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Application of biodegradable plastic and their environmental impacts: A review

Shileer Sulaiman Omer and Najmaldin Ezaldin Hassan *

Environmental Sciences Department, College of Science, University of Zakho, Kurdistan region, Iraq.

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Abstract

The increasing environmental concerns linked to the extensive use of traditional plastics have led to a rising interest in bioplastics, mostly because of their capacity to biodegrade and their reliance on organic materials. This study examines the harmful impacts of petroleum-derived plastics on the ecosystem, animals, and human health, highlighting the pressing requirement for sustainable alternatives. The enduring characteristics of plastics, together with their role in exacerbating global warming and emission of harmful gases when burned, highlight the urgency of discovering environmentally-friendly alternatives. The research promotes the use of biodegradable materials as a practical alternative, highlighting their ability to break down through the action of microorganisms without causing harm to the environment. In addition, the text discusses the constraints of recycling and highlights the importance of developing alternatives such as polylactide, polyhydroxyalkanoate, polyhydroxy butyrates, starch, and cellulose to reduce the negative environmental impact of conventional plastics. This work adds to the current discussion on shifting towards sustainable materials in order to address the growing problem of plastic pollution.

Key words: Bioplastics; Plastic pollution; Biodegradability; Recycling; Sustainable alternatives.

1. Introduction

Bioplastics have gained significant interest in recent years due to their environmental benefits (Rujnić-Sokele & Pilipović, 2017). The name "bioplastics" originated by European Bioplastics, which is a European umbrella body dedicated to the field of bioplastics. Bioplastics has the characteristic of being either biodegradable, bio based, or exhibiting both properties (Tonuk, 2016). Plastics have become integral to all aspects of modern daily life. Its flexibility size, light weight, and lower cost make it a highly desirable material for a wide range of domestic and industrial applications, providing numerous benefits. However, the excessive and imprudent utilization of plastic leads to environmental degradation and has detrimental implications for human health (Albuquerque & Malafaia, 2018). Plastics are produced from finite petroleum resources, the excessive use of which has resulted in the exhaustion of these natural assets. These compounds are organic in nature, and their inappropriate disposal leads to the loss of countless animals due to asphyxiation. These substances have deleterious impacts on both aquatic organisms and terrestrial creatures, as they diminish soil fertility and heighten the likelihood of eutrophication (Rochman et al., 2016). An inherent issue with plastics is their non-biodegradability, causing them to endure in the environment for extended periods of time, often spanning up to thousands of years (Unmar & Mohee, 2008).

The extensive manufacture of disposable plastic, fueled by consumer demand, has resulted in a significant environmental hazard known as plastic pollution. This issue arises from the generation of large quantities of plastic garbage. Petroleum-derived plastics are not capable of undergoing natural decomposition, and the majority of plastic trash is either disposed of in the environment or stored in landfills. Traditional petroleum-based plastics are resistant to microbial breakdown and build up in ecosystems and food systems (Boey et al., 2021). Additionally, the process of burning petroleum-based plastic trash to produce energy results in the emission of greenhouse gases and hazardous

* Corresponding author: Najmaldin Ezaldin Hassan

substances, specifically dioxin, furans, and the polychlorinated biphenyls (Giacovelli, 2018). The release of greenhouse gases, including methane, nitric oxide, and carbon dioxide, contributes to the intensification of global warming (Gironi & Piemonte, 2011). The combustion of these polymers is environmentally harmful due to the emission of toxic gases and chemicals. This can result in various health issues such as respiratory illnesses, vomiting, pulmonary and cardiac conditions, irritation of the skin, cancer, weakened immune system, disruption of hormonal balance, birth defects, and significant damage to reproductive and nervous systems in humans (Kharb & Saharan, 2022).

