Enhancing the Production of Bioplastics for Sustainable Recycling and Biodegradation- Short Review.

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Abstract: The shift from the production and utilization of synthetic non-plastics to bio-based plastics is on the high side. To curb the environmental nuisances, the synthetic plastics have presented over time. Consequently, it is required to consider some factors that can be manipulated or adjusted to facilitate the biodegradation process. The factors that determine the rate of biodegradation of bio-based and fossil-based plastic and the features of biodegradable plastics are highlighted in this review. This is projected to secure a sustainable bio-plastic synthesis and catalyze bio-recycling and biodegradation strategies.

Keywords: Bioplastic; Biodegradable; Agrowaste; Environment; Biodegradation; Recycling

1.0 INTRODUCTION

“Bio-plastics” simply refers to a type of plastic that is obtained from renewable feedstock products from agro-materials or microorganisms. In contrast, conventional plastics are produced from fossil-based hydrocarbon [1]. The first generation of bio-plastics was sourced from traditional agricultural and renewable resources such as corn, cassava, beans. The second-generation sources progressed to the utilization of non-food renewable sources, which include switch grass, sawdust, hemp and the by-products obtained from the processing of the first generation sources such as husks, peels and chaffs [1]. According to Kjeldsen et al., [2], bio-plastics can be divided into two categories, namely Bio-based plastic and Biodegradable plastics.

(i) Bio-based plastic refers to a category of plastics that are produced from natural monomers formed by either plants, animals, or microorganisms. They can be derived from either natural polymers or artificially synthesized polymer mixed with natural polymers. They are often, but not always fully biodegradable depending on additives and components utilized in the production process [3].
(ii) Biodegradable plastics: This category of plastics possess the ability to degrade into carbon dioxide (CO₂), methane (CH₄), water (H₂O) and biomass through biological or enzymatic actions in a positive environment such as composting, anaerobic digestion, marine, and soil [3].

It is important to note that not all bio-based plastics are biodegradable [1]. This is because biodegradation does not depend on the resource basis of material but rather on its chemical structure [3]. With this in view, bio-plastics are categorized into three groups;

(i) Bio-based non-biodegradable bioplastics: This category of bio-plastics comprises of many specific polymers such as bio-based polyamides (PA), Polyesters, Polyurethanes (PUR), and Poly epoxides [4].

(ii) Bio-based biodegradable plastics: This group includes starch blends made from the mixture of thermo-plastically modified starch and biodegradable polymers [5].

(iii) Biodegradable bioplastics based on fossil resources: This is a comparatively small category of bio-plastic that are commonly employed in combination with other bio-plastics to improve their performance [6].

2.0 BIODEGRADATION OF PLASTICS

The concept of plastic waste being biodegradable is considered to be the most sustainable approach to reduce environmental pollution. This concept has led to a spike in the research and development of a class of plastics termed biodegradable plastics, which undergo a process known as biodegradation [4].

2.1 Mechanism of Biodegradation of Plastics

Biodegradation is simply a chemical process that involves the breaking down of substances by the action of naturally occurring microorganisms such as bacteria, fungi, and algae producing carbon dioxide (CO₂) and methane (CH₄) as of end products [5]. When biodegradation occurs in the presence of oxygen, it is referred to as aerobic degradation, while biodegradation in the absence of oxygen is called anaerobic degradation. The biodegradation process caused by microorganisms entails the following steps:

(a) Attachment of the organisms to the surface of the polymer [8]
(b) Secretion of enzymes from microorganisms that de-polymerize the polymer into low-molecular weight compounds [5].
(c) Ultimate degradation of the polymer. Once the microorganisms attach itself to the surface of the polymers, it begins to grow as it draws carbon supply from the polymer causing it to breakdown. Ultimate degradation of the polymer occurs when the microorganisms secrete extracellular enzymes causing it to chemically malfunction into low-molecular-weight fragments like oligomers, dimers, or monomers [6].

The breakdown of the polymer caused by a microorganism can be of three different types, namely: Biophysical effect: This involves the biodegradation of the bio-plastic as a result of cell growth, which results in mechanical damage [9]. Biochemical effects: This involves the breakdown of the bio-plastic as a result of the substances secreted from the micro-organisms.

