Acta Scientific Microbiology (ISSN: 2581-3226)

Volume 7 Issue 2 February 2024

Review Article

Microbial Biodegradation of Plastic: A Noble Approach

Tanmay Ghosh[1]*, Owrena Sharkhel[2] and Nabamita Nandi[2]

[1]Department of Microbiology, Dinabandhu Andrews College, Baishnabghata, West Bengal, India

[2]Department of Microbiology, Rabindra Mahavidyalaya, Champadanga, Hooghly, West Bengal, India

***Corresponding Author:** Tanmay Ghosh, Department of Microbiology, Dinabandhu Andrews College, Baishnabghata, West Bengal, India.

DOI: 10.31080/ASMI.2024.07.1344

Received: January 17, 2024

Published: January 21, 2024

Abstract

Plastic assume a significant part in economy all around the world broad use in farming, building and development and wellbeing and buyer merchandise. Usually involved strategies for plastic removal were ended up being lacking for compelling plastic waste administration, and subsequently there is developing worry for utilization of proficient microorganisms implied for biodegradation of non-degradable manufactured polymer. The biodegradable polymers are intended to debase quick by microorganisms due their capacity to corrupt the majority of the natural and inorganic materials, including lignin, starch, cellulose and hemicelluloses. Plastics aggregation ashore and ocean has stimulated interest to corrupt these polymers. That is a necessary to involve satisfactory biodegradable strategies to decrease plastics trouble from the climate. To defeat plastics related ecological issues, comprehension of the communication among organisms and polymers is of prime significance. Many living organic entities yet overwhelmingly microorganisms have advanced systems to get by and corrupt plastics. The current survey centers around the kinds of plastics based on warm and biodegradable in nature, corruption and types of biodegradation, sorts of plastics which are degradable, portrayal of biodegradation , and variables influencing biodegration. Plastic corruption and bioremediation potential make these microorganisms auspicious for green science to take out destructive plastics from the biological system.

The current survey examines the ongoing status, components of biodegradation of plastics, methods for describing corrupted plastics and elements influencing their biodegradation.

Keywords: Plastic; Degradation; Microorganisms; Polymer

Introduction

From various types of hydrocarbons and petrol subsidiaries high atomic weight natural polymers are gotten. These polymers are known as plastic [23] "Plastic" came from the Greek word "Plastikos", that implies which can be formed into various shapes. Plastics expressed as the polymers what begin continuing on warming that's why it can be casted into molds [17]. For the most part, plastic materials are gotten from petrochemicals with the exception of biodegradable bioplastic. Plastic comprises of chloride, oxygen, hydrogen, carbon, silicon and nitrogen. Polyethylene comprises of 64% of absolute plastic and its overall recipe is C_nH_{2n} [17].

For bundling and numerous different purposes like agrarian movies arrangement, diaper bundling and fishing nets plastics are utilized. Plastics have a significant impact in each area of economy from one side of the planet to the other. In exceptionally developing regions for example horticulture, building and development, wellbeing and shopper merchandise, use of plastics guarantees that they are popular and without nobody can take care of business. Plastics, the foundation of numerous enterprises, are utilized in assembling of different items that are utilized in our day to day routine for example safeguard materials, sterile products, tiles, plastic jugs, fake cowhide and different other family things. Plastics are likewise utilized in bundling of food things, drugs, cleansers and beauty care products [3].

One of the quickly developing fields in worldwide industry is the creation of engineered plastics. Plastics are more better than different materials due than their special characteristics. These characteristics have been directed to build the plastic creation scale to 20 folds starting around 1964 (Ellen MacArthur Establishment 2016), and creation scale surpasses 300 million tons/year (Plastics Europe 2015) in 2015 it came to 335 million tons (Plastics Europe 2017). There are benefits and weaknesses of plastics. Plastics are solid, strong, and light weight. Then again, they are hurtful to the common habitat, impervious to debasement and prompting ecological contamination. On our earth, plastics represent a serious danger by collecting in enormous amounts [43]. Plastics can be separated into degradable and non- degradable polymers based on their substance properties. Plastics that are acquired from sustainable assets are biodegradable plastics. These are normally degradable, as a wellspring of cellulose, starch and algal material, a significant part in plants, creatures and green growth. These polymers are additionally created by microorganisms. Non-degradable plastics, commonly known as engineered plastics, are gotten from petrochemicals and are higher in atomic load because of the reiterations of little monomer units [23].

