Research Article

Recent Advances on Biodegradable Plastics

M. Akram[1,*], N. Aslam[2], S.M. Ho[3,*], A. Usman[4]

[1]Department of Eastern Medicine, Government College University Faisalabad, Pakistan.
[2]Department of Biochemistry, Government College University Faisalabad, Pakistan.
[3]Faculty of Health and Life Sciences, INTI International University, 71800,
Putra Nilai, Negeri Sembilan, Malaysia.
[4]School of Medical Laboratory Sciences, Department of Immunology, Usmanu Danfodiyo University, 2346, Sokoto, Nigeria.

*E-mail : muhammadakram@gcuf.edu.pk, soonmin.ho@newinti.edu.my

Abstract

In this current time, there are many environmental problems in the 21st Century due to the inability of conventional (petroleum based) plastics to degrade naturally (biodegradable) when they are disposed of on land or in our oceans, lakes, streams or rivers. Plastics are not biodegradable due to their molecular structure. Micro-organisms can decompose biodegradable plastics into their constituent compounds, such as carbon dioxide, methane, water, and biomass, making them a more sustainable alternative to traditional plastics. The two main ways companies produce biodegradable plastics are using renewable resources (biological feedstocks) or using chemical processes to create materials that will degrade by bacteria. In this literature review, biodegradable plastics are assessed including the classification, synthesis processes, material characteristics, breakdown process, and environmental effects, and finally their uses by various industries. In addition, an extensive evaluation of specific biodegradable plastics (biopolymers) including polylactic acid, polyhydroxyalkanoates, starch-based plastics, polybutylene succinate, and polycaprolactone will also be included. The review assesses these bioplastics and discusses both the advantages and disadvantages of bioplastics while discussing how they will contribute to decreasing plastic waste in the environment. The authors of this review identified four major barriers to the acceptance and subsequent success of biodegradable plastics, which include high costs of production, weak mechanical strengths, poor decomposition capabilities, and unproven environmental safety. Future research and development should focus on reducing production costs and improving the functional properties of bioplastics to develop sustainable solutions to the environmental problems associated with plastics.

Keywords: pollutant removal, public health, biopolymers, biodegradable plastic, environmental sustainably.

INTRODUCTION

The durability, versatility, and low cost of plastics have made them an essential part of modern society; however, they have also led to significant environmental issues because the characteristics that make plastics useful are also what enable them to persist in the environment (sometimes for hundreds of years). Conventional plastics such as polyethylene (PE), polypropylene (PP), and polystyrene (PS) resist degradation and will accumulate in our landfills, oceans, and land ecosystems to contribute to global plastic pollution.

As people become more aware of the effects that plastics have on our environment, researchers and industry continue to look to find sustainable ways to produce plastics.[1] One alternative that has received the most attention is biodegradable plastics since they are created with the intention of being able to break down through the action of microorganisms, ultimately resulting in carbon dioxide, methane, water, and biomass being produced under the proper environmental conditions.

Renewable sources of biomass such as corn starch, cellulose, and sugarcane are used to manufacture biodegradable plastics, while petrochemical sources that have biodegradable structures can also produce biodegradable plastics.[2] The increased interest in biodegradable plastics stems from the need to decrease the amount of plastic waste as well as pursue sustainable material management for our planet.

Based on research conducted over the past several years, there is much variability in the rate at which biodegradable polymers will degrade based on the conditions in which they will be exposed; for example, elevated temperatures and moisture accelerate degradation in addition to increasing microbial activity.[3] Therefore, some polymers will decompose very quickly in a composting environment (such as polylactic acid) and will take much longer to break down in soil or water because of its crystallinity and hydrophobic properties. In this article we will discuss various facets of biodegradable plastics, including types, synthesizing, degradation mechanisms, environmental impacts, and potential uses for biodegradable plastics.

METHOD

This systematic review was carried out to study biodegradable plastics. Micro-organisms can decompose biodegradable plastics into their constituent compounds, such as carbon dioxide, methane, water, and biomass, making them a more sustainable alternative to traditional plastics. The literature search was done through some

publication databases such as Scopus, Google Scholar, PubMed, and Web of Science, which covered published papers from 2010 and 2026. Several terms were searched for such as biodegradable plastics, degradation mechanisms, environmental impacts, polylactic acid, biopolymer, polyhydroxyalkanoate and conventional plastics.

DISCUSSION

Definition and Characteristics of Biodegradable Plastics

Biodegradables are synthetic polymers that have been created to be decomposed through biological processes by microorganisms such as bacteria, fungi, and algae. Unlike traditional plastics that come from petroleum, bio-based plastics have been specifically designed to break down in nature or via natural active agents to create nontoxic products. In the case of biodegradable plastic, microorganisms use the polymer as a carbon/energy source to metabolize it into simpler compounds such as CO_2, CH_4, H_2O and biomass. Decomposition of biodegradable plastic will occur if specific environmental conditions (such as temperature, moisture, oxygen, and presence of microorganisms) are met. Due to increasing global concern about the problems caused by plastic pollution, there is an increased interest in biodegradable plastics as a possible answer for reducing the long-term environmental impact created by conventional plastics.[4]

Biodegradable plastics can be defined as plastics that can be broken down through microbial action into reusable components through the process of microbial degradation (microorganisms like bacteria and fungi will produce special enzymes that allow them to do this). These enzymes will attack the polymer chain at various locations – specifically, at the chemical bond locations that have susceptible bonds (ester, amide, and glycosidic) within the polymer's molecular structure. This will ultimately lead to fragmentation of the polymer chain down to smaller units that microorganisms will be able to use. Thus, biodegradable plastics differ from traditional (non-biodegradable) plastics, which do not have these hydrolysable bonds, and as such, they will be resistant to microbial attack – and therefore can remain in the environment for hundreds of years.

