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Petroleum-Based Plastics Versus Bio-Based Plastics: A Review

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ABSTRACT

Plastic needs have expanded along with population growth, industrialization, and urbanization. Plastic is unrivaled due to its useful properties and is used to prepare numerous important goods daily. This paper encloses the different kinds and applications of petroleum-based plastic and the drawbacks related to their use, i.e., its nonbiodegradability which leads to their stay in the environment for a very long time. Additionally, there are not enough effective disposal techniques for the large volume of plastic waste produced; thus, plastic garbage builds up in the environment and endangers it. Limiting the usage of plastic is necessary to protect the environment. This can be done with the help of bioplastic, which is an excellent substitute for plastic. The different kinds of bioplastic and their biodegradability in different mediums, viz., soil compost and aquatic systems, are addressed in this paper. Along this, the different areas of application of bioplastic have been explored. The present study also addresses the underlying mechanism of plastic polymerization and biodegradation and the current status of bioplastics in the global market.

INTRODUCTION

Synthetic plastic finds vast applications due to its excellent characteristic properties (Luckachan & Pillai 2011). Plastic is widely used from the domestic to the industrial level to produce carry bags, storage containers, water bottles, jugs, glass, water pipes, chairs, tables, and agricultural products. Having excellent properties and being present at a low cost, the importance of plastic cannot be ignored (Sangale et al. 2012). However, the overuse of plastic has given birth to many environmental problems. Over a million tons of plastic waste is generated annually from different sources (Pathak & Navneet 2017). Most plastic debris is non-biodegradable, and its management has become a global challenge. Sea beaches are the depository sites for plastic, as plastic waste is carried to aquatic sources through rivers, canals, etc. (Singh et al. 2016). The accumulation of plastic waste in the ocean affects marine fauna and flora adversely (Laist 2006). Plastic debris also affects terrestrial ecosystems and human health. So there is a need for proper management of plastic waste. The environmental problems caused by plastic waste have triggered the need to develop environmentally friendly materials.

Bio-based plastic is a perfect alternative to synthetic plastic as they are made of renewable and natural sources like corn starch, potato starch, inedible food waste, and lingo-cellulosic crop residue (Saharan & Ankita 2012). The raw material used for bioplastic production greatly impacts bioplastic properties and production expenses. Bioplastics are generally biodegradable or compostable based on their composition. The production and use of such plastic material may help resolve many environmental problems, and their production and consumption are expected to grow soon. Thus, there is a need to evaluate these bioplastics carefully. There are many reviews available on the investigation of bioplastics.

Palaniswamy & Venkatachalam (2020) critically reviewed the different kinds of bioplastic, their advantage, and their disadvantage. The global statistics related to bioplastics were also discussed. Hong et al. (2021) reviewed bioplastic as a material for food packaging. The various characteristic properties of bioplastic for food packaging are discussed. Different kinds of bioplastic used for packing fruits, vegetables, eggs, fish, meats, etc., were also included in the study.

Similarly, most review studies covered only one aspect of either bioplastic or synthetic plastic, and their detailed comparative study was unavailable. Therefore, the current review encloses synthetic plastic and bioplastic aspects. This review focuses on polymerization, the various kinds of plastic materials used in daily life, and the harmful effects of plastic waste. Further, the various kinds of bioplastic and different feedstock used for their production were discussed.

The mechanism of biodegradation, the biodegradability of bioplastic in different mediums, viz., soil, compost, and aquatic system, and the role of microorganisms in biodegradation are included in the present study. The review also highlights the application, global market status, global producers of bioplastic, and limitations of bioplastics.

PETROLEUM-BASED PLASTICS

Plastic, a synthetic polymer, is a petroleum product. Natural gas, coal, and crude oil are the precursors for preparing synthetic plastic. In 1907 Baekeland obtained the first synthetic polymer named Bakelite, which was formed by polycondensation of phenol with formaldehyde. Plastics are lightweight, strong, and cheap to produce polymers with high molecular weight and consist of hundreds to thousands of repeating units of monomers (Kuhn et al. 2007). Production of synthetic plastic begins from distilling crude oil in an oil refinery. This distillation step separates heavy crude oil into its lighter constituents; these more lightweight components are called segments. Each segment consists of a hydrocarbon chain of varying sizes and structures. Naphtha is one such segment required to produce monomers, say ethylene, propylene, and styrene, which act as a precursor for the production of plastic. The conversion of monomers into a polymer through polymerization releases greenhouse gases and other toxic pollutants into the environment. The characteristic properties of plastic play an essential role in deciding its applications. The molecular weight of plastic determines many physical properties and affects the plastic's toughness, tensile strength, adherence, and resistance. The increase in molecular weight increases the tensile and impact strength. Crystallization controls the structural formation process of plastic.

A few important mechanical properties of plastic are tensile strength, flexural and compressive strength, hardness, fatigue resistance, and impact resistance. The tensile strength of plastic material tells about the load or stress the material can bear before permanent deformation (Goswami et al. 2015). The transport properties describe how rapidly any molecule can pass through the plastic material. There are several kinds of plastics, and they are used for various purposes.

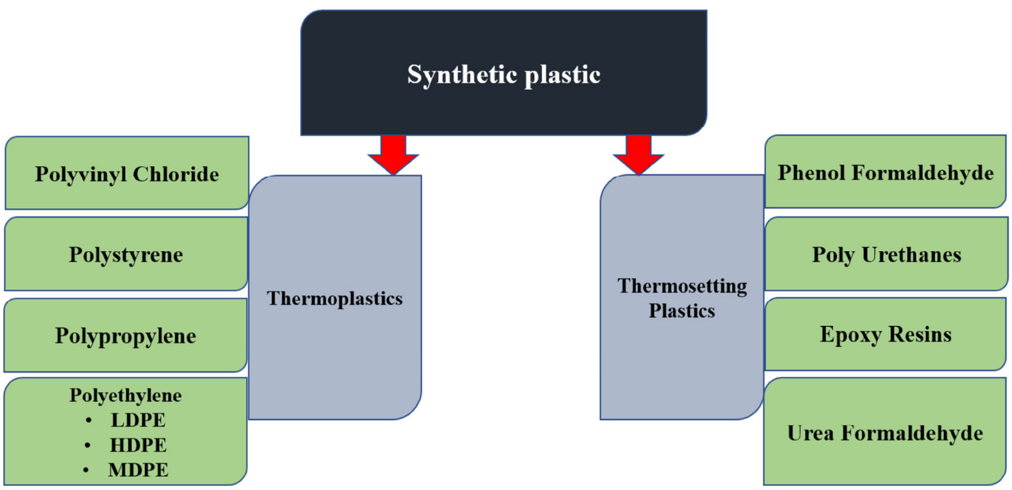
Type of Plastics Based on Thermal Properties

Based on the thermal properties, there are only two kinds, namely thermoplastic and thermoset plastic, which are discussed further. Fig. 1 shows the kind of plastic based on thermal properties and their subtypes.

Thermoplastics

This kind of plastic is brittle and glossy in appearance and can be softened and remolded into different kinds of shapes by applying heat and then cooling at room temperature. There is a minimum or no change in the properties after remolding. A few examples of thermoplastic are polyolefin, polyethylene, nylons, Poly-ethers, and Polyvinyl chloride (PVC). This plastic can be a linear or branched chain with an intermolecular force between the elastomers and fiber (O'Neil 2010).

Thermosetting Plastics



(LDPE: Low-density Polyethylene; HDPE: High-density Polyethylene; MDPE: Medium-density Polyethylene)

Fig. 1: Classification of synthetic plastics based on thermal properties.

This plastic cannot be remolded or reshaped to form a new product. On application of heat, these plastics undergo some chemical reactions, resulting in changes in their properties, and thus cannot be reused. These polymers are generally robust, durable, and resistant to high temperatures. Thermosets are mostly cross-linked polymers. A few examples of thermoset plastic are phenolic, Bakelite, resins, urea, and epoxy resin (O'Neil 2010).

Commonly Used Synthetic Plastics

Polystyrene

Styrene monomer is a predecessor of polystyrene. It is a very hard, lightweight, and mouldable plastic. Styrofoam is formed by heating polystyrene and then blowing air through this mixture. Polystyrene makes furniture, glasses, and utensils (Casado et al. 2013).

Polyvinyl Chloride (PVC)

PVC is obtained by polymerization of vinyl chloride. A plasticizer is added to it to enhance the properties of PVC and make it soft and mouldable. They are cheaper and more durable. PVC is used to prepare pipes and plumbing materials (Chung et al. 2011).

