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Bio-Conversion Of Plastic Waste Into Sustainable Biofuels: A Comprehensive Review Of Microbial Degradation Approaches

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Abstract:
Plastic's pervasive presence in contemporary society has revolutionized industries and daily life but has concurrently birthed environmental concerns necessitating innovative and sustainable solutions. This review navigates recent strides in plastic-to-fuel conversion, with a particular focus on the transformative potential of microbial degradation. Beginning with a critical assessment of environmental challenges linked to conventional plastic disposal, this review meticulously dissects microbial degradation. Unveiling the intricate processes orchestrated by bacteria and fungi, it delves into the unique advantages this method offers, including reduced land dependency, cost efficiency, and minimal environmental impact, setting it apart from traditional approaches like pyrolysis and gasification. Navigating challenges inherent in plastic-to-fuel conversion, such as energy consumption and emissions, this review synthesizes the latest research, technological breakthroughs, and ongoing initiatives. It culminates in a comprehensive overview of microbial degradation's potential for sustainable plastic waste management and biofuel production. As a synthesis of cutting-edge knowledge, this review not onlyq1 informs current scientific discourse but also charts course for future research, policy, and industrial practices, steering towards a harmonious equilibrium between the benefits of plastic and environmental considerations. This work serves as a beacon for those dedicated to fostering a sustainable future through a nuanced understanding of plastic waste management, environmental sustainability, and the evolving landscape of biofuel production.

Keyword: *Environmental impact, Microbial degradation, Plastic waste management, Sustainable biofuel.*

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I. Introduction

A synthetic or artificial polymer that resembles the naturally occurring resins found in trees and other plants is called a plastic. The Greek term plastikos, which meaning "able to be moulded into varied shapes," is where the word plastic originates [1]. Plastics are a geological indicator for the Anthropocene era that have recently become an environmental hazard due to their resistance to degradation and long-term persistence in the environment [2]. Over many years, plastic waste has become a matter of great international concern, especially plastic debris that which majorly effects Aquatic ecosystem. The levels of both macro (e.g. large particles) and micro plastics. (e.g. plastic fragments less than 5 mm in length) have increased significantly in connection with the consumption of plastic based materials in various sectors like transportation, packaging, medicines, medical instruments [3]. This concern has been intensified during the COVID-19 pandemic, in the context of which the amount of plastic waste has increased substantially. Despite growing mistrust, plastics are crucial to modern life, making many possessions cheaper, lighter, safer, and stronger. Scientists are developing bioplastics, made from plant crops, to make plastics more sustainable [4].

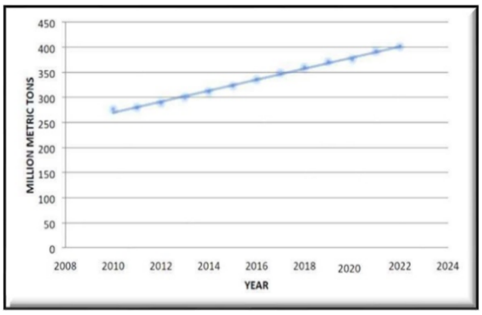

Figure-1: Global Plastic Production (In Million Metric Tons) From 2008 To 2022.

As seen above Figure 1, global plastic production has steadily increased from approximately 275 million metric tons in 2008 to 400 million metric tons in 2020. The trend shows an average annual increase of around 8.33 million metric tons. Based on the linear growth rate observed from 2008 to 2020, we can project that by 2024, global plastic production will reach approximately 433 million metric tons, assuming similar growth trends continue [5]. The steady rise in production of plastic, it is an indicative industrial growth and the critical role plastic plays in modern economies, also highlights growing environmental concerns. Though, plastic remains integral part to economic development, these projections also emphasize the urgent need for improved waste management strategies and the development of sustainable alternatives to mitigate the environmental impact of escalating plastic production [5].

Plastic Production is a global problem. Every year 19-23 million tonnes of plastic waste leaks into aquatic ecosystems, polluting lakes, rivers and seas. Plastic pollution can alter habitats and natural processes, reducing ecosystem ability to adapt to climate change, directly affecting millions of people's livelihoods, food production capabilities and social well-being [6].

Major Classification of plastics include:

1. Thermoplastics
- **Definition**: Plastics that can be melted and casted into different shapes multiple times without altering their chemical properties.
- **Examples**: Polyethylene (PE), Polypropylene (PP), Polyvinyl Chloride (PVC), Polystyrene (PS), Polyethylene Terephthalate (PET).
- **Uses**: Packaging, bottles, toys, pipes, containers.