Direct enzymatic action: This is the breakdown of the bio-plastic as a result of the effect of the enzymes secreted by the microorganisms on its components [7].

2.2 Bio-degradation Stages
Bio-degradation of plastics has been observed to occur in three stages namely;

(i) **Bio-deterioration**

This is the first stage of degradation that occurs at the end of a plastic’s useful lifecycle characterized by a change of elastic and tensile strength as well as the brittleness of the plastic [2]. This stage is also referred to as surface-level degradation that changes the mechanical, physical, and chemical properties of the plastic. The mechanisms involved in the physical and chemical changes that occur during the initial stages of degradation are considered to be abiotic [4]. These mechanisms are a combination of various factors namely; Mechanical degradation occurs as a result of physical forces such as compression, tension, and shear forces acting on plastics, compression, pressure, and shear forces, which include water turbulence, animal tearing leading to the damage of the plastic. Light/Photo Degradation occurs via chemical reactions by destabilizing the polymers on exposure to ultra-violet rays from the sun. Thermal degradation occurs when heat impacts the organized framework of polymers and Chemical degradation which occurs when the polymer is exposed to chemicals such as atmospheric pollutants or agrochemicals which causes it to breakdown [5].

(ii) **Bio-fragmentation**

This stage of degeneration is known as the lytic stage, which is necessary for the assimilation of the plastic molecules. It involves fragmenting high molecular weight polymer by dissolving the bonds within it into a mixture of oligomers and monomers of smaller molecular weight when plastics undergo fragmentation they become more susceptible to biodegradation by enzymes [6].

(iii) **Microbial Assimilation and Mineralisation**

This is the last and final stage of the bio-degradation process, which involves the absorption of the monomers produced after fragmentation into a microorganism/microbial cell to generate biomass and carbon dioxide in the presence of oxygen or methane in the absence of oxygen [2].

### 2.3 Factors Affecting Bio-Degradation of Bio-plastics

The biodegradability of bioplastics is a complex process which is influenced by various factors such as the nature of organisms present in the soil, soil properties, environmental factors, the characteristics of the polymer, such as its molecular weight, crystallinity, the functional groups present in the polymer and the nature of the plasticizer used in making the polymer. All these factors play a vital role in the bio-degradation process of a bio-plastic [8]. Furthermore, some major biological factors could provoke chemical and physical alteration of the structures of plastics resulting in molecular chain disruption. The process of polymer biodegradation is induced primarily by the consortium of microorganisms acting upon it. Still, several other conditions, such as thermal degradation, chemical hydrolysis, and irradiation, might enhance the process. The factors that enhance biodegradation are summarized below [9].
2.4 Abiotic factor

Abiotic factors are essentially physical components of the environment that influence the biodegradation process. These factors include moisture content of the soil, pH level, temperature amongst many others.

2.4.1 Moisture

The abundance of moisture catalyzes the biodegradation of plastics. Moisture allows the interaction of the microbial cells with the molecules of the plastics and hydrolysis; the abundance of water enhances the proliferation of microbial cells, which consequently increase the release and action of extracellular enzymes. Ho et al. [10] reported the increase in biodegradation during humid conditions compared to dry conditions. Ahimbisibwe et al. [11] also observed an increase in the biodegradation of bio-plastics when placed in distilled water and tap water compared to those under normal conditions.

2.4.2 pH

The degree of acidity or alkalinity (pH) of the environment also impacts the rate of biodegradation of plastics. The pH value affects the rate of hydrolysis reaction and microbial growth [12, 13]. pH changes the acidic or alkali condition, thereby increasing the rate of hydrolysis of bio-plastics. Reports have shown the optimal rate of hydrolysis of a biopolymer (Polylactic Acid Capsules) at pH 5 [13, 14].

2.4.3 Temperature

One of the desirable factors required for the degradation of polymers is temperature [15], and various materials have specific temperature required for their degradation. Microbial growth and activities increase with a rise in temperature. However, extremely high temperatures diminish microbial activities as high temperatures could kill microbial cells [16]. The rate of
hydrolysis, which aids the further performance of microbial cells, has been shown to increase with an increase in temperature [13].

