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Sustainable Innovations For A Greener Future: Exploring Biodegradable Plastic Applications

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Abstract
Plastics have become an indispensable part of modern life due to their versatility, durability, and cost-effectiveness. However, their widespread use has led to severe environmental consequences, primarily due to their persistence in natural ecosystems. Conventional fossil-fuel-based plastics degrade very slowly, contributing to pollution in terrestrial and marine environments and threatening biodiversity. As a result, there is a growing global demand for sustainable alternatives such as biodegradable plastics, which are designed to decompose naturally and return carbon to the environment through microbial action. Despite their potential, biodegradable plastics have not yet achieved large-scale replacement of conventional plastics, even after more than a decade of commercial availability. This paper critically reviews the current landscape of biodegradable plastics, exploring why they fall short in contributing to a truly circular economy. It discusses key challenges including limited material performance, inconsistent degradation across environments, lack of standardized testing protocols, restricted application domains, and inefficient waste management systems. To address these barriers, interdisciplinary collaboration is essential—spanning materials science, industry stakeholders, policymakers, and waste management authorities. The article also highlights recent innovations and emerging research in plastic biodegradation, along with the growing role of machine learning in accurately assessing biodegradability. Such technologies can facilitate targeted recycling, improve product design, and support regulatory compliance. By examining both the limitations and the future prospects, this work aims to provide a comprehensive perspective on enabling sustainable plastic solutions.
Keywords: *Sustainability, Biodegradable Polymer, Plastics, Artificial Intelligence, Machine Learning*

1. INTRODUCTION

Conventional plastics, which can persist for millions of years, have sparked a global crisis, posing severe environmental, social, economic, and health risks that threaten ecosystems and human well-being. Social impairments have come about because of factors very few thinks of and one of them is the issue of plastic that has widely been overused. Waste management has now become a world crisis for every country with oceans and land fill every year for millions and billions of tons of plastic put in use. Biodegradable Plastics are usually sourced from replenishable things like corn, potato and also wheat starch, plant-based polymers and even bacteria, making them relatively easier to decompose than the conventional plastic, thereby providing a solution to the problem of plastic waste. These polymers undergo rapid degradation in natural environments under appropriate conditions (e.g., moisture, oxygen, temperature), without releasing toxic residues [1].

The environmental consequences of plastic reliance are significant, especially in marine ecosystems, where approximately 8 million tons of plastic waste enter the oceans annually. This waste accumulation has detrimental effects, including physical harm to marine species, disruption of ecosystems, and pollution in the food chain. The long-lasting nature of traditional plastics, initially seen as beneficial, has now turned into a major issue, as only around 9% of the total plastic waste ever produced has been recycled [2-3]. Biodegradable plastics represent a promising solution to the global plastic waste problem, offering environmental benefits and supporting a more sustainable future. These materials are designed to break down more quickly and completely than traditional plastics, offering a potential pathway toward reducing plastic pollution. Continued research, innovation, and policy support will be essential to overcome current challenges and unlock the full potential of biodegradable plastic applications. With ongoing advancements, biodegradable plastics could play a pivotal role in reducing pollution and fostering a circular economy for a greener planet [3].

Starch-based plastics, made from affordable materials like corn, are commonly used for packaging and dining utensils. Plastics made from bacteria, such as PHA, show significant potential but remain costly to produce. Soy-based polymers, derived from soy protein, are useful in automotive parts and food packaging, while cellulose-based plastics, sourced from plants, are inexpensive and environmentally friendly. Lignin, a byproduct of the paper industry, holds promise for use in composite materials and offers UV stability, and natural fiber-reinforced plastics, which incorporate fibers like jute and bamboo, are particularly valued in the automotive and packaging industries for their strength [4-6]. Unlike plastics that persist for decades or even centuries, biodegradable plastics decompose through microbial action, breaking down into non-toxic byproducts such as water, carbon dioxide, and, in some cases, methane [7].

Biodegradable plastics not only benefit the environment but also advance a circular economy by enabling materials to be effectively recycled or naturally broken down, thereby reducing their lasting ecological impact. With ongoing research aimed at improving their biodegradability, mechanical strength, and cost-effectiveness, these plastics are well-positioned to contribute significantly to reducing environmental pollution [8-9]. The biodegradable plastics are only influenced by a few environmental conditions such as temperature, climate changes, humidity and also presence of different kinds of microorganisms. These factors pave the way for determining how fast and effectively the plastics can decompose [10-11].

