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Review on the characterization and degradation of microplastics present in wastewater through microorganisms

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ABSTRACT

Plastic has become an essential commodity in present world scenario and is widely used because of its desirable characteristics such as durability, flexibility, low cost and resistance to degradation. The increasing consumption of plastic resulted in the ever-growing presence of plastics in water bodies that held an invisible threat of severe harm to human beings. As the needs of the human population are increasing steadily, the production of plastic in various forms is increasing, which in turn increases the accumulation of plastic in the water bodies exponentially. When the threat related to plastics pollution in water is discussed, the primary or real potential hazard comes from the minute fragments of plastics called microplastics. Researchers have used various analytical methods with no set standard in either sampling or units. Also, the increasing pollution of plastics in water can either be due to the improper disposal of plastic waste or the limited efficiency of current conventional treatments of plastic waste. The review scenario is tilted towards microplastics' analyses and characterization in water. The ability to remove plastic waste from water is high for the larger size of plastics. The present review study deals with the identification and biodegradation of microplastics through microbes. A simple and novel process for biodegradation of microplastics to overcome the environmental concerns was proposed.

Keywords: Plastic, wastewater, microplastic, biodegradation, analytical techniques.

INTRODUCTION

Microplastics

Plastics are made up of large chains of polymer molecules. Plastics and its products are extensively used in different sectors of market due to its high durability and high stability [1]. Plastics are highly stable and not degraded easily, therefore causing harm to the environment. As for instance, the world population of plastics almost reaches 350 million tonnes in 2015 and plastics consumption will be projected to 20 million tonnes by 2020 [2]. The growing depends of plastic consumption has resulted in massive accumulation of plastic waste of around 25940 tonnes per day [3]. Plastic pollutant is ubiquitous and have been reported from environment close to urban centers, terrestrial areas and fresh water environment. It was estimated that 80% of plastic in sea originates from inland sources and was transferred by river into oceans [1, 4].

However, plastic degrades under the influence of solar radiation, mechanical abrasion, waves and temperature fluctuation. Therefore, on its degradation the plastic transforms into different categories of plastics i.e., microplastics and nano plastics having different size range.

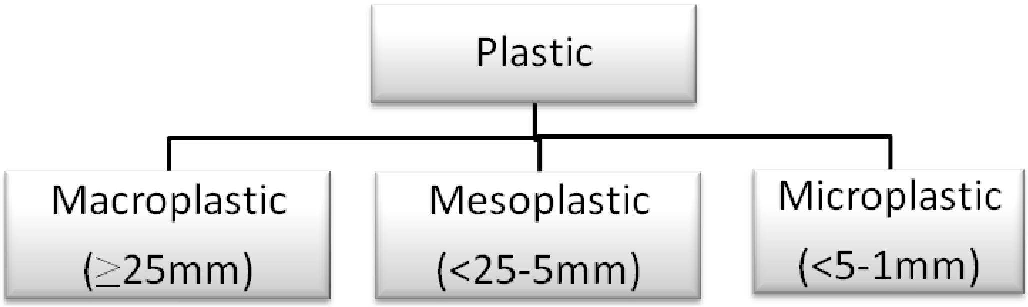

Fig 1: Types of plastic pollution size categories

Microplastics are plastics having size range less than 5mm and present in fresh water, in cosmetics, in urban centers, on sea surface, etc. MPs can transfer harmful organic chemical into food chain and due to their persistent nature, they are causing dreadful impact on the biological chain [5]. Primary MPs are produced in smaller scale and used in different daily used items like cosmetics, toothpaste, scrubs, clothing, etc. whereas weathering of primary MPs debris results in secondary MPs [7]. Plastic fragmentation in extremely small size particles results in easier and faster transfer to living organism through air and water. MPs ingestion possess risk to marine organism by causing false satiation, reproductive stress and accumulation of lipid in liver and inflammation [5, 8].