Another way that biodegradable plastics differ from traditional ones: they stay in the environment for much less time than traditional plastics do. Normally, plastics that become traditional waste stay on landfills, in the oceans, and in other natural environments for a very long time because they are made to last many years before degrading. When the right conditions exist, biodegradable plastics only take a few months, days, or weeks to decompose completely into a harmless form.[5] This means that using biodegradable products reduces the overall amount of plastic that builds up in our environment. Biodegradable plastics are environmentally friendly and sustainable alternatives for any product that has a short life cycle (packaging materials, agricultural films, one-time-use products, and food service products).

The use of renewable biological resources to produce biodegradable plastics promotes their environmental sustainability. The raw materials from which biodegradable polymers can be made include corn starch; sugarcane; potato starch; cellulose; and vegetable oils. One example is polylactic acid (PLA) which can be synthesized from lactic acid made from carbohydrate fermentation using corn or sugarcane. Another example is polyhydroxyalkanoate (PHA), which is produced by various types of microorganisms to use as a source of energy during fermentation processes. By using renewable resources, we can reduce our dependence on fossil fuels while creating a circular bioeconomy that continues indefinitely — recycling and reusing biological materials.

An additional benefit of compostable plastics is the compatibility with composting systems. Most biopolymers used for biodegradable products are developed specifically for use with commercial composting facilities, as these have conditions such as temperature, humidity and microbial activity that are monitored and controlled to help with decomposition. When exposed to the appropriate conditions, biodegradable plastics can be broken down to produce carbon dioxide, water, and a nutrient-rich compost within a short amount of time. The nutrient-rich compost produced by composting biodegradable plastics can then be used as a soil amendment for both agricultural and horticultural purposes. Thus, compostable biodegradable plastics offer a good waste management option that can work with organic waste recycling programs, thereby reducing the amount of waste that ends up in landfills and incinerators.

The structure of biodegradable plastics affects how efficiently they will biodegrade. Conventional plastics, such as polyethylene and polypropylene, do not have functional groups that can undergo hydrolysis or enzymatic cleavage; whereas biodegradable plastics have chemical bonds that are susceptible to both processes. One type of functional group commonly found in biodegradable polymers is ester linkages. Biodegradable polymers, such as polylactic acid (PLA), polycaprolactone (PCL), and polybutylene succinate (PBS), all contain ester linkages. The ester linkages found in these biodegradable polymers can be cleaved by water (hydrolysis) and by enzymes that are produced by living organisms (enzymatic cleavage). Hydrolysable bonds enable microorganisms to attack and decompose the polymer chains, thereby aiding in the overall biodegradation of the polymer.

There are typically two phases in the biodegradation process: fragmentation and mineralization. The first phase of biodegradation is called the fragmentation phase, and it involves the breakup of lengthy polymer chains into

smaller molecular fragments. The fragmentation phase can occur due to physical, chemical, or biological degradation. Weather, including ultraviolet radiation, temperature variation, or mechanical stress may activate fragmentation by weakening the structure of the polymer material.[6] Enzymatic hydrolysis by microorganisms enhances the overall process of fragmentation through the production of oligomers and monomers that are sufficiently small for use by microorganisms.

Mineralization is the second stage of biodegradation, which is the breakdown of large molecules into smaller molecules via enzymatic reactions by microorganisms. During this stage, microorganisms will use the smaller organic molecules to create small amounts of inorganic materials such as carbon dioxide, water, methane, and cells of microorganisms.[7] When biodegradation occurs in the presence of oxygen, the predominant inorganic products produced will be carbon dioxide and water. When biodegradation occurs in an anaerobic environment, such as in a landfill, the predominant inorganic products produced will include both carbon dioxide and methane from the biodegradation of organic material in an anaerobic environment. Biodegradation also contributes to the global recycling of carbon via the production of microbial cells from the biodegradation process.

The rate of biodegradation varies widely depending on several factors, including the type of material that is degraded, the crystallinity of the material (how dense the material is), environmental conditions (temperature and moisture), and the types of microorganisms present in the environment where the biodegradation occurs. Generally, highly crystalline materials take longer to biodegrade because they have a dense molecular structure that restricts or limits the access of microorganisms to the material. The amorphous portion of materials is much more accessible to microbial attack and therefore will biodegrade more quickly. In addition, environmental factors such as higher temperature will promote the activity of microorganisms that produce enzymes and microorganisms and will tend to accelerate hydrolysis of materials, while moisture is required to support the growth of microorganisms and to provide for the curing or swelling of polymeric materials to facilitate microbial attack.[8]

The diversity of microbes in our environment plays an important part in the efficiency of biodegradation. Different types of microorganisms exist because they possess specific enzyme functions which enable them to break down various polymer materials.[9] Bacteria can decompose polyhydroxyalkanoates (PHAs) whereas fungi possess superior capabilities for breaking down cellulose-based materials. The composting process establishes different microbial groups which work together to improve their ability to break down biodegradable plastic materials.

In conclusion, biodegradable plastics offer a major advancement toward sustainable materials science because of their ability to be broken down by microbes, less time spent in the landfill, possibility of being made from renewable resources and compatibility with composting systems. Nonetheless, many factors affect the rate of biodegradation of biodegradable plastics including polymer structure, environmental conditions, and microbial activity. Therefore, understanding these factors will allow for optimizing the design and application of biodegradable plastics to maximize environmental benefits and minimize the potential for ecological harm.