Biodegradable plastics have emerged as a promising approach to mitigating the environmental impact of traditional plastic waste. They are designed to decompose more rapidly and completely than conventional plastics, making them a viable solution for reducing the accumulation of waste in both landfills and marine ecosystems. This aspect is crucial, given that around 60% of global plastic waste originates from packaging, with over 80% of that waste consisting of single-use items discarded after just one use [12-13]. Advancements in this field are imperative to unlock their full potential, particularly in improving the properties of these materials to be competitive with traditional plastics. Innovations in biodegradable plastic technology are opening new avenues for their application in various sectors, from packaging to medicine and agriculture [14].

1.1 Types of Biodegradable Plastics

Biodegradable plastics are sourced from 100 % renewable materials such as corn, potatoes, bacteria, soy-based plastics and wheat starch and currently only these have been commercialized and offer great promise in many commodity applications. Here are two types of degradable plastics: photodegradable and biodegradable. Photodegradable plastic is usually made of plastic polymers and is oil-based. These plant-based materials have a much larger carbon footprint [15].

Biodegradable plastics available in the market include the following types: Starch-Based Plastics, these are generally derived from wheat, rice and corn. Among all the three the cheapest one is corn and starch is the most expensive one.

Bacteria-Based Plastics are based on polyhydroxyalkanoate, a polymer that is produced within the bacterial cells. Soy-Based Plastics use the high protein contempt and these can be molded into films and plastics materials and typically used for coating food containers and bottles. Cellulose-Based Plastics are produced from wood pulp, hemp and cotton, cellulose is the most important component to produce biodegradable plastics. Lignin-Based Plastics is a residue from the paper-making process and is renewable, they also enhance the polymer with UV stability. Natural Fiber Reinforced Plastics are made up of fibers such as bamboo, jute, sisal and kenaf which aims to reduce carbon emissions.

The below sections explore the topics including advancements, sustainability goals, economic and environmental drivers, potential risks, and research challenges associated with biodegradable plastics. Many recent innovations are done with using marine elements like seaweed converted into compostable water soluble and edible. Sustainable feedstocks such as algae, wheat straw, and rice husks are the alternatives to traditional sources like corn and sugarcane in improving strength, flexibility, and other barrier properties. The world is producing 430 million tons of plastics per year and 11 million leaks into oceans harming the marine life entering into our food chain. Economically this industry is set to reach a 26 billion global market. The section also highlights the role of biodegradable plastics in minimizing the reliance on petroleum-based plastics.

Further, it addresses potential environmental risks, such as microplastic formation and methane emissions, as well as recycling challenges. But the main concerns the mass adoption of biodegradable plastics is difficult economically. Rising awareness of plastics and carbon taxation and increase in the petroleum products can attract people towards biodegradable plastics as a better alternative. Furthermore, the presence of microplastics in agricultural soils and food products raises concerns about environmental and human health impacts, addressing these challenges requires continuous research and other effective way of production and disposal methods and global standards to implement policies to reduce overall plastic consumption and production.

2. Experimental

2.1 Advances and Innovations in Biodegradable Plastics

Recent advances in biodegradable polymers have focused on improving the quality so that they can also compete with the normal plastics used in day-to-day life. Enhanced Degradation in Marine Environments have played a critical role in reducing the marine plastics pollution, these new formulations of biodegradable plastics incorporated enzymes and microorganisms that were capable of breaking down polymers in aquatic conditions, specific enzymes, such as hydrolases, accelerates hydrolytic degradation in saline environments by achieving 60% decomposition within 120 days in simulated marine conditions. **Figure 1(a) and Figure 1(b)** depicts the flow of converting biodegradable plastic into a usable plastic item.