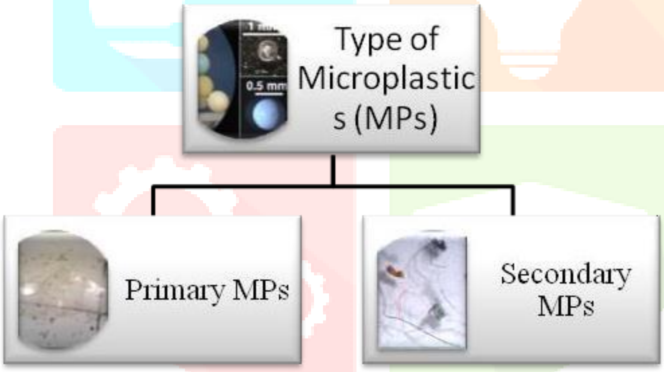

Fig. 2: Types of Microplastics

This nature of plastic getting fragmented into smaller and smaller particles has become a significant cause of concern as more minor the particle more harm it can cause because it can be inhaled from air or consumed through water by the living organisms. Although there are no fatal effects seen in human beings, the primary cause of concern is the unknown effect a long- term exposure can cause [12]. From the study of aquatic animals, it has been suggested that microplastics can accumulate and cause toxicity in the body of living organisms. Microplastics ingestion poses extreme threats to marine organisms by causing reproductive stress and accumulation of lipids in the liver and inflammation. It was reported that 130 t (annually) of microplastics in oceans from daily products was discharged from the household drains [3, 7]. Around 40 tons of the microplastics reported to the Baltic Sea because of the inadequate filtering by waste treatment plants.

Microplastics are found to be carriers of other toxic chemicals and microbial pathogens because of the growth of biofilm. Insufficient knowledge of the plastic content in our environment as well as its toxic effect to human beings if exposed for a longer-term has shifted the focus of many researchers towards the analyses of microplastics to get the better understanding of their origin, their characteristics and their concentration in the environment [5]. Still, no standardized method has been established for the sampling, processing, and qualitative and quantitative analyses of microplastics, which poses a massive gap in this research area. Along with understanding the threat, the need for its removal is also there [8]. Various techniques exist in the studies like filtration, sedimentation, biodegradation, and chlorination, and many more, but the efficiency achieved by these techniques for removal of microplastics lower than 100 μm in size is still very low [9]. For this gap, an optimized method can be used to achieve the desired results.

Despite availability of various conventional and advanced techniques with up to 99% efficiency, for the removal of microplastics, substantial amounts of microplastics of less than 100 μm size, are being released in the water bodies. Hence, optimizing the biodegradation process in order to increase the efficiency to remove microplastics of smaller size, is required. Also, recent extensive research works related to microplastics, are mostly concerned with their analysis in both freshwater systems or wastewater water bodies, but there is a lack of standard method for the characterization of microplastics mainly due to the disparity in sampling and processing techniques and the use of different unit systems. Hence there is the need for more research in this field of microplastic removal and exploration.

Identification of Microplastics

The characterization of the shapes, size and types of microplastics is important aspect to investigate the biodegradation of microplastics [10]. Various characterization techniques are required for evaluation of various properties considering the complex nature of microplastics. The characterization techniques usually involve microscopy, spectroscopy and thermal analysis as shown in Table. 3 [13]. It is popular to use combination of numerous techniques of three categories to characterize the microplastics for better precise and concise results.

Table 1. Different techniques and their application and limitation [13,24]

Identification methods	Advantages	Limitation
Microscopic identification	Easier to use Quick analysis Simple	Chemical composition cannot be determined No polymer composition data. High possibility of missing small size particles.
FTIR	Detection of particles size less than 20um	High capital cost Tedious and extended time required . Contact analysis

Raman Spectroscope identification	Detection of particles size less than 100µm Non-destructive analysis Higher accuracy and results are in agreement with chemical analysis for even small particles	High capital cost Expensive instrument.