2. Thermosetting Plastics
- **Definition**: Plastics that undergo a chemical change when heated and moulded,
- **Examples**: Epoxy resins, Phenolic resins, Polyurethane, Bakelite.
- **Uses**: Electrical insulation, adhesives, automotive parts, kitchenware.

3. Biodegradable Plastics
- **Definition**: Plastics designed to decompose naturally by the action of microorganisms.
- **Examples**: Polylactic Acid (PLA), Polyhydroxyalkanoates (PHA), Starch-based plastics.
- **Uses**: Disposable cutlery, packaging, agricultural films, medical implants.

4. Elastomers
- **Definition**: Polymers with elastic properties, ability to stretch and retain its original structure.
- **Examples**: Rubber, Silicone, Neoprene.
- **Uses**: Tires, seals, gaskets, medical devices.

Plastics can degrade into micro to nano sizes, and those fine particles are more spreadable in air, water, and soil. Therefore, both terrestrial and aquatic animals are prone to silicosis, cardiovascular disease, chronic obstructive pulmonary disease, lung cancer, entangling, ulcers, low reproduction, and oxidative stress. Microplastics also degrade human health due to cardiovascular diseases, chronic kidney disease, birth defects, cancer, etc [7,8]. Major portion of the plastic has been deposited in the oceans as it is in the downstream from every near terrestrial location. It estimated that at least 5.25 trillion individual plastic particles weighing roughly 244,000 metric tons (269,000 short tons) were floating on or near the surface. A 2021 study determined that 44 percent of plastic debris in rivers and oceans, and on shorelines, was made up of bags, bottles, and items related to takeout meals [9].

Biofuel is a type of renewable energy source derived from microbial, plant, or animal materials (10). Biofuels play a particularly important role in de-carbonizing transport by providing a low-carbon solution for hard-to- abate sectors such as trucking, shipping and aviation. The liquid biofuels can be utilized as an alternative source for conventional fuels in the transportation sector, contributing to approximately 18% of primary energy consumption. Today, approximately 80% of liquid biofuel is manufactured in bioethanol, and the rest is via bio-diesel. They have oxygen levels ranging from 10% to 45% compared to petroleum products that have none [11]. Biofuels also has lower Sulphur and Nitrogen levels when compared to Petroleum sources.

According to International Energy System; the demand for biofuel will increase by 11 % in 2024 world-wide; the United States, Brazil, and Indonesia are the top three leading countries in the field of biofuel production [12].

This paper reviews and compares different strategies for biofuel production and concludes about their reliability against conventional fuels. Finally, the paper discusses some cost-effective and En-vironmental friendly methods for plastic waste to biofuel production from the future perspective.

There are several methods to convert plastic waste into fuel, also known as plastic-to-fuel (PtF) processes. Some of the most common methods include: Pyrolysis, Gasification, Hydrocracking, Catalytic Cracking, Alkaline depolymerization, Microbial degradation.

This review focuses on environment friendly approach i.e., converting the plastic into fuel using Microorganisms: This method, also known **as** Bioplastic-degradation/Bio-conversion/Microbial-degradation, offers a more environmentally friendly and sustainable approach to plastic waste management compared to traditional methods like incineration or landfilling.

II. Bioconversion Method Transforming Plastic Waste To Bio-Fuel

1.Using Bioconversion method for transforming plastic waste to Bio-fuel is the sustainable approach for the environment. It involves breaking down of large polymers into smaller molecular weight polymers with the required and capable microorganisms and with optimum conditions.

2. Factors affecting the following approach [13]:
a. Biological Factors: Selection of Microorganism and Enzyme specificity and activity.
b. Environmental-Factors: Levels of temperature, pH, nutrient medium and oxygen play a quiet major role in the process.
c. Technological Factors: Pre and Post treatment methods and reactors design influence the degradation process
d. Plastic properties: Depending on the structure and properties of the plastic the efficiency of the plastic will vary.

3. Steps involved in Bio-conversion of Plastic to fuel [14]:
a. Identification of suitable Micro-organisms: Identifying and isolating the capable micro-organism is the foremost step involved in the process.
Example: Ideonella Sakaiensis is capable for the break-down of polyethylene terephthalate (PET). *Ideonella sakaiensis* produces two key enzymes—PETase and MHETase—that work in tandem to degrade PET. PETase breaks down PET into an intermediate product, mono(2-hydroxyethyl) terephthalic acid (MHET), and then MHETase further degrades this intermediate into terephthalic acid and ethylene glycol [15,22]. After microbial degradation, the products (terephthalic acid and ethylene glycol) can be converted into hydrocarbons, suitable as fuel using the process of fermentation or convert TPA into simpler molecules (e.g., catechol, acetyl-CoA) for fuel production using engineered microbes [16,23].
b. Pre-treatment of Plastic waste: Plastic waste pretreatment is done through Mechanical shredding or to the direct exposure to the sun-light. It is mainly performed to increase the surface area.
c. Bio-degradation: The pre-treated plastic is inoculated and incubated with the capable micro- organisms and with the optimum temperatures, nutrients and pH maintained. Here the breakdown of complex polymers into monomers, oligomers, low molecular weight compounds.