During plastic debasement the age of plastic particles with a size of < 5 mm are known as microplastics (MPs) which lead to potential ecotoxicological impacts. Sinewy MPs might be breathed in, may endure in the lung , and alongside related impurities including colors and plasticizers could prompt wellbeing impacts like cancer-causing nature and mutagenicity [17]. For the most part, it is acknowledged that plastic waste can for all time be dispensed with through cremation. Notwithstanding, unburned material actually exists in the base debris as a strong build up from incinerators that can deliver 360 to 102,000 microplastic particles for each metric ton after cremation. This base debris is a possible wellspring of microplastics delivered into the climate [1]. It is accounted for that plastic sections in the <100nm size range, alluded to as nanoplastics (NPs), may likewise be framed in the oceanic climate and may cause potential wellbeing impact [33].

Different types of non-biodegradable plastics

Polyethylen

Polyethylene (PE), otherwise called polyethene (IUPAC name) or polythene, is a significant gathering of thermoplastic polymers, delivered by the polymerization of ethylene. Contingent upon the polymerization interaction utilized, different sorts of polyethylene with contrasting properties can be gotten. They are arranged in light of their thickness, atomic weight, and stretching structure. For example, high thickness polyethylene (HDPE) is utilized for items, for example, milk containers, cleanser bottles, margarine tubs, trash bins, and water pipes. Ultra high atomic weight polyethylene (UHMWPE) is utilized in can-and bottle-dealing with machine parts, course, cog wheels, joints, and butchers' hacking sheets, and may try and be tracked down in tactical armour carriers. Low thickness polyethylene (LDPE) is utilized for the creation of inflexible compartments and plastic film. Starting around 2017, north of 100 million tons of polyethylene pitches are being delivered every year , representing 34% of the complete plastics market.

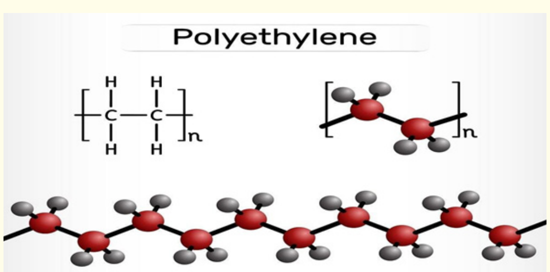

Figure 1

Name of bacteria	%Weight loss/month	Reference
Pseudomonas sp.	20.54 ± 0.13	[53]
Staphylococcus sp.	16.39 ± 0.01	[53]
Moraxella sp.	7.75 ± 0.61	[53]
Micrococcus sp.	6.61 ± 0.42	[53]
Streptococcus sp.	2.19 ± 0.15	[53]

Table 1: Biodegration of polyethylene by bacteria.

Polypropylene

Polypropylene, a manufactured pitch developed by the polymerization of propylene. One of the significant group of polyolefin tars, polypropylene is shaped or expelled into numerous plastic items where strength, adaptability, light weight, and intensity opposition are required. It is additionally turned into strands for work in modern and family materials. Propylene can likewise be polymerized with ethylene to create a versatile ethylene-propylene copolymer. PP (CnH2n) is the most broadly involved plastic in the auto business. Be that as it may, its spines, involving high atomic weight (10k-40k g/mol), long carbon chains and added stabilizers and cell reinforcements during blend, keep PP from barometrical oxidation [5]. The organism *Aspergillus niger* and microbes in the genera Vibrio and Pseudomonas have been accounted for to debase PP. Pretreated PP has likewise been utilized to direct debasement studies. UV-light, warm therapy, and gamma-illumination pretreatment strategies have been performed to make PP more powerless to debasement, as these pretreatment procedures diminish the hydrophilicity of PP. Additionally, UV-pretreated PP is biodegradable by the Bacillus flexus microorganism [28]. In any case, biodegradation of PP can undoubtedly be improved by mixing it with cellulose or starch mix; sugar mixes give the attachment of microorganisms to the PP surface.