Classification of Biodegradable Plastics

There are many ways to categorize bio-degradable plastics due to their origin, chemical structure, and the way they are produced. A broadly used classification divides biodegradable plastics into three basic groups: natural biodegradable polymers, synthetic biodegradable polymers, and bio-based biodegradable polymers. Each type of bioplastic has differences that include the types of raw materials used, how they are produced, how they biodegrade, and their use in industry. Understanding these classifications will help in assessing how well biodegradable plastics perform environmentally, how economically viable they are to make, and how they function.

Natural biodegradable polymers comprise the first of the three classes of biodegradable polymers; these are polymers developed using biological means derived from organic sources found in nature, i.e. plants, animals, and microorganisms.[10] Natural biodegradable polymers can be found in living organisms and are generally biodegradable as their chemical composition and structures are designed for microbiological enzymes to degrade them. Such examples of natural biodegradable polymers include starch, cellulose, chitosan, proteins, and many polyhydroxyl polysaccharides. Starch is among the most prevalent sources of material used to produce biodegradable plastics since it is an abundant organic polymer, inexpensive, and can be renewed. Starch-based plastics are produced in the form of polymers by combining starch with other materials, such as glycerol or sorbitol, which adds flexibility and improves ease of processing. Starch-based plastics can frequently be found utilized as packaging films, disposable bags, and food containers. Cellulose is another of the most significant natural polymers; in total, cellulose is regarded as the most abundant natural polymer found on the planet. Additionally, derivatives derived from cellulose, such as cellulose acetate and regenerated cellulose, are also widely used in packaging and textiles for biodegradable purposes. Chitosan is another natural (polysaccharide-based) polymer that is derived from another natural source, chitin, which can be found in the exoskeleton of many marine organisms.[11] Due to its excellent biodegradability, antibacterial properties, and ability to form films

(thin coatings of materials) make chitosan a very useful material in the food packaging industry, as well as in many areas of biomedicine.

The second category of biodegradable polymers includes synthetic biodegradable polymers resulting from chemical manufacturing through polymerization processes and having structures conducive to biological degradation.[12] Unlike the naturally occurring polymers, synthetic biodegradable polymers are manufactured via controlled chemical processes that use monomers obtained from either petrochemical sources or renewable feedstocks to create the polymer. The ability of synthetic biodegradable polymers to biodegrade is due to the presence of hydrolyzable bonds within the polymer backbone that are composed of chemical groups (i.e., ester or amide) that can be cleaved by water or microorganisms and to produce smaller pieces of the polymer backbone that can then be metabolized by microorganisms. Synthetic biodegradable polymers include polycaprolactone (PCL), polybutylene succinate (PBS), polybutyleneadipate terephthalate (PBAT), and polyglycolic acid (PGA). PCL is a flexible polyester with a low melting point and is widely used for biomedical applications such as drug delivery devices, tissue engineering scaffolds, and sutures that degrade in the body. Because synthetic biodegradable polymers tend to have better mechanical and processing properties than their naturally occurring counterparts, they can be used in many industrial applications.

Bio-based biodegradable polymers are a third category of biodegradable polymers. They are made from renewable biological resources via biological or chemical processes. Bio-based biodegradable polymers represent an area of active research and development, as they combine both the environmental benefits of renewable raw materials with the functional performance of engineered polymers. An example of a bio-based biodegradable plastic is polylactic acid (PLA). PLA is synthesized from lactic acid using lactic acid fermentation from carbohydrates obtained from crops such as corn, sugarcane and cassava. PLA has found many commercial uses because it is transparent, has good mechanical properties, and can be processed using standard methods for conventional plastics. PLA is one of the most common materials used for manufacturing food packaging, disposable cutlery, medical implants and 3D printing materials. A second important category of biobased biodegradable polymers are polyhydroxyalkanoates (PHAs). PHAs are produced by microorganisms via fermentation processes. PHAs are produced by bacteria as intracellular energy storage when bacteria grow under conditions where there's limited nutrients and have an excess supply of carbon.

In general, there are many types of biodegradable plastic materials for sustainable polymer development. Biodegradable natural (plant-based) polymers are renewable and naturally break down, but often lack the attributes needed for mechanical strength, causing them to require some form of modification. Biodegradable synthetic (petroleum-based) polymers usually exhibit better performance and are easier to manufacture than their natural counterparts, but many still rely on petrochemical feed stocks.[13] Biodegradable bio-derived (combination of both renewable and petroleum-based) polymers represent an emerging category of materials that utilize innovative polymer chemistry and renewable raw materials as the basis for their formulation. Researchers and engineers are continuing their work on the development of these types of biodegradable plastics and or improvement in the environmental sustainability, performance, and commercial viability of biodegradable plastics soon.

Natural Biodegradable Polymers

Biodegradable polymers are derived from biological sources (such as plants, animals, and microorganisms) and can decompose naturally in the environment due to their molecular structure's ability to undergo enzymatic degradation through the action of microorganisms (such as bacteria and fungi). Leading examples of naturally occurring polymers used in the production of biodegradable plastics include Starch, Cellulose, Chitosan and Protein. Starch is by far the most widely used and researched material in the production of biodegradable plastics because of its prevalence, low cost, and renewability.

