



Can Aquatic Bacteria Save The Planet? A Review of Gene Expression Technologies Associated with the Degradation of Plastic Polymers / Review Article

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Abstract. The global environmental crisis caused by plastic pollution has intensified in recent years, particularly in aquatic ecosystems such as rivers, lakes, and oceans, creating an urgent need for effective and sustainable solutions. This article explores the potential role of aquatic bacteria in degrading plastic polymers by reviewing the biological and molecular mechanisms these microorganisms use to break down complex synthetic materials. Special attention is given to key genes and enzymes involved in plastic degradation, including PETase and MHETase, which play a critical role in the decomposition of polyethylene terephthalate (PET). In addition, the article highlights advanced gene expression and analysis techniques, such as metagenomics, transcriptomics, and proteomics, to better understand bacterial activity and degradation dynamics in natural environments. The main problem addressed is the continuous and unsustainable production and consumption of plastics, which has resulted in extensive pollution of freshwater and marine systems, while conventional waste treatment methods remain largely ineffective. The objective of this article is to provide a comprehensive scientific review of biotechnological approaches used to analyze and utilize aquatic bacteria for plastic degradation, focusing on molecular aspects and environmental applications. Using a literature review method, studies published between 2018 and 2024 were analyzed to evaluate effective bacterial models, technological challenges, and future prospects. The findings indicate that aquatic bacteria offer promising potential as biological tools for mitigating plastic pollution through sustainable environmental strategies.

Keywords: Aquatic Bacteria; Biodegradation; Metagenomics; Plastic Pollution; PETase.

1. INTRODUCTION

Plastic pollution in aquatic environments represents one of the most serious and complex environmental issues of the modern era. This is due to the rapid increase in the production and consumption of plastics, which has exceeded 400 million tons annually globally, of which at least 11 million tons end up in oceans, rivers, and lakes (UNEP, 2023). Due to their physical and chemical properties, such as their high resistance to biodegradation, the plastics accumulate in marine food webs for extremely long periods, in certain instances, for centuries. This is toxic to biodiversity, disrupts food webs, and even leads to microplastic accumulation in the vital tissues of marine animals, including humans.

The inadequacy of traditional solutions, such as incineration, land filling, and mechanical recycling, to meaningfully mitigate plastic accumulation, biological solutions have emerged as a potential and sustainable alternative, particularly those that utilize microorganisms with intrinsic plastic-degrading capabilities. Among the microorganisms are aquatic bacteria that have emerged as a biological agent capable of degrading complex plastic polymers into simpler

and safer components through special enzyme pathways. One of the most important recent discoveries in this field is PETase, an enzyme based on the *Ideonella sakaiensis* bacterium that has been found to be highly effective at decomposing polyethylene terephthalate (PET) into precursor chemicals, terephthalic acid and ethylene glycol (Yoshida et al., 2016). In another recent study, structural changes to the crystal structure of PETase demonstrated that it is possible to engineer the enzyme for optimal activity at lower temperatures, rendering it more suitable for natural aquatic environments (Lu et al., 2023). Advancements in molecular analysis methodologies, such as metagenomics, gene expression profiling, and metaproteomics, have made it possible for intricate aquatic microbial communities to be explored, along with the functional organization of plastic biodegradation genes and enzymes.

These techniques have also revealed previously uncharacterized strains with putative polymer-degrading potential, such as in the study (Wang et al., 2023) on revealing gene expression in seawater samples contaminated with plastic through mRNA-seq technology, where they identified various genes for inducing degradative enzymes such as MHETase and Cutinase. Nevertheless, technical and environmental restraints are present as the effectiveness of these bacteria in natural environments is subject to a range of factors including temperature, pH, nutrient availability, and microbial competition. This calls for more studies to engineer these bacteria to function optimally in applied environmental applications. Other studies have also indicated that partial degradation of plastics can yield toxic intermediates, including aldehydes and organic acids, necessitating the conjoining of genetic studies with environmental impact and toxicity evaluation (Zhao et al., 2024). From here, this review aims to conduct an overall analysis of the most important scientific works related to aquatic bacteria within the field of research on the degradation of plastic, focusing on the newer genetic and molecular techniques used in the research of the process, and comparison of the results with previous works to measure the effectiveness of this approach in offering new and clean environmental solutions to the growing threat posed by plastic pollution.