Bio-degradation process involves in 3 stages:
i. Biodeterioration: This initial stage involves the weakening and alteration of the material's properties by involving the abiotic factors like sunlight, temperature, and mechanical stress. This weakens the material and makes it more susceptible to further breakdown by micro-organisms [24].
ii. Bio-fragmentation: This is the stage where microorganisms actively break down the material's complex molecules into smaller fragments. Enzymes produced by the microorganisms play a crucial role in this process [24]. It can occur under aerobic conditions and under an-aerobic conditions. The specific breakdown process and products differ depending on the presence or absence of oxygen.
iii. Assimilation: In this final stage, the microorganisms absorb the smaller fragments produced during bio-fragmentation and incorporate them into their own cells for growth and energy.
d. The simpler compounds produced will be undergoing fermentation, catalytic upgrading with green catalysts or other chemical treatments which will produce high quality bio-fuels.

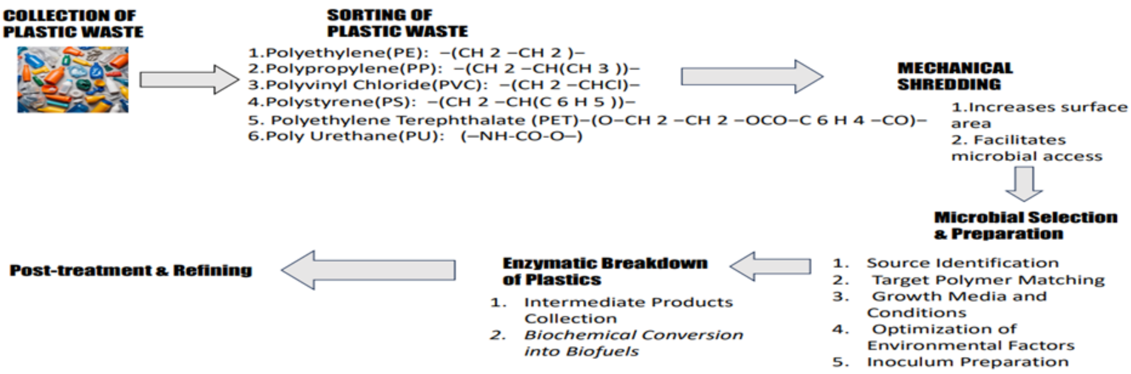

Figure 2: Transforming Plastic Waste To Bio-Fuels In A Sustainable Way

Advantages of Bio-fuels over Conventional fuels:
1. Biofuels contains more energy than diesel [25].
2. Biofuels decreases the dependence on conventional fuels [25].
3. Biofuels are safe to use.
4. Biofuels are renewable sources but conventional fuels are non-renewable.
5. Bio-fuels emits less pollutant than conventional fuels.

Efficiency of Bio-fuels:
1. Biofuels have lesser efficiency than conventional fuels.
2. It consumes more amount of fuel in order to get same amount of energy to be produced by conventional fuel which would be generally in less amount.

Properties of Bio-fuels and Conventional fuels
1. Viscosity: Biofuels, such as ethanol and biodiesel, generally have lower viscosities compared to fossil fuels like gasoline and diesel. It improves flow capacity of the fuel [26].
2. Density: The density of biofuels is typically lower than that of fossil fuels [27].
3. Boiling point: Biofuels generally have lower boiling points compared to fossil fuels. Which in turn effect the evaporation rates of the fuel [28].
4. Solubility in Water: Biofuels are more soluble than conventional fuels [28].
5. Lubrication: Biofuels have lower lubricity than conventional fuels; additives are added into bio-fuels to increase lubricity [29].

Which microorganism is better to degrade plastic?
Bacteria has priority in selecting to degrade plastic.

What do Bacteria do on plastic?

The Bacteria harvested the carbon in the plastic for energy which they used to grow, move and divide into even more plastic-hungry Bacteria.

Why efficiency of Bacteria is high than other microorganisms in degradation of plastic?

Bacteria has (ideonella-sakaiensis) 75% of efficiency because the enzymes of Ideonella-sakaiensis will break down plastic directly whereas fungi enzymes are incorporated gene sequence in plasmid [22,23].