Polytetrafluoroethylene

It was first produced in 1938 by Dupont. When the monomers of tetrafluoroethylene are polymerized, it results in the formation of polytetrafluoroethylene. It is also called teflon and is stable, strong, and resistant to high temperatures. It makes cookware and waterproof coating (Cole et al. 2013).

Polyethylene

It is the most common and widely used plastic material. The polymerization of ethylene monomer obtains it. The first polyethylene was produced in 1934 (Della et al. 2014). Polyethylene is tough, chemically inert, possesses low moisture adsorption, and are bad conductor of electricity. The properties vary according to the type of branching and crystal structure (Huang et al. 2007). They are used in making electric wires and cables, pipes, medical devices, and automotive and space applications (Fang et al. 2005, Zhang et al. 2006, Dey & Tripathi 2010, Manu et al. 2013).

There are three kinds of PE-1) HDPE (High-density polyethylene), 2) LDPE (Low-density polyethylene, and 3) MDPE (Medium-density polyethylene).

LDPE is ductile, flexible, tough, transparent, and has weak intermolecular interactions due to high chain branching. Its long chain irregular packing contributes to low crystallinity. LDPE possesses tensile strength lower than HDPE and finds uses in preparing containers, plastic films, and plastic bags.

HDPE is the most versatile plastic material with the highest crystallinity degree. It is highly stable due to the presence of many short branches. HDPE makes milk jugs, water pipes, and detergent bottles (Pasch & Eselem 2018). HDPE has a higher melting point than LDPE (Della et al. 2014).

MDPE is a combination of LDPE and HDPE. It has drop resistance and better-cracking resistance than HDPE but is softer than HDPE and harder than LDPE. It is used in making carry bags, packaging, gas pipe, and fittings

Polypropylene (PP)

Karl Ziegler and Givlionatta first produced it in 1953. PP is obtained from the combination of propylene monomers. It is the second most used plastic, possesses good mechanical properties, and is highly available at a moderate cost. PP is used in packaging, electronics, household appliance, battery cases, bottle tubes, filaments, and bags (Castro et al. 2009)

There are three kinds of PP.

1) Atactic PP has a low melting point and consists of methyl groups on the main chain in random order.
2) Syntactic PP is semi-crystalline and is more homogenous than atactic PP.
3) Isotactic PP possesses a high degree of crystallinity and is homogenous and highly stable (Maddah 2016).

Process of Making Plastics: Polymerization

The polymerization process involves linking a large number of monomers to form a polymer molecule. Monomers are low molecular units that join with the help of chemical reactions forming large molecules having high molecular weight called polymers.

Different methods of polymerization can be used to produce various kinds of plastic materials, which are as-

A. Condensation Polymerization

It is also called step-growth polymerization. It is a chemical reaction in which a low molecular weight by-product called condensate (NH_3, H_2O, HCL) is released, and the polymer is formed.

B. Addition Polymerization/Chain Polymerization

In this process, two or more monomer molecules combine to form a polymer, and no by-product is formed. This involves a chain reaction linking the monomer molecule (Karana 2012).

C. Ionizing Radiation Polymerization

Ionizing radiations generate free radicals, which initiate the polymerization process. Both solid and liquid mediums can be used for achieving ionizing radiation polymerization. There is not much influence of temperature in this process. Sometimes the process continues even after moving away from the radiation source, and the phenomenon is called post-polymerization.

D. Non-ionizing Radiation Polymerization

It is a kind of chain-growth polymerization. The absorption of visible or UV light influences the process. In this process, the reactant monomer can absorb light directly and by a photosensitizer, which absorbs light and transfers the energy to the monomer.

Disadvantages of Petroleum-Based Plastics

Plastic is produced from non-renewable energy sources and is non-biodegradable (Anderson, 2006). The Chemical structure of plastic cannot be modified by the microorganism, which leads to their nonbiodegradability (Tokiwa et al. 2009, Babu et al. 2013). High molecular weight, high degree of crystallinity, and high hydrophobicity reduce the degradability of plastic (David et al. 2019). The production and disposal of plastic are increasing every year. As plastic is non-biodegradable, there is no method for its proper disposal (Yadav et al. 2020). Plastic waste has dramatically influenced the environment by causing land, water, and air pollution and contributes to global warming (Khyalia et al. 2022). It also affects human and animal health by causing infectious and chronic diseases. Groundwater movement can be obstructed by a massive amount of plastic waste (Silva 2014). Plastic waste may contain heavy metals, impeding the soil and reaching water sources. Soil fertility is also influenced by plastic. Incineration and open burning of plastic waste produce dioxins and toxic gases. The lack of suitable landfill sites is another issue in waste disposal.

Plastic debris accumulated in marine ecosystem leads to aesthetic concerns and affect tourism. Large amounts of plastic debris also affect fishing activities, as debris is trapped in the fishing net along with fish (Gregory 2009). Ingestion of plastic waste by aquatic animals affects their health adversely. Further, this may affect other animals and human beings because the ingestion of plastic by marine animals leads to their introduction into the food chain, and toxic substances are transferred from one organism to another (Thomson et al. 2009).

Another matter of concern is very small fragments of plastic, commonly called microplastics. They are thread-like in appearance, and their size varies from 0.1 mm to $\leq$ 5 mm (Yadav et al. 2023). A number of studies evidence the presence of microplastics in plankton, fishes, and human beings. Phthalates and Bisphenol A (BPA) are added as an additive during the manufacturing of plastic and are very toxic and can bioaccumulate in organisms. Recycling is a good method to reduce plastic waste, but it is not cost-effective because sometimes the expense of the production of new plastic is much lower than that of recycling (Faris et al. 2014, Faure et al. 2015).

BIOPLASTICS

Bioplastics are polymers obtained from natural resources and are entirely or partially biodegradable depending upon the renewable sources and additives used in bioplastic production. Under natural conditions, bioplastic degrades into CO_2, H_2O, and other inorganic compounds, by the action of enzymes of different organisms. No toxic residue is left after the degradation process is completed. In addition, the production and use of bioplastic conserve the petrochemicals used to make conventional plastic, and it lessens environmental damage brought on by improperly discarding plastic garbage. Bioplastic poses a lower carbon footprint than synthetic plastic, helps in the reduction of CO_2 emission, saving fossil fuels, and removes non-biodegradable plastic waste. The selection of raw materials and other additives affects the cost of bioplastic production (Mostafa et al. 2018). These days' bioplastic is used for making plastic films. With technological advancement and research, other high-value products for automobiles and electronics can be produced shortly (Chen 2014).

Types of Bioplastics

Bioplastic can be produced from renewable, edible, and in-edible raw materials like starch, cellulose, proteins, and bacteria like PHA, PHB, PLA, etc. They are mainly divided into starch-based, cellulose-based, and microbes-based. The different kinds of bioplastic and the sources for their production are illustrated in Fig. 2.

Cellulose-based Bioplastics

Cellulose is a natural polymer having molecular formula $(C_6H_{10}O_5)n$ and consists of a linear chain of 100-1000 of $\beta(1\rightarrow4)$ linked D-glucose units. It is the most abundant biopolymer made from thousands of monosaccharide units. Cellulose is mainly found in the primary cell wall of green plants and can be obtained from plant biomass with the help of synthetic and natural methods. Cellulose is produced from fibers, and these fibers are not soluble in water and thus are treated at high temperatures with acids and sodium chloride to obtain cellulose.

Cellulose is highly crystalline and hydrophilic, producing brittle packaging material that cannot be used for packaging

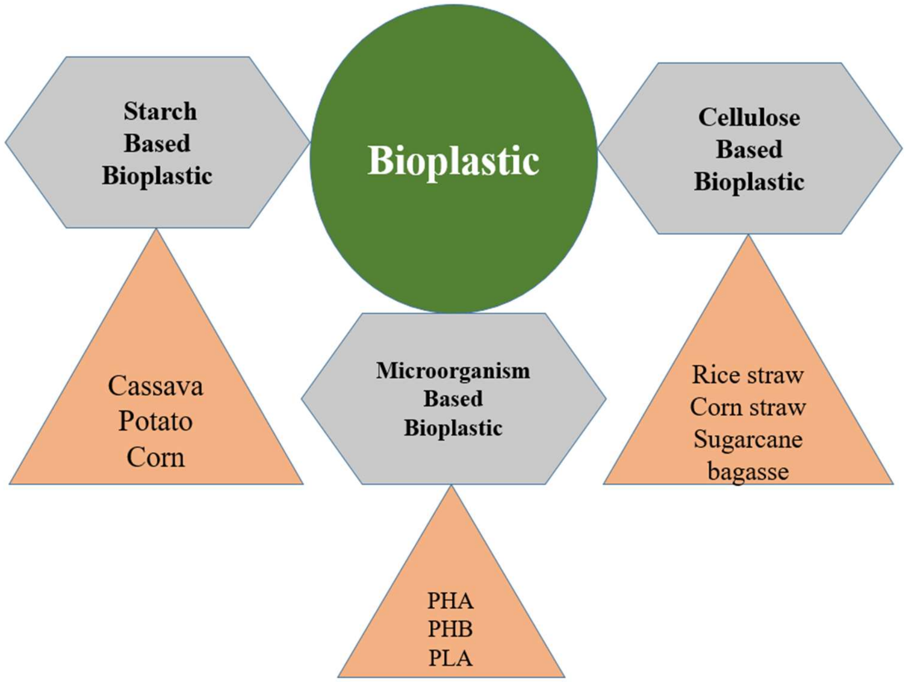


Fig. 2: Different kinds of bioplastics and their sources.

purposes due to poor flexibility and tensile strength. However, cellulose derivatives like hydroxypropyl cellulose, hydroxypropyl methylcellulose, carboxymethylcellulose, and methylcellulose are suitable for packaging applications (Morillon et al. 2002).

