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ANIMAL DERIVED BIOPLASTIC: AN ENVIRONMENT RESPONSIVE SUBSTITUTE TO COMBAT CLIMATE CHANGE

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ABSTRACT

Plastics derived from fossil fuels are an important part of modern life and it is the most commonly used material in every industrial sector. The use of plastics is increasing day by day and its degradation has become a great challenge. Moreover, non-degradable plastic polymers tend to accumulate as waste in the environment posing a major ecological threat and climate change issues. Therefore, the identification of microbes that can grow easily on plastic and the novel biological agents with exert degradative potential on plastic material have been reviewd herein. In light of these, the enzymatic process can lead to the conversion of plastic into water, carbon dioxide, and methane as a byproduct. Furthermore, fossil fuels utilized to make plastic items are going to be shortened, therefore scientists are finding novel biobased alternatives. In this regard, starch can be promising biopolymer for bioplastic synthesis after understanding underlysing the biological deterioration process and biotic as well as abiotic mechanisms. Hence, this review specifically presents an extensive evaluation of bioplastic from animal waste that can bring revolutionary changes in the environment to mitigate the climate changes.

Keywords*: Plastic bags; Fossil fuels; Bioplastic; Starch-based plastic; Novel biological agents*

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1. INTRODUCTION

The most commonly used material in homes as well as in every industrial sector is plastic which is synthesized artificially and manufactured in massive amounts worldwide. The utilization of plastic is steadily increasing worldwide due to its easily molding property. The plastic term originates from the Greek word "plastikos," which designates a material that can be formed into any shape. Plastic is chemically synthesized from a high molecular mass containing hydrocarbons that are cross-linked with each other in a long chain. Mainly Plastic is synthesized from fossil-based petrochemicals such as natural gas, crude oil, cellulose, coal, and salt through a crosslinking process or condensation. The plastic that is synthesized from petroleum products is polyethylene (PE), polyester, polyvinylchloride (PVC), polystyrene, and polyethylene terephthalate (PET) [1, 2] .

Plastics are used extensively in multiple applications due to its followings properties such as strength, lightness, durability, and non-biodegradability, as a result, they have replaced all the packaging materials such as paper and glass, and have become an essential component of practically all sectors [3]. Plastics have been used in practically all fields and industries due to their valuable material qualities and inexpensive manufacturing costs, including those in infrastructure, construction, automotive, electrical accessories, and packaging, among others [4]. Due to the rise in the usage of single-use containers, packaging makes up the majority of the plastic consumed among all of these [5].

According to research from 2014, the production of plastics utilizes oil as a precursor and produces 311MT of plastic yearly. This production leads to the utilization of the world 6% of the total raw oil. Only 5% of the total plastic consumed was recycled for future use, resulting in a loss of £62–92 billion in economic value. Of the entire quantity of plastic consumed, 26% by volume was utilized in the packaging industry. By 2050, it is predicted that the utilization of oil for plastic synthesis reaches up to 20% which is now 6% due to the gradually increasing demand for plastics. Annual plastic manufacturing would be twice up by 2034 and increase up to 1124 MT by 2050 [6].

2. TYPES OF PLASTICS

Plastics are characterized into four basic groups based on their point of origin and their biodegradability capacity. Biodegradable and non-biodegradable plastic is represented on a horizontal axis while the vertical axis explains the petroleum-derived and biobased plastics (**Fig. 1**). Market share percentages for several synthetic plastic types are given in **Fig. 2**.

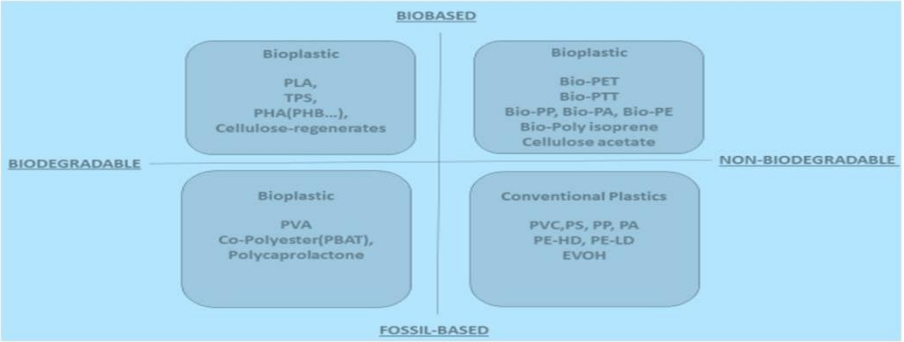

Fig. 1: Plastic classification based on their origin

1. **Petrochemical-based, non-biodegradable plastics**: The most commonly available plastics are polyvinyl chloride (PVC), Polyethylene (PE) and polystyrene are petroleum-derived plastics. These plastics are also known as conventional plastics.
2. **Sustainable resource-based biodegradable plastics**: Biobased plastics such as polyhydroxyalkanoate (PHA) and polylactic acid (PLA) are made from starch-based raw materials that can

easily degrade in the environment. These biobased plastics are made of pure starch-based particles along with water and other compounds. The carbohydrates include in this are glucose, sorbitol, and mannose.

3. **Fossil resource-based biodegradable plastics**: Some plastics which are derived from petroleum-based products can degrade the environment. This plastic includes polybutylene adipate terephthalate (PBAT), polycaprolactone (PCL), and polybutylene succinate (PBS). These plastics are utilized by combining some quantity of starch polymers with fossil fuels. Starch and various bioplastics perform better in some applications due to their biodegradable capacity and structural attributes.

4. **Renewable-source polymers that are non-biodegradable**: The plastic which is synthesized by using biobased resources of starch but cannot have degrading capability comes under this type. The most commonly used resource to produce plastic is bioethanol which can be easily formed by using sugar cane as a starch. Ethylene and bio-ethylene-based plastics come under this category. Brazil is producing bio-PE polyethylene on a massive scale [7].