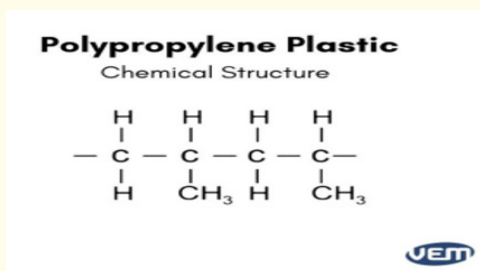

Figure 2

Name of bacteria	% weight loss/ month	Reference
Pseudomonas sp.	9%	[15]
Aneurinbacillus sp. and *Brevibacillus* sp	56%	[15]
Bacillus sp. and *Rhodococcus* sp.	6%	[15]

Table 2: Biodegration of polypropylene by bacteria.

Polystyrene

Polystyrene is an inflexible, solid tar that is incredibly straightforward. It is the most widely utilized plastic and is produced using the polymerization of styrene. The thermoplastic polymer is a strong at encompassing temperature, however it streams when warmed over 100 °C. Polystyrene is water-insoluble. With a couple of exemptions, polystyrene is a non-biodegradable material. Numerous sweet-smelling hydrocarbon solvents and chlorinated solvents disintegrate it rapidly. It's normally used in the foodservice business as unbending plate, holders, dispensable eating plates, and bowls, among other things. Polystyrene is a polymer of styrene. It is an engineered sweet-smelling hydrocarbon. It is hydrophobic in nature. Its IUPAC name is poly(1-phenylethane-1,2-diyl). Its overall recipe is (C8H8)n. PS squanders result from boundless business utilization of extended PS (EPS), otherwise called Styrofoam, in building protection and pressing, and of expelled PS (XPS) in holders, for example, espresso cups and food plate. The special design of PS, with its direct carbon spine and exchanging spine iotas joined to phenyl moieties, makes its biodegradation truly challenging. Consequently, debasing PS has turned into a basic worldwide issue. The biodegradation of polystyrene by Tenebrio molitor was explored by reproducing and raising the mealworms in the presence and nonappearance of polystyrene. An examination was made between those took care of with a typical eating routine and those benefited from polystyrene. The mealworms which were taken care of with polystyrene were then analyzed and the guts were gathered to confine and recognize the microscopic organisms in their guts. The reduction in mass of the polystyrene as feedstock affirmed that the mealworms were relying upon polystyrene as their only carbon diet. The frass egested by mealworms likewise affirmed the biodegradation of polystyrene as it contained exceptionally minuscule build-ups of polystyrene. Three detaches were acquired from the mealworms guts, and all were viewed as gram-negative. The sequencing results showed that the disconnects were *Klebsiella oxytoca* ATCC 13182, *Klebsiella oxytoca* NBRC 102593 and *Klebsiella oxytoca* JCM 1665.

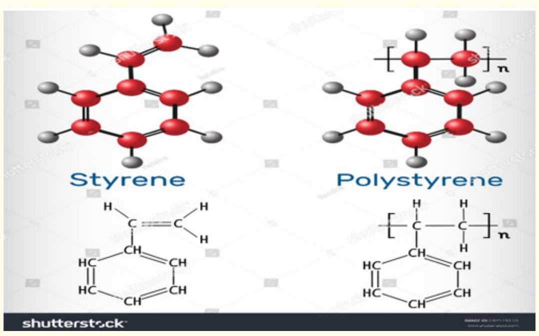

Figure 3

Name of bacteria	% weight loss/ month	Reference
Bacillus paralicheniformis	34%	[50]
Pseudomonas lini	-	[50]
Acinetobacter johnsoni	-	[50]

Table 3: Biodegration of polystyrene by bacteria.