Microscopic identification

Dissecting microscopy is used for the detection for microplastics with size in microns. The microscope facilitates the image of microplastics, through which the shape and size of plastic can be seen clearly. Larger particles (i.e., more than 100µm) can be easily identified by microscope, whereas, small particles (i.e., <100 µm) with no proper color or definite shape are difficult to characterize as plastics [12,16].

Fourier transform infrared (FTIR) spectroscopy

Fourier spectroscopy is a widely accessible tool to identify unknown polymer particles and the chemical bond present in them. Fourier identifies the stretch of bonds having carbon present in it (C-H, CH_2, CH_3) [1, 51]. The FTIR spectrum library helps in the confirmation of plastics and also in the identification of polymer. The reflectance and ATR mode don't need the sample preparation step for thick microplastics, unlike that of the transmission mode [7, 24]. Microplastics as small as the diameter of the IR beam aperture of the ATR probe is detectable [24].

Raman Spectroscopy

Raman spectroscopy is a tool to identify small-sized microplastics (<20um), and its use is widespread, even after having a long measurement time and distortion by fluorescence [19]. Raman spectroscopy releases a monochromatic light (laser beam) that falls upon the sample and provides different frequencies, depends on the molecular structure present in the sample [24]. The various polymers have a diverse spectrum for the microplastics analysis. Raman includes profiling to the sample depending on their polymer composition [44].

Scanning electron microscopy

Scanning electron microscopy (SEM) is a tool for the high-magnification and vivid images of microplastic particles. High-resolution images expedite the discrimination of microplastics from both organic and inorganic particles present in the sample [2, 4]. Further, the elemental composition of the same object is obtained through analysis with energy-dispersive X-ray spectroscopy (EDS). This aids in identifying microplastics' carbon in major from inorganic particles [9, 11]. SEM-EDS have several disadvantages, such as being expensive and time- consuming for sample preparation, restricting the number of samples.

Table 2. Literature review of microplastics detection through instrument

S. No.	Detection technique used	Type of plastic found	Reference
1	Fluorescence microscopy, FTIR and SEM techniques	Polyethylene (43%) > polyethylene terephthalate (17.3%)	[18]
2	Raman spectroscopy.	LDPE dominant	[35]
3	Stereoscopic microscope, SEM and FTIR were used	Polyethylene terephthalate and polypropylene were the dominant polymer-types	[37]
4	FTIR analysis	Majorly PES and PE.	[44]
5	Raman spectroscopy	90% of the detected microplastics smaller than 5 µm	[43]
6	Preferred FTIR or Raman spectroscopy, pyrolysis-GC/MS	globally detected polymers in these studies are PE > PP > PS > PVC > PET	[31]

Degradation of Microplastics

As seen, plastics do not naturally degrade in no small amount when released into the environment [18]. The application of polymers is extensive because of their exceptionally high stability and durability [14]. Plastics degradation occurs in the environment through four different mechanisms that are, photodegradation, physical degradation, chemical degradation, and biodegradation [19, 20]. Plastic degradation starts with photodegradation, which leads to thermo-oxidative degradation. The activation energy for the occurrence of the degradation of the plastics or polymer is provided by the ultraviolet (UV) lights and, this result in the initiation of incorporation of O_2 atom [14, 15]. Therefore, the plastic becomes brittle and breaks into smaller particles till the polymer chains reaches to the low molecular weight that can be used by microorganisms [13]. These microorganisms convert the C of the polymer chains to CO_2. However, this entire process is tedious, and it can take up to 40 or more years for plastic to degrade fully [12, 17].