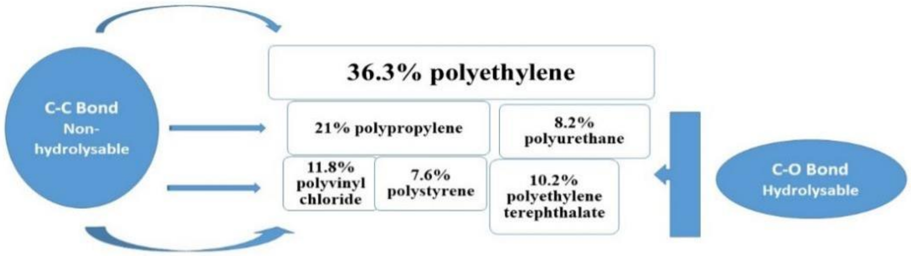

Fig. 2: Market share percentages for several synthetic plastic types.

2.1. Petroleum-derived Plastics – An environmental hazard

Although Petroleum-derived plastics have numerous advantages, since they cannot degrade, they are significantly damaging to nature. It is now clear how dangerous it is for the oceans, land, and water bodies to become clogged with this very stubborn plastic garbage [8]. According to Rahimi and Garcia (2017), worldwide production of plastic waste reaches up to 150 million tonnes annually [9]. In 2015 consumption of plastic reached over 300 MT worldwide. Plastic wastes are present everywhere, including in the oceans, lakes, rivers, and streams as well. The plastic sector also has several drawbacks connected to issues with the economy and the environment [10].

Due to their inability to biodegrade, they might stay in the environment for a very long time after being disposed of as garbage [11]. A tremendous amount of energy is utilized in the production of plastics. They represent a significant environmental danger [12]. Humans' reliance on plastic causes a variety of problems, including hazards to human and animal health. Issues with sewerage and freshwater pollution are examples of environmental pollution [4]. Plastic pollution is dispersed throughout the world's seas due to the non-biodegradable nature of plastics and their propensity to float in water. It is commonly recognized that marine species, including cetaceans, seabirds, and reptiles, are negatively impacted by plastic pollution as a result of plastic eating and entanglement [13].

- Due to their inability to biodegrade, they might stay in the environment for a very long time after being disposed of as garbage [11].
- A tremendous quantity of energy is used in the production of plastics.
- They pose a serious threat to the ecosystem [14].
- Because of our dependence on plastic, there are many issues, including risks to our health and the health of animals.
- Issues with sanitation and groundwater pollution are examples of environmental pollution [4].
- Plastic contamination has spread over all of the world's oceans since plastics are not recyclable and have a propensity to float in water.
- All the sea creatures such as fish, seabirds, and other animals die due to entrapment in plastics and its consumption leads to their ultimate death.

2.1.1. Effects of Plastic on human health

The consumption of seafood can expose people to microplastics such as by eating fish and crustaceans, through contaminated air, and by utilizing microplastic-containing water [8]. Humans are suffering from serious health problems due to their utilization daily because the size of microplastic is less than 5 millimeters. There are multiple ways by which plastics can adversely affect health such as toxins produced in the plastic due to chemicals, toxins due to small entrap Particles in plastics, and thirdly the toxins of parasites and microbes in plastics [15]. Research on the toxins generated by particles indicates that microplastic may harm the lungs and small intestines very seriously. These microplastic particles can breach various parts of the body such as they can cross the placental barrier and enter into the fetus. It can also cross the blood-brain barrier and the plasma membrane which ultimately leads to several health issues [16]. Thus, plastic particles are made up of two basic types of molecules that can be micro molecules having low molecular weight and high molecular mass containing macromolecules.

The example of macro molecules includes different types of polymers that cross-linked to form a polyester and micro molecules consist of a variety of chemicals used to form plastic and make it resistant to environmental impact. The two most dangerous chemicals that are present in plastics are Phthalates and the second one is Bisphenol-A. Phthalates are such chemicals that make plastic more flexible and durable. The adverse effect of these chemicals includes disruption of hormones especially endocrine-releasing hormones as well as retardation of growth. Bisphenol A (BPA) is also used in plastic formation, especially polycarbonate. This chemical can cause serious health-related issues such as heart problems, insulin resistance issues, and hormonal problems [8].

Plastic acts as a source of nutrients for the growth of microbes [17]. For example, plastic is a source of carbon for bacterial growth as well as acts as a medium for bacterial growth. When this infectious microplastic enters into the sewage and other household using water then it ultimately enters into the human body and causes serious health hazard diseases. Microplastic can also become a major cause of viral infection. Plastic leads as a microbial growth stimulator in standing water and ultimately this water can spread various diseases in humans such as dengue as well as the Aedes mosquito that transmit the Zika virus. This mosquito is mostly present in stagnant water. Due to the excessive use of petroleum-based products for plastic production the emission of greenhouse gases is continually increasing such as CO_2 and methane gas which leads to more environmental threats. Along with environmental issues, the excessive use of fossil fuel and petroleum products for plastic production makes it a finite resource on the earth and its price has been steadily rising, experts are actively looking for suitable replacements for it [15].

2.2. Biodegradable Plastic

Plastic that can be degraded by environmental factors and by other conditions is known as biodegradable plastic such as polybutylene succinate (PBS) and polylactic acid (PLA). In contrast to biodegradable plastic, biobased plastic can be defined as such plastic that is produced from raw material such as by using starch and other polymer-containing macromolecules [18]. Many types of macromolecules make plastic and this specific nature of plastic can be determined by the specific type of enzyme that can degrade the specific polymer [19]. Multiple factors are involved that decide the biodegradation period of a plastic such as environmental impacts, the type of material from which plastic is made, the structural properties, and the final stages of plastic.