Polyethylene terephthalate

PET is delivered by the polymerization of ethylene glycol and terephthalic corrosive. Ethylene glycol is a dismal fluid gotten from ethylene, and terephthalic corrosive is a glasslike strong gotten from xylene. At the point when warmed together affected by synthetic impetuses, ethylene glycol and terephthalic corrosive produce PET as a liquid, thick mass that can be turned straightforwardly to filaments or cemented for later handling as a plastic. In compound terms, ethylene glycol is a diol, a liquor with a subatomic construction that contains two hydroxyl (Goodness) gatherings, and terephthalic corrosive is a dicarboxylic fragrant corrosive. At a somewhat higher sub-atomic weight, PET is made into a high-strength plastic that can be molded by every one of the normal techniques utilized with different thermoplastics. PET movies (frequently sold under the brand names Mylar and Melinex) are created by expulsion. Liquid PET can be blow-formed into straightforward holders of high strength and inflexibility that are likewise essentially impermeable to gas and fluid. Here, PET has become broadly utilized in carbonated-refreshment bottles and in containers for food handled at low temperatures. The low relaxing temperature of PET — roughly 70 °C (160 °F) — keeps it from being utilized as a holder for hot food sources. PET is the most broadly reused plastic. In the US, notwithstanding, around 20% of PET material is reused. PET jugs and holders are normally broken down and turned into strands for fibrefill or floor coverings. At the point when gathered in a reasonably unadulterated state, PET can be reused into its unique purposes, and techniques have been contrived for separating the polymer into its compound antecedents for resynthesizing into PET. Among the distributions that pre-owned wild-type PET-corrupting microorganisms, 56.3% utilized microbes [54] 32.4% involved organisms [44], 7.0% both (microorganisms and growths) (Avendaño Toledo CA, Castro Velazco AM (2020) Determination of the most effective pretreatment on polyethylene terephthalate to increase the efficiency of the degradation process carried out by fungi and native microbes from landfill leachate. Universidad Libre, Socorro Santander), 1.4% utilized microalgae [27]. Among the microorganisms, Bacillus sp. Was the most successive sort [54].

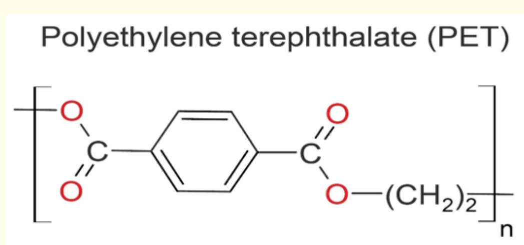

Figure 4

Name of bacteria	% weight loss/ month	Reference
Bacillus subtilis	56.3%	Int J Recent Adv Multidiscip., *et al.* 2015
Pseudomonas aeruginosa	3.62 ± 0.32%	[54]
Priestia aryabhattai	40%	[54]

Table 4: Biodegration of polyethylene terephthalate by bacteria.

Mechanism of biodegration of plastic by microorganisms

The mechanism of biodegradation by bacteria involves several processes that allow bacteria to break down complex organic compounds into simpler, more manageable forms. Bacteria have evolved various strategies to degrade different types of organic matter, including pollutants, plant materials, and animal waste. Here's a general overview of the mechanisms involved.