Starch-based Bioplastics

Starch comprises monomeric glucose units joined by α-1,4-linkage and has the molecular formula $(C_6H_{10}O_5)_n$. It is a polysaccharide having amylose and amylopectin as its major constituents. It is a granular, tasteless, soft organic chemical, white in appearance. Starch is a biodegradable, inexpensive, abundant, and renewable polymer from green plants. It possesses good polymeric properties and is used to produce bioplastic. Further starch can be blended with non-degradable polymer to enhance the biodegradability process. The mechanical properties of starch can be improved by modifying it into thermoplastic starch by heating it with a plasticizer and other additives (Sun et al. 2014).

The production of bioplastic film from starch involves a wet process and a dry process. The wet process is a laboratory-scale method that includes casting. In contrast, the dry process involves advanced methods like extrusion and molding and can be applied to an industrial scale (Zhong et al. 2018, Liu et al. 2020). Generally, the casting method has two types- solvent casting and tape casting. The solvent casting method includes gelatinizing starch and heating it with some additives to get a filmogenic solution.

Further, the fibrogenic solution is dried onto Teflon sheets or petri plates to get thin plastic films. The tape casting method is different from the solvent casting method in that the drying of the fibrogenic solution is controlled by heat convection. To produce high-quality plastic products, the modified thermoplastic starch can be subjected to advanced methods like thermoforming, compression molding, injection molding, and extrusion (Emin 2017). Starch-based bioplastic is used as a food packaging material and for disposable utensils. About 80% of the total bioplastic production is contributed by starch-based bioplastic.

Microorganisms-based Bioplastics

Polylactic acid (PLA): The monomer precursor for PLA is lactic acid, produced by the chemical synthesis of carbohydrates. The process involved in the production of PLA includes bacterial fermentation and enzymatic hydrolysis of lactide (Lim et al. 2008). Ring-opening polymerization and direct condensation of acid-free in the solution are also used for producing PLA (Mehta et al. 2005, Rasal et al. 2010). PLA is a thermoplastic with high transparency, gloss, stiffness, printability, brittleness, processability, low melting strength, and aroma barrier (Lim et al. 2008). After modification, PLA is used with additives such as plasticizers, starch, and fillers.

Further, the stiffness and tensile strength can be improved by blending PLA with biodegradable polymers. Recently, PLA has been used in food packaging. PLA can be used for various applications after modification (Mehta et al. 2005, Rasal et al. 2010).

Polyhydroxyalkanoates (PHA): PHA is obtained as a result of bacterial fermentation of lipids and sugars. The fermentation of PHA involves two stages, viz., producing a high-density culture followed by increasing the concentration of PHA. Balanced pH, low stirrer speed, and temperature ranging between 30°C -37°C are conditions for optimal production. Whenever a bacterial cell experience nutrient imbalance, it accumulates PHA as a nutrient reserve (Kawaguchi et al. 2016). It is required to break the bacterial cell to obtain PHA, followed by solubilizing this cellular material (Snell & Peoples 2009). Various prokaryotes, including bacteria and archaes, *Pseudomonas aeruginosa, P. putida,* and *E. coli* are suitable for PHA production. In addition, several kinds of bacterial cultures are capable of PHA production.

Gram-negative, as well as gram-positive bacteria produce PHA. Different kinds of bioplastic are obtained by selecting high PHA-producing bacterial species, altering and managing the process conditions, and using additives (Keenan et al. 2006, Suriyamongakol et al. 2007). A big constraint in PHA production is cost, which could be resolved by selecting appropriate media capable of producing large quantities of PHA. Further, starchy wastewater, corn, whey, rice bran, and industrial waste effluents can be utilized as a cheap source of fermentation. PHA is usually combined with monomers to enhance their properties. They possess characteristic properties similar to synthetic polymers like Polypropylene (PP) and Polyethylene (PE) (Mannina et al. 2019). PHA is brittle, ductile, thermosensitive, and has a high production cost, which limits its applications (Keskin et al. 2017, Vandi et al. 2018, Valentini et al. 2019, Kim et al. 2005). PHA are eco-friendly and biodegradable and are used as packaging material.

Polyhydroxybutyrate (PHB): PHB is transparent, biodegradable, and resembles polypropylene in many characteristic properties. PHB is obtained as a result of the action of the bacteria. The synthesis of PHB includes a complex enzymatic process. Firstly, the condensation of two molecules of acetyl CoA leads to the production of acetocetyl-CoA; β-ketothiolase act as a catalyzer in this process. Further, acetoacetyl CoA reduces itself, producing β-hydroxybutyryl-CoA. Finally, the polymerization of β-hydroxybutyryl-CoA results in the synthesis of PHB. PHB exists as cysts in the cytoplasm of the bacterial cell, and these cells are destroyed to obtain PHB. PHB is produced and accumulated by a wide range of bacteria. About 300 species of bacteria are found to produce PHB, but the amount of PHB capable of producing bioplastic is present in very few species. Although PHB can be utilized for a number of applications, the high production cost is a matter of concern (Singh et al.

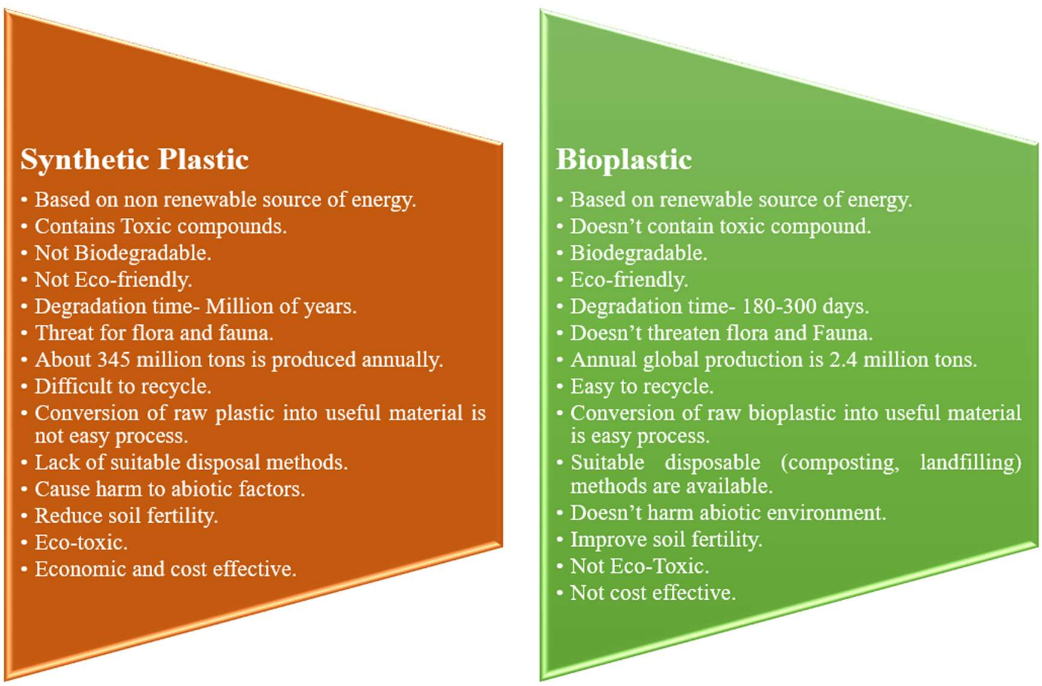


Fig. 3: Comparison of synthetic plastic with bioplastic.