To address this issue, it is necessary to develop an alternate solution, such as the creation of biodegradable plastic. Biodegradable plastic is a type of plastic that can break down in the environment through the activity of microorganisms like bacteria, fungi, and algae. The primary benefit of utilizing biodegradable plastic lies in its capacity to undergo rapid breakdown without causing any detrimental impact on the environment. The plastic is environmentally benign and manufactured from potentially low-cost raw materials (Albuquerque & Malafaia, 2018). Recycling can be seen as a progressive solution for managing plastic waste. However, its effectiveness is restricted due to the intricate composition of plastic, the various varieties of plastic, and the degradation of material quality that occurs with each recycling step. Around nine percent of the plastic garbage has undergone the process of recycling (Giacovelli, 2018; Singh et al., 2017). Additionally, it is worth noting that 99% of the plastic originated from non-renewable fossil fuel sources, specifically petroleum and natural gas (Bioplastics, 2020). Various biodegradable polymers, such as polylactide (PLA), polyhydroxyalkanoate (PHA), Poly hydroxybutyrates (PHB), starch, and cellulose are currently under investigation for diverse uses (Venkatachalam & Palaniswamy, 2020). Hence, it is imperative to create an environmentally benign and biodegradable alternative to the petroleum-based traditional plastics (Santana et al., 2022). The excessive use of polymers and their goods has caused significant environmental repercussions, prompting the exploration of plastics that degrade in research (Bharti & Swetha, 2016). These alternatives are deemed commercially and environmentally viable as substitutes for conventional petrochemical plastics (Panchal & Vasava, 2020).

The study aims to tackle environmental concerns associated with conventional plastics, highlighting their detrimental impacts and advocating for sustainable alternatives. The text emphasizes the importance of embracing environmentally friendly materials, namely biodegradable alternatives like PLA, PHA, PHB, the starch, and cellulose. The study acknowledges the limitations of recycling and emphasizes the importance of investigating new methods to reduce the environmental consequences of traditional plastics.

2. Biodegradable Plastics

Biodegradable polymers are a type of eco-friendly plastic derived from renewable materials such biomass, starch, fats, and oils (Babu et al., 2013). Waste materials such as food, agriculture and vegetable wastes, as well as renewable feedstock like biomass, are important sources of bioplastics. These bioplastics have the advantage of not causing any environmental pollution, not depleting fossil fuel resources, and ultimately not posing any danger to humans (Paul et al., 2021). Microbial populations can be utilized to derive biodegradable plastics from bio-wastes, offering a beneficial application (Kalia et al., 2000). Biodegradable polymers naturally decompose in the environment. This process occurs when microorganisms present in the environment metabolize and decompose the molecular structure of recyclable plastics into simple molecules that are environmentally benign. There are two types of degradable plastics: one that can break down through aerobic processes such as composting, and another that can break down in an anaerobic environment like a landfill. The process involves the conversion of the substance into carbon dioxide (CO_2) methane (CH_4), water (H_2O), and biomass by microorganisms within a specific timeframe and under specific conditions (Leja & Lewandowicz, 2010). Some examples of biodegradable plastics include Polylactic acid (PLA), thermoplastics starch, and Poly-3-hydroxybutyrate (PHB) (Kharb & Saharan, 2022).

Biodegradable plastics are a suitable alternative to conventional plastics because they can be used in similar ways (Onen Cinar et al., 2020). These materials offer a practical option for achieving environmental sustainability because they can easily break down and are compatible with living organisms. Additionally, they are made from renewable and natural resources like starch, wood pulp, and vegetable oils, making them highly effective for various uses in industries such as biomedical, surgical implants, piping, agriculture, packaging, textiles, phone cases, bags, containers, carpets, and more (Prasanth et al., 2021). The main advantages of using biodegradable plastics are their use of sustainable feedstock and their capacity to biodegrade (Mohammadi Nafchi et al., 2013).