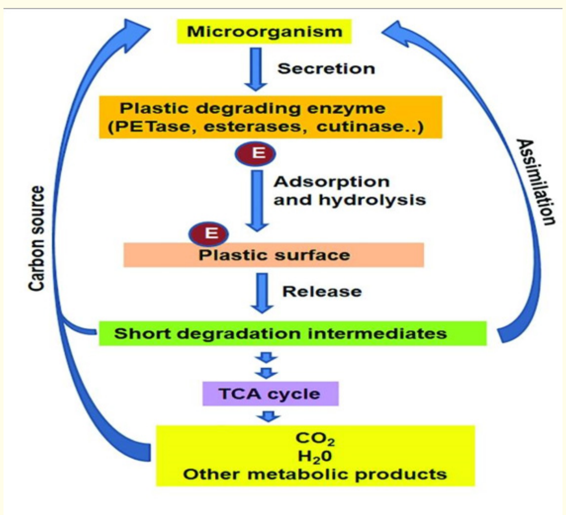

Figure 5: Mechanism of biodegration of plastic by microorganisms.

Bacteria produce and release a wide array of enzymes into their surrounding environment. These enzymes, such as proteases, lipases, cellulases, and ligninases, are specific to different types of organic compounds and help break them down into smaller components. Bacteria possess mechanisms to recognize and adhere to the target substrate. This can involve specialized surface structures or appendages that allow the bacteria to attach to the organic material, providing direct access to the nutrients. Once attached to the substrate, bacteria secrete enzymes that degrade the complex organic compounds into simpler molecules. For example, cellulases break down cellulose, a complex carbohydrate found in plant cell walls, into glucose units. These simpler molecules are more easily metabolized by the bacteria. Bacteria have metabolic pathways that allow them to utilize the breakdown products generated by the enzymes. The simpler molecules are taken up by the bacterial cells and undergo further metabolism to produce energy and essential building blocks for growth and reproduction. In some cases, biodegradation involves a consortium of bacteria working together. Different bacterial species may have complementary enzymes or metabolic pathways, enabling them to break down complex compounds more efficiently as a team. Some bacteria possess the ability to detoxify harmful substances during the biodegradation process. They can transform or degrade toxic compounds into less harmful forms, reducing the environmental impact of pollutants.

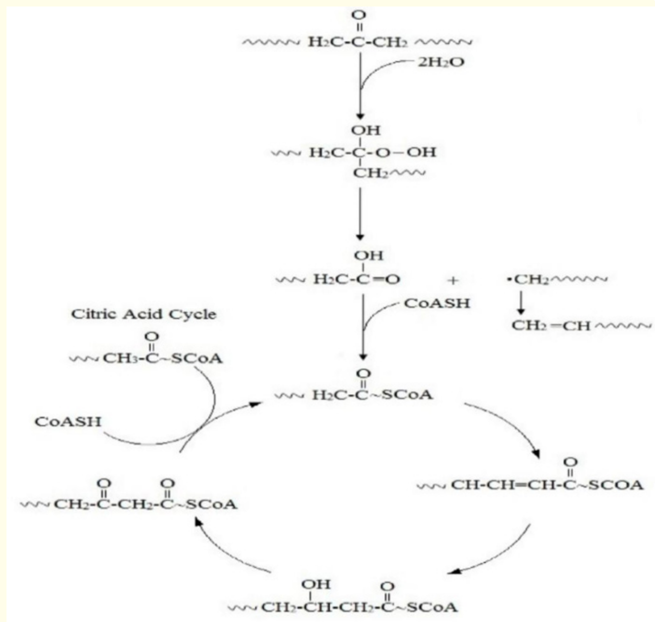

Figure 6: Mechanism for the biodegration of polyethylene.

It's important to note that different bacteria have specific capabilities and preferences for degrading different substances. Their effectiveness in biodegradation depends on their genetic makeup, environmental conditions, availability of necessary nutrients, and other factors. Scientists and engineers often leverage these natural abilities of bacteria for bioremediation purposes to clean up contaminated environments or for the treatment of wastewater and industrial waste.