2009). After suitable pre-treatment, agricultural waste and industrial waste effluents may be utilized in the production of PHB to reduce the cost constraints. A few bacterial species capable of producing PHB are *Pseudomonas, Ralstonia eutropha, Staphylococcus,* and *Bacillus*. Fig. 3 shows the general points of comparison between synthetic plastic and bioplastic.

Biodegradation of Bioplastics

Biodegradation of plastic involves specific changes in plastic material's chemical and physical properties by the action of microorganisms like fungi, bacteria, actinomycetes, etc. (Ishigaki et al. 2004). Plastics are degraded both aerobically and anaerobically. Aerobic biodegradation involves the degradation of plastic in the availability of oxygen. The microbes use oxygen as an electron acceptor to break down plastic material into more minor organic compounds, leaning behind CO_2 and water as the by-product. Anaerobic biodegradation is the breakdown of plastic waste in the unavailability of oxygen. Microbes use nitrate, sulfate, and CO_2 as electron acceptors, breaking the organic chemicals into smaller components. In this process, methane is produced as a by-product (Mohe et al. 2008, Priyanka & Archna 2011, Haider et al. 2019).

Mechanism of Biodegradation

The primary mechanism behind plastic biodegradation is microorganisms sticking on the polymer surface's hydrophilic end. After being attached to the polymer surface, the microbes use the latter as a carbon source and obtain nutrition for growth. These microorganisms reduce extracellular enzymes, which act on specific sites in the plastic material (Shah, 2014).

These enzymes work directly on the plastic, transforming the polymer into a shorter chain and low molecular weight fragments like dimers, monomers, and oligomers. The monomer of small size enters the cell to be hydrolyzed by an internal enzyme (Shah et al. 2008, Sivan 2011). The final stage of biodegradation is the assimilation of monomers into a microbe to generate cellular biomass, CO_2, and methane, depending upon oxygen availability. The mechanism behind biodegradation of bioplasic is shown in Fig. 4. Several factors affect the process of degradation. The type of organism, molecular weight and density of the polymer, molecular composition, hardness, physical form of polymer, pH, and moisture content. Fig. 5 shows the various factors that affect the process of biodegradation.

Biodegradability in Compost

Composting involves the microbes-assisted conversion of organic matter into CO_2 and humus. Compostable plastic is considered biodegradable (Kale et al. 2007). Several studies have been conducted on the biodegradability of plastic in compost. Various environmental conditions like temperature, pH, and humidity affect the process of biodegradation of bioplastic in compost (Rudnick et al. 2011). Bioplastic degradation in compost took about 90-110 days, and the degradability rate was 79.9- 85% (Sarasa et al. 2009, Gomez & Michel 2013, Weng et al. 2011). Biodegradability of PLA ranged from 13-84% under different temperatures and

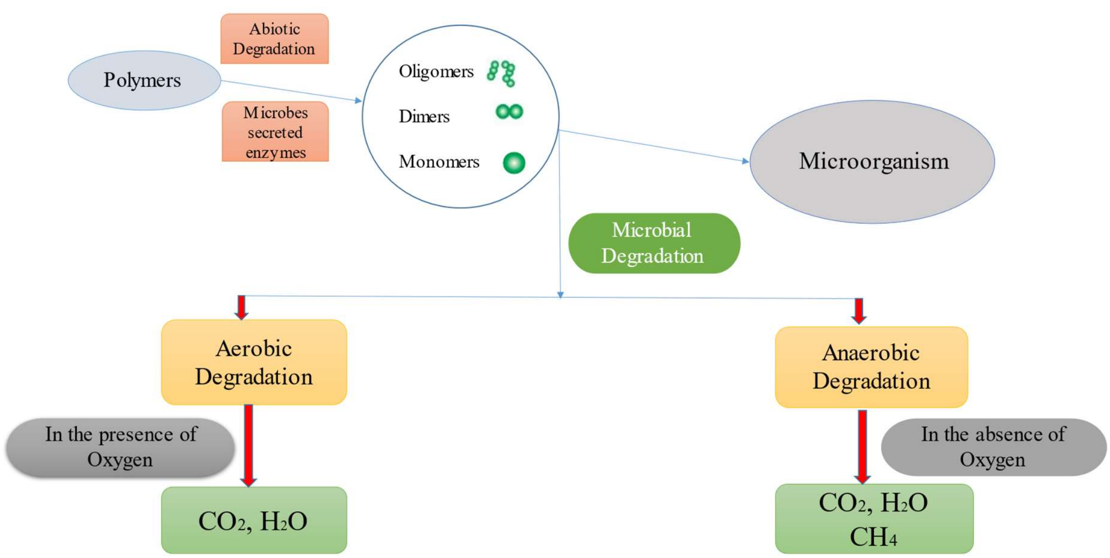


Fig. 4: Mechanism of biodegradation of bioplastics.

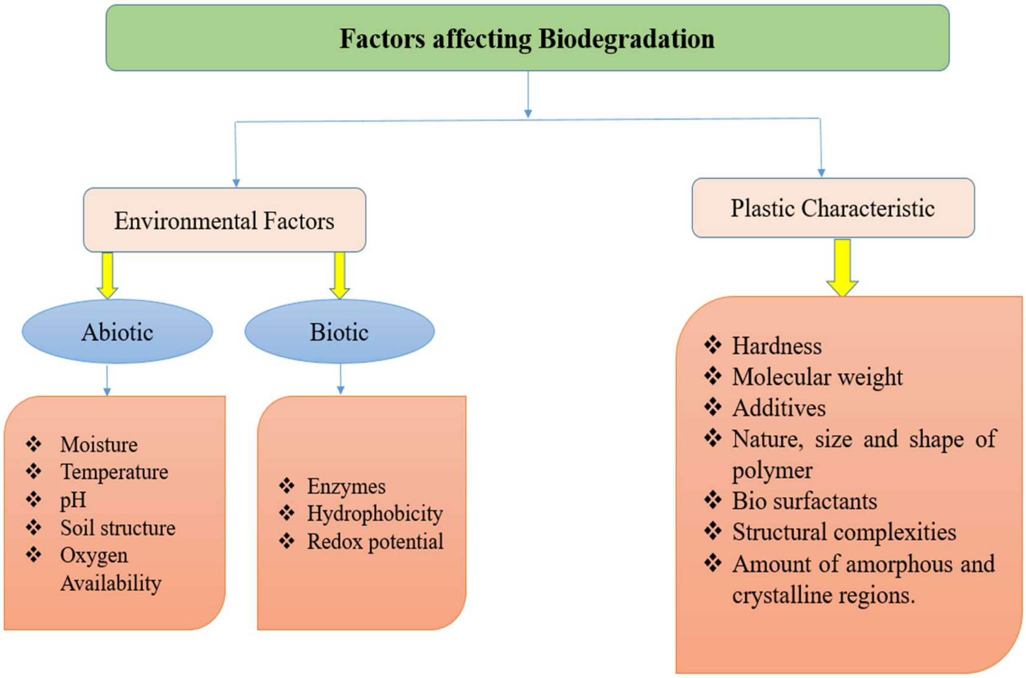


Fig. 5: Factors affecting the process of biodegradation.

humidity conditions in compost (Kale et al. 2007, Ahn et al. 2011, Mihai et al. 2014, Tabasi & Ajji 2015).

Biodegradability in Soil

A huge number of microorganisms are found in the soil environment. The action of this microorganism on the bioplastic accelerates the process of biodegradation. The rate of biodegradation depends on the soil environment and the microorganisms present. The rate of biodegradation ranged from 10-53%, 31.5-98%, 40-48.5%, and 60% for PLA, PHB, PHA, and starch-based bioplastic, respectively (Adhikari et al. 2016, Jain & Tiwari 2015, Jain & Verma 2015, Harmaen et al. 2015, Wu 2014, 2012, Gomez & Michel 2013, Boyandin et al. 2013).

Biodegradability in Aquatic Systems

The degradation rate varied in different kinds of seawater (Sekiguchi et al. 2011). Biodegradation is affected by the shape and type of bioplastic and water temperature (Volova et al. 2007). In their study, Volova et al. 2010 found that the degradation rate of PHA films is faster/higher than PHA pellets. The addition of sediments positively affects biodegradation (Thellen et al. 2008).