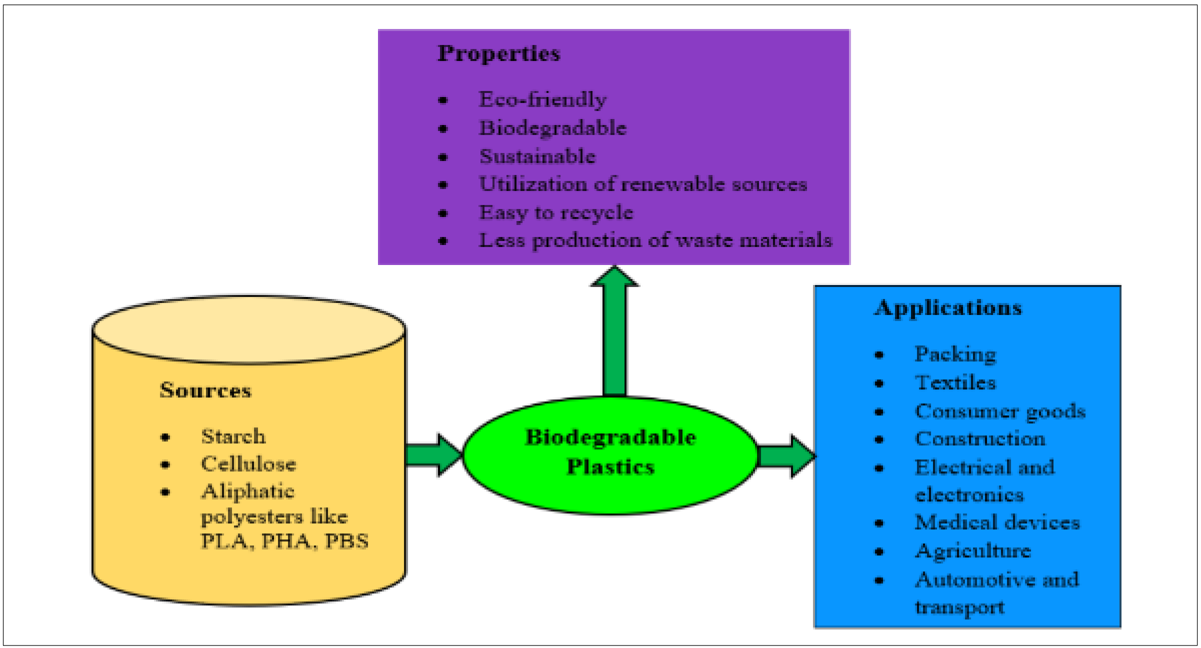

Figure 1 Biodegradable plastics: sources, properties, and uses.

The majority of environmental issues created by polymers can be eliminated by utilizing bio-based fiber and biopolymers derived from natural and sustainable biological resources. Biodegradable plastics are an important invention that can make a big contribution to the development of the bio economy and reduce our dependence on traditional fossil fuel-based resources in favor of bio-based products (Nanda et al., 2022).

Biodegradable polymers are environmentally benign since their production leads to the emission of less carbon dioxide, which contributes to global warming. The use of renewable feedstock in plastic manufacture can reduce the emission of greenhouse gases, such as CO_2 and CH_4, into the atmosphere compared to traditional plastic syntheses from petroleum or coal (Barker, 2009).

Biodegradable plastics are utilized in a wide range of applications. Their dominant market share lies within the packaging business. PLA, PHA, PBS, starch, and cellulose polymers possess inherent sustainability and biodegradability, making them highly suitable for replacing synthetic plastics in numerous applications (Kharb & Saharan, 2022).

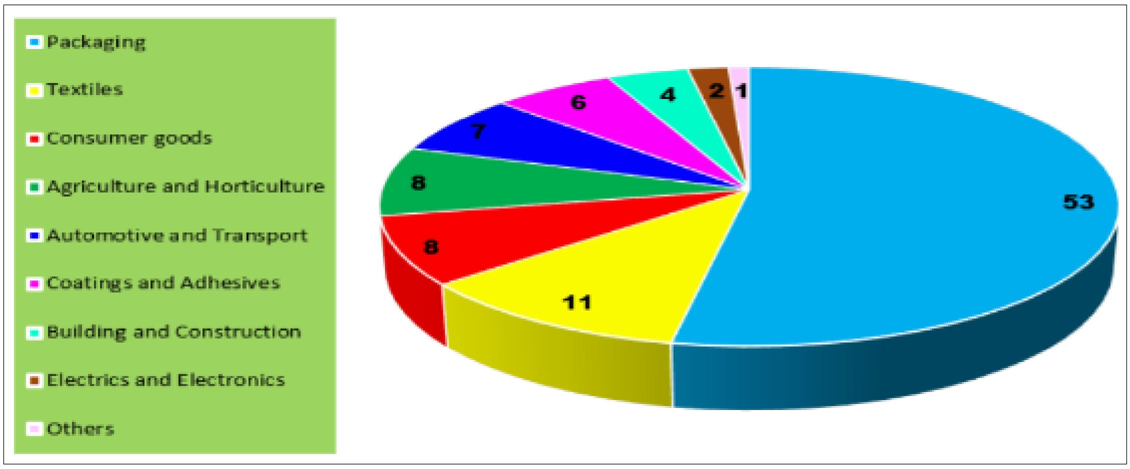

Figure 2 Utilizations of Bio-based and Degradable Plastics in diverse Industries (Fu, 2022).