Table 3. Methods of degradation and its limitation [12]

Degradation methods	Advantages	Limitations
Physical degradation (abrasive forces, heating/cooling, freezing/thawing, drying)	Easy to be done	Time consuming Least effective
Photodegradation (by UV light)	Efficient	Harmful Expensive
Chemical degradation (by chemicals, oxidation)	Easy Not harmful	Expensive
Biodegradation by organisms (bacteria, fungi)	Cheap, easy	Time consuming

Table 4. Biodegradable and non-biodegradable plastics table [17]

Biodegradable Plastic	**Uses**	**Biodegradability**
Polyhydroxyalkanoate (PHA)	Food wrapping, and utensils such as plate, cup Paper coating and cardboard applications Numerous medical applications, e.g., gauzes, sutures.	2 months [13, 38]
Polylactide Acid (PLA)	Grocery bags Packaging (Food) Bottles, cups and plates Medical equipment's such as sutures.	1-6 months [12, 34]
Polybutyrate adipate terephthalate (PBAT)	Garbage collection bags Wrap cover Disposable containers Tableware	2 months [36]
Polycaprolactone (PCL)	Manufacturing of bags (Compostable) Medical devices such as fibers and sutures Coating material and adhesives (shoes, leather)	15 days [6, 30]
Non-biodegradable plastics	**Properties**	**Uses**
Polyethylene Terephthalate (PET)	High strength High toughness, High resistant	Plastic bottles (soft drinks, beer) Drinking water bottle Mouthwash bottle [22, 27]
High-Density Polyethylene (HDPE)	Deflection resistant (stiff) Good strength and toughness Corrosive resistant in various chemical Excellent formability	Drinking water bottles Milk packets Juice containers Cosmetic and laundry containers [6, 24]

Low-Density Polyethylene (LDPE)	Good formability and ease of manufacturing Moisture resistant Good toughness	Dry cleaning Squeezable bottles bread Frozen food bags [16, 28]
Polypropylene (PP)	Strength / toughness Resistance to chemicals Resistance to heat Barrier to moisture	Food containers Bottles for drug and medical applications [32]
Polystyrene (PS)	Excellent insulator (insulation property) Ease for formation of various shapes	Grocery store meat trays Aspirin bottles Egg cartons Cups, plates, cutlery [33]

Biodegradation of Microplastics

Organic substances dissociated using the living organisms present in the environment during the biodegradation process [4]. Degradation of the organics can occur aerobically, with oxygen, or anaerobically, without presence of the oxygen. Plastics degrade aerobically, anaerobically, and landfills and partly aerobic and partly anaerobic in composts and soil [15,16], which further produce Carbon dioxide and water produced during aerobic biodegradation as an end product, and CO2, H2O and CH4 production in the anaerobic degradation as the final product [9].

Microorganisms (micro-bacteria, yeasts, fungus) are mainly used in the degradation of the natural and synthetic plastics materials [14, 19]. In general, the plastic biodegradation can proceed under different conditions depending on the properties of plastics as the responsible microorganisms for the degradation varies for each case. They have their own nutrients requirements and have their optimal growth conditions like temperature, pH in the soil [17, 21]- biodegradation processes by various factors including the polymer characteristics, type of organism, and nature of pre-treatment [40,41].

Table 5. Biodegradation of polymers through different microorganisms.

Polymer	Microorganisms	Days	Biodegradability	References
Polyethylene	*Rhodococcus ruber*	30	8%	[4]
	Brevibacillus borstelensis	30	11%	[29]
	Bacillus cereus	30	1.7%	[18]
	Aspergillus niger	40	3.6%	[14]
	Streptococcus lactis	30	12.5%	[17]
	Pseudomonas aeroginosa	120	9-20%	[11]
	Pseudomonas putida	120	9-20%	[25]
	Pseudomonas siringae	30	2%	[11]
Polypropylene	*Bacillus gottheilii*	40	3.6%	[18]
Polystyrene	*Bacillus cereus*	40	7.4%	[13]
	Bacillus gottheilii	40	5.8%	[42]
High Density Polyethylene (HDPE)	*Bacillus sp.*	30	2.5%	[46]
	Aspergillus niger	40	1.6%	[26]
	Aspergillus oryzae	40	1.4%	[23]
Low Density Polyethylene (LDPE)	*Bacillus sp.*	30	4.8%	[5]
	Bacillus cereus	30	4.8%	[39]
	Staphylococcus sp.	60	7.2%	[21]
	Aspergillus versicolor	90	6%	[10]
	Pseudomonas stutzeri	30	4.1%	[16]
	Pencillium pinophilum	30	11%	[45]
	Aspergillus niger	30	11.07%	[8]
	Rhodococcus ruber	60	7.5%	[14]

