Journal of Environmental Studies [JES]
An International Journal
https://jesj.journals.ekb.eg/
doi: *10.21608/JESJ.2025.300943.1081*

The degradation of microplastic by microorganisms: A generous way to treat Plastic waste

B S Sreelakshmi[0], Minhaj Ahmad Khan[*1]

[1]Department of Microbiology, Lovely Professional University, Phagawara 144411, Punjab, India

Citation: *Sreelakshmi, B.S.; Khan, M. A. (2025). The degradation of microplastic by microorganisms: A generous way to treat Plastic waste. Journal of Environmental Studies, Vol. 37(1): 63-70.*

Article Information
Received 2 July 2024,
Revised 16 Jan. 2025,
Accepted 16 Jan. 2025,
Published online. 1 Mar. 2025

Abstract: Plastics are used for packaging and manufacturing of pipes, bags, medicines and utensils due to its low price, processing ease, flexibility, and corrosion resistance due to its low price, processing ease, flexibility, and corrosion resistance. The overuse of plastics leads to its accumulation in soil. Major reasons for the deposition of plastic in the soil environment are plastic mulching, usage of plastic materials in contact with soil, sewage waste, and by the manual deposition of plastic products into soil. These plastic go through a process called disintegration and becomes microplastics. It is very essential to remove these microplastics from the soil environment, as their absorption by plant roots lead to microplastic presence in fruits of those plants. But there are microorganism that have the capability to degrade these microplastics such as Bacillus subtilis and Bacillus gottheilii. Utilizing these microorganisms is a effective method to remove microplastics from the environment.

Keywords: Microplastics, Degradation, Soil, Plastic, Bacillus Species.

1. Introduction

Plastic is a flexible, inexpensive, lightweight, robust, long-lasting, and corrosion-resistant materials made up of long chain polymer, discovered in the 1990s. They are highly useful and have great thermal and electrical insulation values. Plastic is a semi-synthetic polymer which is made by using silicon, carbon, chloride, hydrogen and oxygen which are typically found in fossil fuels like oil, coal, and natural gas. Each polymer chain comprises thousands of repeating units, with the chain's backbone connecting numerous repetition units along the primary path (Sul & Costa *et al*., 2014). These plastics undergo process namely disintegration which makes them tiny ductile pieces called microplastics (size < 5mm) that poses one of the largest environmental hazards (Andrady, 2017). These plastic fragments are categorised into two which are primary and secondary microplastics. Primary microplastics are synthetic microplastics that is synthesized for commercial uses like cosmetics, textiles, micro beads and plastic pellets. Secondary microplastics are emerged by the degradation of large plastic materials like plastic bottles, bags, and pipes by the process of natural weathering. Nanoplastics are so minute so that they can readily evade any standard water filtration procedure. But due to their widespread applications in a variety of industries, including semiconductors, clothing, drug carriers, and cosmetics, they become the standard manufacturing material (Laskar & Kumar, 2019). Plastics have gradually taken the role of various traditional materials, including wood, metals, and paper, in important applications (Boerger *et al*., 2010). The increase of plastic products in the world in modern society is the main reason for the microplastic pollution in the environment, causing soil pollution. Plastic and microplastic waste has detrimental effects on the environment, society, and the economy. It also harms and sometimes kills soil and marine creatures or plant crops and enters the food chain, which results in health issues. But the natural degradation of microplastics present in the soil is very slow process, because it is very resistant to plastic materials and takes decades to degrade (Andrady, 2011). Therefore the microplastic content remain in the soil environment for hundred or even thousand years which significantly harm the ecosystem. Microplastics may be able to take in metals and other organic pollutants from the environment and

* Corresponding author E-mail: minhaj.15324@lpu.co.in

transport them to the body, where they can then be consumed. Therefore, it is urgent to remove microplastic from soil and other available environments (Bajt *et al*., 2021). There are physical, chemical, and biological treatments are available for the degradation of microplastics. Physical treatment techniques include photocatalytic, UV, and incinerator therapy where as chemical treatments include treatment with photocatalytic, UV, and incinerator therapy. Chemical additives such EG (ethylene glycol), MgO

(nano-magnesium oxide), DEG (diethylene glycol), and Ca/Zn (Kasmuri *et al*., 2022). But the degradation by physical treatment have lot of after effects like it affects the ecosystem and living beings where as chemical treatments cause alteration in the microflora of the soil and affect worms. However a natural, cost effective, and non-toxic technique used to degrade the microplastic is biological degradation (Othman *et al*., 2021). In this technique, microorganisms that have the capability to degrade microplastic are used to degrade microplastic present in the soil. Major microorganisms that have the capability to degrade the microplastics are Bacillus cereus and Bacillus gottheilii which are already present in the soil microflora. These microbes utlizing the plastic as their carbon source and helps us to remove the microplastic content from the soil. Other than these microbes, there are other microbes also that are directly or indirectly involved in microplastic degradation. For example, Staphylococcus epidermis can degrade low density polyethylene with the help of their specific enzymes. Moreover, the selection of microorganism for the degradation is based on the type of microplastic to degrade. Hence, as the amount of microplastics in the earth is continuously increasing, it is becoming necessary to do research in this field to mitigate the escalating risks associated with the increase. This review is discuss about the microplastic degradation by using microorganisms and formulating them into a usable form to treat the microplastic contaminated soil.