Conclusion

Plastics are petrol inferred polymers and are utilized for different purposes. PE sacks are utilized all around the world at large levels. The accessibility of miniature and nanoplastics in oceanic climate has been expanded many folds because of biodegradation, thermooxidative corruption, photodegradation, warm and hydrolysis processes in the environment and postures serious danger to the amphibian life (new and marine) and human existence through food web. There is a need to utilize sufficient biodegradable strategies to destroy these polymers from the environment. Because of the hydrophobic and inactive nature, it is challenging to eliminate or debase polymers. Other than physical and substance techniques, microorganisms have shown promising potential to debase these polymers. The likely utilization of organisms for polymers expulsion should be additionally assessed utilizing unique polymers sullied wastewater. The evacuation of microplastics/nanoplastics, their poisonousness and the usage of organisms still need to be tended to. The exchange of plastic polymers from the loss into the sea-going environment including streams and seas through various cycles and the methodology to move these polymers from the wastewater to a reasonable spot for statement/burning ought to appropriately be supported. Long haul composed cleanup activities are expected to assess the dynamic biological system impacts.

Future Prospect

White contamination, because of plastic waste amassing, is of major ecological concern, these days. The issue of polymers' biodegradation lies in their own temperament that obstructs the polymer breakdown into monomers. Truth be told, the microbial catalyst frameworks are pointless against non-hydrolyzable engineered polymers. The event and movement of polymer-corrupting microorganisms differ as per the predominant natural circumstances.

Bibliography

1. Al-Thawadi S. "Microplastics and nanoplastics in aquatic environments: challenges and threats to aquatic organisms". *Arabian Journal for Science and Engineering* 45.6 (2020): 4419-4440.
2. Agustien A., *et al*. "Screening polyethylene synthetic plastic degrading-bacteria from soil". *Der Pharmacia Lettre* 8.7 (2015): 183-187.
3. Akmal D., *et al*. "Biosynthesis of copolymer poly (3-hydroxybutyrate-co-3-hydroxyvalerate) from palm oil and n-pentanol in a 10L bioreactor". *RASAYAN Journal of Chemistry* 8 (2015): 389-395.
4. Allen NS., *et al*. "Influence of ozone on styrene-ethylene-butylene-styrene (SEBS) copolymer". *Polymer Degradation and Stability* 79.2 (2003): 297-307.
5. Alshehrei F. "Biodegradation of synthetic and natural plastic by microorganisms". *Journal of Applied and Environmental Microbiology* 5.1 (2017): 8-19.
6. Andrady AL., *et al*. "Effects of increased solar ultraviolet radiation on materials". *Journal of Photochemistry and Photobiology B: Biology* 46.1-3 (1998): 96-103.
7. Awasthi S., *et al*. "Biodegradation of thermally treated high-density polyethylene (HDPE) by Klebsiella pneumoniae CH001". *3 Biotech* 7.5 (2017): 332.
8. Begum MA., *et al*. "Biodegradation of polythene bag using bacteria isolated from soil". *International Journal of Current Microbiology and Applied Sciences* 4.11 (2015): 674-680.
9. Chen Q., *et al*. "Effects of exposure to waterborne polystyrene microspheres on lipid metabolism in the hepatopancreas of juvenile redclaw crayfish, Cherax quadricarinatus". *Aquation and Toxicology* 224 (2020a): 105297.
10. Chen Y., *et al*. "Identification and quantification of microplastics using Fourier-transform infrared spectroscopy: Current status and future prospects". *Current Opinion in Environmental Science and Health* 18 (2020b): 14-19.
11. Corami F., *et al*. "A novel method for purification, quantitative analysis and characterization of microplastic fibers using Micro-FTIR". *Chemosphere* 238 (2020): 124564.
12. Danso D., *et al*. "Plastics: Environmental and biotechnological perspectives on microbial degradation". *Applied Microbiology and Biotechnology* 85.19 (2018): e01095-19.
13. Das K and Mukherjee AK. "Characterization of biochemical properties and biological activities of biosurfactants produced by Pseudomonas aeruginosa mucoid and non-mucoid strains isolated from hydrocarbon-contaminated soil samples". *Applied Microbiology and Biotechnology* 69.2 (2005): 192-199.
14. Kathiresan K. "Polythene and Plastic-Degrading Microbes in an Indian Mangrove Soil". *Revista de Biologia Tropical* 51 (2003): 629-633.
15. Hyun Jeong Jeon and Mal Nam Kim. "Isolation of mesophilic bacterium for biodegradation of polypropylene". *International Biodeterioration and Biodegradation* (2016).
16. Luís Gabriel Antão Barboze., *et al*. "Marine microplastic debris: An emerging issue for food security, food safety and human health". *Marine Pollution Bulletin* (2018).
17. Kumar., *et al*. "Plastic Impacts of Plastic Pollution on Ecosystem Services, Sustainable Development Goals, and Need to Focus on Circular Economy and Policy Interventions". *Sustainability* (2021).
18. Dhaka., *et al*. "Dhaka Sitting on a Plastic Bomb: Issues and Concerns around Waste Governance, Water Quality, and Public Health". *Earth* (2022).
19. Hou., *et al*. "Sustainable catalytic strategies for the transformation of plastic wastes into valued products". *Chemical Engineering Science* (2022).
20. Sinosh Skariyachan., *et al*. "Enhanced polymer degradation of polyethylene and polypropylene by novel thermophilic consortia of Brevibacillus sps. And Aneurinibacillus sp. Screened from waste management landfills and sewage treatment plants". *Polymer Degradation and Stability* (2018).
21. Abraham J., *et al*. "Microbial degradation of low density polyethylene". *Environmental Progress and Sustainable Energy* 36.1 (2017): 147-154.
22. Acero E H., *et al*. "Enzymatic surface hydrolysis of PET: Effect of structural diversity on kinetic properties of cutinases from Thermobifida". *Macromolecular Rapid Communications* (2015).