There are two categories of biodegradable plastics:

1. Plastic originates from biological macromolecules (carbohydrates and proteins) and lignocellulosic material such as cellulosic-based plastic.
2. The second group includes such biodegradable plastic that originates from fossil fuels e.g. polycaprolactone (PCL).

2.3. Bio-based Plastics

The most significant bio-derived degradable plastics are:

- Thermoplastic starch polymers, which are made of starch (TPS)
- Plastics made from Polylactic acid (PLA)
- PHA-derived plastics such as PHB and PHBV
- Cellulose-derived plastics (cellophane)
- Animal waste based Plastic

The primary component for plastic synthesis is a polymer that can be fossil based derived or can be bio-based. Along with it the other necessary components of plastic includes additives (organic or inorganic), colors, lubricating agents, oxidants blockers, and a variety of additional additives. The basic purpose of additives in plastic synthesis is to make the plastic formation process easy and provide physical characteristics and strength. The most important thing about biodegradable plastic is that all the supporting elements for biodegradable polymers should be degradable. The requirements for biodegradable plastics demand that all additives used in the creation of the ultimate plastic product should be tested; neither of the components should harm the recycling procedure [20, 21].

2.3.1. Thermoplastic starch polymers

Starch is a polysaccharide and is the most plentiful on earth after cellulose [22]. Starch is commonly present in different cereals rice, wheat, bread, tubers, barley, etc [23]. The greater portion of starch consists of amylopectin while amylose contributes less in starch formation [24].

The utilization of starch for plastic manufacturing is due to its multiple properties such as high accessibility, easy decomposing ability as well as low price making starch the best compound for plastic synthesis. Additionally starch does not produce any harsh chemicals and other compounds after decomposition. Because starch can be easily degraded by specific enzymes present in the environment and glucose monomers are available to be reused by plants and soil [25].Thermoplastic (TPS) is a basic type of plastic that comes under the category of starch-derived plastics. The starch after passing multiple steps such as the heating process, mechanical process, and chemical process yields TPS. Thermoplastic has two types of properties it can be firm like polystyrene and it can be elastic like polyethylene (PE). The starch-based plastics are used to make biodegradable shopping bags, and mail bags that come under loosened wrapping. Starch-based plastic is also used to make different sanitation products like babies swaddle and other related products [21].

2.3.2. Polylactic acid or polylactide

Carothers, a well-known DuPont researcher, created Polylactic acid for the first time in 1932. He produced lactic acid by boiling it under high pressure, but its manufacturing was never widely adopted for commercial use. Glucose, which can be derived from a variety of sugar sources is fermented to form lactic acid. Despite being water resistant, Halogenated hydrocarbons cause Polylactic acid to lose its stability. Its basic purpose is to make the Polylactic acid plastic accessible to decompose within 3 to 4 weeks. The first polymer made from bio-based materials on an industrial basis was polylactide [22].

Multiple factors are involved in Polylactic acid degradation such as it depends on the size and structure of the material, its monomeric proportion, and the temperature. PLA degrades in the environment over a period of 6 months to 2 years [26]. Currently, PLA is used for portable dinnerware, injectable stretch blow-shaped bottles, and containers. It is widely used to make sanitary goods (baby diapers), agriculture and kitchenware wrapping paper, and packaging products of the kitchen such as bowls, plates, sheets, and food storage boxes [27].

2.3.3. PHA-derived plastics (PHB and PHBV)

Polyhydroxyalkanoate (PHA) is known as a naturally degrading polymer as they originate from aliphatic polyesters. Many natural organic molecules such as glycolide (GL) and Lactide (LA) are the main source of aliphatic ester chains that combine to form polyester. Polyhydroxyalkanoate (PLA) comes under the category of natural aliphatic polyesters chain. This type of plastic is formed by a fermentation process in which bacteria and other microbes grow on carbohydrates and lipid molecules. The sugar molecules used for bacterial growth are fructose, glucose, and sucrose. In lipids, a variety of vegetable oils come under this category. The microbes grow during the fermentation process by utilizing carbohydrates and oil as energy-containing molecules. The microbes during the growth stages secrete many polymers that can join more than 150 monomeric units to form copolymer chains and homopolymer chains. These polymers are the building block of PLA molecules. Copolymer types have very less crystalline properties as compared to homopolymers. That is the reason copolymer can be easily degraded in comparison to homopolymer [28]. Polyhydroxyalkanoate are bio based product thus it can be easily degraded in the environment [21]. Polyhydroxybutyrate (PHB) is used in many products such as in different packaging processes, and different plastic pots formation. PHBV is a Polyhydroxy butyrate -CO- β-hydroxy valerate that is used in different medical applications such as making disposable syringes and in the packaging of papers. The plastic is mainly resistant to water thus it provides full protection from water vapors. The PHA is mostly used in making packaging plastic. Copolymers are used more commonly as compared to homopolymers due to the low tensile strength of homopolymer plastic [29].

2.3.4. Cellulose-derived plastics

The most prevalent carbohydrate on earth is cellulose. It is a fundamental part of the cell wall of plants. Now cellulosic materials are used to make cellulosic plastic. Plants are the major source of cellulose production. The cellulose in plants is present with different cross-linking components such as pectin, hemicellulose, and lignin. Therefore purified cellulose is hard to achieve from plants. Besides this, the bacteria can also be used for cellulose production. The cellulose made from bacteria is free from any linked compounds. The bacterial specie used for cellulose production is acetic acid bacteria (AAB). Different species of bacteria such as *Komagataeibacter, Acetobacter,* and *Gluconacetobacter* are specific species for cellulose production [30]. Different glucose units combine to produce the linear chain polymer known as cellulose. The linkage between the glucose units is beta1-4, glycosidic linkage [31]. From plant material, the wood of trees and cotton are the main source for the textile industry. Cotton is also used to make cellulosic papers and lignocellulose plastic material [32].