2. Plastics and their types

Plastic is a synthetic or manufactured polymer that can be moulded or sculpted generally by using heat or pressure inorder to make variety of products like pipes, bags, medicines and utensils. It is widely used in different industries because of its plasticity, low density, low electrical conductivity, transparency, and toughness. The majority of plastics are produced using petrochemicals, consisting of higher amounts of plasticity and higher molecular mass (Costa *et al*., 2016). There are different variety of plastics are available as mentioned in the Figure 1.

Polyethylene (PE), Polyethylene terephthalate (PET), High density polyethylene (HDPE), Low density polyethylene (LDPE), Polyvinyl chloride (PVC), Polypropylene (PP), Polystyrene (PS), and Expanded polystyrene (EPS) are some of the important microplastics. One of the most significant thermoplastics is polyethylene (PE), however due to its low melting point and swelling when exposed to hydrocarbons, and propensity to crack under stress, its usage is limited in several applications (Kanagaraj *et al*., 2007). Another type of plastic is PET which is processed directly into fibre fillings for furniture, cushions and safeguarded textiles. Artificial silk is created from it in very fine filaments, while carpets are made from it in large-diameter strands. Yarns for car tyres, conveyor and transmission belts, reinforcements for fire hoses and garden hoses, seat belts (in which nylon has been substituted to a considerable extent), nonwovens for stabilising drainage

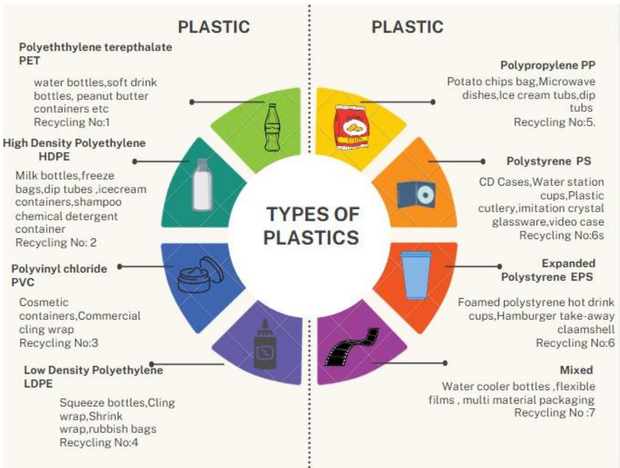

Figure 1: Pictorial representation of different types of plastics and uses

ditches, culverts and railroad beds, and nonwovens for diaper covers and disposable medical clothing are just some of the industrial uses of PET. When it comes to the weight produced and the price, PET is the most significant of the synthetic fibres. PET is produced by polymerisation of terephthalic acid and ethylene glycol and when PET is created, it is a sticky, molten substance that may either be spun immediately into fibres or subsequently solidified and utilised to form plastic. HDPE is another type of versatile plastic which is produced from ethylene ny gaseous phase polymerisation. This process uses mainly petroleum and cracks it by applying intense heat under controlled conditions which produces ethylene gas, which becomes HDPE as ethylene molecules polymerise. HDPE is mainly used for manufacturing pipes and storage containers. Its melting point is 120-130°C which is very higher when compared to other polymers (Ward *et al*., 1961). PVC is another important type of plastic that is used in world wide in construction, electrical/electronic, transportation, packaging, and healthcare industries. PVC is naturally amorphous, making it easy to mix with other substances and chemicals. The main raw material for the production of PVC is resin which is a granular or powdered solid, white, and brittle substance. Vinyl chloride monomer is polymerised to create PVC via a chemical reaction. Due to its versatility PVC is now replacing traditional building materials like ceramics, metal, concrete, wood, rubber, and many more (Khonakdar *et al*., 2003). Numerous properties, including anti-mist, various colours, elasticity, fire retardancy, flexibility, impact resistance, and microbe prevention, can be added to products depending on the additives used in PVC manufacture (Skelly *et al*., 2022). Vinyl plays an important role in safety when administering vital drugs via medical tubing and IV bags (intravenous). Because blood collection bags are flexible as well as unbreakable, the introduction of the PVC blood bag was an important advancement that helped ambulatory medicine advance and laid the groundwork for current blood banks. Another strong and bendable low density polyethylene (LDPE) has lengthy branches that do not compact into crystallites. The manufacturing and end properties of low-density polyethylene are primarily influenced by the distribution of its molecular weight, long-chain branching and short-chain branching. Another important plastic called Polypropylene is a polymer produced catalytically from propylene and its advantages is that it can withstand high temperatures, which makes it ideal for items like bottles, carboys, instrument jars, trays, funnels, and pails that frequently require sterilisation (cleaning) before use in a clinical environment. Polypropylene is superior to polyethylene for the reasons listed above because it is a material that can be dyed freely and has excellent mechanical properties (Santagata *et al*., 2020). Another plastic namely, Polystyrene, is a versatile polymer that has been utilised for a wide range of items, including packaging, consumer goods, etc. However, because it is not biodegradable, when these products are disposed of, environmental damage results. As a result, more emphasis is placed on their recycling, reuse, and other methods to make them biodegradable (Bajdur *et al*., 2002). Expanded Polystyrene (EPS) is a dependable insulation product with a lightweight, stiff foam that offers strong thermal stability and high shock resistance. It also has high load-bearing capacity with low weight, complete water and vapour barrier, air tightness for controlled spaces, long service life, low maintenance, and fast and cost-effective construction. Small polystyrene beads, produced by polymerisation from styrene, make up the bulk of Expanded Polystyrene (EPS). The bead size distribution has an impact on the EPS foam quality. Insulation, packaging, buoyancy, and moulding are the important applications of EPS.