The standard temperature range for biodegradation experiments is between 20°C and 28°C, with 25°C seen as the most optimal in the EN 17033 (European Committee for Standardization). This is important to note as the temperature has been observed to affect microbial activity, as well as reactions that are chemical and biochemical [5]. These effects are best studied with the use of a thermal performance curve (TPC) from which three significant phenomena are depicted in respective regions. The first shows increased activity as the temperature is increased; the second is a mesa phase with a level activity that shows the highest temperature activity can occur, while the third shows a sharp decline in business as temperatures continue to increase [14].

Generally, the rate of microbial activity grows with temperature until it reaches the range when the killing off the microorganisms starts to dominate. Also, degradable enzymes produced by microbes are affected by an increase in temperature [16]. Ahimbisibwe et al. [11] also observed that rise in temperature influences the loss of weight in bio-plastics. Still, at a temperature of 50°C and above, the rate of degradation slowed down, which was attributed to reduced moisture content hence inhibiting the production and activity of hydrophilic enzymes and microbes except for thermo-tolerant organisms such as termites whose activities continued despite the high-temperature condition.

2.5 Biotic Factors

Biotic factors are concerned with biological agents that promote the biodegradation of the various forms of plastics.

2.5.1 Enzymes

Enzymes are biological compounds that catalyze a chemical/natural process. There are essential microbes (primarily bacteria and fungi) that often release extracellular enzymes that aid in the execution of this process [17]. Bacteria and fungi aid in degrading these polymers into simpler compounds and further to the end product; CO2 and H2O via various enzymatic production and metabolic pathways. The enzymatic nature and the catalysis process of the microbes vary with its species and even the strains, therefore generally, classifying the metabolic mechanism is challenging. However, they can be classified based on the type of enzymes they produce [17].

Protease-producing enzyme; Bacillus sp. and Brevibacillus sp. have been implicated in the biodegradation of various polymers [18]. Laccases-producing fungi that degrade lignin accelerate aromatic and non-aromatic compounds via an oxidation process [19]. The biodegradation process via microbial enzymes is economical and environmentally sustainable. However, there is a need for the exploration of the novel microbial enzyme to optimize conditions for efficient biodegradation of bio-based and fossil-based plastics [20].

2.5.2 Polymer Characteristics

The characteristics of polymers play an essential role in the degradation process. Some of these critical characteristics include molecular weight, polymer chain, additives, and biosurfactants.

(i) Molecular weight of the polymer

The relationship between the molecular weight of a compound and its solubility is inverse; this implies that higher molecular weight plastics are less soluble, which also diminishes the
activity of microbial cells [13]. Tokiwa et al. [20] reported a slow degradation of a higher molecular weight biopolymer by lipase of \textit{R. Delemar} compared to a lower molecular weight biopolymer.

(ii) Polymer Chain

These are the bonds/ linkages between the monomers and the individual atoms. The more the flexibility of these compounds, the lesser temperature required to break the bonds and the more accessible they are to attack by microbial cells [21], and this increases the rate of biodegradation [22] Larger polymer size implies a small surface area which reduces the rate of biodegradation [23, 24]

(iii) Additives

The addition of natural polymeric substances such as starch and cellulose synthesized from plant materials in plastics affect its rate of biodegradation positively. Abioye and Obuekwe [25] Dalta and Halder [26] reported an increase in Low-density Poly-ethene (LDPE) with starch additives compared with LDPE with no additives.

(iv) Biosurfactants

The production of biosurfactants, which are amphipathic compounds, is on the surface of microbial cells. Microorganisms synthesize these compounds to aid in dissolving the surface of hydrophobic compounds, especially plastics, which support the accessibility of the microbial cells to the plastic compounds [26]. The addition of biosurfactants can accelerate the biodegradation of bio and fossil-based plastics, and this is attributed to their reduced toxicity, specific functional groups, and their ability to be active under extreme environmental conditions [27].