Role of Microorganisms in Biodegradability

Different microorganisms, including eukaryotic, aerobic, and anaerobic bacteria, catalyzed and accelerated bioplastic biodegradation (Lee et al. 2005, Kumaravel et al. 2010). Table 1 shows the different kinds of bioplastics and the microorganism responsible for their biodegradation. Both intracellular and extracellular enzymes aid in the enzymatic degradation of bioplastic. Enzymes like depolymerase, lipase, and esterase obtained from different microorganisms are very effective in bioplastic degradation (Tokiwa & Calabia 2004, Chua et al. 2013, Trivedi et al. 2016).

Application of Bioplastics

Bioplastics are used mainly in food packaging and agriculture (Briassoulis et al. 2010). With the advancement in technology and increased interest of researchers in bioplastics, the quality of bioplastics is improved. Thus, it can be used for preparing automobile parts like dashboards. Bioplastic is used in the manufacturing of sanitary products and medical implants. Table 2 shows the different kinds of bioplastic and their applications.

Market Status and Future

Different kinds of bioplastics have been introduced in the global market. The annual global production is about 2.4 million tons, which accounts for 2% of the total plastic production. The production of bioplastic is expected to increase in the future. Bioplastic is widely used for packaging (about 48%) and can be used as single-use plastic. The most commonly used and produced bioplastic is starch-based

Table 1: Different kinds of bioplastics and their degrading microorganisms.

Bioplastic	Degrading Microorganism	Reference
Polyhydroxybutyrate (PHB)	• *Streptomyces* sp. • *Bacillus* sp. • *Mycobacterium* sp. • *Nocardiopsis* sp. • *Streptomyces bangladeshensis* • *Pseudomonas lemoignei* • *Entrobacter* sp. • *Bacillus* sp. • *Gracibacillus* sp.	(Hoang et al. 2007) (Kumaravel et al. 2010) (Volova et al. 2010
Polyhydroxyalkanoates (PHA)	• Pseudomonas putida • *Leptothrix* sp. • *Variovorax* sp. • *Psedomonas aerugusina* • *Bacillus subtilis* • *Psedomonas fluorescens* • *Psedomonas putida* • *Psedomonas* sp.	(Volova et al. 2007) (Bhatt et al. 2008)
Starch-based Bioplastic	• Clostridium acetobutylicum • Laceyella sacchari	(Yoshida et al. 2016)

Table 2: Applications of different kinds of Bioplastics.

Bioplastics	Polyhydroxyalkanoates (PHA)	Starch-based Bioplastics	Cellulose-based bioplastics	Polylactic Acid (PLA)
Application	Tissue Engineering, Pharmaceutical applications, Packaging, Bottles, Pens, Cosmetic containers, Composting bags, Fishing net.	Mulch films, Fruits and vegetable packing tray, Food packaging.	Gardening products, Polymer blend, Agriculture net and films, Disposable gloves, Food packaging.	Agricultural mulches, Food packing films, Medical applications (Implants, nails), Cosmetic packaging, Automobile applications (Dashboard and door treadplates).

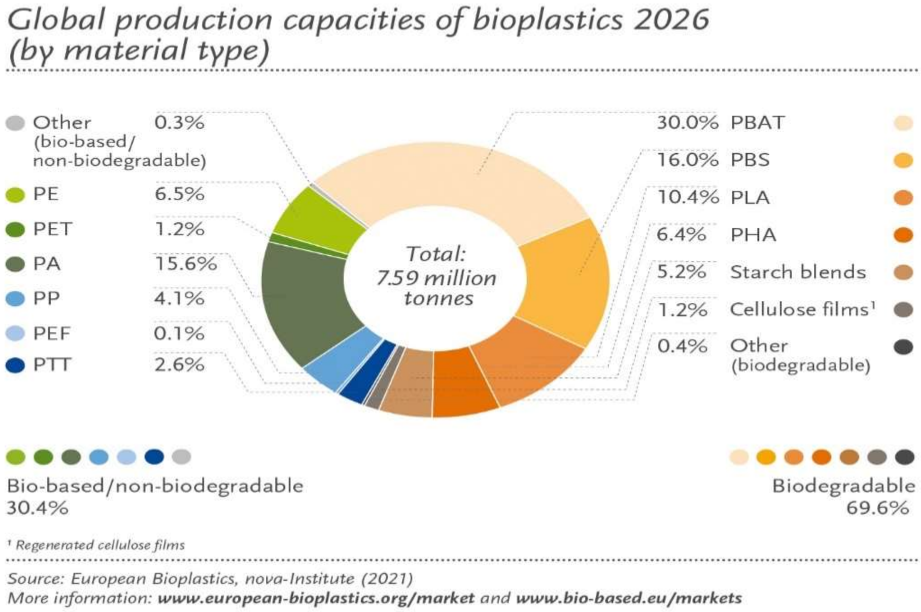
(Source: Muniyandi et al. 2020, Zhang et al. 2019, Luchese et al. 2017, Nunes et al. 2020, Mozaffari et al. 2019, Rahman et al. 2019).

(European Bioplastics 2020). There is estimated to be a 25% growth in the global bioplastic market by 2023 (European Bioplastics 2018).

According to the latest report of European Bioplastic in cooperation with nova institute, global bioplastic production is expected to be approx. 7.59 million tons by the year 2026 (Fig. 6). PLA, PHA, and starch-based bioplastic account for more than 64% of bioplastic production capacities. Bioplastic has found many applications in packaging, electronics, automobiles, etc. (European Bioplastic 2021).

There are many global producers and suppliers of bioplastics based on starch, PLA, PHA, and cellulose. Various global producers and suppliers of various kinds of bioplastic are listed in Table 3. Asia has the largest manufacturing capacities of about 50-55% of the bioplastic. The bioplastic market is not much developed in India; the significant bioplastic producers in India are m/s NatureTec, m/s Biotec Bags, m/s Envigreen, Ecolife, Truegreen, and Plastobag. According to a report of the Central Pollution Control Board (CPCB), India, 120 sellers have been granted licenses for selling compostable and biodegradable products in India. The bioplastic market shall grow considerably in the next few years. Many big companies have also started using biobased products. McDonalds uses bowls made with PLA for serving fresh salad, Mosburger uses cups made with PLA for beverages (Sudesha & Iwata 2008), Walmart uses biobased trays wrapped with cellulose films for packing kiwi, and Boulder Canyon uses metalized cellulose films for packing potato chips.

The commercialization of bioplastic has also become a global challenge because bioplastic production is not sustainable and economic. The cost of production of bioplastic is 2-4 times higher compared to synthetic plastic. The high production cost is a major issue and is mainly contributed to a lack of adequate technologies, slow growth of microbes, and high energy requirements (European



(Source: European Bioplastics, nova-institute 2021.)

Fig. 6: Global production capacities of bioplastic by the year 2026.

Table 3: Global producers and suppliers of various kinds of bioplastics.

Kind of bioplastic	Brand Name	Country
Cellulose-based	Natural flex	UK
	Tenite	USA
	Biograde	Germany
	Sateri	China
Starch-based	Mater-Bi	Italy
	Livan	Canada
	Ever corn	Japan
	Plaststa rch	USA
	Rodenburg biopolymers	Netherlands
	Cardia Bioplastics	Australia
	GreenDot Bioplastics	USA
	GXT Green Products Pvt Ltd	India
	EnviGreen	India
Polylactic Acid (PLA)	Biofoam	Netherland
	Ingeo	USA
	Hisun	China
	Biofront	Japan
	Greengran	Netherlands
	Good Natured Products Inc.	Canada
	Total Corbion PLA	Netherlands
	NatureWorks LLC	US
Polyhydroxyalkanoates (PHA)	Minerv	Italy
	Biogreen	Japan
	Biocycle	Brazil
	Green Bio	China
	Metabolix	USA
Polyamide	Arkema	France
	Evonik	Germany
Polyhydroxybutyrate (PHB)	Kaneka Corp	Japan

(Source: Palaniswamy & Venkatachalam 2020, Goel et al. 2021)

Bioplastic 2020, Hatti-Kaul et al., 2020, Bhatia et al. 2021).

Another issue is using first-generation feedstock like sugarcane, corn, wheat, and cassava for bioplastic production (Okolie et al. 2019). Using renewable and inedible feedstock (crop residue, woody biomass) and multiple fission to increase microbes' growth rate and optimize culture conditions may prove useful (Bhatia et al. 2021, Prasanth et al. 2021).

The technologies used for bioplastic production are relatively new and are used at a small scale. The large-scale production of bioplastic may help in substituting traditional plastic and also in resolving problems related to environmental problems.

