Vacano *et al.* 2023).

Ultimately, the true sustainability of a bioplastic does not rest on its chemistry alone. What matters is how well the material is integrated into existing waste management systems in the real world (Molina-Besch 2022).

**Fig. 11.** Preferred and actual end-of-life pathways for mainstream bioplastics

LEAKAGE BASED FRAMEWORK FOR ENVIRONMENT BEHAVIOR OF BIOPLASTICS

The environmental behavior of bioplastics can be understood through an environmental leakage pathway that integrates production, consumption, leakage, transport mechanism, and transformation pathway. In the early stage, the characteristics of materials defined during the manufacturing such as crystalline structure, material density, and composition additive play a critical role in determining the ecological response. Bioplastic consumed for single use applications such as packaging are often discarded rapidly during the consumption phase, thereby increasing the risk of leakage into the natural environment. This release follows the path of littering, improper landfill management, wastewater effluent, and surface runoff. These occurrences reflect the failure of managed systems within circular bioeconomy frameworks that allow material escape in natural ecosystem (Tyagi *et al.* 2022). Once materials escape, they can be transported, crossing different environmental compartments including soil, freshwater, and marine systems within these environments. The bioplastics undergo transformation processes driven by both biotic mechanisms such as microbial degradation, and abiotic factors including ultraviolet radiation and hydrolysis. This transformation process may result in partial degradation, resulting in the formation of micro- and nano-scale particles and soluble intermediates (monomers, oligomers) with altered mobility and bioavailability. Organisms therefore may encounter bioplastic through ingestion, physical contact, or environmental assimilation, potentially driving environmental impacts determined by both exposure routes as well as transformation derivative (Zhang *et al.* 2025). This framework highlights that environmental risk cannot be fully predicted by summing the combined effects of material properties, environmental conditions, and leakages across system (Fig. 12).

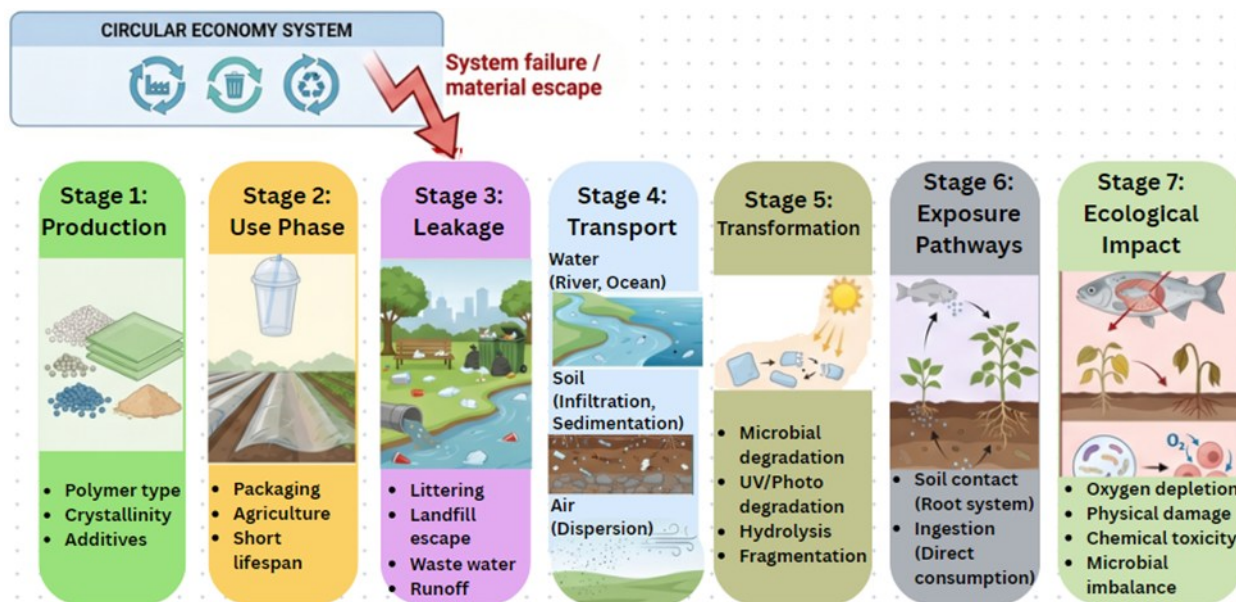


Fig. 12. Leakage based pathway of bioplastic degradation (system failure of circular bioeconomy)

BIOPLASTIC DEGRADATION AND ITS TOXICITY

Recent studies have indicated that the biodegradable plastics (BPs), upon degradation in a brief period, may undergo incomplete mineralization and depolymerize quickly due to their unstable structure (Hu *et al.* 2025). Incomplete polymer degradation may result in formation of microplastics (MPS) or nano plastics (NPs), monomers, and oligomers. These can cause threats to environmental health. Lab research indicates that the MPs and NPs generated from bioplastics can be consumed by organisms such as earthworms, tadpoles, and zebrafish (Scalia *et al.* 2025). Almost 99% of PLA particles that are consumed get removed from the body within a week. A small percentage of them may break down into smaller parts in the digestive system and can pass to other organs, and when consumed by humans, they can cause serious health issues (Ali *et al.* 2023b). Studies showed that 2%(w/w) PLA micro-nano plastic was fed to the juvenile perch for about 6 months led to reduced locomotion and fewer anti-predator responses (König Kardgar *et al.* 2023). When zebrafish were exposed to 10 mg/L PLA particles for 15 days, the gut microbiota was affected. The exposure also induced neurotoxicity and stress in larvae of dragonflies and tadpoles (Li and Chen 2024). They are also responsible for reproductive problems in ascidians, demonstrating measurable ecological risks even at low concentrations. Studies also indicated that elevated PBAT (MPs) concentration (5%) has reported to reduce soil pH by 5.1% due to release of acidic monomer (adipic acid) (Cao *et al.* 2024). Similarly, high dose of PBS (MPs) has been reported to reduce root length of *Triticum aestivum* by 15 to 20% (Chen *et al.* 2024). Other reported data about the bioplastic toxicity after biodegradation are shown in Table 4.