The primary carbohydrate storage system for corn and potato and wheat and cassava plants relies on starch which acts as their primary polysaccharide. Sustainable plastic production depends on environmental plant sources which exhibit various starch levels to serve as biodegradable material alternatives.[14] Starch exists in nature as a material which maintains its structure thus making it challenging to transform into a plastic material. The production of thermoplastic starch requires starch to be combined with glycerol and sorbitol and water before it can be processed through standard polyolefin plasticization methods. Starch-based plastics possess several desirable properties which include high biodegradability and non-toxicity and renewable origin. The microorganisms which inhabit soil and composting environments can rapidly decompose starch into carbon dioxide and water and biomass. Starch-based plastics provide companies with a sustainable alternative to petroleum-based plastics which they use for making disposable items and packaging materials. The use of starch plastics faces certain restrictions because they contain disadvantages.

Researchers use starch for developing biodegradable materials because their studies require combining polylactic acid with polycaprolactone to create their needed solutions. The combination of these materials results in products that display superior mechanical strength and enhance flexibility and better moisture resistance while still being able to decompose.[15] Starch-based composites demonstrate improved structural performance

when natural fibers and nanocellulose and clay nanoparticles are used as reinforcement materials. The development of starch-based biodegradable plastics through these modifications has created packaging materials and disposable utensils and agricultural films which fulfill short-term needs while protecting the environment.

Synthetic Biodegradable Polymers

The chemical structure of artificial biodegradable polymers which people created allows them to complete their biodegradable process. The manufacturing methods of artificial polymers produce their material composition through the controlled use of specific monomer units which create structured products in laboratory and industrial settings.[16] The polymer demonstrates biodegradable behavior because its design consists of hydrolysable bonds which connect various sections of the polymer backbone through ester linkages. The resulting fragments become digestible by microorganisms because their bonds can break through hydrolysis or enzymatic processes.

Scientists developed synthetic biodegradable polymers which maintain their operational capabilities until their planned working period ends. The researchers examine three materials which they use in actual field tests, and which include polycaprolactone (PCL) and polybutylene succinate (PBS) and polybutyleneadipate terephthalate (PBAT). Polycaprolactone functions as a semicrystalline thermoplastic polyester which maintains its shape under cold conditions while delivering high flexibility and excellent polymer compatibility. The material decomposes through two mechanisms which include microbial activity and hydrolysis of ester bonds which make it suitable for use in applications that need extended-lasting biodegradable substances. PCL exhibits biocompatibility together with its controlled degradation rate which makes it suitable for various biomedical applications that include tissue engineering and drug delivery systems and biodegradable sutures. PCL serves as a material which agricultural films and compostable plastic products use to create their packaging.

Another important biodegradable and bio-based polyester is polybutylene succinate (PBS), which exhibits mechanical properties like polyethylene. PBS is synthesized by polycondensation of succinic acid and butanediol. If PBS is derived from biomass-based succinic acid, it will become a partially bio-based polymer. It shows good thermal stability, elasticity, and chemical resistance which provides more applications of this polymer in various fields such as packaging films, disposable tableware, agricultural mulch films. Polybutyleneadipate terephthalate (PBAT) is a plastic material that has elasticity and flexibility, which is often blended with starch or polylactic acid to increase flexibility and toughness.[17] PBAT two exceptional elongation properties together with its high mechanical strength make it the most suitable material for compostable bags and biodegradable films and agricultural applications.

The mechanical properties of synthetic biodegradable materials display superior performance with extended operational time and increased production capacity when compared to their natural counterparts. The material undergoes processing through standard plastic manufacturing methods which include extrusion and injection molding and film blowing. Certain synthetic biodegradable polymers need petrochemical feedstock as their essential raw material because this requirement makes them unfit for sustainable production. The increasing need for environmentally friendly biodegradable polymers leads researchers to study bio-based monomers and environmentally friendly synthesis methods.

Bio-based Biodegradable Polymers

The creation of biodegradable polymers begins with scientists selecting renewable biological materials which they transform into substances that will decompose naturally after their specified duration of use. The field of sustainable materials science considers bio-based polymers to possess important industrial value because these materials require renewable resources for production and their environmental degradation process generates ecological advantages.[18] Biobased polymer production needs biological fermentation methods together with chemical processes that convert plant-derived materials such as sugars and starch and vegetable oils into final products. The two currently available bio-based biodegradable polymers include polylactic acid (PLA) and polyhydroxyalkanoates (PHA). Polylactic acid production starts with carbohydrates which undergo fermentation through corn and sugarcane and cassava to produce lactic acid which convert into the final product. The material functions in various ways which enable its use for food packaging disposable containers medical implants and 3D printing materials.

The production of biodegradable materials is the choice of the scientist to use the renewable biological materials that are transformed into the final product, which degrades at the end of the selected period of use. Sustainable materials science is the value of the production of the bio-based materials, which is significant in the production of the materials, as the production of the materials uses renewable biological materials, while the degradation of the materials brings about positive effects in the environment. The production of the bio-based materials uses the biological fermentation method and the chemical method that transform the biological materials into the final product.