3. Microplastics and their occurrence

Plastics are complex chemical structure which has been widely using for different purposes in the modern world. Due to its complex structure, it is very difficult and slow to degrade them. However, a natural process known as disintegration can breakdown the plastics into small pieces with approximate size of 5mm known as microplastics (Jiang *et al*, 2018). The wide applications of plastics leads to the production large amount of plastic products in the world. Due to the poor management of plastic wastes, the plastics are accumulated in the soil and water environment. By the natural disintegration process, the plastics became concerted to microplastics with less than 5mm size. Some important reasons for the conversion of plastics inti microplastics are wind, waves, microbial degradation, and UV-radiation (Xu *et al*., 2020). In soil environment, agriculture is the one of the most important presence where microplastic presence are seen. It is due to mulching , weed-barrier 40 sheets, and greenhouse are the area where plastic covers are used. If these material isn't retrieved from the field, it undergoes weathering, turning fragile and deteriorating into microplastics. In the case of weed barrier sheets, they are woven materials which is used for the packaging of agricultural products like seeds and grains. When cutting into appropriate pieces, the remaining small portion of the sheets get deposited in the soil and leads to microplastic pollution in the soil environment (Huang *et al*., 2020). Moreover, in some countries like Japan, they have been using plastic bags for regulating the water flow in the field. Due to the UV- radiation and oxygen, these bags get degrade and cause microplastic contamination in soil (Horton *et al*., 2017). In addition, the incorporation of cuticle remover in the toothpastes and facial cleansers have been resulted in the deposition 94500 microbeads in the soil and water environment combined.

The discharge from the waste water treatments entering to the fresh water is another source contamination of microplastic in aquatic environment (Rillig & Bonkowski, 2018). In the experiment done by Grause *et al*. (2021), they detected the presence of microplastics in the soil sample. They detected 74.9×10^3 amount of particles at a distance 1 metre and 30.5×10^3 at a distance of 7 metre. In another the study done by Sadri & Thompson. (2014), the amount of microplastics they found on the surface water of was around 0.028 particles/m3. Similarly, in another study done by Yin *et al*. 2019, the amount of microplastic found from the water from urban lakes was in between 2425 to 7050 particles/m^3. Similarly, Wang *et al*. 2017 tested the microplastic contamination of Bei lake and Huanzi lake which is located in the centre of the city containing high density population. The result showed that the amount of plastic present in the Bei lake and Huanzi lake were 8925 items/m^3 and 8550 items/m^3 respectively. In conclusion, as the amount of microplastic in the soil and water environment is increasing day by day due to the due to the improper handling of plastic wastes and the over production of plastic products. Therefore, it is necessary to remove the microplastic contamination from the soil and aquatic environment as it causes several problems like microplastic accumulation in the body aquatic organisma as well as humans.