Nanotechnology Applications have revolutionized biodegradable plastics, the changes have made the biodegradable plastic is that they have improved its strength, flexibility, and barrier properties. Some of the nanoparticles are nanoclays, graphene oxide, or cellulose nanofibers. Sustainable Feedstocks for Bioplastic Production is an alternative to corn and sugarcane as well, the alternative raw materials are algae, wheat straw and rice husks. The main advantage is that the materials are available in abundance. **Figure 2** represents the biodegradation process of polymers, breaking down from high molecular-weight polymers to low-weight fragments. This initial transformation is facilitated by environmental factors like UV radiation, temperature, and physical wear or by microbial enzymes. Once fragmented, these simpler molecules become accessible for microbial degradation, which can occur aerobically (in the presence of oxygen) or anaerobically (without oxygen).

Under aerobic conditions, microbes convert these fragments into carbon dioxide, water, and biomass, while anaerobic conditions yield methane, carbon dioxide, and biomass. The entire degradation process depends heavily on environmental factors such as temperature, moisture, and microbial community composition. In ideal environments, like industrial composting, these plastics degrade more efficiently; however, in natural settings, degradation can be slow, challenging the practical environmental impact of biodegradable plastics.

One of the primary goals of biodegradable plastics is to reduce reliance on petroleum-based plastics, which are derived from non-renewable resources and contribute significantly to carbon emissions. The shift from conventional plastics also lowers greenhouse gas emissions and also minimizes the dependence on fossil fuels.

Biodegradable plastics are intended to decompose more quickly in the environment than traditional plastics, which linger in the environment and endanger animals and ecosystems. The biodegradable plastics also aim at preventing soil contamination and improving soil health by using biodegradable mulching films in farming [16].

2.2 Economic and Environmental Drivers

Research shows that out of 368 million tons of bioplastic produced globally, only one percent of it is biodegradable [17]. This industry is expected to grow at a rate above 300% by the end of 2026. The desire for adopting biodegradable plastics is driven mainly due to environmental factors. Rising awareness about the harmful impact of conventional plastics has led to a growing demand for environmentally-friendly alternatives. Introduction to carbon taxes have made biodegradable plastics a more appealing option to their higher initial costs and rising cost of petroleum has exposed us to other alternatives. Biodegradable plastics can be feasible when manufacturing expenses are reduced [18]. Cost is still a significant obstacle to the broad use of biodegradable polymers, though. To make these materials more widely available and financially feasible for companies and consumers, continuous efforts to enhance production procedures and lower manufacturing costs are essential [19]. Techniques that can preserve cost-effectiveness, the environment, human, and social capital over an extended period of time should be investigated in order to ensure the economic effects of long-term biodegradable plastics.

The cost of producing biodegradable plastics is higher than that of their fossil fuel-based counterparts, and it cannot be attributed to a single input or technology because the process involves a variety of intricate feedstocks, technologies, and procedures. Globally, there are significant differences in the production conditions, technological setup, and processes used to create biodegradable polymers. Another aspect influencing the price of biodegradable polymers is feedstock prices. Nonetheless, the cost of some biodegradable plastics, like PLA, is currently relatively competitive when compared to commercially available plastics. In terms of cost, it now dominates the market for bio-based and biodegradable plastics [20].

2.3 Potential Environmental Risks and Recycling Challenges

Despite their benefits, biodegradable plastics are not completely environmentally friendly. When these plastics are disposed of improperly or in unsuitable conditions, they can break down into microplastics and nanoplastics which are indeed harmful because through the breakdown of bioplastics, methane which is a greenhouse gas is produced during the anaerobic breakdown of bioplastic in landfills [20]. Because bioplastics need different streams than conventional plastics because of their differing chemical compositions and degrading characteristics, there is uncertainty and possible contamination in the recycling process. To guarantee appropriate recycling procedures, this calls for clear labeling and public knowledge. Third, recycling, organic recovery, and energy recovery are the best end-of-life solutions for bioplastics because they prevent landfilling. These procedures necessitate a well-structured recovery chain that involves routine collecting and sorting. Finally, whereas anaerobic digestion presents a viable option toward the end of life [20].

3. RESULTS AND DISCUSSION

3.1 Current Research Challenges

Biodegradable plastics are very expensive to produce and making them with a lesser price is very competitive and not feasible to the people as they are way more costly as compared to the normal plastics which are 2 to 10 times less cheap [21]. These Biodegradable plastics also require industrial composting so composting in normal environment would in fact harm the environment and in natural settings, they may not decompose as intended. As of now there is no infrastructure and only limited infrastructure is available for composting which means many biodegradable plastics end up in landfills, where they degrade slowly. Misunderstanding between the term’s "biodegradable" and "compostable" lead to improper disposal, reducing environmental benefits. The main disadvantage of Biodegradable plastics is that incomplete degradation, especially in oceans and lands, can lead to the formation of microplastics, which again contribute to pollution. Global standards have not been set, so it makes it challenging for consumers and industries to manage bioplastics effectively.