These materials have a wide range of uses in several industries including packaging, textiles, consumer products, horticulture and agricultural, transportation and automotive, adhesive and coatings, building, electrical and electronics, and more. The packaging sector accounts for about 50% of the overall utilization of bio-based and bio-degradable polymers. The textile industry accounts for around 11% of the overall utility. The agriculture sector accounts for 8% of the overall contribution. The remaining fraction of applicants consists of all other sectors (Keränen et al., 2023). The predominant forms of biodegradable plastics used in various industries include PLA, PHA, Bio-PBS, Starch, Cellulose, and their combinations with other polymers (Kharb & Saharan, 2022).

2.1. Polylactic acid (PLA)

Polylactic acid belongs to the group of aliphatic polyesters that are made up of individual units of lactic acid. Lactic acid is a carboxylic acid that contains the -OH group. It is created through bacterial fermentation of sugars and starch obtained from sustainable and natural sources. PLA possesses notable characteristics like a lustrous look, strong stiffness, high transparency, and the capacity to endure various processing conditions. It exhibits efficient thermal resistance and mechanical characteristics (Nakajima et al., 2017). Its extensive range of characteristics allows for widespread application across various domains(Kharb & Saharan, 2022). It is mostly employed in the packaging of food products, including as bottles of water, cups, plates, cutlery, meal trays, films, containers, and wrapping sheets. Currently, PLA fibers are effectively substituting synthetic plastics in textile sectors. These materials are utilized in the textile industry to produce items such as gentle baby wipes, athletic wear, looks drapes, shirts, diapers, and hard landscaping materials (Wang et al., 2015).

Polylactic acid is combined with various substances to enhance its mechanical robustness and ability to withstand high temperatures. The NEC Corporation from Japan combined PLA with carbon and the kenaf fibers to improve its resistance to heat and ability to resist flames. Computer housing have been fabricated by utilizing a combination of PLA and polycarbonate blends. It is also utilized in the chemical and automotive sectors for the production of membrane materials. PLA and its mixes have also been used in medical applications involving human patients. These are utilized to manufacture bioresorbable scaffolds, which are employed for cultivating cells that live in implants, bone-supporting splints, and other applications (Bano et al., 2018).

2.2. Polyhydroxy alkanoates (PHA)

Polyhydroxyalkanoates (PHAs) are a class of polyesters derived via bacterial fermentation. These possess the capacity to replace conventional non-renewable resources derived from petroleum. While PHA can be found in various naturally existing species, its manufacture has primarily been focused on microbes. These are derived from diverse bacteria that utilize various forms of renewable and garbage feedstock (Tarrahi et al., 2020). The generation of PHA by bacterial fermentation involves three distinct stages. The initial stage entails bacterial fermentation. The second phase involves the isolation of the byproducts from bacterial cells, while the third step focuses on purifying the compounds from the fermentation liquid (Babu et al., 2013).

These thermoplastic biopolymers possess diverse qualities that are determined by their chemical makeup and the specific bacterium they are derived from. Polyhydroxyalkanoates (PHAs) are polymers that are capable of undergoing biodegradation and are compatible with living organisms (Yu et al., 2020). Polyhydroxyalkanoates (PHAs) exhibit excellent mechanical and thermal characteristics. These possess notable resistance to moisture and have odor barrier properties. The number 32 is enclosed in square brackets (McChalicher & Srienc, 2007).