3.0 MONITORING OF BIODEGRADATION OF PLASTICS

In the investigation into the biodegradability rate of plastic buried in soil, environmental analysis should be carried out on the system. The ecological considerations include the: Predominance of implicated microorganisms commonly involved, moisture content of the soil, rate of oxygen consumption, light, and thermal conditions [25].

A host of methods are applied in monitoring the mechanisms of biodegradation and levels to which it occurs by examining changes in chemical, physical, and mechanical properties before, during, and after degradation [12] The microorganisms, polymer layers, and the resulting products of the reaction are observed, and changes in features such as growth or depletion are noted. As was said earlier, the moisture and microorganism content, as well as the light and thermal conditions, play a considerable role in the biodegradation process. The effects of these things are observed either at constant or varying levels, and the observations are noted [28].

Depending on the type of environment, there are standards in existence for characterizing the biodegradability of items. For simulation purposes, there are several standardized testing procedures for plastics that can be degraded in the marine environment. Weber et al. [28] gave the ASTM D6691, ASTM D7473, ISO 16221, ISO 18830, and OECD/OCDE 306 as those currently in use as a few others have been withdrawn for revision. Some standards that exist as guidelines for testing in terrestrial environments are ASTM D5988, ISO 17556, UNI 11462, and NF U52-001. There exist, also, several standards for anaerobic and aerobic biodegradation like ISO 14853 and ISO 14851, respectively [29], where the evolution of
methane (CH₄) and carbon dioxide (CO₂), as well as oxygen where applicable, is monitored by respirometry.

Experiments guided by these standards and methods bring forth specific results. However, they are but simulations. In the laboratories, they are carried out under particular conditions, which might or might not be experienced in actual field applications [22]. Environmental conditions change, especially with seasons, and the rates at which biodegradation will occur might be different. Certain factors like environmental pH, precipitation, air temperature, and moisture content are variable and cannot be controlled by man. Microbial activity also differs per set, and along with the other variables, can alter the degradation rates and extents [30]. The chemical, physical and mechanical properties of the polymers are analyzed before and after the degradation process is enacted to ascertain the modes, extents, and effects of the process.

3.1 ENVIRONMENTAL IMPACTS & SUSTAINABILITY OF BIOPLASTICS

BIODEGRADATION

In today’s society, plastics are considered essential materials and are popularly utilized in the packaging industries for single-use. Over the years, they’ve posed severe threats to the environment due to the failure to effectively discard plastic waste, sparking an increase in concern for the environment. The disposal issue has led to the adoption of bioplastics as sustainable alternatives due to their ability to degrade when disposed of in our environment. [33-35] These bio-based plastics have quite an array of positive impacts along their production process on our environments, such as significant reduction of carbon footprint and greenhouse gas emissions, an increase in resource efficiency, independence off of fossil resources, amongst many others. According to European bioplastics, the production of bioplastic impacts the environment quite positively. However, the lack of strict standards in today’s society makes it impossible to classify if these plastics are capable of being disposed of in our environment without posing any significant threats. From the results of Chavez et al. [36] sustainability analysis of bioplastics, it was stated that although these materials offer more positive impacts than conventional plastics on our environment, complete sustainability is yet to be achieved [37]

4.0 CONCLUSION

The production and utilization of bio-plastics have gradually emerged as an alternative support to reduce environmental issues caused by the improper disposal of the synthetic plastic products, and it is imperative to assess the economic and sustainable means to improve the quality of the bio-plastics overtime consistently. This review analyses the factors that can be considered for enhancing excellent condition in the production of bioplastics and to design strategies for recycling and disposal management.

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References

[1].Korawit C., (2016), Bioplastic Industry From Agricultural Waste In Thailand, Journal Of Advanced Technologies. 3:4
[2].Kjeldsen, A., Price, M., Lilley, C., and Guzniczak, E (2019). (n.d.). A Review of Standards for Biodegradable Plastics
[3]. European Bioplastics. (2016). Bioplastics Market Data.