23. Ahmed T., *et al*. "Biodegradation of plastics: current scenario and future prospects for environmental safety". *Environmental Science and Pollution Research International* 25.8 (2018): 7287-7298.

24. Al-Salem S M., *et al*. "Insights into the evaluation of the abiotic and biotic degradation rate of commercial pro-oxidant filled polyethylene (PE) thin films". *Journal of Environmental Management* 250 (2019): 109475.

25. Ali M I., *et al*. "Biodegradation of starch blended polyvinyl chloride films by isolated Phanerochaete chrysosporium PV1'. *International Journal of Environmental Science and Technology* 11.2 (2014): 339-348.

26. Alimba C G and Faggio C. "Microplastics in the marine environment: Current trends in environmental pollution and mechanisms of toxicological profile". *Environmental Toxicology and Pharmacology* 68 (2019): 61-74.

27. Almeida E L., *et al*. "In silico screening and heterologous expression of a polyethylene terephthalate hydrolase (PETase)-like enzyme (SM14est) with polycaprolactone (PCL)-degrading activity, from the marine sponge-derived strain Streptomyces sp. SM14". *Frontiers in Microbiology* 10 (2019): 2187.

28. Alshehrei F. "Biodegradation of synthetic and natural plastic by microorganisms". *Journal of Applied and Environmental Microbiology* 5.1 (2017): 8-19.

29. Amobonye A., *et al*. "Plastic biodegradation: Frontline microbes and their enzymes". *Science of the Total Environment* 759 (2021): 143536.

30. Andrady A L and Neal M A. "Applications and societal benefits of plastics". *Philosophical Transactions of the Royal Society B: Biological Sciences* 364.1526 (2009): 1977-1984.

31. Antipova T V., *et al*. "Biodegradation of poly-ε-caprolactones and poly-l-lactides by fungi. *Journal of Polymers and the Environment* 26.12 (2018): 4350-4359.

32. Austin H P., *et al*. "Characterization and engineering of a plastic-degrading aromatic polyesterase". *Proceedings of the National Academy of Sciences, USA* 115.19 (2018): E4350-E4357.

33. Bahl S., *et al*. "Biodegradation of plastics: A state of the art review". *Materials Today: Proceedings* 39 (2021): 31-34.

34. Banerjee S., *et al*. "Enzyme producing insect gut microbes: an unexplored biotechnological aspect". *Critical Reviews in Biotechnology* 42.3 (2022): 384-402.