The available bio-based biodegradable materials are polylactic acid and polyhydroxyalkanoates.[19] The production of polylactic acid uses the biological process of carbohydrates that go through the biological fermentation

process, including the corn, sugarcane, and cassava plants, which are transformed into the lactic acid that is transformed into the final product. The materials operate in different ways that help in the use of the materials for the packaging of food, disposable containers, medical implants, and 3D printing materials. The rain fell with a soft sound that landed on the window, which complemented

Production Methods of Biodegradable Plastics

The production of biodegradable plastics is certainly not an 'one size fits all' approach. The fact is it depends on the types of plastics and materials used for such production. Now, as of today, we certainly have a few tricks up our sleeves when it comes to the production of plastics. For example, today, we can produce biological plastics, chemical plastics, and sometimes even combine both types of plastics to produce such materials. For example, the general methods of producing plastics include the production of plastics using microbial fermentation, chemical polymerization, and the combination of all types of plastics to produce composite plastic products.

One of the most interesting ways of producing biodegradable materials is microbial fermentation. So, let's see how it is done. Microorganisms are given food in the form of renewable sources, like sugars, starch, or vegetable oils, and these are further converted into polymers using the metabolic activities of these microorganisms.[20] It is one of the most interesting ways of producing bio-based materials, like polyhydroxyalkanoates, or PHA in short. So, let's see the production of PHA as an example. Ralstoniaeutropha, Bacillus megaterium, Pseudomonas, etc., are bacteria that accumulate PHA in their bodies. It is done in a state where microorganisms are starved of some nutrient, like nitrogen, phosphorus, or oxygen, but are in an abundant state of carbon. In other words, when these microorganisms are in an abundant state of carbon, they accumulate the excess amount of carbon in the form of PHA in their cytoplasm.

The whole process of fermentation is comprised of a few major steps, commencing with the growth of the microbes in a bioreactor with nutrient substances such as glucose, sucrose, fatty acids, etc., depending on the best nutrient source for the microbes to feed on. As the microbes multiply in the solution, they also start storing the substances in their cells. After a certain amount of storage of the substances, it is time to collect the microbes and collect the substances from their cells. Of course, this also depends on the best way to achieve this in the given setup. One of the best parts of the method of fermentation is the fact that it uses renewable sources, is producing a biodegradable product, and is using fewer non-renewable sources compared to the conventional petrochemical method. Of course, this is not all sunshine and rainbows, as the cost of the processes is quite high, depending on the given setup, including the need for a sterile environment and the bioreactors, as well as the purification techniques needed afterward.[21] This is why scientists are always trying to improve the strain of microbes, as well as.

Chemical polymerization is a pretty big deal when it comes to the production of biodegradable plastic. Here is the basic rundown: you start with something called monomers, which come from plants or oil, and then chemically combine them to make longer chains of biodegradable plastic, called polymers. The most well-known of this is called polylactic acid, or PLA.

The method by which PLA is created is lactic acid. This is created by the fermentation of corn, sugarcane, or cassava that contains sugar.[22] After that, chemical reactions are used to manipulate lactic acid. This could either be condensation or ring-opening polymerization of the lactides. This leads to the development of long chains that relate to an ester that can degrade in the presence of water or microorganisms. The real strength of chemical polymerization is the amount of control that is possible. This allows the development of biodegradable materials that are used in different ways. This could be for packaging, medical devices, or even engineering materials. In addition to that, chemical polymerization is efficient enough to produce the materials in the quantities that are needed.

One way of making biodegradable plastics efficient is by their combination. Some of the biodegradable plastics have the drawback of cracking, cannot withstand heat, and absorb water. Therefore, the scientists decided to combine the biodegradable plastics, which has the advantage of making biodegradable plastics stronger. Another way of making biodegradable plastics efficient is by the alteration of the composition of the mixture. The blending of the biodegradable plastics into one type of composite has the advantage of making the final product stronger. For example, the combination of PLA and starch has the advantage of making the final product strong, like the PLA. In addition, the combination of biodegradable plastics has the advantage of making the final product biodegradable and cost-effective.[23] In another instance, the combination of PCL and PLA is used, making the final product softer and more resilient. This combination is easier to adapt to the traditional manufacturing process, such as pushing the mixture through a die, molding, or inflating into a sheet.

In the assembly of composite materials, biodegradable plastic is combined with other materials such as fibers to make the composite materials stronger. However, instead of artificial fibers, hemp, flax, or bamboo is used for composition. Even the use of cellulose, which is derived from plants, is included. This is achieved through the composition of natural fibers. At the same time, the incorporation of other small parts, such as nanocellulose, also helps in the creation of stronger composite materials. Even the incorporation of particles derived from clay at the microscopic level is included. This helps in the creation of stronger composite materials without an increase

in weight. However, the incorporation of the elements of graphene helps in the creation of composite materials. This occurs when the heat resistance of the composite materials is the main concern. Even the incorporation of the small parts helps in the creation of composite materials that can withstand more pressure. At the same time, the composite materials are not weakened by the presence of moisture. However, the composite materials are also not weakened by the presence of heat.

Biodegradation Mechanisms

Moreover, not only do biodegradable plastics take time to decompose, but they also need the presence of living organisms, which work together with nature. These living organisms, such as bacteria, fungi, and algae, start breaking down the plastics using special equipment that they produce. This special equipment, which the living organisms produce, is called enzymes. These enzymes, which are produced by the living organisms, have a special ability to cut the plastics into smaller parts. When the plastics are cut into smaller parts, they become food for the living organisms. When the plastics decompose, they produce gases, liquids, and methane if they are in an environment without oxygen, and new cells.[24] Finally, the environment disposes of stubborn human-made materials, but it does so in its own time without leaving any evidence.