2.3.5. Animal waste-based plastic

Animal waste-based plastic is counterproductive and under-exploited non-meaty products like skin, blood, and viscera. It is produced by meat refining and animal carcasses that are used to make animal waste-based plastic. The primary significant biopolymers derived from animal products are keratin, myofibrillar protein, collagen, gelatin, and chitosan. They could be utilized to create bioplastics and have a variety of uses in the food and pharmaceutical industries [33].

According to studies, animal proteins are highly functional and nutrient-dense [34]. These proteins are cheap and natural and can be a great choice for the production of biodegradable films due to their exceptional qualities. Additionally, protein films have an enriching effect on the soil during breakdown because they are biodegradable. The mostly fibrous protein found in skin, bones, ligaments, tendons, cartilage, and aquatic animals such as fish, jellyfish, and sponges is called collagen. According to Avila Rodriguez *et al*. (2018), it displays outstanding viscoelastic behavior with high tensile strength and minimal deformation. When collagen is moderately hydrolyzed, a protein called gelatin is formed. Because of their excellent visibility and impermeable qualities, gelatin films are appropriate for use in food packaging [35]. Other proteins including myofibrillar proteins, blood proteins, and keratin films were used in film production [36].

2.4. Fossils-derived biodegradable plastics

Fossil fuel-derived plastics are the inverse of bio-based plastics. These plastic types are mostly obtained from fossil-based sources such as natural coal, petroleum, and natural gases. The plastic produced from this method is resilient to biodegradability. Therefore different types of bonds are added to fossil-based plastics to make them biodegradable. The introduction of the ester bond, ether bonds, and amide bonds in synthetic plastic make it accessible to cleavage. The term "fossil-based plastic" refers to materials like polybutylene adipate terephthalate (PBAT), polybutylene succinate (PBS), polyvinyl alcohol (PVOH/PVA), oxy-degradable polymer and polycaprolactone PCL [37].

2.4.1. Polybutylene succinate (PBS)

PBS is a biodegradable plastic that originates from an aliphatic chain and its linkages. The synthesis of PBS includes the utilization of activators that act as a catalyst such as metals (titanium) act as a catalyst. PBS can be synthesized by condensation process. In this process the succinic acid and 1, 4 butanediol link in a long chain and polymerize to give PBS. It can be obtained from petroleum-based sources as well as bio-derived sources. Mainly its major production comes from fossil-based sources. PBS is most widely used in making different plants vessels, plastic films for packing, farming plastic films, and sanitary products. It can be utilized in food factories as well as medical fields to make different products. It takes up to 74 days for complete degradation [37].

2.4.2. Polybutylene adipate terephthalate

One of the fossils derived from biodegradable plastic is Polybutylene adipate terephthalate (PBAT) is a. It can be synthesized by combining 3 different compounds such as terephthalic acid, adipic acid and last one is butanediol. These compounds combine in a polymerization reaction to give PBAT. The two diacids combine with one molecule of diol to form PBAT. Polybutylene adipate terephthalate is most widely used in different industries due to its numerous qualities such as it has excellent degrading capacity. It has more tensile strength than other polymers and it can undergo processing very easily. Polybutylene adipate terephthalate (PBAT) is mostly used in making plastic waste bags, farming plastic films, and one-time-use bags. It can be easily modified with bio-based plastics to make an excellent biodegradable plastic [38].

2.4.3. Polycaprolactone

Polycaprolactone is a biodegradable plastic with a long aliphatic chain. Its synthesis begins with an opening of a closed ring structure of caprolactone. The caprolactone is a closed ring structure and after processing it converts into an open structure. The polycaprolactone is most widely used in medical fields. It is used to transfer the drugs into human body. It is used to make surgical threads (sutures) that are used after every injury or surgery. It is also used in plant tissue engineering. It can be easily modified with bio-based plastics such as (PHA/PLA) to attain the biodegradation property [38].

2.4.4. Polyvinyl alcohol

Polyvinyl alcohol (PVA) is a hydrophilic polymer. It can easily undergo a biodegradation process. It can be safely used on living tissues and cells. The presence of hydroxyl groups gives it the ability to cross-link. The OH groups are present on the polyvinyl structure as side chains. Due to hydrophilicity it can be easily soluble and undergo a rapid breakdown process. The macromolecules cannot be easily attached to the pure structure of polyvinyl due to their bio-inertness. Due to its hydrophilic property, it is used to make plastic films that can be easily dissolvable. The other uses of polyvinyl alcohol include uses in dyes, different farming chemicals, industry-related chemicals, and disinfectants [39].

2.4.5. Oxo-degradable plastics

Oxo-degradable plastics are derived from petroleum-based products. It can be combined with metals so that it can rapidly undergo a degradation process. The addition of metals like titanium, copper, tungsten, and iron inside the oxo-degradable plastic makes it accessible to exposure to light and heat. Polyethylene (PE) is used to make many products such as plastic films that are biodegradable in nature. These plastic films are also known as oxo-degradable plastic.

The oxidation reduction process which is known as redox reaction is the main cause of oxidative degradation by oxo plastics. Light, heat, and other factors act as a stimulant and produce hydroperoxide groups (ROOH). The transition metals such as iron, copper, and tungsten act as redox pair as they can accept the electrons from hydroperoxide groups (ROOH) and convert the hydroperoxide group into $RO^{\bullet}$ and OH^{-} groups. These free radicals interact with the plastic polymers and ultimately they interact with themselves to form ketones (carbonyl compounds). The formation of ketones acts as a plastic polymer cutter and the plastic is converted into small pieces. The chain breakage leads to the loss of stability as well as mechanical properties of plastic and hence plastic is completely degraded [40]. Oxo plastics that are made of Polyethylene and other petroleum-based products are used in agriculture fields as well as in markets as degradable bags that degrade over time [41].