4. Microplastic and human health

Microplastic present in the natural environment is increasing day by day due to the increased production of plastic products and failure in controlling the plastic waste. Microplastics has been found in the human foods and air, posing serious health issues to individuals (Karbalaei *et al*., 2018). According to studies, humans consume at least 50,000 microplastic particles annually. The tiny microplastic particles are within the approximate size range of zooplankton food, which enter the food web and are accidentally consumed by marine animals, which is subsequently consumed by humans (Andrady, 2003). It has been determined that MPs are prevalent in soil and freshwater environments, including places where people get their drinking water (Oliveira *et al*., 2020). By consuming the soil based products like plants,fruits and vegetables and marine based foods like drinking water and fishes, microplastic accumulation in the human body is increasing. Moreover,

the microplastics can escape the waste water treat techniques which also lead to microplastic accumulation in humans (Eriksen *et al*., 2013). These accumulation of MPs in the human body can cause serious health problems to individuals like DNA damage, inflammation, metabolic disorder, reproductive and developmental toxicity, oxidative stress, and other health problems. According to Xuan *et al*. 2022, microplastics can induce reactive oxygen species (ROS) accumulation, there by preventing some important signalling pathways like PI3K/Akt which is responsible for controlling physiological and biological functions, and results in apoptosis and inflammation. Particularly if the inflammation persists over a long period of time, it can lead to potentially serious health problems like diabetes, malignancy, renal diseases and auto immune diseases (Hernandez *et al*., 2017). Similarly, MPs triggered ROS can disturb the oxidative/antioxidative balance, and cause oxidative stress. Likewise, Domenech *et al*. 2021 reported that MPs have the ability to harm the DNA molecules even at very less amount. They treated Coco-2 cells, lung cancer cells, and macrophage cells with 0.26 µg cm−2 plastic and observed that the cells treated with plastics were undergo DNA damage after the exposure. In the study done by Kwon *et al*. 2022, they observed that MPs can upregulate NF-κB signalling pathway and inflammatory which leads to the apoptosis of microglia in human brain cells. Large proteins may adhere to plastic particle surfaces, affecting the stomach's immune system and possibly causing regional inflammation (Jassim, 2023). Hou *et al*. 2020 tested the reproductive toxicity of microplastics by sperm damage analysis and histopathological analysis before and after the exposure to microplastic. The result showed that mice exposed to MPs causes alteration in the sex ratio of their offspring post-birth, impacts the weight of the offspring, and triggers disorders in lipid and amino acid metabolism. These findings suggest that microplastic pollution can influence the health of subsequent generations through reproductive pathways. Similarly, in another study done by Caputi *et al*. 2022, they concluded that treating the human gingival fibroblasts with MPs lead to lower the metabolic activity of the cells by distracting the viability of the cells. Unless, there are also indirect bad affects to human health due to the presence of microplastics in the natural environment. For example, the additives like dyes and plasticisers used to enhance the colouring effect and flexibility separate from the microplastic and accumulate in the water. Consumption of this water resources causes toxicity, carcinogenicity, mutagenicity, and other unknown health impacts (Blackburn & Green, 2020). These toxic effects of microplastic make the researchers necessary to find a natural, cost-effective, and simple technique inorder to degrade these toxic substances from the natural environment. In

conclusion, the pervasive presence of microplastics in our natural environment poses a significant and growing threat to human health. Studies indicate that microplastics not only accumulate in soil and freshwater environments but also persist in human bodies through the consumption of contaminated produce and seafood. Evidence suggest that microplastics exerts reproductive toxicity, DNA damage, inflammation and ROS production. Given these concerning findings, urgent action is needed to mitigate the proliferation of microplastics in the environment and develop effective strategies for their removal.

5. Microplastic degradation methods

As we all know that the degradation of microplastic is very difficult due to its complex structure, still there are different physical, chemical and biological methods are available for the degradation of microplastics as mentioned in the Figure 2.

5.1. Physical methods

5.1.1. Incineration

Incineration is a physical process that is typically thought of as a terminator for the elimination of plastic trash and has the potential to finally convert polymers into carbon dioxide and mineral components (Kershaw, 2015). In this technique, microplastics can be removed by burning, but the byproduct (ash) will spread in the environment. Another disadvantage of incineration is that the heavy metals that attached with the microplsatics will enter into the environment after burning out the microplastics that affects living organisms including humans. Formation of green house gases, carbon dioxide, hazardous substances, and air contaminants are also some other general disadvantages of this method that can lowers the air quality and has ruinous effect on human and animal health (Webb *et al*., 2012). Furthermore, if plastic trash is burned aggressively in incinerators, more microplastics or even nanoplastics may emerge.