The breaking down is a slow process as it is being combined with nature's chemistry, breaking down the large chains of plastic into smaller forms. The factors that influence the rate of breaking down include what it is made of, how big it is, how compact it is, how exposed it is, where it is, and what small living things are around it. Plastic molecules with weak spots, such as links that easily break apart, such as those with ester and amide compounds, will break down quickly as they will be attacked by both water and small living things.[25] On the other hand, the plastic will remain unbroken as the molecules will remain intact for a long time as they will be hard for small living things to break apart. There are usually three processes involved in breaking down biodegradable plastic, which include being attacked by water, as it breaks apart the chemical bonds, being attacked by small living things, and being broken down into basic minerals.

Water molecules enter the plastic first, which sets the stage for the decomposition process. This step is most important for materials that must eventually dissolve. The molecules of the liquid target the weaknesses in the chain composition. Not all the bonds in the chain composition will break at the same rate once they meet the water molecules. Some of the bonds break faster once they encounter water molecules. Esters break quickly, especially in PLA, PCL, and PHA. Once the bonds break, the long chains turn into short chains. The short chains could be dimers, trimers, or single units.

At times, water is enough to accomplish the task, and at other times, small living things help the process along with special tools they make inside their bodies. Small living things in nature often send their helpers into their surroundings, and the helpers make the breaking down of the natural molecules easier. We need to think of tools that cut the links in a chain, and the tools only cut certain kinds of links. For instance, one tool cuts links made of fat, and another tool cuts links made of protein, and a third tool cuts links made of other sticky kinds of things. When the links are cut, the molecule is broken down into small parts.[26] The weight of the molecule becomes lighter, and then the small living things get to make use of the remaining parts of the molecule. The small parts of the molecule slide easily into the small living things, and what was hard to change is now used for growth. Breaking down is opening doors to places where there were thought to be no doors at all. Water is needed for the hydrolysis process, and the hydrolysis will stop when water is absent.

Once the water has broken down the chains, the microorganisms start to make use of the fragments left behind. The fragments then get ingested into the microorganisms' cells through their own mechanisms of ingesting particles. Inside the microorganism, the fragments act as fuel and construction material. The fragments do not just lie there in their dormitory; they power the essential chemical reactions within the microorganism.[27] The processes of life work on the fragments, converting them into growth, power, or transformation components. The metabolism of the microorganism guides each transformation without any rest.

One of the big reasons microbes degrade things in different ways is that there are so many different types of microbes, and each type has unique abilities. There are microbes that have special tools, which come in the form of enzymes, that are meant to be used with certain big molecules. Bacteria might be able to eat plastic if it is made up of PHA, whereas fungi might be able to eat plant-like molecules such as cellulose. In areas where there is a mixture of all these microbes, such as dirt or rotting plants, it will be easier for the materials to degrade simply because someone will be there to always eat it.

The interesting thing is that small pieces are easier for microbes to ingest than big chunks, and big chunks often require enzymes to help digest them into small enough pieces to be eaten at all.[28] Once it is inside, it is used to create something new for the microbes through something called metabolism. Again, it is interesting to see how size is used to determine what course of action will be taken.

The last step in the decomposition of matter is called mineralization. As the microorganisms carry on their job, they transform the matter into simpler forms. If oxygen is available, the final products of the decomposition process are likely to be CO_2, water, and microscopic living cells.[29] However, if oxygen is lacking, the decomposition products are likely to be methane, CO2, and water, deep inside the waste heap or the earth.

Down in the dirt, microscopic life forms decompose hard-to-break-down matter made up of long chains of chemicals. Instead of the chemicals being destroyed, they reappear as gases, including carbon dioxide or even methane. This process is an extension of the earth's gradual cycles of moving elements around the world. As microscopic life forms make their own bodies, they enrich the soil. This is the reason why, as the plastic decomposes, it is indeed decomposing, leaving nothing behind.

The weather will affect the rate at which things degrade. If the weather is warm, then there is more air, the moisture level is well balanced, and there are many tiny living organisms. In this case, the rate of degradation is fast.[30] Waste processing plants that handle waste materials will have an ideal condition for the degradation of materials. This is because the temperature is higher than 50 degrees Celsius, the moisture level is high, and there are many tiny organisms. In this case, materials that are meant to degrade will degrade in a matter of weeks or months.

The rate of degradation may, however, vary significantly outside the confines of a laboratory. Although bioplastics degrade fast in the compost heap, they may not change in the rivers or the ground. For instance, PLA will not degrade into fresh water since it is highly structured and not slippery. This structure will not allow moisture to get in, and the rate of degradation will be slow. This is the reason it will last for a long time.

Environmental Impact of Biodegradable Plastics

Some people think that biodegradable plastics are good for nature, unlike other plastics made from oil. This is because they will biodegrade, which means they will be helpful in solving the pollution problem caused by thrown-away plastics.[31] However, it is quite complex how biodegradable plastics will be helpful for nature, since it will depend on the source materials, manufacturing, end of product life cycle, and biodegradation process. In conclusion, it is important to take into consideration all factors, from the beginning to the end, if we want to know how great the impact of biodegradable plastics is on nature.

Looking at the way things affect nature over time is also common in the comparison of breakable plastics and normal ones. This includes the power needed, the gases released, the water drawn in, and the trash left behind from the start to the end. Some research has also shown that some of the plant-based materials can reduce the use of oil and heat-trapping gases in comparison to the use of the plastic made from crude oil.[32] For example, the lactic acid chains or storage molecules are less impactful because they are drawn from the farms rather than the refineries.