Along with advantages, there are also many side effects of oxo plastics on marine species. These plastics don't meet the conditions for decomposing and stay in the environment for a very long time [42]. As this plastic when decomposes into small particles then these fragments of plastic remain in the oceans for a very long period and ultimately effects the marine environment. The other drawback of oxo plastics is that they cannot be recyclable as these plastic fragments have lost their mechanical strength and hence these remain in the environment without any use. In Europe, the use of oxo plastic is prohibited. The use of oxo-plastics, according to the European Parliament and Council (EPC), only contributes to further environmental damage and increases the threat rate for marine life. The parliament of Europe that access the ocean environment completely declared in March 2019 that oxo plastics cannot be used anymore [43].

3. STARCH – A PROMISING BIOPOLYMER

Starch is a promising biopolymer with numerous advantages in plastic production [44]. It is easily available in plant-based food such as cereals rice, bread, grains, and legumes. The most commonly available starch supplement is potatoes that is a rich source of starch. Along with its nutritional value starch is widely used to produce bioplastics. The bioplastics made of starch are easily decomposable and eventually recyclable in the environment with no harmful effects [45]. Starch has found its application in many areas such as in the food industry, pharmaceutical production, agriculture, packing process, and many more [46]. In studies conducted between 2012 and 2018, a variety of starches were utilized to create bioplastics. Working on sago starch started in 2012 to create bioplastics [47]. In 2016 Yusoff *et al* worked on banana peel starch [48]. In 2018 Lenz *et al* worked on maize starch [49] while Dawale and Bhagat worked on sweet potato starch [50]. Moreover, Cassava starch was used for bioplastic synthesis in 2017 [51].

3.1. Banana peels as a starch

The bioplastic can also be produced from banana peels. The peels are the essential components of fruits and vegetables that are a rich source of many nutritional compounds. The banana peels are a rich source of starch (20% -30%). These peels are used for the production of bioplastic sheets. A plasticizer (such as glycerol) is used to make bioplastic sheets softer and more elastic [52]. Sometimes the microbial resistant compounds were added to it to stop microbial growth such as sodium metabisulphite was used as an anti-microbial agent. The banana peels are also widely used to make eatable plastic films. In this, clove oil is also used as a microbial-resistant compound, and glycerol is used as a plasticizer [48].

3.2. Corn as a starch

The corn is the best source of starch. It is mostly used as a corn flour and corn starch. It is free from protein as it only contains carbohydrate components. Corn starch is widely used to make bioplastic. Along with corn starch, many reinforcing components are added to make the plastic more strong and stiff. Reinforcing fillers are the specific material that can be small fibers used to build up or strengthen metallic compounds and plastic. It can be obtained from natural as well as synthetic sources. The curious fiber is *a lignocellulosic leaves fiber* stuff that is used as a reinforcing filler in bioplastic synthesis. The corn starch and curious fibers undergo different cyclic processes and ultimately give rise to bioplastic. The bioplastic made from this method has very unique chemical and physical properties. In 2018 the corn starch biofilms were introduced with the addition of different algal species (*Spirulina*) as reinforcing fillers. The addition of fillers enhances the properties of a bioplastic [49].

3.2. Cassava as a starch

Cassava starch is also known as tapioca starch. It is obtained from the Cassava plant [53]. The word cassava is derived from the roots of plants and tapioca is the name of starch-related compounds [54]. The cassava is used to make bioplastic along with the addition of reinforcing fillers such as cellulose is used as a filler [55, 56]. Sorbitol is used as a plasticizer. Sorbitol has two benefits in the manufacturing of bioplastics. Firstly its high concentration makes the bioplastics more elongate. Secondly, sorbitol is used to accelerate the degradation process in bioplastic [57].

3.3. Rice as a starch

The rice is a natural source of carbohydrates as it consists of both amylose and amylopectin as a component of starch. Recently the use of rice starch for bio-plastic synthesis has gained a lot of attention. The use of rice starch for eatable bio-plastic film synthesis involves the utilization of plasticizers as well as different reinforcing fillers to strengthen the bioplastic [58]. A plasticizer such as sorbitol and glycerol are used in this process. The bio-plastic characteristics such as chemical and physical properties can be determined by the type of plasticizer. The bio-plastic made from rice starch can undergo biodegradation and their biodegradability can be find out by various tests. In 2010 Naggar and Faraq used different concentrations of rice starch to check which one has the best biodegradability rate [59]. In this process, the bio-plastic biodegradation was examined by contact with different ultraviolet radiations that range from 300 nm to 400 nm. In 2011 Bario rice starch was used for bio-plastic synthesis. The use of plasticizer and natural rubber in this process provided the best rice starch-based bioplastic [60].

3.4. Sago and Tapioca as a starch

The other sources of starch are sago as well as tapioca. The sources of sago starch are palm trees and tapioca starch is obtained from cassava roots. Both types are recently used to make bio-plastic. Tapioca starch is used to make bio-plastic along with Hyacinth fiber pulp [61]. Bio-plastic made from tapioca starch is also investigated by using a plasticizer such as Acetyl Tributyl Citrate. Acetyl Tributyl Citrate is a commonly used plasticizer in bio-plastic synthesis. It is also used in different industries like the paint industry, food industry as well as in skin and nail care cosmetics. It is used in polyvinyl chloride as a safe biodegradable compound and other resins [62]. Sago starch is commonly used as a food item that has many nutritional benefits. It was investigated to make bio-plastic along with glycerol as a plasticizer. In this different concentration of sago starch along with glycerol was used to make degradable bio-plastic [47].

3.5. Potato as a starch

The potato is a rich and easily available source of starch. Different research has been investigated to explore the potato starch for making bio-plastic. In 2018 potato starch was used to make bio-plastic films along with calcium chloride is used as a reinforcing filler. The production of eatable biofilms from potato starch and gelatin starch was investigated [63].

Bio-plastic can also be produced by combining more than two sources of starch. It is the most recently developed method to make amalgams that are employed to make bio-plastic. Various researchers use different combinations of starches to make bio-plastic such as combining rice starch and cassava starch to make bio-plastic [64], combining potato starch and wheat gluten protein to make bio-plastic [63], combining corn starch and banana starch [65] and rice starch and sago starch as a composite [60].