3.1.1 Application Areas for Biodegradable Plastics

Biodegradable plastics like Polylactic Acid (PLA) and Polyhydroxyalkanoate (PHA) are widely used to manufacture in making food containers, shopping bags, and beverage bottles in packaging Industry. Advantage of using biodegradable plastics is that they are biocompatible making them ideal for direct contact with food and drinks. In the agricultural sector, the biodegradable plastics are primarily and mainly used in the form of mulch films. These films also help in maintaining the soil moisture and also reduces weed growth also regulating soil temperature. Unlike the regular mulch films which also contribute to the long-term soil pollution. Biodegradable plastics such as PLA and PHA are making significant and remarkable contributions to the medical field due to their biocompatibility and biodegradability, most of the medical equipment is made up of plastics which is of single-use. These advancements underscore the potential of biodegradable plastics to revolutionize modern healthcare and enhance patient safety [22-23].

Moreover, consumer goods like disposable cutlery, straws, and bags are increasingly being made from biodegradable plastics, reducing the environmental impact of single-use products [24]. Integrating biodegradable plastics with natural fibers such as flax, hemp, or kenaf has also led to the development of composite materials with enhanced mechanical properties. These natural fiber-reinforced bioplastics are finding applications in the automotive and construction industries, where lightweight and durable materials are in high demand [25-26]. **Figure 3** illustrates wide-ranging applications of biodegradable materials, categorized into aliphatic polyesters and natural macromolecules, across fields such as environmental protection, medicine, and material science.

Aliphatic polyesters like PLA, PBS, and PCL are synthetic biodegradable polymers used in applications from food packaging and environmental protection (e.g., oil-water separation membranes) to advanced medical uses, such as tissue engineering, drug delivery systems, and surgical sutures. These polymers degrade naturally, reducing waste and minimizing environmental impact. On the other hand, natural macromolecules—such as cellulose, chitin, and lignin—offer renewable alternatives derived from plants and marine organisms. Cellulose is converted into useful materials for textiles and flame retardants, whereas chitin is widely employed in biomedical applications such as wound dressings and water treatment due to its antibacterial qualities.

3.2 Triple bottom line approach

The Triple bottom line approach had three components that are people, planet, profit. The triple bottom line maintains that companies should commit to focusing as much on social and environmental concerns as they do on profits [7]. The main aim to this is knowing the importance of balancing economic goals with the contributions made to the society using sustainable practices.

- Popple (social responsibility): Biodegradable plastics can contribute in a positive way to the people by potentially reducing the plastic hazards such a toxic chemical getting leached into the atmosphere and food chain adversely affecting the people creating awareness and educating people to adopt the sustainable practices.
- Planet (Environmental Stewardship): Many studies and researchers have been focusing on the potential to reduce pollution in the environment, especially in the marine and terrestrial ecosystem [26].
- Profit (Economic Viability): Economically speaking, biodegradable polymers may be more expensive initially, but they offer substantial value over time in terms of decreased carbon emissions and waste management costs. The market expansion offers economic opportunities for businesses investing in biodegradable plastic technologies [26].

3.3 Future Directions and Technological Advancements

Innovative Production methods by using biotechnological processes and advancements in genetically engineered microorganisms play a role in producing biodegradable plastics. These can be efficiently converted into biomass. Targeted Biodegradation can be a critical area of research on enhancing the degradation rates. This involves the development of specific enzymes and microorganisms that are tailored to break down the plastics more efficiently and ensure they decompose in the timeframe

3.4 Circular Economy Approaches

Integrating biodegradable plastics into a circular economy emphasizes on reusing, reducing, recycling and reducing materials to maximize the resource consumption. To implement this infrastructure, we need to have effective way of composting, waste management practices. Furthermore, we need to have clear standards to ensure economic viability which is crucial for fostering a sustainable model, this circular economy model not only reduces the reliance on the virgin materials but aligns with broader sustainability goals by reducing the carbon footprints. **Figure 4** depicts how biodegradable polymers are sustainable in a closed-loop system.