Polyhydroxyalkanoates, with its distinct and diverse characteristics, has been specifically adapted for numerous packaging, industrial, and therapeutic uses (Choi et al., 2020). PHA polymers have been utilized in many food packaging applications, including disposable utensils (such as spoons, forks, and knives), food trays, containers tops, closures, caps, tubs, and plates. PHAs are also useful in injection-molded products like fibers, films, laminated materials, sheets, and coated objects. PHAs have been utilized to produce a wide range of products, including disposable items, nonwoven textiles, feminine hygiene products, paper-like synthetic products, paints, adhesives, foams up, waxes, binders, cosmetics, medical packaging materials, and housewares (Jariyasakoolroj et al., 2020). PHAs and their copolymers are also employed in biomedical applications. These include devices for repairing the meniscus, surgical mesh, sutures, fasteners for sutures, patches for tissue repair, patches for cardiovascular applications, plates for bone repair, methods for promoting stem cell growth, agents for controlling biological processes, agents for fighting germs, agents for treating cancer, and substances for enhancing memory, as well as rivets. The utilization of PHAs in delivering drugs has also expanded to encompass its applicability (Kharb & Saharan, 2022).

2.3. Polybutylene succinate (PBS)

Polybutylene succinate refers to an aliphatic and sustainable polyester synthesized through the condensation reaction of succinic acid with 1, 4-butanediol. The monomers can be obtained either from petroleum-derived sources or by bacterial fermentation. The primary source of raw materials to Bio-PBS is derived from the monomers extracted from maize and sugarcane plants. Succinic acid is derived from glucose obtained from sustainable sources, while 1, 4-butanediol is derived from bioethanol. The manufacture of bioethanol from sugarcane requires three stages: sugarcane plantation, conversion of sugar into molasses by sugar milling and refining, and the turning of the molasses into bioethanol through fermentation (Cheroennet et al., 2017). Bio-PBS exhibits a semi crystalline structure and possesses a high melting point. The thermal and mechanical properties of the material are influenced by its crystal structure (Jacquel et al., 2011). The material has excellent flexibility, tensile strength, biocompatibility, and heat resistance. The mechanical rigidity and strength of PBS can be enhanced by including monomer for adipic acid or as sebacic acid into its structure, resulting in the formation of copolymers (Kharb & Saharan, 2022).

Bio-PBS and its composites with other plastics have been utilized in several industries including agricultural, packaging, textiles, building, forestry, medical care, consumer products, fishery, car manufacturing, electronics, and interiors (Zeng et al., 2011). Additionally, it is utilized in the production of bottles, filaments, plant pots, mulching films, trays, containers, garbage bags, hygiene items, laminated paper, gloves, and more (Urbanek et al., 2020). Plastic utensils, dishes, bowls, diapers, and other items are also being manufactured utilizing Bio-PBS. Combinations of PBS or PLA are widely used to create various types of fibers, sheets of paper, flat films, and blown films, among other applications. Due to their biocompatibility, these materials are also utilized in the production of food packaging (Su et al., 2019).

2.4. Starch

Starch is one of the most abundant naturally occurring carbohydrate on Earth. It is a biodegradable, sustainable, and renewable substance that is synthesized by plants through photosynthesis and stored as their food. Starch can be obtained from various sources, including tubers like tapioca and potato, as well as cereals like rice, wheat and corn. Additionally, cashew nuts can also serve as a source of starch (Kharb & Saharan, 2022). Potato, corn, wheat, and tapioca are the primary botanical source of starch (Ali et al., 2017).

Starch consists of two kinds of glucose units connected by 1, 4- α connections. One type is amylose, which is a linear component, and the other type is amylopectin, which is a branching component (Aranda-García et al., 2015). The polymers make up 98 – 99% of the overall mass of starch. The remaining 0.5 to 2% of starch consists of protein molecules, non-starchy polysaccharides, lipids, ash, and other substances. The amount of amylopectin and amylose has a major impact on the distinctive features of starch (Niranjana Prabhu & Prashantha, 2018). Starch is widely utilized as a biopolymer due to its ample availability, ability to naturally break down, and cost-effectiveness (Kharb & Saharan, 2022). Thermoplastic starch is created by combining starch with various polymers and plasticizers. It has excellent mechanical robustness, thermal durability, and reduced fragility. The characteristics of starch are determined by its chemical makeup (Pfister & Zeeman, 2016).

