Indexing and Abstracting in Following Databases

1. Bowker: A ProQuest Affiliate

2. Crossref

ISBN 9789392804229

9 789392 804229

₹ 701 US$ 14

Published by
Bright Sky Publications,

Office No.3, 1st Floor, Pocket - H34, Sec - 3,
Rohini, New Delhi-110085, India
Phone: +91-9911215212, +91-9999744933
Email: brightskypublications@gmail.com

Peer Reviewed & Refereed

Advances in Sustainable Bioprospecting Methods

CHIEF EDITOR

DR. GANGA G.

VOLUME - 1

BRIGHT SKY PUBLICATIONS
NEW DELHI

Advances in Sustainable Bioprospecting Methods

Volume - 1

<u>Chief Editor</u>

Dr. Ganga G.

Assistant Professor, Department of Microbiology, Sree Ayyappa College, Eramallikkara, Chengannur, TDB-University of Kerala, Kerala, India

Bright Sky Publications
New Delhi

Published By: Bright Sky Publications

Bright Sky Publications
Office No 3, 1st Floor,
Pocket - H34, SEC-3,
Rohini, Delhi, 110085, India
Phone: +91-9911215212, +91-9999779515
Email: brightskypublications@gmail.com

Chief Editor: Dr. Ganga G.

Publication Year: 2022

Pages: 78

ISBN: 978-93-92804-22-9

Book DOI: https://doi.org/10.22271/bs.book.40

Price: ₹ 701/-

Contents

Chapter - 5
Polymer Degrading Microbial Association of Microplastics in Mangrove Ecosystem

Authors

Rohini P
Research Center and Post Graduate Department of Environmental Sciences, All Saints' College, Thiruvananthapuram, Kerala, India

Ayona Jayadev
Research Center and Post Graduate Department of Environmental Sciences, All Saints' College, Thiruvananthapuram, Kerala, India

Chapter - 5

Polymer Degrading Microbial Association of Microplastics in Mangrove Ecosystem

Rohini P and Ayona Jayadev

Abstract

Global increase of plastic production occurred since the 1950s including polymer with additives and filters. Nowadays plastics are integrated into our everyday lives. Uncontrolled use of plastics results in threats to the ocean, wildlife and even human health. Environmental degradation increases as the fragmentation of large plastics into microplastics lead to microplastic pollution. Mangroves a biodiversity-rich ecosystems. They also act as sinks for diverse contaminants. Microplastic pollution in the mangrove ecosystem causes a serious threat to diversity. Some microorganisms of the mangrove ecosystem can degrade polymer materials through their metabolic activities. Hence this chapter deals with polymer degrading microbial association in the mangrove ecosystem.

Keywords: Microplastics, mangrove ecosystem, microorganisms, biodegradation

Introduction

Plastics are synthetic polymers, made up of carbon, hydrogen, oxygen, silicon, chloride and nitrogen. The main sources of synthetic polymers are oil, coal and natural gas [1]. The wide accessibility of plastic is not only due to its thermal and mechanical properties but also due to its high stability and durability [2]. In the environment, the degradation process of plastics is very difficult due to their resilient properties. The physical-chemical and biochemical process that take place in the surroundings leads to the degradation of the macroplastic into smaller molecules called microplastics [3]. Microplastics are less than 5 mm in size [4]. The pollution due to microplastic badly effects on the ecosystem, food chain and even human wellbeing. Transport of microplastics occurs through stormwater overspill, wind movement and atmospheric discharges and waste from the water treatment plants. It may enter into the water resources such as brooks, rivers, mangrove ecosystems, seas and oceans [5]. The major impact of microplastic pollution is that can be taken by many marine organisms into their body by different processes [6]. Ingestion of microplastic leads to the transport of pollutants, monomers and additives of plastics to different levels of organisms which cause different consequences for their health. Microplastic has the capacity to accumulate in higher species, including the human body [7]. Microplastics can absorb hydrophobic pollutants like heavy metals and could carry them to the food chain [8]. Microplastic is a good carrier of various pollutants in water because of its properties like small size, large specific surface area and strong hydrophobicity [9]. Mangrove ecosystems are a diverse ecosystem given that foods and habitats for different terrestrial and ocean organisms [10]. Mangrove ecosystems also transports carbon and nutrients to the nearest coastal zone or ocean [11]. The presence of microplastic in the mangrove ecosystem was detected by various researchers. Surface current and waves are the main driving force for microplastic into mangrove ecosystem from the oceans [12]. Some of the polymers like polyethylene, polyurethane, etc. can be degraded by the microorganisms, they use it as an energy source for their growth [13]. The metabolic activities of microorganisms (bacteria, fungi and algae) could degrade polymer materials [14].

Plastics

Plastics are synthetic long-chain polymeric molecules [15]. In the manufacturing process of synthetic polymer, there are two main processes. The first process in the manufacturing of polymer is breaking the double bond to form a carbon- carbon single bond. The second process is the condensation process, elimination of water occurs between alcohol and carboxylic acid or amine to form polyamide or polyester. Polyurethane is also made by this general reaction [15]. Plastic is two types thermoplastic and thermoset plastic. Thermoplastics are made by monomers by breaking the double bond in the alkenes by additional polymerization. Through the heating and cooling process, the thermoplastics can be repeatedly softened and hardened. Thermoplastics form long carbon chains. Thermoset plastics are formed by condensation polymerization. They are obtained by irreversible hardening a soft solid or the liquid state [16]. Some of the thermoplastics are low density polyethylene (LLDPE), high-density polyethylene (HDPE), polyvinyl chloride (PVC), low polyethylene (LDPE), polypropylene (PP), polystyrene (PS), etc. The thermosetting plastics include polyester, polyethylene terephthalate (PET) and polyurethane (PUR) [17].