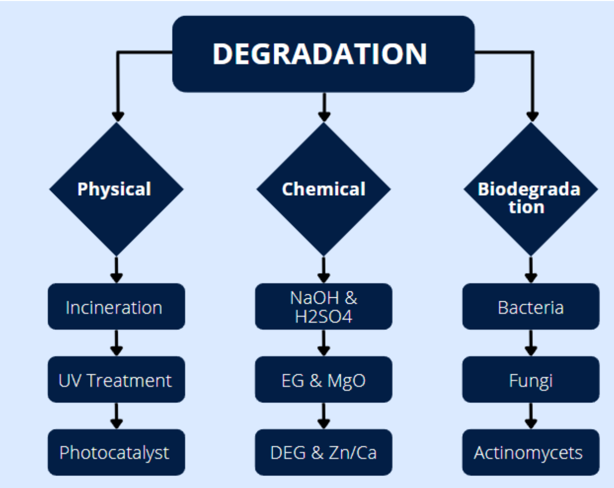

Figure 2: Pictorial representation of different types of degradation

5.1.2. UV Treatment

Exposing microplastic contaminated sample to ultra violet rays is an effective method for the deterioration of microplatics. It is highly effective to degrade microplastics in the bio-solids suspension. UV-A is more efficient in degrading microplastics when comapred to UV-C. UV light results in photooxidative degradation, which eventually yields useless materials after causing polymer chains to be broken, radicals to be produced, molecular weight to be decreased, and mechanical characteristics to be destroyed (Petroody *et al*., 2023). In the presence of UV exposure, the synthetic polymer might deteriorate. But it leads to increase fragmentation and causes the generation of microscopic particles. In the case of soil environment, treatment of microplastic contaminated soil with UV lead to cause problems in surrounding plants, worms, and soil microflora. Therefore, solution for one problem may leads to the emergence of plenty of other problems.

5.1.3 Photocatalyst

Photocatalyst, an area of chemistry, explores how the speed of a chemical process changes when exposed to light, utilising both light and semiconductors (Yousif & Haddad, 2013). A photocatalyst is a substance that absorbs light to produce a high level of energy and a chemical reaction occurs in the substance by using the energy. By using this method, it is possible to degrade microplastics by utlising green visible light. In the study done by Uheida *et al*. 2021, he utlized the visible light photocatalyst method for the degradation of polypropylene particles ranging in size from 154.8 to 1.4 m. Degradation by this method results in the release of hazardous by-products to the environment which makes this method less competence.

5.2 Chemical treatments

Chemical treatment, in order to speed up the deterioration process, substances that are additive are used in the chemical treatment of waste plastic. Hussein et al. (2018) used nano-magnesium oxide (MgO) as a catalyst and ethylene glycol (EG) to study the chemical breakdown of PET plastic bottle fragments.The results of the experiment showed that the plastic polymer PET transforms from a fragment into a white powder through a chemical process. Combining two compounds can speed up the conversion process and function as a catalyst. O-H and C-H groups in the FTIR study demonstrates that the chemical degradation is done by the process called glycolysis (Osheida, 2013). Similarly in another study done by Amaro et al. (2015), diethylene glycol (DEG) and (Ca/Zn) stearate were used as a catalyst in a Brabender Plastograph mixer at a temperature of 250° C for 20 minutes to speed up the chemical breakdown of PET and pulverise PET water bottle garbage. PET samples are molten after the deterioration process, changing into a green, adhesive fluid at higher temperatures and becoming fragile at room temperature.

5.3 Microbial degradation of microplastics

A biochemical's transformation into a compound with the help of microbes is known as biodegradation (Shah *et al*., 2008). Some microorganisms like Bacillus subtilis and Bacillus gottheilii have the capability to degrade microplastics. Plastics break down due to a variety of reasons, including the type of functional groups they contain, their molecular weight, mobility, crystalline structure, and additives added to the polymers (Bahl *et al*., 2021). The biodegradation of plastic by microorganisms is done by converting polymers into monomers and then into carbon dioxide, water, and methane by mineralisation process and results in the reduction of molecular weight of plastic. Although certain microorganisms can break down microplastics, but our lack of knowledge on how they interact with microplastics make this method less impact (Brooks *et al*., 2011; Krueger *et al*., 2015). An approximate microplastic degradable capability of microorganisms are mentioned in Table 1. Actinomycetes can perform a variety of various environmental activities and have a wide variety of diverse metabolisms. Some of them can digest incompatible carbohydrates such as cellulose and chitin, while some of them are utilised in bioremediation because they can break down toxic substances or participate in the reusing of organic carbon molecules and, more recently, the decomposition of complex polymers. In a study done by Sivan et al. (2006), they utlized Rhodococcus ruber strain C208 for treating with microplastics in their experiment. The result showed that this organisms started degrading plastics after 16 days of incubation. Another important type of microorganism that can degrade microplastics are fungi.

Table 1: Ability of microorganism to degrade plastics.