Limitations of Bioplastics

The major drawback of bioplastic is its cost of manufacturing, which is much higher than synthetic plastic. Bioplastics get mixed with synthetic plastics and affect the recycling process of synthetic plastic. Thus, segregating them is needed (Arikan & Ozsoy 2015). Bioplastics are made from starch, cellulose, and other feedstocks and have many limitations. They possess poor mechanical strength and thermal instability. Their biodegradability and long-term stability are another matter of concern. These bioplastics give brittleness and poor processability because they are hydrophilic (Palaniswamy & Venkatachalam 2020). Bioplastics are generally regarded as compostable and biodegradable. But not all the bioplastics are compostable. Their biodegradability and compostability vary with their composition. Composting of bioplastic requires treatment at the industrial level. Certain kinds of bioplastics are degradable only under certain temperature ranges and humidity. There is no appropriate legislation regarding the production and applications of bioplastic, and there is a lack of standards for waste management (Arikan & Ozsoy 2015). Many edible food substances, such as corn and potato, extract starch from them for the production of bioplastic, which may affect food safety. And the over-utilization of these raw materials may reduce their reserves for future use. Many unedible food by-products and agro-residues can be used for preparing bioplastic (Lagaron & Lopez-Rubio 2011).

CONCLUSIONS

This review has disclosed the types of plastic material being used, the different methods of polymerization and problems caused by their overuse, and the alternative solution, "bioplastic," their sources, applications, and biodegradability. Bioplastics are biodegradable, made from natural and renewable sources, compostable, and able to be recycled and burned without producing toxins. This is high time to go for further growth of bioplastics. There is a need to develop standards for bioplastic production and waste management. Based on various studies, it can be concluded that it takes about 3-4 months for the biodegradation of bioplastic. The biodegradability of bioplastic must be popularized, and society must be made aware of the benefits of using bioplastic. The government must deal with the retailer and food industry to enhance the use of bioplastic. Starchy food waste, lignocellulosic agro-residue, starchy wastewater, and industrial waste effluent have been used by many researchers for preparing bioplastic. The production of bioplastic from different kinds of feedstock should be explored. There is a need for environmental awareness and improved methods for manufacturing biomass into plastic. This article studied the global market status of bioplastics. There are many producers and sellers of bioplastic globally, yet the bioplastic market is not much developed. Leading brands and Companies must invest in the production of bioplastic. Currently, these bioplastics find application in filmmaking and food packaging. But with the help of further research and improved technologies, the properties of the bioplastic may be improved.

REFERENCES

Adhikari, D., Mukai, M., Kubota, K., Kai, K., Kaneko, N., Araki, K.S. and Kubo, M. 2016. Degradation of bioplastics in soil and their degradation effects on environmental microorganisms. J. Agri. Chem. Environ., 5: 23-34.

Ahn, H.K., Huda S.M., Smith, M.C., Mulbry, W., Schmidt, F.W. and Reeves, B.J. 2011. Biodegradability of injection molded bioplastic pots containing polylactic acid and poultry feather fiber. Bioresour. Technol., 102(7): 4930-4933.

Andersen, M.E., Clewell, H.J., Tan, Y.M., Butenhoff, J.L. and Olsen, G.W. 2006. Pharmacokinetic modeling of saturable, renal resorption of perfluoroalkyl acids in monkeys—probing the determinants of long plasma half-lives. Toxicology, 227(1-2): 156-164.

Arikan, B.E. and Ozosy, D.H. 2015. A review: investigation of bioplastic. J. Civ. Eng. Arch., 9: 188-192.

Babu, P.R., O'Connor, K. and Seeram, R. 2013. Current progress on bio-based polymers and their future trends. Prog. Biomater., 2(1): 1-16.

Bhatia, S.K., Otari, S.V., Jeon, J.M., Gaurav, R., Choi, Y.K., Bhatia, R.K., Pugazhendhi, A., Kumar, V., Banu, J.R. and Yoon, J.J. 2021. Biowaste-to-bioplastic (polyhydroxyalkanoates): conversion technologies, strategies, challenges, and perspective. Biores. Technol., 326: 124733.

Bhatt, R., Shah, D., Patel, K.C. and Trivedi, U. 2008. PHA–rubber blends: Synthesis, characterization, and biodegradation. Bioresour. Technol., 99(11): 4615-4620.

Boyandin, A.N., Pudnikova, V.S., Karpov, A.V., Ivonin, V.N., Lanh Do, N., Nguyen, T.H., Hiep Le, T.M., Filichev, N.L., Levin, A.L., Filipenko, M.L., Volova, T.G. and Gitelson, I.I. 2013. Microbial degradation of polyhydroxyalkanoates in tropical soils. Int. Biodeter. Biodegrad., 83: 77-84.

Briassoulis, D., Dejean, C. and Picuno, P. 2010. Critical Review of Norms and Standards for Biodegradable Agricultural Plastics Part II: Composting. J. Polym. Environ., 18(3): 364-383.

Casado, M.P., Macken, A. and Byrne, H.J. 2013. Ecotoxicological assessment of silica and polystyrene nanoparticles assessed by a multitrophic test battery. Environ. Int., 51: 97-105.