The first process starts off with the production of biodegradable plastics in which production is done from sustainable materials and this method is focused on minimizing the impact of the environment through reducing the impact on the nature. Implementing waste management strategies and effective ways to ensure that biodegradable plastics are sorted and processed correctly preventing them from ending up together with the petroleum-based plastics which may be unsuitable. Biodegradable plastics need to composted using industrial methods and decomposed under controlled conditions. composition breaks down into biomass, carbon dioxide and water which in turn enrich the soil. Some biodegradable plastics are also processed in anaerobic digestion which facilities the generation of biogas. The ultimate goal of this system is to maintain a closed-loop system where materials are cycled back to the economy rather than being converted waste. This ensures minimizing the leakage into the environment [26].

A certain limitation of the present situation is that actual customers may have different understandings of the biodegradability concept. The awareness of biodegradable plastics is less heard because people feel that the biodegradable plastics are more expensive. Buyers that are consumers play a pivotal role in encouraging the adoption of biodegradable plastics, directly impacting on the demand, compelling all the factories and industries to shift from those harmful plastics to biodegradable plastics. However, many consumers may not know that the conditions in home composters and in the open environment are very different compared to industrial composting plants. This affects the rate and extent of breakdown. **Figure 5** illustrates the key elements—consumer awareness, public education, transparent labeling, and awareness campaigns—that support the adoption and correct disposal of biodegradable plastics.

To fully realize the benefits of biodegradable plastics, several policy interventions are needed. Governments should consider offering subsidies and incentives for the production and development of biodegradable plastics, helping these alternatives compete with traditional plastics. Standardization of Testing and Certification is the first step where the manufacturers develop globally recognized, standardized biodegradability tests to ensure consistent evaluation across regions. Mandatory Implementation of mandatory certification for all biodegradable plastics, requiring conformity with established biodegradability standards. Manufacturers to invest in research to create cost-effective, time-efficient biodegradability tests that closely mimic real-world conditions while maintaining accuracy. Clarification of biodegradability categories to standardize biodegradation metrics, such as theoretical oxygen demand, to enhance consumer understanding and trust. Infrastructure development to be done to provide incentives for industries to develop localized disposal and recycling facilities. Figure 5 depicts the big picture for the consumer awareness about biodegradable plastics

Monitoring and controlling the use of additives in biodegradable plastics to prevent potential environmental risks during degradation is to be done. Providing funding for academic and industrial research to improve the material properties and cost-efficiency of biodegradable plastics. Highlight the specific conditions (e.g., industrial compost, soil degradation) required for effective biodegradability to increase its usage. Incorporate Biodegradable Plastics in Circular Economy Goals by promoting the role of biodegradable plastics in achieving circular economy objectives by incentivizing reuse, recycling, and proper disposal.

4. CONCLUSION

Currently Renewable and biodegradable plastics derived from soy protein isolate (SPI) offer a promising alternative to conventional petroleum-based plastics. To compete with traditional plastics, biodegradable materials must exhibit comparable mechanical strength. Recent advancements involve reinforcing soy protein isolate (SPI) with cellulose nanocrystals (CNCs) to develop bio-nanocomposites. Biodegradable plastics can be an alternative solution in the future replacing the petroleum-based plastics and biodegradable plastics can be enhanced in future using nanoparticles as well for industrial use. This ensures that these biodegradable plastics have an ability for long term use as well and also have shown quite remarkable results in terms of durability, mechanical properties, and flexibility. The only drawback which can be seen is limited recyclability due to its chemical structure and also tedious and industry level recycling processes. Looking at the present situation it can primarily use for short term applications like packaging using biodegradable plastics like chitosan, PLA (Polylactic Acid), PHA (Polyhydroxyalkanoates), PBS (Polybutylene Succinate) and PCL (Polycaprolactone) disposable cutlery and agricultural films which has faster degradation. However, widespread adoption is hindered by challenges like high production costs, limited performance under certain conditions, and the need for specialized disposal infrastructure. Research trends also based on environment Impact Assessments like understand ecological footprints of biodegradable plastics is also crucial.