35. Barbeş L., *et al*. "ATR-FTIR spectrometry characterisation of polymeric materials". *Romanian Reports in Physics* 66.3 (2014): 765-777.

36. Bardají D K R., *et al*. "Isolation of a polyethylene degrading Paenibacillus sp. From a landfill in Brazil". *Archives of Microbiology* 201.5 (2019): 699-704.

37. Belhouari Y., *et al*. "International Coastal Cleanup 2017 Report". Washington, DC: Ocean Conservancy; (2017).

38. Bhagwat G., *et al*. "Understanding the fundamental basis for biofilm formation on plastic surfaces: Role of conditioning films". *Frontiers in Microbiology* (2015).

39. Bhardwaj H., *et al*. "Communities of microbial enzymes associated with biodegradation of plastics". *Journal of Polymers and the Environment* 21.2 (2013): 575-579.

40. Arumugam K., *et al*. "Investigation on paper cup waste degradation by bacterial consortium and Eudrillus eugeinea through vermicomposting". *Waste Management* 74 (2018): 185-193.

41. Chalup A., *et al*. "First report of the lesser wax moth Achroia grisella F. (Lepidoptera: Pyralidae) consuming polyethylene (silo-bag) in northwestern Argentina". *Journal of Apicultural Research* 57 (2018): 569-571.

42. Child J and Willetts A. "Microbial metabolism of aliphatic glycols bacterial metabolism of ethylene glycol". *Biochimica et Biophysica Acta* 538 (1978): 316-327.

43. China Plastics Industry. Data from: In 2017, the Total Output of China's Plastic Products was 751.155 Million Tons, an Increase of 3.4% Year-on-Year (EB/OL) (2017).

44. Choi K Y., *et al*. "Molecular and biochemical analysis of phthalate and terephthalate degradation by Rhodococcus sp. Strain DK17". *FEMS Microbiology Letter* 252 (2005): 207-213.

45. Christova N., *et al*. "Rhamnolipid biosurfactants produced by Renibacterium salmoninarum 27BN during growth on n-hexadecane". *Z. Naturforsch* C 59 (2021): 70-74.

46. Cosgrove L., *et al*. "Fungal communities associated with degradation of polyester polyurethane in soil". *Applied and Environmental Microbiology* 73 (2007): 5817-5824.

47. Crabbe J R., *et al*. "Biodegradation of a colloidal ester-based polyurethane by soil fungi". *International Biodeterioration and Biodegradation* 33 (1994): 103-113.

48. Cregut M., *et al*. "New insights into polyurethane biodegradation and realistic prospects for the development of a sustainable waste recycling process". *Biotechnology Advances* 31 (2013): 1634-1647.

49. Delacuvellerie A., *et al*. "The plastisphere in marine ecosystem hosts potential specific microbial degraders including Alcanivorax borkumensis as a key player for the low-density polyethylene degradation". *Journal of Hazardous Materials* 380 (2019): 120899.

50. Eisaku O., *et al*. "Isolation and characterization of polystyrene degrading microorganisms for zero emission treatment of expanded polystyrene". *Environmental Engineering Research* 40 (2003): 373-379.

51. Engel P and Moran N A. "The gut microbiota of insects-diversity in structure and function". *FEMS Microbiology Review* 37 (2013): 699-735.

52. Erlandsson B., *et al*. "Correlation between molar mass changes and CO2 evolution from biodegraded 14C-labeled ethylene-vinyl alcohol copolymer and ethylene polymers". *Acta Polymer* 49 (1998): 363-370.

53. Filip Z. "Polyurethane as the sole nutrient source for Aspergillus niger, and Cladosporium herbarum". *Applied Microbiology and Biotechnology* 7 (1979): 277-280.

54. Fischer-Colbrie G., *et al*. "New enzymes with potential for PET surface modification". B*iocatalysis and Biotransformation* 22 (2004): 341-346.