Table 1: Microorganisms and Enzymes Required for Plastic Degradation

S.N0	Plastic Polymers	Microorganisms Required for Degradation	Enzymes	Results Obtained	Reference
1	Polyethylene terephthalate (PET)	*Aspergillus, Ideonella sakaiensis, Aspergillus niger*	Cutinase, Lipase, Carboxylesterase, PETase	75% at28°C in 70 days; Ideonella sakaiensis degraded 92.4% in 30 days using Aspergillusniger	I.B. Kotova, Ya. V. Taktarova, E.A. Ivshakovsa, et al (2021) [15]
2	Poly-Lactic acid (PLA)	*Amycolatopsis, Saccharothrix*	Alcalase, Esterase, Protease, Lipase	Protease DePolymerises specific poly(L-lactic acid), lipase type preferred for D-lactic poly.	Nor Faishah Zaaba, Maraiti Jaafar (2020) [16]
3	Polyvinyl Chloride (PVC)	Fungal-isolates, *Pseudomonas citronellolis* DSM 50332	Fungal Laccases, Peroxidases	17% degradation by bacterial strains and 32% degradation by fungal strains	S. Iqbal, A. Deeba, F. (2022) [17]
4	Polypropylene	*S.globisporus, Bacillus cereus*	Cutinase, Lipase, PETase	4% weight degradation in 26 days	Akhivinder Kumar Rana, Manja Kumari Thakur et al (2022) [18]
5	Polystyrene	*Exiguobacterium*	Cytochrome D45005, Alkanes hydroxylase, Bacillus cereus	7% by Bacillus cereus CH6 after 50 days of incubation	Yan Zhang, Jacob Pedersen et al (2022) [19]
6	Nylon	*Pacmanobacter ureafaciens* KI72	6-aminohexanoate dimer hydrolase (EI), 6-aminohexanoatecyclic dimer hydro-lase	Superficial layers broken down, fragmenting into soluble parts. Molecular weight decreased from 16,000 to 5600 during 60-day incubation	Neha Tiwari, Deena Santhiya, Jai Gopal Sharma (2024) [20]
7	Polyester polyurethane (PUR)	*Aspergillus niger*	Esterase	Isolate of 15 kinds of bacteria from polyester PUR pieces following their burial in soil for 28 days	Swapnil K. Kale, Amit G. Deshmukh (2015) [21]
8	Polyethylene (PE)	*Bacilluscereus, Pseudomonas tuo-murensis*	Fungal Laccases, Peroxidases	32.72% degradation by bacterial strains and 40% degradation by fungal strains in 4 weeks	Manisha M. Sangale, Mohd. Shahnawaz, Avinash B. Ade (2012) [21]
9	Polyhydroxyalkanoate (PHA)	S Marine Fungal Isolates	P(3HB) Depoly-merase	First, PHA is degraded into monomers and dimers. Second, hydrolyase cleaves the oligomers into monomers in 4 weeks	Swapnil K. Kale, Amit G. Deshmukh (2015) [21]

III. Conclusion:

Plastic waste generation is a significant environmental issue that has been growing rapidly in recent years. It occurs due to the excessive use and improper disposal of plastics, which are not biodegradable and can take hundreds of years to decompose. This leads to pollution, harm to wildlife, and disruption of ecosystems. To mitigate plastic waste generation, we should focus on reducing our plastic consumption, recycling, and adopting sustainable alternatives. The energy utilization of plastic wastes is one of the effective way for its proper disposal. Bio-Fuel conversion from plastics can reduce harmful emissions and pathogen contaminants compares to incineration and landfill disposal. Extraction of oil from waste plastic has attracted the attention of industry and academia as a feasible measure to mitigate the challenge of fossil fuel depletion, clean environment, global warming and growing demand for fossil fuels. Currently, plastic wastes can be converted into fuels by various technologies and processes such as pyrolysis, gasification, hydrocracking, catalytic cracking, solvolysis, alkaline depolymerization and microbial degradation. Out of which the bioconversion of plastic waste into sustainable Bio-fuels through microbial degradation is a promising approach to mitigate the environmental issues caused by plastic pollution.

Microorganisms, such as bacteria and fungi and their enzymes, possess the ability to break down plastics through various mechanisms, including enzymatic hydrolysis and oxidation. Factors like the type of plastic, environmental conditions, and microbial species influence the efficiency of degradation. It's hard to eliminate plastic waste completely especially when linked with production of biofuels, but with significant measure it can be minimized. There are some upgrades and shortcomings of bioconversion of plastic waste to fuel through microbial degradation. Further research in the field can lead to the successful implementation of bioconversion technologies for plastic waste management, promoting a circular economy and reducing the negative impact of plastic waste on the environment.

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