[4]. Ozdanmar E. and Ates M. Rethinking Sustainability: A research on starch-based bioplastic, 3(3): 249 – 260

[5]. Guzman, A., Janik, H. Z., Mastalerz, M., and Kosakowska, A. (2011). A pilot study of the influence of thermoplastic starch-based polymer packaging material on the growth of the diatom population in a seawater environment. Pol. J. Chem. Tech. 13, 57–61

[6]. Fesseha, H., and Abebe, F. (2019). Degradation of Plastic Materials Using Microorganisms: A Review. Public Health – Open Journal, 4(2): 57–63.

[7]. Angaji, T., and Reza, H. (2004). Preparation of Biodegradable Low-Density Polyethylene by Starch – Urea Composition for Agricultural Applications. 23(1): 7–11.

[8]. Abioye, O. P, Abioye, A. A, Afolalu, S.A, Akinlabi, S. A and Ongbali, S. O, A Review of Biodegradable Plastics in Nigeria. International Journal of Mechanical Engineering and Technology 9(10), 2018, pp. 1172–1185.

[9]. Muthukumar, A., and Veerappapillai, S. (2015). Biodegradation of plastics – A brief review. International Journal of Pharmaceutical Sciences Review and Research, 31(2): 204–209.

[10]. Ahmed T., Shahid M., Azeeem F., Rasul I., Shah A., Noman M., Hameed A., Manzoor N., and Manzoor I., and Sher M (2018), Biodegradation Of Plastics: Current Scenario And Future Prospects For Environmental Safety. Environmental Science and Pollution Research, 25:7287–7298

[11]. Ho K., Pometto A. and Hinz P. (1999), Effects of temperature and relative humidity on polylactic acid plastic degradation. Journal of Environmental Polymer Degradation, 7(2):83–92.

[12]. Ahimbisibwe M., Banadda N., Seay J., Nabuuma B., Atwijukire E., Wembabazi E., Nuwamanya, E (2019) Influence of Weather and Purity of Plasticizer on Degradation of Cassava Starch Bioplastics in Natural Environmental Conditions. Journal of Agricultural Chemistry and Environment, 8:237-250

[13]. Trivedi P., Hasan A., Akhtar S., Siddiqui M., Sayeed U., Khan M. (2016) Role Of Microbes In Degradation Of Synthetic Plastics And Manufacture Of Bioplastics. J Chem Pharm Res, 8: 211–216. 37

[14]. Auras R, Harte B, Selke S (2004) An Overview Of Polylactides As Packaging Materials. Macromol Biosci, 4:835–864. 38

[15]. Abioye, A. A., Fasanmi, O. O., Rotimi, D. O., Abioye, O. P., Obuekwe, C. C., Afolalu, S. A., & Okokpujie, I. P. (2019, December). Review of the Development of Biodegradable Plastic from Synthetic Polymers and Selected Synthesized Nanoparticle Starches. In Journal of Physics: Conference Series (Vol. 1378, No. 4, p. 042064). IOP Publishing.

[16]. Henton D., Gruber P., Lunt J., and Randall J. (2005) Polylactic Acid Technology. Biopolymer Biocompos, 16:527–577.

[17]. Cossu, R., Morello, L.(2018) Stegmann, R. 3.1-Biochemical Processes in Landfill. In Solid Waste Landfilling. Elsevier: Amsterdam, The Netherlands, pp. 91–115.

[18]. Santella C, Cafiero L, De Angelis D, La Marca F, Tuffi R, Ciprioti SV (2016) Thermal And Catalytic Pyrolysis Of A Mixture Of Plastics From Small Waste Electrical And Electronic Equipment (WEEE). Waste Manag, 54:143–152.

[19]. Shah A., Hasan F., Hameed A. and Ahmed S (2008) Biological Degradation Of Plastics: A Comprehensive Review. Biotechnol Adv, 26:246–265

[20]. Sivan A (2011) New Perspectives in Plastic Biodegradation. Curr Opin Biotechnol, 22:422–426
[21]. Mayer AM, Staples RC (2002). Laccase: new functions for an old enzyme. *Phytochemistry*, 60: 551-565

[22]. Tokiwa, Y., Calafia, B. P., Ugwu, C. U., and Aiba, S. (2009). Biodegradability of plastics. *International Journal of Molecular Sciences*, 10(9), 3722–3742.