CONCLUSION

This study concludes the characterization of plastics and the potential of bacteria to degrade microplastics. There is a lack of standardized analytical methods to identify the microplastics present in the water as no substantial study has been done to analyze microplastics in Indian water system. Further, unavailability of degradation systems which are harmless to the environment as well as efficient in removing the microplastics from the water system and optimized biodegradation techniques, for removal of microplastics from the water, have been critical concerns in the field.

Furthermore, work can be done regarding the degradation of microplastics where we can work with an amalgam of bacteria. Moreover, we can do the treatment process before or after the degradation of microplastics i.e., pre-treatment or post-treatment. Pre- or post-treatment can be done with the help of ultraviolet light, chemicals to increase the efficiency of degradation. Environmental impact of plastics can be significantly reduced by employing adequately optimized. The use of microorganisms is also considered environmentally friendly.

REFERENCES

1. Analytical characterization of polymers used in conservation and restoration by ATR- FTIR spectroscopy. Anal. Bio anal. Chem. 395 (7), 2081–2096. Asensio, R.C., Moya, M.S.A., de la Roja, J.M., Gómez, M., 2009.
2. Assessment of the biodegradation of polythene. Bioinfolet 2008; 5: 239-245. 69. Aswale P, Ade A.
3. Biodegradability of Polythene and Plastic by the Help of Microorganism: A Way for Brighter Future. J Environ Anal Toxicol 2011; 1: 111. 70. Priyanka N, Archana T.
4. Biofilm development of the polyethylene degrading bacterium *Rhodococcus ruber*. Appl Microbiol Biotechnol 2006; 72(2): 346- 352. 71. Sivan A, Szanto M, Pavlov V.
5. Biodegradation of low-density polyethylene by microorganisms from garbage soil. J Exp Bio Agri Sci 2015; 3(1): 15-21. 65. Deepika S.
6. Biodegradation of disposable polyethylene by fungi and Streptomyces species. Polym Degrad Stab 1998; 62: 361- 365. 76..
7. Biodegradation of polyethylene by the thermophilic bacterium *Brevibacillus borstelensis*. J Appl Microbiol 2005; 98:1093-1100. 79. Hadad D, Geresh S, Sivan A.
8. Biodegradation of low-density polyethylene (LDPE) by fungi isolated from marine water- a SEM analysis. Afr J Microbiol Res 2011; 5: 5013-5018. 83. Pramila R, Ramesh KV.
9. Biodegradation of low-density polyethylene (LDPE) modified with dye sensitized titania and starch blend using Stenotrophomonas pavanii. Int. Biodeterior. Biodegrad. 2016, 113, 276–286. Mehmood, C.T.; Qazi, I.A.; Hashmi, I.; Bhargava, S.; Deepa, S.
10. Biodegradation of physiochemically treated LDPE by a consortium of filamentous fungi. J Appl Polym Sci Limon-Gonzalez M, Favela-Torres E (2004).