Plastic name	Approximate biodegradability (%)
PET	7.9%
HDPE	12.4%
PVC	10%
LDPE	17.4%
PP	19.4%
PS	3.2%
EPS	3%
Other plastic	26.7%

Fungal species that can break down plastic pieces can be found in microplastic biofilms, which is a promising source. Importantly, biofilms serve as a hub for microbial activity such as growth of fungal species, because their microbial communities clearly differ from those in the adjacent environment. *Aspergillus niger*, *Aspergillus versicolor*, *Penicillium pinophilum*, *P. frequentan*, *P. oxalicum*, and *P. chrysogenum* were among the strains of the *Aspergillus*, *Penicillium*, and *Trichoderma* species that could break down polyethylene (Matavulj & Molitoris, 2009). Another important and widely used microorganisms for biodegradation of microplastics are bacteria. Bacteria can utlise the carbon source of the plastic polymer and reduces the dry weight, average molecular weight, and molecular dispersion of polymers and causing morphological and chemical structural changes (Kettner *et al*., 2017). This suggests that these microorganisms may actually be employed to lessen environmental contamination from plastic and microplastics. The use of pure strains allows the identification of metabolic pathways to analyse the effects of various sustainable factors on the degradation of microplastics (Lee & Liew, 2021). The Bacillus species namely *Bacillus cereus* and *Bacillus gottheilii* can utlise the carbon source of polymers like PS, PE, PP, and PET that are smaller than 300 m in size. Both strains can change the microplastics' surfaces, causing them to develop fractures and grooves as well as different structural, functional groups and other properties. Compared to *Bacillus gottheilii*, *Bacillus cereus* have strong microplastic degrading ability.

6. Conclusion

The over production of plastics due to its wide applications is became a serious problem as the plastic and microplastics are accumulated in the aquatic and soil environment. The accumulation of microplastics leads to cause several problems to aquatic organisms, human beings, and plant. Presence of microplastics in the human body can cause toxicity, carcinogenicity, and mutagenicity to humans. However, there are several physical and chemical methods are available for the breakdown of plastics. But those methods have several disadvantages that make them unfit to practise. The biodegradation of microplastics, with the help of microorganisms or their enzyme activity, is introduced into nature with the aim of preventing or reducing the microplastic contamination. Research has been done on how bacteria can biodegrade plastic trash to keep the environment safe and lessen the negative effects of plastics on the environment. The microbes that degrade plastics into simpler units like oligomers, monomers, carbon dioxide and water. Numerous bacterial and fungal taxa, including Bacillus, Cladosporium, Aspergillus, and Penicillium, have been found to degrade a variety of polymers, including PP, PET, and PVC. As it is necessary to remove the microplastic from the soil and aquatic environment, it is obligatory to utlize cost effective and non-side effect methods to remove microplastic from the environment.

7. Aknowledgments

The authors like to thank the infrastructure of Lovely Professional University, Phagwara for providing the suitable environment for writing the paper.

8. References

Alavian Petroody, S.S.; Hashemi, S.H.; Škrlep, L.; Mušič, B.; van Gestel, C.A.; Sever Škapin, A. (2023). UV light causes structural changes in microplastics exposed in bio- solids. *Polymers*, 15(21): 4322.

Amaro, L.P.; Coiai, S.; Ciardelli, F.; Passaglia, E. (2015). Preparation and testing of a solid secondary plasticizer for PVC produced by chemical degradation of post- consumer PET. *Waste Manage. (Oxford)*, 46: 68-75.

Andrady, A.L. (2003). An environmental primer. *Plastics and the Environment*, 1-75.

Andrady, A.L. (2011). Microplastics in the marine environment. *Mar. Pollut. Bull*., 62(8): 1596-1605.

Andrady, A.L. (2017). The plastic in microplastics: A review. *Mar. Pollut. Bull*. 119(1): 12-22.

Bahl, S.; Dolma, J.; Singh, J.J.; Sehgal, S. (2021). Biodegradation of plastics: A state of the art review. *Materials Today: Proceedings*, 39: 31-34.

Bajdur, W.; Pajączkowska, J.; Makarucha, B.; Sułkowska, A.; Sułkowski, W.W. (2002). Effective polyelectrolytes synthesised from expanded polystyrene wastes. *Eur. Polym. J*. 38(2): 299-304.

Bajt, O. (2021). From plastics to microplastics and organisms. *FEBS Open Bio.*, 11(4): 954-966.

Bartczak, Z.; and Kozanecki, M. (2005). Influence of molecular parameters on high- strain deformation of polyethylene in the plane-strain compression. Part I. Stress–strain behavior. *Polymer*, 46(19): 8210-8221.

Blackburn, K.; Green, D. (2022). The potential effects of microplastics on human health: What is known and what is unknown. *Ambio*, 51(3): 518-530.

Boerger, C.M.; Lattin, G.L.; Moore, S.L.; Moore, C.J. (2010). Plastic ingestion by planktivorous fishes in the North Pacific Central Gyre. *Mar. Pollut. Bull*., 60(12): 2275- 2278.

Brooks, A. N., Turkarslan, S., Beer, K. D., Yin Lo, F., & Baliga, N. S. (2011). Adaptation of cells to new environments. Wiley Interdiscip. Rev. Syst. Biol. Med. 3(5), 544-561.