Chen, Y.J. 2014. Bioplastics and their role in achieving global sustainability. J. Chem. Pharm. Res., 6(1): 226-231.
Chua, T.K., Tseng, M. and Yang, M.K. 2013. Degradation of poly(e-caprolactone) by thermophilic *Streptomyces thermoviolaceus* Subsp. *thermoviolaceus* 76T-2. AMB Express, 3(1):1-8.
Chung, S.Y., Yettella, R.R., Kim, J.S., Kwon, K., Kim, M.C. and Min, D.B. 2011. Effects of grilling and roasting on the levels of polycyclic aromatic hydrocarbons in beef and pork. Food. Chem., 129(4):1420-1426.
Cole, M., Lindeque, P., Fileman, E., Halsband, C., Goodhead, R. and Moger, J. 2013. Microplastic ingestion by zooplankton. Environ. Sci. Technol., 47(12): 6646-6655.
David, A., Thangavel, D.Y. and Sankriti, R. 2019. Recover, recycle and reuse: An efficient way to reduce the waste. Int. J. Mech. Prod. Eng. Res. Dev., 9(3): 31-42.
Della, T.C., Bergami, E., Salvati, A., Faleric, C., Cirino, F., Dawson, K.A. and Corsi, I. 2014. Accumulation and embryotoxicity of polystyrene nanoplastic at a bearly stage of development of sea urchin embryos *Paracentrotus lividus*. Environ. Sci. Technol., 48(20): 12302-12311.
Dey, K.T. and Tripathi, M. 2010. Thermal properties of silicon powder filled High-density Polyethylene composites. Thermochim. Acta., 502(1-2): 35-42.
Emin, M.A. and Schuchmann, H.P. 2017. A mechanistic approach to analyze extrusion processing of biopolymers by numerical, rheological, and optical methods. Trends Food Sci. Technol., 60: 88-95.
European Bioplastics 2018. Bioplastics market data 2018. https://www.european-bioplastics.org/wp-content/uploads/2016/02/Report_Bioplastics-Market-Data_2018.pdf
European Bioplastics 2020. Bioplastics - facts and figures. https://docs.european-bioplastics.org/publications/EUBP_Facts_and_figures.pdf
European Bioplastics 2021. Bioplastics Market Development Update 2021. https://docs.european-bioplastics.org/publications/market_data/Report_Bioplastics_Market_Data_2021_short_version.pdf
Fang, L., Leng, Y. and Gao, P. 2005. Processing of hydroxyapatite-reinforced ultrahigh molecular weight polyethylene for biomedical applications. Biomaterials, 26(17): 3471-3478.
Faris, N.A., Noriman, N.Z. and Sam, S.T. 2014. Current research in biodegradable plastic. Appl. Mech. Mater., 679: 273-280.
Faure, F., Saini, C., Potter, G., Galgani, F., Alencastro, L.F. and Hagmann, P. 2015.An evaluation of surface micro- and mesoplastic pollution in aquatic ecosystems of the Western Mediterranean Sea. Environ. Sci. Pollut. Res., 22(16): 12190-12197.
Goel, V., Luthra. P., Kapur, S.G. and Ramakumar, V.S.S. 2021. Biodegradable/bioplastics: Myths and realities. J. Polym. Environ., 29: 3079-3104.
Gomez, E.F. and Michel, F.C. 2013. Biodegradability of conventional and bio-based plastics and natural fiber composites during composting, anaerobic digestion, and long-term soil incubation. Polym. Degrad. Stab., 98(12): 2583-2591.
Goswami, G., Goswami, M.G. and Purohit, P. 2015. Bioplastics from organic waste. Int. J. Eng. Res. Technol., 3(23): 1-3.
Gregory, M.R. 2009. Environmental implications of plastic debris in marine settings-entanglement, ingestion, smothering, hangers-on, hitch-hiking, and alien invasion. Phil. Trans. R. Soc. B., 364: 2013-2025.
Haider, T.P., Volker, C., Kramm, J., Landfester, K. and Wurm, F.R. 2019. Plastics of the future? The impact of biodegradable polymers on the environment and society. Angew. Chem. Int. Ed., 58(1): 50-62.
Harmaen, A.S., Khalina, A., Azowa, I., Hassan, M.A., Tarmain, A. and Jawaid. M. 2015. Thermal and biodegradation properties of poly(lactic acid)/fertilizer/oil palm fibers blend biocomposites. Polym. Compo., 36 : 576-583.
Hatti-Kaul, R., Nilsson, L.J., Zhang, B., Rehnberg, N. and Lundmark, S. 2020. Review designing biobased recyclable polymers for plastics. Trend. Biotech., 38(1): 50-67.
Hoang, K.C., Tseng, M. and Shu, W.J. 2007. Degradation of polyethylene succinate(PES) by a new thermophilic *Microbispora* strain. Biodegard., 18(3): 333-342.
Hong, G.L., Yuhana, Y.N. and Zawawi, E.Z.E. 2021. Review of bioplastic as food packaging materials. AIMS. Mater. Sci., 8(2): 166-184.
Huang, X., Ke, Q., Kim, C., Zhong, H., Wei, P., Wang, G., Liu, F. and P. Jiang. 2007. Non-isothermal crystallization behavior and nucleation of LDPE/AI nano- and microcomposites. Polym. Eng. Sci., 47(7):1052-1061.
Ishigaki, T., Sugano, W., Nakanishi, A., Tateda, M., Ike, M. and Fujita, M. 2004. The degradability of biodegradable plastics in aerobic and anaerobic waste landfill model reactors. Chemosphere, 54(3): 225-233.
Jain, R. and Tiwari, A. 2015. Biosynthesis of planet-friendly bioplastic using renewable carbon source. J. Environ. Heal. Sci. Eng., 13: 11.
Jain, R. and Verma, V.K. 2015. Synthesis and characterization of cadmium selenide nanoparticles for optoelectronic application. Int. J. Sci. Engine. Technol., 2: 11-16.
Kale, G., Auras, R., Singh, S.P. and Narayan, R. 2007. Biodegradability of polylactide bottles in real and simulated composting conditions. Polym. Test., 26(8): 1049-106.
Karana, E. 2012. Characterization of 'Natural' and 'High-Quality' Materials to Improve Perception of Bioplastics. J. Clean. Prod., 37: 316-325.
Kawaguchi, H., Hasunuma, T., Ogino, C. and Kondo, A. 2016. Bioprocessing of bio-based chemicals produced from lignocellulosic feedstocks. Curr. Opin. Biotechnol., 42: 30-39.
Keenan, T.M., Nakas, J.P. and Tanenbaum, S.W. 2006. Polyhydroxyalkanoate copolymers from forest biomass. J. Ind. Microbiol. Biotechnol., 33(7): 616-626.
Keskin, G., Kızıl, G, Bechelany, M. and Pochat-Bohatier. 2017. Potential of polyhydroxyalkanoate (PHA) polymers family as substitutes for petroleum-based polymers for packaging applications and solutions brought by their composites to form barrier materials. Pure Appl. Chem., 89(12): 1841-1848.
Khyalia, P., Gahlawat, A., Jugiani, H., Kaur, M., Laura, S, J. and Nandal, M. 2022. Review on the use of microalgae biomass for bioplastic synthesis: A sustainable and green approach to control plastic pollution. Pollution, 8(3): 844-859.
Kim, H.S., Yang, H.S., Kim, H.J., Lee, B.J. and Hwang, T.S. 2005. Thermal properties of agro-flour-filled biodegradable polymer bio-composites. J. Therm. Analy. Calorimet., 81(2): 299-306.
Kuhn, P., Semeril, D., Matt, D., Chetcuti, J.M. and Lutz, P. 2007. Structure–reactivity relationships in SHOP-type complexes: tunable catalysts for the oligomerization and polymerization of ethylene. Dalton. Trans., (5): 515-528.
Kumaravel, S., Hema, R. and Lakshmi, R. 2010. Production of polyhydroxybutyrate (bioplastic) and its biodegradation by *Pseudomonas lemoignei* and *Aspergillus niger*. J. Chem., 7(S1): S536-S542.
Lagaron, J.M. and Lopez-Rubio, A. 2011. Nanotechnology for bioplastics: Opportunities, challenges, and strategies. Trend Food. Sci. Tech., 22(11): 611-7.
Laist, D.W. 2006. Overview of the biological effects of lost and discarded plastic debris in the marine environment. Mar. Pollut. Bull., 18(6): 319-326.
Lim, T.L., Auras, R. and Rubino, M. 2008. Processing technologies for poly (lactic acid). Prog. Polym. Sci., 33: 820-852.
Liu, W., Wang, Z., Liu, J., Dai, B., Hu, S., Hong, R., Xie, H., Li, Z., Chen, Y. and Zeng, G. 2020. Preparation, reinforcement, and properties of the thermoplastic starch film by film blowing. Food. Hydrocoll., 108: 106006.
Luchese, C.L., Sperotto, N., Spada, J.C. and Tessaro, I.C. 2017. Effect of blueberry agro-industrial waste addition to corn starch-based films for the production of a pH-indicator film. Int. J. Biol. Macromol., 104: 11-18.

Luckachan, G.E. and Pillai, C.K.S. 2011. Biodegradable polymers- A review of recent trends and emerging perspective. J. Polym. Environ., 19: 637-676.

Maddah, A.H. 2016. Polypropylene as a promising plastic: A review. American J. Polym. Sci., 6(1): 1-11.

Mannina, G., Presti, D., Montiel-jarillo, G. and Suarez-ozeda E. M. 2019. Bioplastic recovery from wastewater: A new protocol for polyhydroxyalkanoates (PHA) extraction from mixed microbial cultures. Bioresour. Technol., 282: 361-369.

Manu, M.T., Soni, S., Murthy, K.R.V. and Sebastian, T.M. 2013. $Ba(Zn_{1/3}Ta_{2/3})O_3$ ceramics reinforce high-density polyethylene for microwave applications J. Mater. Sci. Mater. Electron., 24(6): 2098-2105.

Mehta, R., Kumar, V., Bhunia, H. and Upadhyay, S.N. 2005. Synthesis of poly (lactic acid): A review. J. Macro. Sci. C Polym. Rev., 45: 325-349.

Mihai, M., Legros, N. and Alemdar, A. 2014. Formulation-properties versatility of wood fiber biocomposites based on polylactide and polylactide/thermoplastic starch blends. Polym. Eng. Sci., 54(6): 1325-1340.

Mohe, R., Unmar, G.D., Mudhoo, A. and Khadoo, P. 2008. Biodegradability of biodegradable/degradable plastic materials under aerobic and anaerobic conditions. J. Waste Manag., 28(9): 1624-1629.

Morillon,V., Debeaufort, F., Blond, G., Capelle, M. and Voilley, A. 2002. Factors affecting the moisture permeability of lipid-based edible films: A Review. Crit. Rev. Food Sci. Nutr., 42(1): 67-89.

Mostafa, N.A., Farag, A.A., Abo-dief, H.M. and Tayeb, A.M. 2018. Production of biodegradable plastic from agricultural wastes. Arab. J. Chem., 11(4): 546-553.

Muniyandi, K., Punamalai, G., Sachithanatham, P., Chandersekaran, N. and Kamaraj, Y. 2020. The perspective of bioplastic: A review. Int. J. Sci. Technol. Res., 9: 374-381.

Nunes, L.A., Silva, M.L.S., Gerber, J. Z. and Kalid, R.D.A. 2017. Waste green coconut shells: Diagnosis of the disposal and applications for use in other products. J. Clean. Prod., 255: 120169.

O'Neil, C. 2010. So many polymers, so little time. MD+ DI, 32(9): 162-172

Okolie, J.A., Rana, R., Nanda, S., Dalai, A.K. and Kozinski, J.A. 2019. Supercritical water gasification of biomass: a state-of-the-art review of process parameters, reaction mechanisms, and catalysis. Sustain. Energy Fuels., 3: 578-598.

Palaniswamy, R. and Venkatachalam, H. 2020. Bioplastic world: a review. J. Advan. Scient. Res., 11(3): 43-53.

Pasch, H. and Eselem, B.P.S. 2018. Branching and molar mass analysis of low-density polyethylene using the multiple preparative fractionation concept. Polym. Chem., 9: 1116-1131.