Currently, starch and thermoplastic starches are utilized in diverse industries like medicines, packing food, horticultural and agricultural technology, textiles, paint, building, paper and cardboard industries, and automotive industries (Liew & Khor, 2015). Starch-based biodegradable polymers have been widely utilized in the manufacturing of films, grocery bags, food storage containers (such as cups, plates, and trays), overwraps, and sanitary goods (Kharb & Saharan, 2022). Starch-based biopolymers have been acquired as packaging materials for food goods (Ferreira et al., 2016). Starch is utilized in the production of mulch films and goods required for the controlled release of fertilizers, which are highly successful in agriculture. Starch and polymer mixes have been effectively employed in the medical field to create films for drug release, bone cement, and other applications (Çalgeris et al., 2012).

2.5. Cellulose

Cellulose constitutes the main component of a cell wall of plant. Additionally, it is included in the cellular structure known as a cell wall of algal and certain bacteria. Cellulose is a crystalline structure and is composed of glucose units that are linked together by β-1, 4-glycosidic bonds. The primary sources used as raw materials to cellulose manufacturing are wood and cotton fibers (Nanda et al., 2013). Cellulose is a strong and durable polymer with a remarkably high tensile strength, making it well-suited for the production of biodegradable polymers. The thermal stability of this is commendable. Cellulose is altered into cellulose ethers, cellulose esters, and regenerated cellulose to enable its use in the manufacturing of biodegradable plastics (Kharb & Saharan, 2022).

Cellulose exhibits a diverse range of uses across various domains. Hydroxyethyl cellulose or carboxymethyl cellulose, which are types of cellulose ethers, are widely used in various industries such as food packaging, personal care products, construction, paint, adhesives, medical equipment, and tools (Kamel et al., 2008). Cellulose esters, such as cellulose acetate and the cellulose nitrate, have been utilized to create packaging fibers and films. Regenerated cellulose fibers and films are effectively used in various applications such as home decor materials, clothes, textiles, and hygiene disposables (Edgar et al., 2001).

Cellulose possesses a fibrous structure and can be employed in the creation of hydrogels. These hydrogels find applications in bone implantation, tissue engineering, drug administration, cartilage modelling, cell culture scaffolds, and absorption of heavy metal ions (Jeremić et al., 2020). Cellulose nanocomposites have remarkable uses in the field of medicine and healthcare. These devices are utilized for surgical implants in both the orthopedic and dentistry domains. Nano celluloses and their combined forms are effectively utilized in the manufacturing of wound dressings that aim to minimize discomfort and infection while promoting the rapid healing of epithelial tissue. Nano cellulosic materials are being utilized to produce magnetic active and 3D-printed materials (Yaradoddi et al., 2020).

3. Environmental Impacts of Plastic

The production of plastic garbage and consequent unregulated plastic pollution is a significant environmental challenge that governments and organizations must confront in the present day. In 2019, the worldwide plastic production amounted to nearly 370 million metric tons (Mt), with Europe contributing approximately 60 million metric tons to this total. Most of the plastic items that are introduced into the worldwide market are made of long-lasting materials, specifically polypropylene and polyethylene, which are the most popular types of polyolefin in the market. These polymers are primarily used for packaging purposes (Di Bartolo et al., 2021). In 2017, the global production of plastics was expected to be 8300 Mt. However, by 2015, it was found that 79 percent of all plastic generated was sitting in landfill or surroundings (Geyer et al., 2017). According to the UNEP, a mere 9% of the total plastic produced has undergone recycling, while 12% has been sent to incineration, leaving the remaining majority to amass in landfills or natural environments. Currently, the annual production of plastic waste amounts to 300 million metric tons, and approximately 80% of marine litter is caused by plastic debris. The well-known "Great Pacific Garbage Patch" serves as a distressing example of this issue. Additionally, it is estimated that between 75,000 to 300,000 tons of micro plastics enter habitats within the European Union each year (Di Bartolo et al., 2021).

The presence of plastic waste in the natural world is highly enduring, with the process of breaking down in seawater anticipated to take hundreds of thousands of centuries (Gallo et al., 2020). Plastic marine waste has a significant and detrimental impact on the ecosystem. Due to its extended period of decay and water-repellent properties, plastic waste creates favorable circumstances for the growth and diversification of many microorganisms, resulting in the development of an ecosystem known as the "plastisphere". The combination of microbial activity, mechanical stress, temperature deterioration, and UV-light exposure causes the waste to break down into micro plastics. This process is so extensive that plastic remnants may be detected in numerous aquatic creatures, as well as in birds and other mammals. Consequently, this presents a potential hazard to human well-being when it infiltrates the food web (Di Bartolo et al., 2021).