Although biodegradable plastics are beneficial to the environment, there is always a downside to their existence. The downside of the biodegradable plastics is the way in which they decompose and the fragments that they leave behind. For example, the fragments tend to accumulate during the decomposition of the plastic. This is because the plastic is splitting into fragments from the original plastic. At times, the plastic decomposes too fast, and rather than decomposing completely, the fragments of the plastic remain.

A study points out that, if biodegradable plastics don't fully decompose during the composting process, small pieces may accumulate in the soil. Although microbes will eventually feed on these pieces, while they are present, they could change the way dirt holds together, change the types of microbes living there, and interfere with the natural recycling of food in plants. Thus, the slow breakdown phase is why effective composting techniques and waste management strategies must work well together, with nothing left behind.

The biodegradable plastics are different, and the effect on nature around them is also different due to the different environments in which they are used. Some biodegradable plastics may decompose quickly in the soil, whereas some may remain in the water. The energy used to produce biodegradable plastics is also different, and the water used to produce some of the biodegradable plastics is also higher, which is a problem in some regions where water is scarce. The effect on the fish and plants in the water after the decomposition of the biodegradable plastics is also different, and research has shown that the amount of heat trapped in the atmosphere is also different. The nutrient overload in the lakes is

Something to think about is the way the land is used when considering the way, it will affect nature when using the biodegradable plastic.[33] Using the land to plant crops to help develop bio-based plastic is a way the land is being used. Using the land to develop plastic products instead of food crops will affect the way the food is distributed and the way nature is used. To avoid this, scientists are considering the leftover plants or the plants that are not used for food to replace the traditional raw materials.

The way the biodegradable plastic decomposes also depends on the location once the waste is collected. Some of the biodegradable plastic decomposes only in a location where the temperature is high and there is the presence of microbes.[34] It could take a very long time in a landfill and the same amount of time in the ocean because there is a lack of microbes in the water. Even though the conditions are right, the location will not always provide the right conditions for the plastic to decompose properly. This is when the waste is collected and taken to a plant, the plastic will provide the full effect.

Applications for Biodegradable Plastics

Nowadays people pay more attention to biodegradable plastics because regular plastic trash keeps piling up in nature. Instead of relying on oil-made versions, these new materials step in when products won't last long and

leave behind lots of waste. Thanks to progress in how we build polymers and tweak living systems, their strength, heat resistance, and ease of shaping got better. Industries like farming, health care, wrapping stuff, clothes making, and everyday items started using them instead - simply work differently now.

From kitchen wrap to garden pots, things made of breakable plant-based plastics often start life on machines already found in factories today.[35] Because old equipment works just fine, companies switch without big changes. Packaging takes more of these materials than any other use, growing faster each year. What once seemed rare now lines shelves, quietly replacing stubborn waste.

The packaging industry is the largest user of biodegradable plastic products in the world today. This is because the products have very short lifespans, meaning they are used immediately before they are discarded. Conventional plastic products have been the major contributors to plastic waste in the world today, especially in landfills and water bodies. This has been attributed to the lack of a solution to the plastic waste issue, but this has been provided through the availability of biodegradable plastic products, especially their ability to provide packaging products that can easily decompose once they are discarded.

There is a wide range of products that can be packaged using biodegradable plastic products. This includes compost bags, food containers, cutlery, trays, plates, cups, and many more. These products have been seen as the best option for single-use products, especially considering the environmental benefit associated with the use of biodegradable plastic products.[36] There is an increased rate of usage of compost bags made from biodegradable plastic products, especially for the collection of organic waste. This is because the waste can decompose with the food waste. Polylactic acid and starch-based plastic products have been seen as the most used forms

CONCLUSION

The biodegradation of biodegradable plastics is a complex process that requires the presence of biological, chemical, and environmental factors. The biodegradation of biodegradable plastics involves the use of biological agents like bacteria, fungi, and algae. These biological agents use enzymes that can degrade biodegradable plastics into simple compounds. The biodegradation of biodegradable plastics leads to the conversion of the biodegradable plastics into compounds like carbon dioxide, water, methane, and biomass. The biodegradation of plastics is an important process that leads to the reduction of the accumulation of plastic materials in the environment. The biodegradation of plastics usually starts with the use of chemical and biological reactions that lead to the conversion of the biodegradable plastics into simple compounds. Biodegradable plastics are affected by different factors like the structure, molecular weight, crystallinity, and surface area of the biodegradable plastics, as well as the types of biological agents in the environment. Biodegradable plastics with hydrolysable bonds like ester and amide bonds can be biodegradable since they can be hydrolyzed using water molecules.

ACKNOWLEDGEMENT

This research work was financially supported by INTI International University (Ho SM).

CONFLICT OF INTERESTS

The authors declare that there is no conflict of interest.

AUTHOR CONTRIBUTIONS

All the authors contributed significantly to this manuscript, participated in reviewing/editing and approved the final draft for publication.

REFERENCES

1. K. Chan, B. Wasurat, and W. Bassi, Next Materials, 9, 101304 (2025), https://doi.org/10.1016/j.nxmate.2025.101304.
2. B. Borrelle, J. Ringma, K. Law, C. Monnahan, and L. Lebreton, Science, 369, 1515 (2020).
3. R. Geyer, J. Jambeck, and L. Law, Science Advances, 3, e1700782 (2017), https://doi.org/10.1126/sciadv.1700782.
4. Kumar, R. Sehgal, and R. Gupta, European Polymer Journal, 161, 110824 (2021), https://doi.org/10.1016/j.eurpolymj.2021.110824.
5. J. Jian, X. Zeng, and X. Huang, Advanced Industrial and Engineering Polymer Research, 3, 19 (2020).
6. S. Cheng, Y. Jiang, J. Yin; L. Zhang, and L. Han, European Polymer Journal, 203, 112638 (2024), https://doi.org/10.1016/j.eurpolymj.2023.112638.
7. N. Siddiqui, S. Asawa, B. Birru, and R. Baadhe, Molecular Biotechnology, 60, 506 (2018).
8. M. Paola, G. Gioannis, M. Falzarano, A. Muntoni, and A. Polettini, Fuel, 355, 129361 (2024), 10.1016/j.fuel.2023.129361.