11. Biodegradation of Plastics by Pseudomonas putida isolated from Int. J. Adv. Res. Biol.Sci. 2(1): (2015): 90–97 97 Garden Soil Samples. Saminathan, P., Sripriya, A., Nalini, K., Sivakumar, T. and Thangapandian, V. (2014).
12. Biodegradation of low-density polythene (LDPE) by Pseudomonas species. Indian J. Microbiol. 2012, 52, 411–419. Kyaw, B.M.; Champakalakshmi, R.; Sakharkar, M.K.; Lim, C.S.; Sakharkar, K.R.
13. Bacterially Produced Polyhydroxyalkanoate (PHA): Converting Renewable Resources into Bioplastics. Appl Microbiol & Microbiol Biotech A Mendez Vilas (Ed). Chee, J. Y.; Yoga,

S. S., Lau, N. S., Ling, S. C., Abed, R. M. M. and Sudesh, K. L. (2010).Biofilm development of the polyethylene-degrading bacterium Rhodococcus ruber. Appl. Microbiol. Biotechnol. 2006, 72, 346–352. Sivan, A.; Santo, M.; Pavlov, V.
14. Colonization, biofilm formation and biodegradation of polyethylene by a strain of Rhodococcus ruber. Appl.Microbiol.Biotechnol, 65: 97–104. Gilan, O., Hadar, Y. and Sivan, A. (2004).
15. Degradation assessment of low-density polyethylene (LDP) and polyethylene by an indigenous isolate of Pseudomonas stutzeri. Journal of scientific and industrial research. 63: 293-296. Sharma, A. and Sharma, A. (2004).
16. Distribution and characterization of microplastics in beach sand from three different Indian coastal environments. Marine Pollution Bulletin 140, 262-273. M. Tiwari, T.D. Rathod,
P.Y. Ajmal et al., 2019.
17. Distribution and importance of microplastics in the marine environment: A review of the sources, fate, effects, and potential solution.VL-102, Environment international (2008); Fauziah, Shahul Hamid, Emenike, Chijioke, Auta, Helen.
18. Effect of pH on biodegradation of polythene by Serretia marscence. Aswale PN, Ade AB. The Ecotech 2009; 1: 152-153. 81.
19. Enzyme-mediated biodegradation of heat-treated commercial polyethylene by Staphylococcal species. Polym Degrad Stab 2010; 95: 195-200.
20. Ethylene Glycol Metabolism by Pseudomonas putida. Applied and Environmental Microbiology. 78 (24): 8531– 8539. Muckschel, B., Simon, O., Klebensberger, J., Graf, N., Rosche, B., Altenbuchner, J., Pfannstiel, J., Huber, A. and Hauera, B. (2012).
21. High-density polyethylene (HDPE)- degrading potential bacteria from marine ecosystem of Gulf of Mannar, India. Lett Appl Microbiol 2010; 51: 205-211. 78. Balasubramanian V, Natarajan K, Hemambika B, Ramesh, N, Sumathi CS et al.
22. Infrared and Raman analysis of polymers. In: Lobo, H., Bonilla, J.V. (Eds.), Handbook of Plastics Analysis. Marcel Dekker, Inc, New York, pp. 186–316. Nishikida, K., Coates, J., 2003.
23. Isolation and identification of nylon 6 degrading bacteria and study the optimum conditions for degradation. J. Biotechnology Research (JBR) 13: 73-86. Alsaraf, A. A. and Al-Jailawi, M. H. (2013).
24. Isolation and identification of LDPE degrading fungi from municipal solid waste. Journal of Chemical and Pharmaceutical Research. 5(3):78-81. Kumar, S., Das, P. M., Rebecca,
L. J. and Sharmila, S. (2013).
25. Influence of cell surface hydrophobicity in colonization and biofilm formation on LDPE biodegradation. Int. J. Pharm. Pharm. Sci. 2013, 4, 690–694. Das, M.P.; Kumar, S.