Caputi, S.; Diomede, F.; Lanuti, P.; Marconi, G.D.; Di Carlo, P.; Sinjari, B.; Trubiani, O. (2022). Microplastics affect the inflammation pathway in human gingival fibroblasts: a study in the Adriatic Sea. Int. *J. Environ. Res. Public Health*, 19(13): 7782.

da Costa, J.P.; Santos, P.S.; Duarte, A.C.; Rocha-Santos, T. (2016). (Nano) plastics in the environment–sources, fates and effects. *Sci. Total Environ*., 566, 15-26.

do Sul, J.A.I.; Costa, M.F. (2014). The present and future of microplastic pollution in the marine environment. *Environ. Pollut*. 185: 352-364.

Domenech, J.; de Britto, M.; Velázquez, A.; Pastor, S.; Hernández, A.; Marcos, R.; Cortés, C. (2021). Long-term effects of polystyrene nanoplastics in human intestinal Caco-2 cells. *Biomolecules*, 11(10): 1442.

Eriksen, M.; Mason, S.; Wilson, S.; Box, C.; Zellers, A.; Edwards, W.; ... & Amato, S. (2013). Microplastic pollution in the surface waters of the Laurentian Great Lakes. *Mar. Pollut. Bull*., 177-182.

Grause, G.; Kuniyasu, Y.; Chien, M.F.; Inoue, C. (2022). Separation of microplastic from soil by centrifugation and its application to agricultural soil. *Chemosphere*, 288: 132654

Hernandez, L.M.; Yousefi, N.; Tufenkji, N. (2017). Are there nanoplastics in your personal care products?. *Environ. Sci. Technol. Lett*., 4(7): 280-285.

Horton, A.A.; Walton, A.; Spurgeon, D.J.; Lahive, E.; Svendsen, C. (2017). Microplastics in freshwater and terrestrial environments: Evaluating the current understanding to identify the knowledge gaps and future research priorities. *Sci. Total Environ*., 586, 127-141.

Hou, B.; Wang, F.; Liu, T.; Wang, Z. (2021). Reproductive toxicity of polystyrene microplastics: In vivo experimental study on testicular toxicity in mice. *J. Hazard. Mater*. 405: 124028.

Huang, Y.; Liu, Q.; Jia, W.; Yan, C.; Wang, J. (2020). Agricultural plastic mulching as a source of microplastics in the terrestrial environment. *Environ. Pollut*. 260: 114096.

Hussein, A.A.; Alzuhairi, M.; Aljanabi, N.H. (2018). Chemical and Biological Treatment of Plastic Wastes by Bacteria Isolated from Contaminated Soils in Baghdad. *Iraq. Al-Nahrain Journal of Science*, 21(2): 130-137.

Jassim, A.K. (2023). Effect of Microplastic on the Human Health.

Jiang, J.Q. (2018). Occurrence of microplastics and its pollution in the environment: A review. *Sustainable Prod. Consumption*,13: 16-23.

Jordan, J.L.; Casem, D.T.; Bradley, J.M.; Dwivedi, A.K.; Brown, E.N.; Jordan, C.W. (2016). Mechanical properties of low density polyethylene. *J. Dyn. Behav. Mater.*, 2: 411-420.

Kanagaraj, S.; Varanda, F.R.; Zhil'tsova, T.V.; Oliveira, M.S.; Simões, J.A. (2007). Mechanical properties of high density polyethylene/carbon nanotube composites.Compos. *Sci. Technol*., 67(15-16): 3071-3077.

Karbalaei, S.; Hanachi, P.; Walker, T.R.; Cole, M. (2018). Occurrence, sources, human health impacts and mitigation of microplastic pollution. *Environ. Sci. Pollut. Res.*, 25: 36046-36063.

Kasmuri, N.; Tarmizi, N.A.A.; Mojiri, A. (2022).

Occurrence, impact, toxicity, and degradation methods of microplastics in environment—a review. *Environ. Sci. Pollut. Res*., 29(21): 30820-30836.

Kershaw, P.J. (2015). Sources, fate and effects of microplastics in the marine environment: a global assessment.

Kettner, M.T.; Rojas-Jimenez, K.; Oberbeckmann, S.; Labrenz, M.; Grossart, H.P. (2017). Microplastics alter composition of fungal communities in aquatic ecosystems. *Environ. Microbiol*. 19: 4447–4459.

Khonakdar, H.A.; Morshedian, J.; Wagenknecht, U.; Jafari, S.H. (2003). An investigation of chemical crosslinking effect on properties of high-density polyethylene. *Polymer*, 44(15): 4301-4309.

Krueger, M.C.; Harms, H.; Schlosser, D. (2015). Prospects for microbiological solutions to environmental pollution with plastics. *Appl. Microbiol. Biotechnol*. 99: 8857- 8874.