A significant solution to plastic pollution lies in the augmentation of recycling and repurposing efforts for existing plastics, alongside the substitution of various categories of plastic items, especially disposable products, with recyclable alternatives. Additionally, a shift in societal mindset and behaviors is crucial. Simultaneously, fossil resources have a limited supply and their utilization leads to the release of greenhouse gas emissions. According to a report through the Ellen MacArthur Foundation, published in 2016), it is projected that by 2050, the plastics industry will consume approximately 20% of the world's oil and contribute to fifteen percent of the global annual carbon emissions. This carbon budget is crucial for meeting the internationally agreed target of limiting global warming to below a 2°C increase (MacArthur et al., 2016). Producing plastics from renewable resources has been proposed as a means to reduce carbon emissions, as the raw materials absorb atmospheric carbon dioxide through their growth. This approach also aims to reduce the economy's reliance on fossil fuels (Crippa et al., 2019). Technological progress in the bio economy recommends the utilization of recyclable plastics in certain areas, including soil-covering films, baggage carriers, and single-use packaging (Di Bartolo et al., 2021).

4. Advantages and disadvantages of Bioplastic

4.1. Advantages of bioplastic (Venkatachalam & Palaniswamy, 2020; Poliakoff et al., 2002; Reddy et al., 2013).

- The bio plastic items are manufactured using sustainable resources, which helps decrease greenhouse gas emissions by reducing the carbon footprint.
- The user's text is a bullet point. The manufacture of bio plastics entails a 65% reduction in energy consumption compared to the manufacture of petrochemical plastics. The bio plastics will be recycled and used for energy conversion.

- Bio plastics can mitigate environmental issues such as unregulated garbage dumping on land and in the sea, as well as the release of harmful compounds. Nevertheless, in order to maximize the benefits of bio plastics, it is essential to adopt efficient collecting, sorting, and recycling methods, as well as raise public awareness.
- The generation of bio fuel and bio-plastics promotes the rural economy by providing alternative options to oil, which helps protect the environment and ensures energy security. This is particularly important as governments worldwide seek alternatives to oil.
- Plant-based bioplastics effectively handle plant waste and leftovers.

4.2. Disadvantages of bioplastic (Venkatachalam & Palaniswamy, 2020; Cyras et al., 2007; Reddy et al., 2013; Lagaron & Lopez-Rubio, 2011).

- The production cost of bioplastics exceeds that of traditional plastics. As the large-scale industrial manufacturing of bio polymers becomes more prevalent in the future, there is a projected decrease in costs.
- The hydrophilic character of cellulose and starch based plastic packaging materials results in poor process ability, brittleness, susceptibility to deterioration, limited long-term stability, and inferior mechanical properties.
- Contamination can occur in the process of recycling of bio plastic materials if it is not properly segregated from traditional plastics.
- The manufacture of bio plastics may lead to a decrease in raw material stocks.

5. Conclusion

Ultimately, the extensive utilization of petroleum-derived plastics has resulted in a significant ecological catastrophe, characterized by the widespread contamination of plastic, the endangerment of species, and detrimental health consequences for humans. The study emphasizes the inherent difficulties linked to recycling and the restricted achievement in tackling the intricate composition of plastics. The need to transition to environmentally acceptable alternatives is emphasized, with biodegradable plastics appearing as a possible answer due to their capacity to degrade quickly without causing harm. The study presents biodegradable polymers such as cellulose, starch, PLA, PHB, and PHA as viable alternatives to conventional plastics that are both environmentally and commercially sustainable. It therefore calls for their widespread use. Biodegradable polymers are both environmentally and economically viable, making them a progressive solution for reducing the harmful effects of plastic consumption on our planet. This study adds to the increasing evidence that supports the urgent shift towards sustainable and biodegradable products in order to achieve a healthier and more environmentally friendly future, as the negative impacts of traditional plastics continue to worsen.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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