26. Investigation on biodegradability of polyethylene by Bacillus cereus strain MaSu isolated from compost soil. Int Res J Microbiol 2011; 2: 292-302. 82. Suresh B, Maruthamuthu S, Palanisamy N, Ragunathan R, Pandiyaraj KN et al.
27. In Vitro Degradation of Plastics (Plastic Cup) Using Micrococcus Luteus and Masoniella Sp, Sch. Acad J Biosci 2014; 2(2):85-89. 68. Sivasankari S, Vinotha T.
28. Marine microbe-mediated biodegradation of low- and high-density polyethylenes. Int. Biodeterior. Biodegrad. 2008, 61, 203–213. Sudhakar, M.; Doble, M.; Sriyutha Murthy, P.; Venkatesan, R.
29. Microplastics in freshwaters and drinking water: Critical review and assessment of data quality. Water Research 155, 410-422. Albert A. Koelmans, Nur Hazimah Mohamed Nor et al., 2019.
30. Microplastics in fresh- water systems: a review of the emerging threats, identification of knowledge gaps and prioritisation of research needs. Water Res. 75, 63-82. Eerkes- Medrano, D., Thompson, R.C., Aldridge, D.C., 2015.
31. Microplastics in freshwater systems: A review on occurrence, environmental effects, and methods for microplastics detection. Water Research 137, 362-374. Jingyi Li, Huihui Liu, J. Paul Chen, 2018.
32. Microplastics in a Marine Environment: Review of Methods for Sampling, Processing, and Analyzing Microplastics in Water, Bottom Sediments, and Coastal Deposits. Oceanology, 58 (1), 137–143. M. B. Zobkov and E. E. Esiukova, 2018.
33. Microplastic pollution in Vembanad Lake, Kerala, India: The first report of microplastics in lake and estuarine sediments in India. Environmental Pollution 1-8. S. Sruthy, E.V. Ramasamy, 2016.
34. Microplastics pollution in different aquatic environments and biota: A review of recent studies. Marine Pollution Bulletin 133, 191-208. Shahabaldin Rezaniaa, Junboum Park et al, 2018.
35. Microplastics pollution in inland freshwaters of China: A case study in urban surface waters of Wuhan, China. Science of the Total Environment 575, 1369–1374. Wenfeng Wang, Anne Wairimu Ndungu et al., 2017.
36. Mechanical and surface properties of low-density polyethylene film modified by photo- oxidation. Polym J 43, 398–406 (2011). Suresh, B., Maruthamuthu, S., Kannan, M. et al.
37. Polythene and plastic degrading microbes from mangrove soil. Rev Biol Trop 2003; 51: 629-633. 80. Kathiresan K.
38. Screening of Polyethylene Degrading Microorganisms from Garbage Soil. Libyan Agric Res Cen J Int 2011; 2: 200-204. 75. El-Shafei HA, El-Nasser NHA, Kansoh AL, Ali AM.
39. Screening of Plastic Degrading Bacteria from Dumped Soil Area. Ph.D. Thesis, National Institue of Technology of Rourkela, Odisha, India, 2012. 49. J. Hazard. Mater. 2017, 324, 634–644. Thakur, P.
40. Screening and isolation of polyethylene degrading bacteria from various soil environments. IOSR J. Environ. Sci. Toxicol. Food Technol. 2016, 10, 1–7 Divyalakshmi, S.; Subhashini, A.
41. Screening of Bacillus strains isolated from mangrove ecosystems in Peninsular Malaysia for microplastic degradation. *Environ Pollut*. 2017;231(Pt 2):1552-1559. Auta HS, Emenike CU, Fauziah SH.
42. Solutions to microplastic pollution - removal of microplastics from wastewater effluent with advanced

wastewater treatment technologies. Water Res. 123, 401. Talvitie, J., Mikola, A., Koistinen, A., Seta€la€, O., 2017.

43. Soil reveals an untapped microbial potential. Peixoto, J.; Silva, P.L.; Krüger, R.H. Brazilian Cerrado.
44. Studies on the biodegradation of natural and synthetic polyethylene by Pseudomonas sp. J Appl Sci Environ Manage 2010; 14(2): 57-60. 66. Sonil Nanda, Smiti Snigdha Sahu, Jayanthi Abraham.
45. The mechanism of biodegradation of polyethylene. Polym Degrad Stab 18: 73-87. Albertsson, A. C., Andersson, S. O. and Karlsson, S. (1987).