The bio-plastic has gained much attention in the past few years. It is the best alternative to fossil fuels to make plastic with the best biodegradability rate. Natural sources such as carbohydrates provide excellent use in bio-plastic synthesis. Moreover, bio-plastic can easily undergo degradation and can be renewable. It also helps to save costs by minimizing the use of limited petroleum-based plastics. So bio-plastics provide us the future saving promises as well as environmentally friendly products [66]. However, there is also some lack of research regarding the concept of bio-plastic from agricultural resources. There is a need for a lot of research and study to utilize the benefits of the agricultural field. The starch-based sources from the agriculture field are available in surplus amounts and are easily recyclable. There is a need for more research areas, opportunities, and experimental techniques to make bio-plastic a part of our globe [67].

4. ADVANTAGES OF BIO-PLASTICS

1. Less harmful run-off is produced by bioplastics
2. In contrast to bioplastics, oil-based polymers don't require fossil fuels.
3. Decrease Carbon Dioxide Emissions: Bioplastics require just 0.8 metric tonnes of Carbon Dioxide to be produced, which is 3.2 metric tonnes less than conventional plastics.
4. Minimal Greenhouse Gas Production
5. Restricting the use of fossil fuels
6. The decrease in energy consumption
7. It uses less energy.
8. Requiring Less Landfill Space

9. Eco-friendly [68].

5. PLASTIC WASTE DEGRADATION

Plastic waste can decay in two ways:

- Abiotic procedures (Physical and chemical mechanisms)
- Biotic process (Biological degradation that is an eco-friendly mechanism)

The first stage that is typically thought of as being crucial to any degradation process is the breakdown of the plastic substance by mechanically driven physical forces [69].

Plastics can degrade in the surrounding by any one of the four fundamental techniques, i.e.

1. Photo deterioration
2. Hydrolysis
3. Thermal oxidative decay
4. Biodegradation [70].

Common plastics like low-density polyethylene (LDPE), high-density polyethylene (HDPE), and polypropylene (PP) begin to degrade in natural circumstances (such as the sea environment) with photodegradation, which is mostly brought on by UV-B radiation. The deterioration then progresses by thermal oxidative mechanism and by hydrolysis to a lesser degree. Plastics become fragmented (broken into smaller pieces) during degradation processes, and the polymer's molecular size (MW) decreases. Microbes can then digest these substances with their low molecular weight [71].

5.2. Biodegradation- A Novel Biological Agent

A polymer undergoes a biological deterioration process by passing from both biotic as well as abiotic mechanisms. The biotic process includes the utilization of plastic polymer as a carbon source for microbes and in turn microbes break down the plastic and produce metabolic excretory products ($CO2$, biomass, $H2O$, etc.) etc) along with enzymes. Abiotic processes include (the hydrolysis process, oxidation, and photodegradation process) [72]. The degradation process of plastic by biotic mechanism relies on characteristics of microbes such as the kind of microbe present, their distribution, their growth circumstances (nutrients, temperature, moisture content, oxygen, and pH,), and the types of enzymes they utilize (intracellular, extracellular) [73]. Along with the nature of microorganism the type and nature of plastic also has a significant effect on biodegradability. The plastic surface conditions such as water-loving (hydrophilic) or water-hating (hydrophobic), first-order structure (molar mass and chemical configuration), and high-order structure (melting temperature Tm, Temperature at which glass transitions occur Tg) are all plastic properties that have an impact on rate [74].

Biodegradation occurs in two discrete stages

1. In the first stage, polymer chains are broken down and shortened by abiotic processes as well as extracellular enzymatic assault; enzymes preferentially break down the less-ordered amorphous portions of a plastic. As a result, a plastic's crystallinity will rise quickly before leveling out close to 100% [74].
2. The second step happens when the polymer chains are sufficiently short to be transported into the cells of the microorganisms where they can assimilate and mineralize [75].

The degradation rate of bioplastics is defined by various international standards, each of which applies under certain circumstances

Based on the standard EN 13,432:2000, bioplastics must break down by 90% and oxidize in 3 months in an industrial sector between 50 and 60 °C. In theory, it is not essential to dispose of biodegradable plastics because they may be allowed to decompose naturally. This has several benefits including greater soil fertility, less plastic ending up in landfills, and decreased waste management costs [76]. However, in practice, the degree of decomposition of a bioplastic may be substantially slower than anticipated, depending on the kind of bioplastic and the compositional circumstances. The loss of any value inherent in the polymer's molecular structure is another drawback of biodegradation.

6. FACTORS AFFECTING THE DEGRADATION RATE OF PLASTICS

According to Artham and Doble (2008), the degradation rate of plastic is based on factors such as exposure of plastic to different abiotic and biotic variables [74], as well as the properties of the plastic polymer itself (**Table 1**).

Table 1: Factors effects plastic degradation

Factors that affect plastic degradation	**Description**	**Reference**
Carbon chain	As a result of the long repeating unit of carbon, polymeric materials are difficult to biodegrade as in PP. However, the integration of the heteroatoms into the carbon chain makes them vulnerable to light and biological deterioration, much like in the case of polymers that include oxygen (like PU and PET).	[77]
Hydrophobicity	The efficacy of plastic breakdown is often influenced by its hydrophobic nature, with the degree of degradation rising as hydrophilic property rises.	[78]
Crystallinity	Plastic degrades at a different rate depending on the polymer's crystallinity [78]. Crystalline polymers require more oxygen and moisture in comparison to amorphous polymeric structures, which can start the degradation process. The amorphous regions of a polymer are regarded to be more susceptible to heat oxidation [46].	[2]
Molecular weight	The rate of deterioration of the polymer can be influenced by its molecular weight (MW). This theory proposes that the low relative surface area of high MW plastics results in slower degradation.	[77]
Morphological characteristics	Degradability is also influenced by the polymer's structural characteristics. Because the formation of biofilm is encouraged by surface roughness more than by surface smoothness due to the large surface area, its degradation rate will rise with surface roughness.	[79]
Additives	Plastic polymers are made using a variety of techniques and additives, some of which may have an impact on how quickly they degrade. The incorporation of these nanoparticles into the polymeric framework aims to enhance the permeability, structural, thermal, and electrochemical properties of the produced polymer. To reduce the rate of deterioration, stabilizers are widely used as additives during the manufacture of plastics.	[77]
Sunlight intensity	Kitamoto et al. (2011) stated that The amount of sunshine exposure has the most impact on how quickly plastics degrade; this is because more sunlight speeds up the photo-oxidation cycle [80].	[2]