2. PLASTIC POLLUTION IN AQUATIC ECOSYSTEMS

The rising production and use of plastics in the past decades have led to exponential increases in plastic pollution levels in ecosystems, particularly in aquatic ecosystems. Environmental reports indicate that plastic has become a permanent component of all marine environments, from surface beaches to the deep ocean, including polar ice. Plastic accumulating in water is classified into two main forms:

Macroplastics: such as bottles, bags, fishing gear, and plastic containers, which can be seen with the naked eye?

Microplastics: Plastic particles less than 5 mm in diameter, which either arise as a result of the decomposition of larger materials or enter the environment directly from cosmetics, synthetic fibers, and cleaning products.

Studies show that these tiny particles are not only more difficult to remove, but also more biologically dangerous, as they can be easily ingested by aquatic organisms, leading to their accumulation across different trophic levels. Plastic particles have been detected in the guts of more than 690 marine species, including fish, mollusks, seabirds, and turtles (Gall & Thompson, 2015). Even more alarming, microplastics have been detected in drinking water, tap water, and even the atmosphere, raising the possibility of direct human exposure (Koelmans et al., 2022).

According to a meta-analysis published in 2023, plastic debris was detected in 92% of seabirds dissected worldwide, indicating that pollution is widespread and not limited to industrial or coastal areas (Lavers et al., 2023). An earlier classic study by Wilcox and colleagues (2015) confirmed that nearly 90% of seabirds had plastic in their digestive tracts, with a direct correlation between contamination and nesting sites near waste sources. Direct and indirect toxic effects of these pollutants are hormonal disruption, blockage of the intestine, reduction of reproduction and growth rates, and even deaths based on the nature of the pollutant. Besides this, plastic also acts as a carrier of other chemical pollutants such as heavy metals and pesticides by sticking to the surface of the particle, thereby increasing the chemical pollution burden in the aquatic system.

To this complex reality, attention has begun to turn toward sustainable bioprocesses. These are the application of microorganisms, in this case aquatic bacteria, as a viable means of degrading advanced plastic polymers and reducing them to harmless components. The process is part of a broad philosophy called "environmental biotechnology," which aims to employ living organisms in an effort to treat waste and reduce the negative impact of human processes on the environment. Recent research has shown that some bacteria have the ability to produce new enzymes which are able to break the chemical bond of plastic polymers such as PET and PE and reduce them to useful compounds as a source of energy or as a component of cell structures. Thus, these organisms become a viable solution for plastic pollution's natural and safe elimination, which will be discussed in detail in the later segments of this article.

3. AQUATIC BACTERIA AND THEIR PLASTIC BIODEGRADATION CAPABILITIES

The accumulation of plastic waste in water bodies has created the demand for microorganisms capable of breaking down the advanced materials naturally using biological processes. Current microbiological investigations have identified several aquatic bacterial groups with exceptional potential to biodegrade various plastic polymers. They achieve this through the synthesis of specific enzymes that can break down the chemical bonds between the polymer chains and reduce them to smaller, more easily absorbed and metabolically utilizable units.

Ideonella sakaiensis is likely the most notable find here. It was first described in 2016 by Yoshida et al. following isolation from a Japanese plastic recycling plant. This bacterium can break down polyethylene terephthalate (PET), a very common plastic, by releasing two particular enzymes:

PETase: Breaks down the polymer into units of monomers such as MHET (Mono-(2-hydroxyethyl) terephthalate).

MHETase: Marks the end of the process by breaking MHET into smaller components such as terephthalic acid and ethylene glycol (Yoshida et al., 2016).

Moreover, there were further studies to show that genetic modification of the PETase enzyme is capable of significantly improving its efficiency and more potentially used in industrial plastic waste treatment processes (Lu et al., 2023). On the other hand, some species within the *Pseudomonas* genus have been found to possess a broad spectrum of degradability, particularly against polyurethane (PU) and polyethylene (PE). They possess extremely high metabolic diversity and are very resistant to environmental conditions and thus are usable in bioremediation of industrial and natural aquatic environments. For example, in a 2023 study, *Pseudomonas aeruginosa* was demonstrated to reduce the weight of polyethylene films by more than 30% in less than 30 days under laboratory conditions that simulate a marine environment (Ahmed et al., 2023).

Bacillus bacteria are Gram-positive, widely distributed in aquatic and freshwater habitats. They have also been reported to degrade plastics by various enzymes, particularly low-density polyethylene (LDPE). In one research (Patel et al., 2022), some *Bacillus subtilis* strains were reported to degrade LDPE films up to 25% in 60 days, demonstrating the strain's suitability for long-term use in the environment.