Kwon, W.; Kim, D.; Kim, H.Y., Jeong, S.W.; Lee, S.G.; Kim, H.C.; ... and Choi, S.K. (2022). Microglial phagocytosis of polystyrene microplastics results in immune alteration and apoptosis in vitro and in vivo. Sci. Total Environ. 807, 150817.

Laskar, N.; Kumar, U. (2019). Plastics and microplastics: A threat to environment. *Environ. Technol. Innovation*, 14: 100352.

Lee, A.; Liew, M.S. (2021). Tertiary recycling of plastics waste: an analysis of feedstock, chemical and biological degradation methods. *J. Mater. Cycles Waste Manage*., 23(1): 32-43.

Matavulj, M.; Molitoris, H. (2009). Marine fungi: degraders of poly-3- hydroxyalkanoate based plastic materials. *Proc. Nat. Sci Matica Srpska Novi Sad*., 116: 253–265.

Oliveira, J.; Belchior, A.; da Silva, V.D.; Rotter, A.; Petrovski, Ž.; Almeida, P.L. ... and Gaudêncio, S. P. (2020). Marine environmental plastic pollution: mitigation by microorganism degradation and recycling valorization. *Front. Mar. Sci.*, 7: 567126.

Oshida Y (2013) 4 - Oxidation and Oxides. In: Bioscience and Bioengineering of Titanium Materials 2nd edn. *Elsevier*, pp 87–115

Othman, A.R.; Hasan, H.A.; Muhamad, M.H.; Ismail, N.I.; Abdullah, S.R.S. (2021). Microbial degradation of microplastics by enzymatic processes: a review. *Environ. Chem. Lett*., 19: 3057-3073.

Rillig, M.C.; Bonkowski, M. (2018). Microplastic and soil protists: a call for research. *Environ. Pollut.*, 241: 1128-1131.

Sadri, S.S.; Thompson, R.C. (2014). On the quantity and composition of floating plastic debris entering and leaving the Tamar Estuary, Southwest England. *Mar. Pollut. Bull*., 81(1): 55-60.

Santagata, C.; Iaquaniello, G.; Salladini, A.; Agostini, E.; Capocelli, M.; De Falco, M. (2020). Production of low-density poly-ethylene (LDPE) from chemical recycling of plastic waste: Process analysis. *J. Cleaner Prod*., 253: 119837.

Shah, A.A.; Hasan, F.; Hameed, A.; Ahmed, S. (2008). Biological degradation of plastics: a comprehensive review. *Biotechnol. Adv*., 26(3): 246-265.

Sivan, A.; Szanto, M.; Pavlov, V. (2006). Biofilm development of the polyethylene- degrading bacterium Rhodococcus ruber. *Appl. Microbiol. Biotechnol.*, 72: 346-352.

Skelly, P.W.; Li, L.; Braslau, R. (2022). Internal plasticization of PVC. *Polym. Rev*., 62(3): 485-528.

Uheida, A.; Mejía, H.G.; Abdel-Rehim, M., Hamd, W.; Dutta, J. (2021). Visible light photocatalytic degradation of polypropylene microplastics in a continuous water flow system. *J. Hazard. Mater.*, 406: 124299.

Wang, W.; Ndungu, A.W.; Li, Z.; Wang, J. (2017). Microplastics pollution in inland freshwaters of China: A case study in urban surface waters of Wuhan, China. *Sci. Total Environ*., 575: 1369-1374.

Ward, I.M. (1961). The molecular structure and mechanical properties of polyethylene terephthalate fibers. *Text. Res. J*., 31(7): 650-664.

Webb, H.K.; Arnott, J.; Crawford, R.J.; Ivanova, E.P. (2012). Plastic degradation and its environmental implications with special reference to poly (ethylene terephthalate). *Polymers*, 5(1), 1-18.

Xu, S.; Ma, J.; Ji, R.; Pan, K.; Miao, A.J. (2020). Microplastics in aquatic environments: occurrence, accumulation, and biological effects. *Sci. Total Environ.*, 703: 134699.

Xuan, L.; Xiao, L.; Huang, R. (2023). The geno-toxicological impacts of microplastic (MP) exposure on health: mechanistic pathways and research trends from a Chinese perspective. *Environ. Sci. Processes Impacts*, 25(1): 26-36.

Yin, L.; Jiang, C.; Wen, X.; Du, C.; Zhong, W.; Feng, Z.; ... and Ma, Y. (2019). Microplastic pollution in surface water of urban lakes in Changsha, China. *Int. J. Environ. Res. Public Health*, 16(9): 1650.

Yousif E, Haddad R (2013). Photodegradation and photo stabilization of polymers, especially polystyrene: review. *Springer plus* ,2:1–32.