Compliance with ethical standards

Conflict of interest: The authors declare that they have no conflict of interest.

Data Availability: Data will be made available upon request.

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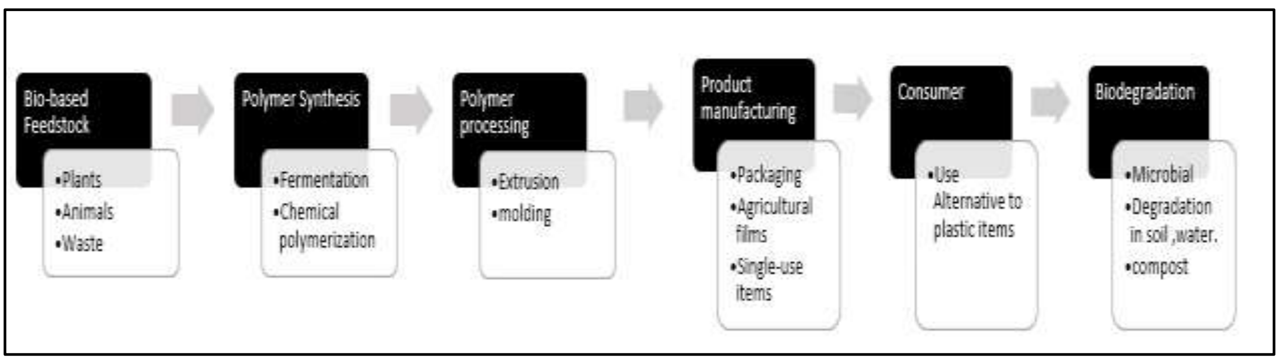

Figure 1(a): Flow of converting biodegradable plastic into a usable plastic item.

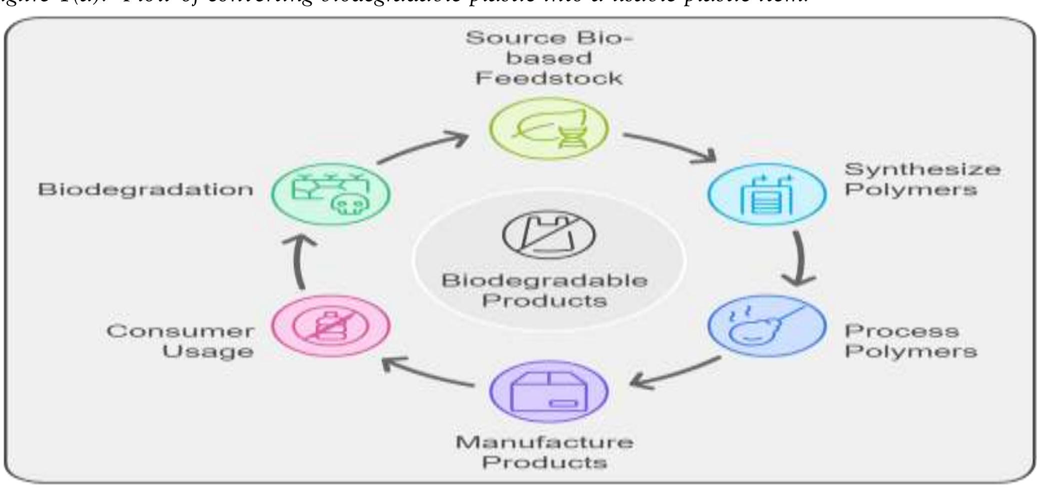

Figure 1(b). Process of converting ***biodegradable plastic*** *into a usable* ***plastic item.***