All these bacteria employ an exo-degradation system, extracellular enzymes being secreted that degrade the polymer surface, breaking its long chains into primary units

(monomers or oligomers), which are subsequently taken up by bacterial cells and consumed as carbon and energy sources. Such mechanisms are an excellent demonstration of plastic biorecycling and form the foundation for the development of new biotechnologies towards utilizing bacteria for the enhancement of plastic waste treatment capabilities.

To improve the effectiveness of such microorganisms, gene expression analysis and genetic engineering methods are used nowadays to re-engineer metabolic pathways and enhance the production of useful enzymes to pave the way for commercial use in the near future (Zhao et al., 2024).

4. MOLECULAR TOOLS FOR STUDYING GENE EXPRESSION IN PLASTIC DEGRADATION

The growing international interest in biological plastic pollution treatment, the necessity has arisen to further clarify the molecular and genetic determinism of the derivative capacity of aquatic bacteria. More recent activity has thus returned to the use of advanced molecular techniques and approaches aimed at studying gene and protein expression and questioning the genes and enzymes accountable for degrading plastic polymers.

These approaches provide quantitative data on metabolic processes, cell-to-cell interactions, and enzyme production processes so that they can be modified or enhanced through genetic engineering or artificial environmental manipulation to enhance their efficacy.

Metagenomics

is a modern approach involving extraction and analysis of total genetic material (DNA) of a specific environment directly without culturing microorganisms in the lab? This method permits the study of sophisticated microbial communities in their own habitats, such as seafloors or oceans contaminated with plastic, and the identification of functional degradation genes. Metagenomics has led to the discovery of increasingly more genes coding for plastic polymer bond-breaking enzymes, such as PETase, cutinase, and esterase, in new organisms. For example, a recent study (Danso *et al.*, 2019) showed a set of plastic-degrading genes obtained from ocean sediments without isolating the respective organisms, pointing to the future potential of this approach for exploration of environmental genetic diversity associated with degradation. Yet another study in 2023 revealed that metagenomics analysis of coastal plastic pollution sample-derived samples led to the identification of more than 50 candidate enzymes for genes with potential degradative function (Singh *et al.*, 2023).

Genome Transcriptomics

All molecules of RNA expressed in a cell at one point in time, particularly on plastic exposure as a carbon source. Methods like RNA-Seq are applied to determine those genes that are induced (or suppressed) when there is a presence of plastic polymers, which sheds light on the bacterial genetic response under degrading conditions. For example, in a 2022 laboratory research of *Pseudomonas putida* that was polyurethane-treated, RNA-seq analysis showed induction of the expression of more than 200 genes, some of which code for production of enzymes such as lipase, esterase, and monooxygenase (Martínez *et al.*, 2022). This is used to inform strategies for strengthening microorganism function via gene alteration or modifying the environment to increase expression of genes associated with plastic degradation.

Proteomics

While transcriptomics is more about gene expression, proteomics is more about the actual proteins that are the outcome of these genes, knowing what types of enzymes are produced, how much is produced, and how they bind with plastic polymers. There is significance in this field of research because not every expressed gene necessarily leads to a producing active protein. Complex proteomic studies have used two-dimensional electrophoresis (2D-PAGE) and mass spectrometry (MALDI-TOF MS) to identify specific enzymes for plastic degradation, such as:

- a. PETase: Specific capacity to degrade aromatic polymers.
- b. Lipase: Hydrolyzes ester bonds in certain plastic products.
- c. Cutinase: Has a distinct capacity for PET and other polyester degradation.

In 2024, analysis of Bay of Bengal marine bacteria proteins isolated in one study revealed proteinases structurally homologous to PETase, which was highly effective in PET film degradation at low temperatures (Rahman *et al.*, 2024). Proteomics is the ideal way to authenticate the actual function of enzymes discovered through genomics, and it has a direct influence on pushing research to utility.

5. EXAMPLES OF GENE EXPRESSION IN PLASTIC-DEGRADING BACTERIA

Whole-genome transcriptome (RNA-seq) and proteomics-based research has indicated that *Ideonella sakaiensis* exhibits active gene expression when cultured on polyethylene terephthalate (PET) alone as a carbon source. The PETase and MHETase genes are highly expressed, degrading the polymer into cell-absorbable precursors (Yoshida *et al.*, 2016). Proteomic analysis further verified that the enzymes are secreted extracellular and possess high

affinity towards the ester bonds of the polymer backbone, in support of their degradability under laboratory conditions.