Temperature	According to Pischedda et al. (2019), the breakdown process of plastic rises with the rise in temperature and the response become doubles every 10 degrees Celsius. Temperature rises also make the polymer chain more mobile, which has an impact on the enzyme activity of the bacteria during biodegradation [81]. Therefore, it is believed that the environment has a big impact on how naturally plastic waste decomposes.	[81]
Water	The presence of water is another crucial element in the degradation process. Synthetic polymer chain fragmentation is brought about by the hydrolysis of accessible functional groups.	[82]
Oxygen availability	Oxygen availability has a favorable impact on the rate of deterioration of plastics. For instance, the increased breakdown of polymers was caused by the faster interaction between carbon-centered radicals and oxygen during the early phases of degradation when oxygen levels were high.	[83]

7. FUNGAL AND BACTERIAL ROLES IN PLASTIC DEGRADATION

The degradation of polymeric materials is significantly influenced by fungi (**Table 2**). The surface of a polymeric substance can be effectively penetrated by fungi to go deeper within and break down more of the substrate (Sanchez, 2020). Additionally, depolymerase is an exoenzyme that is released by the mycelium of fungi that can fragment low molecular weight polymeric substrates into oligomers, dimers, and monomers (Ameen *et al*., 2015). The fungi then take these monomers up and use their internal enzymatic machinery to either absorb or mineralize them. In comparison to bacterial enzymes, fungi manufacture and secrete a large number of enzymes. According to this perspective, Fungi known to effectively break down polymeric materials include white- and brown-rot fungi. The ability of fungi to degrade polymeric materials is associated with their enzymatic mechanism, which excretes several extracellular enzymes including laccase (Lac), manganese peroxidase (MnP), and lignin peroxidase (LiP), all of which may break down lignin before mineralizing it (Ali *et al*., 2020).

Table 2: Fungi-related microbes for plastic deterioration

Fungi specie	**Enzyme secreted**	**Plastic-type**	**Reference**
Basidiomycetes, Ascomycetes, and Deuteromycetes	Laccases	PHA	[84]
Aspergillus flavus	Glucosidases	Polycaprolactone(PCL)	[73]
Phanerochaete chrysosporium	manganese peroxidases	Polyethylene	[85]
white-rot fungi, *Pleurotus spp., Phlebia radiata, Trametes versicolor, Bjerkandera adusta, Dichomitus squalens* and *subvermispora*	Lignin peroxidases, manganese peroxidases, multifunctional peroxidases, dye-removing peroxidase	Polyethylene	[86]
Trichoderma reesei	Cutinases	Polybutylene succinate(PBS)	[87]
Acremonium, Aspergillus, Beauveria,	Lipases	polyurethane (PUR)	[88]

Candida antarctica (CALB) *Fusarium, Geotrichum, Eremothecium, Humicola, Mucor, Ophiostoma, Penicillium, Rhizomucor, Trichoderma and Rhizopus*			
Aspergillus flavus, Aspergillus tubingensis		Polyethylene (PE)	[89]
Beauveria brongniartii	Polyesterases	PET	[90]

In the same way, bacterial strains in polluted water or soil can break down plastic polymeric materials (**Table 3**). According to various research, the biodegradation of plastics by specific bacteria can be an effective bioremediation method for damaged environments [91]. According to our analysis of the available literature, Bacterial species including *Bacillus* species, *Pseudomonas* species, and *Streptomyces* species degrade various polymeric polymers quickly [69].

Table 3: Bacteria species for Plastic Degradation

Bacteria species	Enzyme secreted	Plastic-type	Reference
Pseudomonas spp	Serine hydrolases, lipases and esterases	Polyhydroxyalkanoate (PHA)	[92]
Penicillium, Rhizopus arrises	Lipase	Polyethylene adipate(PEA), PBS, PCL	[73]
Firmicutes	unidentified	PHB, PCL, and PBS	[73]
Rhizopus Delmar	Lipase	Polycaprolactone (PCL)	[73]
Bacillus	lipase, CMCase, xylanase, chitinases, and protease	Polyethylene (PE)	[93]
Ideonella sakaiensis	Glycoside hydrolases	PE, PET	[91]
Paenibacillus amylolytic	protease and esterase	ply	[94]

8. ALGAL ROLE IN THE BREAKDOWN OF SYNTHETIC PLASTIC POLYMERS

The capacity of algae species to reduce white pollution has only recently been the subject of a small number of studies. The ability of filamentous algae to colonize the surface of trash made of plastic was due to environmental factors, such as sunshine, food, and moisture that are necessary for algal development [95]. Microalgae are a viable choice since they lack endotoxins and do not require organic carbon sources to develop under photoautotrophic conditions, unlike bacterial and fungal systems that can be seen as biological pollutants because of endotoxins and their need for a rich carbon supply [96]. The ability of certain non-toxic, non-hazardous algae species from the families of Bacillariophyceae. On plastic surfaces, Chlorophyceae and Cyanophyceae can grow and produce algal biofilms in a variety of polluted aquatic bodies, including lakes, and wastewater [97]. According to Sarmah and Rout (2018), aquatic non-toxic cyanobacteria (Phormidium lucidum and Oscillatoria subbrevis) may colonize on PE surfaces and efficiently break down LDPE without any prior pretreatment [98].