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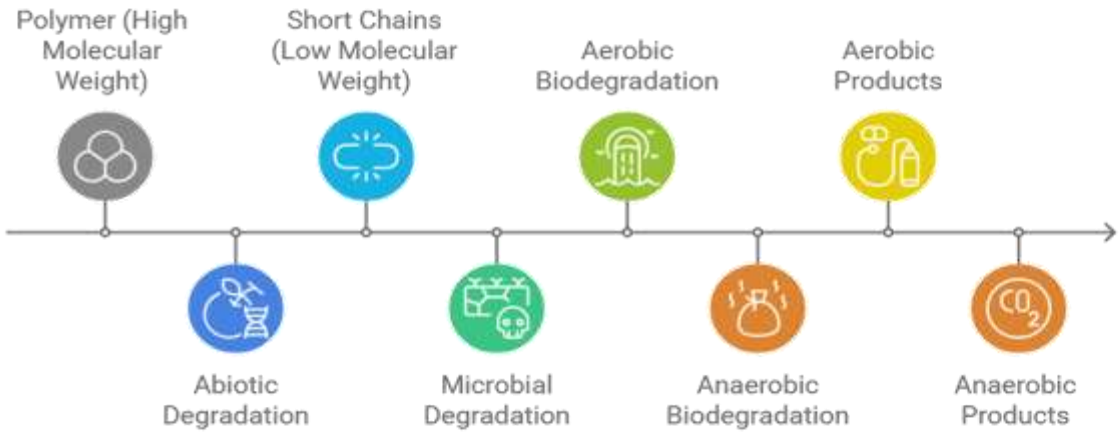

Figure 2. Degradation process of biodegradable plastics from polymer to gases

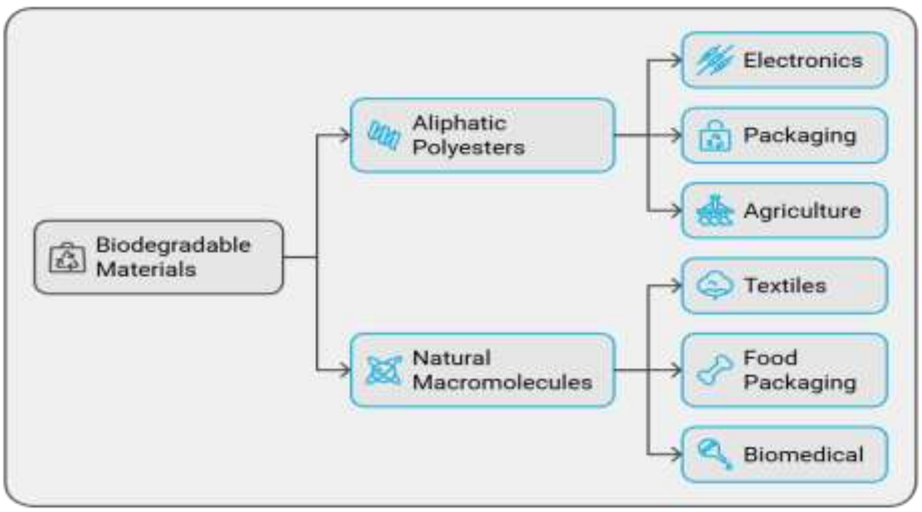

Figure 3. Wide range of Biodegradable plastics in all Sectors.

Figure 4. The process of degradation alongside the components of circular Economy.

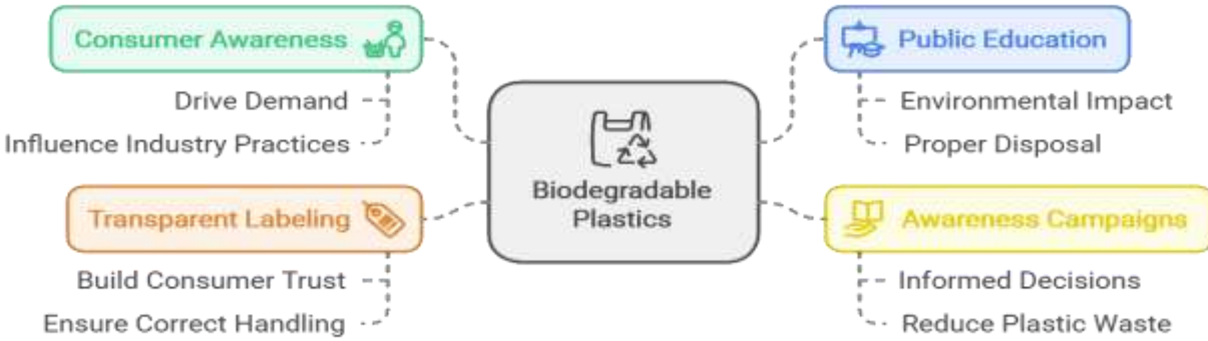

Figure 5. Consumer awareness about biodegradable plastics.