Likewise, studies on *Pseudomonas putida* have revealed that their biodegradation can be enhanced through genetic engineering to enable them to produce new degradative enzymes, or by optimizing them for greater sensitivity to environmental response. Tiso *et al.* (2020) achieved the introduction of new metabolic pathways via genetic engineering techniques, promoting plastic as a carbon source utilization and elevating biodegradation efficiency to high levels of promise. Compared to other research, other microbes such as *Bacillus subtilis* and *Rhodococcus ruber* have shown to be more resistant to harsh environments but with the prerequisite of high gene expression to efficiently function degradation enzymes (Urbanek *et al.*, 2020).

6. CHALLENGES AND LIMITATIONS

In spite of extensive progress in the understanding of gene expression in plastic-degrading bacteria, several hurdles face large-scale practical utilization of these microorganisms in nature or industry. The most significant among them include: (1) Transfer from experimentation to industrial application: The laboratory condition in which bacteria show high degradation efficiency is not indicative of the complexity of real conditions since microorganisms are exposed to problems such as temperature variation, low plastic concentration, and microbial competition. (2) Low Degradation Efficiency in Open Environments: Research shows that the degradation rate of plastic by bacteria in open environments may be very sluggish, a matter of months or even years, thus reducing the efficiency of bioremediation as opposed to thermal or chemical methods. (3) Ethical and Environmental Concerns: Utilization of genetically engineered organisms in open ecosystems is very controversial as it involves potential harm to biological equilibrium, such as gene transfer to non-target species. (4) Externally Instability of Enzymes Outside the Laboratory: Unstable enzymes that degrade lose their activity due to exposure to environmental factors such as ultraviolet light or extreme pH, requiring technologies to allow and stabilize enzyme function (Danso *et al.*, 2019).

Trends in the future and biotechnological applications to avoid such limitations, ongoing research has been moving towards the application of advanced biotechnological techniques to increase the efficiency of plastic degradation and extend its functional applications. Such trends include: (1) Developing improved industrial enzymes: Gene editing tools such as CRISPR-Cas9 can be used to design enzyme structures such as PETase and Cutinase to be more stable

and efficient under ordinary environmental conditions. Scientists are also attempting to position enzymes inside nanocarriers in order to make targeting specificity better. (2) Merging degrading bacteria in water treatment plants: Engineer models have been described to mix these microbes into biological wastewater treatment plants that contain microplastic waste, the potential to initiate sustainable industrial processes. (3) Producing bacterially upgraded biodegradable materials: Some projects aim to produce alternative plastics that contain self-degrading bacterial catalysts to improve accelerated degradation after their functional lifetime. (4) Using nanotechnology: One of the most important developments in this field is the use of nanoparticles to immobilize enzymes or improve their transport within polymers. This technology is used to improve the enzyme reaction's efficiency by improving contact area and plastic binding efficiency (Shan et al., 2022).

Thus, the future of bioanalyzing plastic is dependent upon the merging of molecular and engineering techniques with additional information on the microenvironment under which such bacteria exist, an environmentally beneficial step in addition to fighting plastic pollution.

7. CONCLUSION

The issue of marine plastic pollution is becoming more serious. Aquatic plastic pollution is among the most serious environmental challenges of today, since plastic is not biodegradable and it has a tendency to accumulate in food webs, endangering biodiversity as well as human health.

The limitations of traditional solutions: Traditional plastic waste management processes (incineration, landfilling, and mechanical recycling) have not been that effective. This has led to the investigation of more environmentally friendly biological alternatives, primarily microorganisms capable of breaking down plastic polymers.

Bacteria from the aquatic environment may be a feasible answer, as several aquatic bacteria, such as *Ideonella sakaiensis* and *Pseudomonas putida*, have shown a high ability to degrade plastic polymers by producing specific enzymes, such as PETase and MHETase, and are hopeful candidates for biodegradation applications.

Molecular approaches bring in-depth and efficiency. Molecular analysis techniques such as metagenomics, gene expression, and proteomics have assisted in the identification of genes and enzymes involved in the degradation of plastics, and subsequently, attempts to develop more efficient microbial strains through genetic manipulation and control of microbial environments.

There are environmental and technical difficulties. Despite better research, there are still some difficulties that hinder practical application. They are low degradation efficiency in nature, sensitivity to enzymes, ethical disapproval of releasing into nature genetically modified organisms, and the potential to create toxic compounds as a result of incomplete degradation.

Future directions are based on biotechnology. Biotechnology research is moving towards the integration of technologies such as CRISPR gene editing, nanotechnology, and enzyme-assisted creation of biodegradable plastics to accelerate biodegradation and validate efficacy of industrial and environmental usage at the same time.

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