Furthermore, Moog *et al.,* (2019) produced a designed PETase that was active against both PET and the copolymer PETG by using the *Phaeodactylum tricornutum* (diatom) as a microorganism factory (polyethylene terephthalate glycol) [95]. In addition, Kumar *et al*. (2017) discovered that following algal growth on PE, surface degradation was noticed [99]. Moreover, they discovered that the blue-green alga *Anabaena spiroides*, the diatom *Navicula pupula*, and the green alga *Scenedesmus dimorphus* had degradation percentages of 3.74, 8.18, and 4.44%, respectively. According to Khoironi *et al*. (2019), *Spirulina species* can reduce PET and PPs mechanical strength by 0.9939 and 0.1977 MPa/day accordingly [100]. Algae may adhere to a surface made of plastic and begin the process of destruction by producing extracellular polysaccharides and lignin-degrading- degrading enzymes [98]. Summary of microbial degradation is shown in **Fig. 3**.

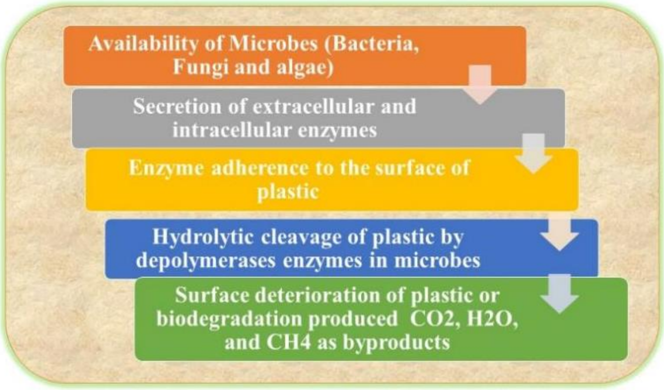

Fig. 3 : Summary of microbial degradation

9. MECHANISM OF ENZYMATIC BIODEGRADATION

Enzymatic degradation is the most promising approach to treating plastic trash. Two phases are involved in the breakdown of polyethylene by microbial enzymes. To catalyze a hydrolytic cleavage, the enzyme must first bind to the polyethylene substrate. Fungi and bacteria break down polyethylene via intracellular and extracellular depolymerase. The accumulating bacteria themselves hydrolyze their endogenous carbon content through intracellular degradation, whereas accumulating microorganisms may or may not use an external carbon source, which results in extracellular breakdown. Short chains of oligosaccharides, dimers, and monomer subunits may pass through bacterial membranes that act as carbon sources. Energy is formed when complex polymers break down. Depolymerization is the term used for this process. Moreover, mineralization is the decomposition process, with water ($H2O$), methane ($CH4$), or carbon dioxide ($CO2$) as the final products. Physical factors such as temperature, pressure, and moisture cause mechanical damage to polymers, which is then triggered by biological forces such as enzymes and other byproducts generated by bacteria [92]. The flowchart makes it simple to understand how plastics biodegrade (**Fig. 4**).

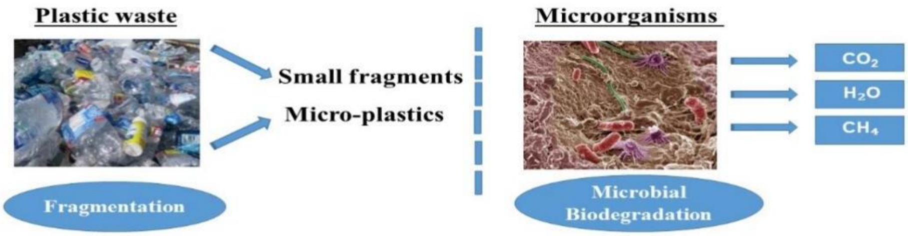

Fig. 4: Mechanism of enzymatic biodegradation of plastic (Shah *et al*., 2008).

Conclusion

As it is plastic age we are using plastic a lot in our daily life, but its excessive use has become a crucial problem for our environment. To clear this hazard people usually bury it in landfills or burn it but these steps are causing great danger to our society. Toxic gasses like furans and dioxins are produced by the burning of plastic. Ozone depletion is caused by greenhouse gases. Human endocrine hormone activity is disturbed by dioxin which is causing serious problems to human health. Soil pollution is also caused by dioxin which is of great concern for worldwide scientists. Fossil-based plastic leads to environmental pollution and its excessive use makes the fossil fuel a limited non-renewable resource on the earth. The best and most eco-friendly method for the production of plastic is bio-based plastic. In bio-based plastic, different macromolecules can be utilized such as animal waste based as well as starch based. The most commonly used biobased material is starch-based plastic. The starch-based plastic can be easily obtained from lignocellulosic material. The best advantage of biobased plastic is its degradability and ease to obtain. Biobased plastic can be easily degraded by microbes as it is economically feasible to degrade plastic by utilizing it as a microbial food. Hence, under such circumstances, the degradation of plastic by microbes is one of the eco-friendly and innovative methods. Many fungal genera and bacterial genera have been reported to degrade various kinds of plastics. Information regarding the biobased plastic, fossil-based plastic, and biodegradation of plastic bags by various novel biological agents is given in this review. It is expected that this review work will encourage young scientists to find out one or more microbial strains from nature for the potential biodegradation of plastic wastes. It also encourages researchers to work on bioplastic so that environment becomes safe from the dangerous toxins of fossil-based plastic.

Author contributions

Muhammad Arshad and Abdur Rahman Ansari: conceptualization, supervision and validation. Esha Sikandar: writing—original draft, review and editing.

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Data availability

All data is available under request.

Declarations

Ethics approval

Not applicable

Competing interests

The authors declare no competing interests.

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