Table 4. Biodegradable Products of Bioplastic and their Toxicity

Bio-plastic Type	Environmental Condition	Reported Degradation Mechanism	Degradation Product	Quantitative Data	References
PLA	Industrial composting (~ 58 °C)	Non-enzymatic hydrolysis+ microbial enzyme activity	Increase the biodegradation rate	Not reported (NR)	(Murcia Valderrama <i>et al.</i> 2020)
	Shore of the deep sea	Resistance crystalline structure	No significant degradation	No degradation	(Hu <i>et al.</i> 2024)
	Artificial sea-water (21 days)	Immersion	Microplastics (MPs)	133.2 ±12.0 MP	(Tong <i>et al.</i> 2022)
	Tea bags dip in cold water	Leaching	MPs	0.172 ± 0.0235 µg per bag	(Wang <i>et al.</i> 2022)
	Tea bag dip in hot water (95 °C)	Thermal exposure	MPs + NPs	12.3 ±0.381 µg MP per bag	(Ubeda <i>et al.</i> 2020)
	Reservoir sediments	Surface aerobic degradation	MPs	53.5 to 491 ng/g (dw)	(Wang <i>et al.</i> 2022)
	Food stimulants	Migration	PLA oligomers	NR	(Ubeda <i>et al.</i> 2020)

PBAT	Terrestrial surface (UV exposure)	Photooxidation, radical formation	Oligomers, monomers, benzophenone derivatives	NR	(Wang <i>et al.</i> 2023)
	Fresh water and sea water	Fragmentation	Plastic fragments	Larger than PE (amount NR)	(Wei <i>et al.</i> 2021)
	Soil (anaerobic) buried for 180 days	Slow microbial degradation	Terephthalic acid monomer	Up to 131 mg/kg	(Ma <i>et al.</i> 2023)
PHA	Deep sea	Microbial degradation	Substantial degradation	NR	(Ma <i>et al.</i> 2023)
PHB	Sterilized ultra-pure water (3 days of agitation)	Hydrolytic breakdown	NPs	75 to 200 nm	(González-Pleiter <i>et al.</i> 2019)
PBS	Artificial seawater (21days)	Immersion	MPs	435.7 ± 4.0 MP	(Tong <i>et al.</i> 2022)
PCL (beads)	Phosphate-buffered saline	Hydrolysis	NPs, oligomers	10 ⁹ to 10 ¹¹ particles/g; >3 mg/g oligomers	(Tamayo-Belda <i>et al.</i> 2022)
PCL (Film)	Enzymatic degradation	Enzyme-mediated depolymerization	Acidic monomers and oligomers	NR	(Tamayo-Belda <i>et al.</i> 2022)

RESEARCH GAPS

Published toxicity studies generally have focused on short-term, high-concentration micro(nano)plastic exposures with an emphasis on polylactic acid, while often overlooking a wider variety of oligomers and monomers. The behaviors and ecotoxicity of the released particles or chemicals from bioplastics are far more complex than those derived from conventional plastics, and the chronic effects of nano(micro)plastics and low-dose exposures remain poorly characterized. There are review papers and research articles that discuss the toxic profile and environmental impact of bioplastics, but they focus on discussing the endpoint, including oxidative stress, developmental toxicity, and do not systematically represent the LC₅₀/LD₅₀ toxicology threshold specifically for bioplastics.

CONCLUSION

This review has explored the raw material, categories, properties, applications, and environmental impacts of bioplastics and compared them with conventional plastics. Bioplastics generally are regarded as a sustainable alternative to traditional fossil fuel-based plastics due to their renewable source, biodegradability (in many cases), and lower environmental impacts. Bioplastics have several applications in different sectors, such as industrial, pharmaceutical, agriculture, food packaging, electronics, and cutlery. The emerging techniques, along with the conventional ones, have been used for particular materials. This review has shown that bioplastics also provide several advantages to the environment, including reducing greenhouse gas emissions and reducing reliance on fossil fuels. But some bioplastics (*e.g.* PLA) show non-biodegradability in marine ecosystems,

whereas others, such as PBAT PCL, and PBS, show the formation of microplastics and nanoplastics, acidic monomers, and oligomers that have toxic effects on living organisms. Crucially, this review has emphasized the need to frame bioplastics within a circular design context, rather than treating biodegradability or renewable sourcing as standalone credentials. It has been argued here that achieving meaningful impact requires simultaneous attention to performance, scalability, end-of-life infrastructure, and the regulatory landscape. Hence, bioplastics are not completely free from environmental impacts and show certain negative effects and limitations. Therefore, further research is required to fully comprehend the life cycle of bioplastics and its toxicity in terms of LC50/LD50 toxicology threshold.

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