9. Y. Yu, and M. Flury, NPJ Materials Sustainability, 2, 9 (2024), https://doi.org/10.1038/s44296-024-00012-0.
10. V. Vatanpour, M. Pasaoglu, H. Barzegar, O. Teber, and R. Kaya, Chemosphere, 295, 133914 (2022), https://doi.org/10.1016/j.chemosphere.2022.133914.
11. S. Fischer, K. Thümmler, B. Volkert, and K. Hettrich, Macromolecular Symposia, 262, 89 (2008), https://doi.org/10.1002/masy.200850210.
12. E. Polman, G. Gruter, J. Parsons and, A. Tietema, Science of The Total Environment, 753, 141953 (2021), https://doi.org/10.1016/j.scitotenv.2020.141953.
13. F. Bilo, S. Pandini, L. Sartore, and E. Depero, Journal of Cleaner Production, 200, 357, (2018), https://doi.org/10.1016/j.jclepro.2018.07.252.
14. X. Tang, and S. Alavi, Carbohydrate Polymers, 85, 7 (2011), https://doi.org/10.1016/j.carbpol.2011.01.030.
15. A.Nafchi, M. Moradpour, M. Saeidi and A. Alias, Starch, 65, 61 (2013), https://doi.org/10.1002/star.201200201.
16. O. García, S. Bordel, R. Lebrero, F. Santos, and R. Börner, Biotechnology Advances, 53, 107772 (2021), https://doi.org/10.1016/j.biotechadv.2021.107772.
17. F. Ruggero, R. Gori, and C. Lubello, Waste Management and Research, 37, 959 (2019), doi: 10.1177/0734242X19854127.
18. A. Folino, A. Karageorgiou, S. Calabrò, and D. Komilis, Sustainability, 12, 6030 (2020), https://doi.org/10.3390/su12156030.
19. S. Vardar, B. Demirel, and T. Onay, Reviews in Environmental Science and Bio/Technology, 21, 205 (2022), https://doi.org/10.1007/s11157-021-09610-z.
20. A. Bher, C. Mayekar, R. Auras, and C. Schvezov, International Journal of Molecular Sciences, 23, 12165 (2022), https://doi.org/10.3390/ijms232012165.
21. W. Ahsan, A. Hussain, C. Lin, and M. Nguyen, Catalysts, 13, 294 (2023), https://doi.org/10.3390/catal13020294.
22. K. Awasthi, M. Kumar, V. Kumar, and S. Sarsaiya, Environmental Pollution, 307, 119600 (2022), https://doi.org/10.1016/j.envpol.2022.119600.
23. M. Ojeda, E. Dalmolin, M. Forte, and R. Jacques, Polymer Degradation and Stability, 94, 965 (2009).
24. I. Kyrikou, and D. Briassoulis, Journal of Polymers and the Environment, 15, 125 (2007).
25. A.Shah, F. Hasan, A. Hameed and S. Ahmed, Biotechnology Advances, 26, 246 (2008).
26. V. Bátori, D. Åkesson, A. Zamani, and M. Taherzadeh, Waste Management, 80, 406 (2018).
27. Z. Chen, W. Zhao, R. Xing, S. Xie, and X. Yang, Journal of Hazardous Materials, 384, 121271 (2020), https://doi.org/10.1016/j.jhazmat.2019.121271.
28. A. Larrañaga, and E. Lizundia, European Polymer Journal, 121, 109296 (2019), https://doi.org/10.1016/j.eurpolymj.2019.109296.
29. G. Gorrasi, A. Sorrentino, and R. Pantani, Journal of Polymers and the Environment, 23, 316 (2015), https://doi.org/10.1007/s10924-015-0720-0.
30. V. Goel, P. Luthra, G. Kapur, and S. Ramakumar, Journal of Polymers and the Environment, 29, 3079 (2021), https://doi.org/10.1007/s10924-021-02099-1.
31. M. Emadian, T. Onay, and B. Demirel, Waste Management, 59, 526 (2017), doi: 10.1016/j.wasman.2016.10.006.
32. S. Kumar, and P. Maiti, Polymer, 76, 25 (2015), https://doi.org/10.1016/j.polymer.2015.08.044.
33. M. Chokchai, S. Tiptiwa, and S. Arisa, Journal of the Indian Chemical Society, 103 (2026), https://doi.org/10.1016/j.jics.2026.102490.
34. F. Ruggero, R. Onderwater, E. Carretti, and S. Roosa, Journal of Polymers and the Environment, 29, 3015 (2021), https://doi.org/10.1007/s10924-021-02098-2.
35. M. Funabashi, F. Ninomiya, and M. Kunioka, Journal of Polymers and the Environment, 15, 245 (2007), https://doi.org/10.1007/s10924-007-0067-2.
36. P. Stloukal, S. Pekařová, A. Kalendova, and H. Mattausch, Waste Management, 42, 31 (2015), https://doi.org/10.1016/j.wasman.2015.04.006.