Pathak, V.M. and Navneet, R. 2017. Review on the current status of polymer degradation: a microbial approach. Bioresour. Bioprocess., 4(15): 1-31.

Prasanth, S.M., Kumar, P.S., Harish, S., Rishikesh, M., Nanda, S. and Vo, D.V.N. 2021. Application of biomass-derived products in mid-size automotive industries: a review. Chemo., 280: 130723.

Priyanka, N. and Archana, T. 2011. Biodegradability of polythene and plastic by the help of microorganisms: A way for brighter future. J. Anal. Toxicol., 1(4): 1-4.

Rahman, R., Sood, M., Gupta, N., Bandral, D.J., Hameed, F. and Ashraf, S. 2019. Bioplastics for food packaging: A review. Int. J. Curr. Microbiol. Appl. Sci., 8(3): 2319-7706.

Rasal, R.M., Janorkar, A.V. and Hirt, D.E. 2010. Poly (lactic acid) modifications. Prog. Polym. Sci., 35(3): 338-356.

Rudnik, E. and Briassoulis, D. 2011. Degradation behavior of poly (lactic acid) films and fibers in soil under Mediterranean field conditions and laboratory simulations testing. Ind Crops Prod., 33(3): 648-658.

Saharan, B.S. and Ankita, S.D. 2012. Bioplastics-for sustainable development: A review. Int. J. Microb. Resour. Technol., 1(1): 11-23.

Sangale, K.M., Shahnawaz, M. and Ade, B.A. 2012. Review on biodegradation of polythene: The microbial approach. J. Bioremediat. Biodegrad., 3(10): 1-31.

Sarasa, J., Gracia, J.M. and Javierre, C. 2007. Study of the biodisintegration of bioplastic material waste. Bioresour. Technol., 100(15): 3764-3768.

Sekiguchi, T., Saika, A., Nomura, K., Watanabe, T., Fujimoto, Y., Enoki, M., Sato, T., Kato, C. and Kanehiro, H. 2011. Biodegradation of aliphatic polyesters soaked in deep seawaters and isolation of poly(e-caprolactone)-degrading bacteria. Polym. Degrad. Stab., 96(7): 1397-1403.

Shah, A.A., Hasan, F., Hameed, A. and Ahmed, S. 2008. Biological degradation of plastics: A comprehensive review. Biotechnol. Adv., 26(3): 246-265.

Silva, V.R., Brito, D.J. and Dhir, R. 2014. Properties and composition of recycled aggregates from construction and demolition waste suitable for concrete production. Constr. Build. Mater., 65: 201-217.

Singh, M., Patel, S.K.S. and Kalia, V.C. 2009. Bacillus subtilis a potential producer of polyhydroxy alkanoates. Microbial. Cell. Factor., 8: 38-48.

Singh, S., Shankar, S. and Shikha. 2016. Microbial degradation of plastic: A review. Int. J. Sci. Innov. Res., 4(1), 112-119.

Sivan, A. 2011. New perspectives in plastic biodegradation. Curr. Opin. Biotechnol., 22(3): 422– 426.

Snell, K.D. and Peoples, O.P. 2009. PHA bioplastic: A value-added coproduct for biomass biorefineries. Biofuels. Bioprod. Biorefin., 3: 456-467.

Sudesh, K, and Iwata, T. 2008. Sustainability of biobased and biodegradable plastics. Clean: Soil, Air, Water., 36(5-6): 43-442.

Sun, Q., Xi, T., Li, Y. and Xiong, L. 2014. Characterization of corn starch films reinforced with $CaCO_3$ nanoparticles. Plos One, 9(9): e106727.

Suriyamongakol, P., Weselake, R., Narine, S., Moloney, M. and Shah, S. 2007. Biotechnological approaches for the production of polyhydroxyalkanoates in microorganisms and plants e a review. Biotechnol. Adv., 25(2): 148-175

Tabasi, R.Y. and Ajji, A. 2015. Selective degradation of biodegradable blends in simulated laboratory composting. Polym. Degrad. Stab., 120: 435-442.

Thellen, C., Coyne, M., Froio, D., Auerbach, M., Wirsen, C. and Ratto, J.A. 2008. A processing, characterization, and marine biodegradation study of melt-extruded polyhydroxyalkanoate (PHA) films. J. Polym. Environ., 16(1): 1-11.

Thomson, C.R., Moore, J.C., Saal, F.S. and Swan, H.S. 2009. Plastics, the environment and human health: Current consensus and future trends. Phil. Trans. R. Soc. B., 364: 2153-2166.

Tokiwa, Y. and Calabia, B.P. 2004. Degradation of microbial polyesters. Biotechnol. Lett., 26(15): 1181-1189.

Tokiwa, Y., Calabia, P.B., Ugwu, U.C. and Aiba, S. 2009. Biodegradability of plastics, Int. J. Mol. Sci., 10 (9): 3722-3742.

Trivedi, P., Hasan, A., Akhtar, S., Siddiqui, M.H., Sayeed, U. and Khan, M.K.A. 2016. Role of microbes in degradation of synthetic plastics and manufacture of bioplastics. J. Chem. Pharm. Res., 8(3): 211-216.

Valentini, F., Dorigato, A., Rigotti, D. and Pegoretti, A. 2019. Polyhydroxyalkanoates/fibrillated nanocellulose composites for additive manufacturing. J. Polym. Environ., 27(2): 1333-1341.

Vandi, L., Chan, C.M., Werker, A., Richardson, D., Laycock, B. and Pratt, S. 2018. Wood-PHA composites: Mapping opportunities. Polym., 10(7): 1-15.

Volova, T.G., Boyandin, A.N., Vasiliev, A.D., Karpov, V.A., Prudnikova, S.V., Mishukova, O.V., Boyarskikh, U.A., Filipenko, M.L., Rudnev, V.P., Bá Xuân, B., Vit Dung, V. and Gitelson, I.I. 2010. Biodegradation of polyhydroxyalkanoates (PHAs) in tropical coastal waters and identification of PHA-degrading bacteria. Polym. Degrad. Stab., 95(12): 2350-2359.

Volova, T.G., Gladyshev, M.I., Trusova, M.Y. and Zhila, N.O. 2007. Degradation of polyhydroxyalkanoates in eutrophic reservoir. Polym. Degrad. Stab., 92(4): 580-586.

Weng, Y.X., Wang, X.L. and Wang, Y.Z. 2011. Biodegradation behavior of PHAs with different chemical structures under controlled composting conditions. Polym. Test., 30(4): 372-380.

Wu, C.S. 2012. Preparation, characterization, and biodegradability of renewable resource-based composites from recycled polylactide bioplastic and sisal fibers. J. Appl. Polym. Scien., 123: 347-355.

Wu, C.S. 2014. Preparation and characterization of polyhydroxyalkanoate bioplastic-based green renewable composite from rice husk. J. Polym. Environ., 22: 384-392.

Yadav, A.A., Phadatare, R.S., Kadam, A.P., Patil, S.D. and Pisal, Y.S. 2020. Utilization of plastic waste for making plastic bricks. Int. Res. J. Eng. Technol., 7(2): 152-154.

Yadav, S., Kataria, N., Khyalia, P., Rose, K.P., Mukherjee, S., Sabherwal, H., Chai, S.W., Rajendran, S., Jiang, J. and Khoo, S.K. 2023. Recent analytical techniques and potential eco-toxicological impacts of textile fibrous microplastic (FMPs) and its associated contaminates: A review. Chemo. J., 23: 138495.

Yoshida, S., Hiranga, K., Takehana, T., Taniguchi, I., Yaamji, H., Maeda, Y., Toyohara, K., Miyamoto, K., Kimura, Y. and Oda, K. 2016. A bacterium that degrades and assimilates poly(ethylene terephthalate). Science, 351(6278): 1196-1199.

Zhang, Q., Rastogi, S., Chen, D., Lippits, D. and Lemstra, P.J. 2006. Low percolation threshold in single-walled carbon nanotube/high-density polyethylene composites prepared by Mel processing technique. Carbon, 44(4): 778-785.

Zhang, X., You, S., Tian, Y. and Li, J. 2019. Comparison of plastic film, biodegradable paper, and biobased film mulching for summer tomato production soil properties, plant growth, fruit yield, and fruit quality. Sci. Horticult., 249: 38-48.

Zhong, Y., Li, Y., Liang, W., Liu, L., Li, S., Xue, J. and Guo, D. 2018. Comparison of gelatinization method, starch concentration, and plasticizer on physical properties of high-amylose starch films. J. Food. Process. Eng., 41(2): e12645.