[23]. Abioye, A. A., Oluwadare, O. P., Abioye, O. P., Obuekwe, C. C., Afolalu, A. S., Atanda, P. O., & Fajobi, M. A. (2019). Environmental Impact on Biodegradation Speed and Biodegradability of Polyethylene and Zea Mays Starch Blends. *Journal of Ecological Engineering*, 20(9).

[24]. Tabasi R. and Ajiji A. (2015) Selective Biodegradation Of Biodegradable Blends In Simulated Laboratory Composting. *Polymer Degradation Stab.*, 120:435-442

[25]. Li M., Witt T., Xie F., Warren F., Halley P. and Gilbert R. (2015) Biodegradation Of Starch Films: The Roles Of Molecular And Crystalline Structure. *Carbohydr Poly.*, 122:115–122.

[26]. Steven D., James J., and Kathy B (2003), Changes In Microbial Community Composition And Function During A Polyaromatic Hydrocarbon Phytoremediation Field Trial, *Appl Environ Microbiol*, 69: 483-48

[27]. Kijchavengkul T and Auras R. (2008), Factors Affecting Biodegradation. *Polymer International*, 57(6): 793–804

[28]. Abioye, A. A., and Obuekwe, C. C. (2020). Investigation Of The Biodegradation of Low-Density Polyethylene-Starch Bi-Polymer Blends. *Results in Engineering*, 5.

[29]. Abioye, A. A., Obuekwe, C., Fasanmi, O., Oluwadare, O., Abioye, O. P., Afolalu, S. A., ... & Bolu, C. (2019). Investigation of Biodegradation Speed and Biodegradability of Polyethylene and Manihot Esculenta Starch Blends. *Journal of Ecological Engineering Vol*, 20, 2.

[30]. Datta, D., & Halder, G. (2018). Enhancing Degradability Of Plastic Waste By Dispersing Starch Into Low Density Polyethylene Matrix. *Process Safety and Environmental Protection*, 114, 143–152.

[31]. Orr I., Hadar Y. and Sivan A (2004) Colonization, Biofilm Formation And Biodegradation Of Polyethylene By A Strain Of *Rhodococcus ruber*. *Applied Microbiology and Biotechnology*, 65(1):97–104

[32]. Weber, M., Lott, C., van Eekert, M.( 2015): Review Of Current Methods And Standards Relevant To Marine Degradation. Open-Bio-Deliverable-5.5

[33]. Massardier-Nageotte, V., Pestre, C., Cruard-Pradet, T., and Bayard, R., (2006). Aerobic And Anaerobic Biodegradability Of Polymer films And Physico-Chemical Characterization. *Polym. Degrad. Stab.* 91, 620–627.

[34]. Adamcová D., Maja R., Joanna F., Jan Z. and Magdalena D. (2017) Research Of The Biodegradability of Degradable/Biodegradable Plastic Material in Various Types of Environments. *Scientific Review Engineering and Environmental Sciences*, 26 (1): 3-14.

[35]. Abioye, O. P, Abioye, A. A, Afolalu, S.A, Akinlabi, S. A and Ongbali, S. O, A Review of Biodegradable Plasctics in Nigeria. International Journal of Mechanical Engineering and Technology 9(10), 2018, pp. 1172–1185.

[36]. Abioye, A. A., Fasanmi, O. O., Rotimi, D. O., Abioye, O. P., Obuekwe, C. C., Afolalu, S. A., & Okokpujie, I. P. (2019, December). Review of the Development of Biodegradable Plastic from Synthetic Polymers and Selected Synthesized Nanoparticle Starches. In *Journal of Physics: Conference Series* (Vol. 1378, No. 4, p. 042064). IOP Publishing.

[37]. Álvarez-Chávez, C. R., Edwards, S., Moure-Eraso, R., & Geiser, K. (2012). Sustainability of bio-based plastics: General comparative analysis and
recommendations for improvement. *Journal of Cleaner Production*, 23(1), 47–56. https://doi.org/10.1016/j.jclepro.2011.10.003