Microplastics

Microplastics are polymer chains of carbon and hydrogen atoms. Phthalates, Polybrominated diphenyl ethers (PBDEs) and tetrabromobisphenol A (TBBPA), are the other compound found in microplastics. Several of these chemical additives leach out of the plastics after entering the environment [18]. Microplastics are differing in their composition, shape and size, the toxicity of the material is also linked to their properties [19]. Depending on the monomer microplastics can be classified into polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC) and polyamides (PA) [20]. Degradation of plastic materials and the small plastics used in cleaning and cosmetics items are the main sources of microplastics [21]. The microplastics formed through the fragmentation of macroplastics are called secondary microplastics and small plastics used in the cleaning and other products are called primary microplastics. Primary microplastics are plastics with microscopic sizes. They are used in various industries like cosmetics [22]. Primary microplastics have also been developed for air-blasting applications [23]. Microplastics used as scrubbers in machine and engines to remove paint and rust [24].

Secondary microplastics are formed by the fragmentation of macroplastics through the different processes [25]. The Physical, chemical and biological processes are involved in the production of microplastics [26].

Microplastic pollution

Now a day’s microplastic pollution occurs in every even in remote area there is no human activity [27]. With increasing environmental microplastic concentrations there is a higher chance of negative impacts in the ecosystem. Microplastics have the capacity to alter the normal stability of the biota [28]. Ingested, microplastics can cause blockages in the digestive system and starvation in the organisms [29]. Plastics transport through the ecosystem also causes the introduction of non-native species and disease- causing organisms attached with it [30]. Plastic can enter the body of the organisms directly or indirectly. The presence of microplastics ranges from detritivores to predators [31]. Decomposition and nutrient cycling are negatively affected by microplastic pollution [32]. Ingestion of microplastics observed in the laboratory conditions in three terrestrial species, the earthworms *Lumbricus terrestris* [33] and *Eisenia Andrei* [34] and the nematode *Caenorhabditis elegans* [35].

Microplastics in the mangrove ecosystem

Mangrove forests are dynamic ecosystems. Mangroves are the regions between tropical and subtropical coastlines. The major advantage of mangroves is they minimize the impacts of natural disasters like hurricanes and tsunamis [36]. Due to the unique feature mangroves are a sink for the contaminants from the land and marine ecosystem [10]. Now a day's plastic Pollution is the main threat to the mangrove ecosystem [37]. Mangrove trees occupy the intertidal area. The special root system of mangroves emerged root system, pneumatophores and prop roots create a filter system that helps to decrease wave energy and turbulence and it also helps to trap the plastics [38]. Surface currents and waves are the main forces giving ocean- based plastic materials to the mangrove ecosystem [39]. Urbanization, industrial activities, tourism, sewage discharges, etc., are the anthropogenic activities that distribute microplastics into ocean, mangroves and other ecosystems [40]. Microplastic intake by organisms are a major impact on the mangrove ecosystem [41]. The main sources of microplastics into the mangrove ecosystem are sewage treatment plants, tourism, fishing activities, agricultural activities, shipping, etc [41]. The microplastic pollution in the sediments of the mangrove ecosystem is mainly due to the domestic sewage from the surrounding population [42]. The Sewage effluents entered into the mangroves through the river or drainage retained for a long period in the ecosystem. [43].

Microbial degradation of microplastics

Microorganisms are organisms that have the ability to adapt to almost every environment [44]. Nowadays it discover that microorganisms have the capacity to transform different compounds including plastics. They can metabolize substances even in the presence of pollutants. In some situation, microorganisms increase the degradation and biotransformation [45]. The usage of microbes in the degradation of microplastics can limit the negative impact on the environment [46]. Microbial degradation of plastics is a bioremediation method that makes a good solution for plastic pollution [47]. Bioprospecting of polymer degrading microbial association of microplastics is essential. Biodegradation of microplastics is a physicochemical and biological process [48]. In microplastic degradation, the microorganisms get a new ecosystem for colonization, growth and a get carbon source for energy through attaching to the surface of microplastics [49]. Various microorganisms are involved in the degradation process.

Bacteria

Bacteria are the main group of microorganisms. They are adapted to live everywhere on the earth. Bacteria can live in soil, water and the atmosphere. Many of the bacterial species are adapted to degrade the pollutants [50]. Now a day's some of the bacterial species are identified, that have the ability to degrade microplastics. A recent study on microplastic degradation has shown that two pure bacterial cultures are able to degrade PP Microplastics [51]. It is identified that Waxworms are capable of eating PE films [52]. Studies have shown that bacteria can change the outlook of microplastics and also can change the properties of microplastics. The activities of bacterias are isolated bacteria from the environment adhering colonizing and damaging the microplastics [49]. *Bacillus cereus* and *Bacillus gottheilii*, can degrade diverse types of microplastics [51]. The studies on the bacterial degradation of microplastics are progressing the number of bacteria selected for screening is still small, with typically isolated taxa including *Bacillus, Pseudomonas, Chelatococcus* and *Lysinibacillus fusiformis* [49].

Fungai

Fungi can involve in the biodegradation of microplastics. They can form a different chemical bonds in the microplastics like carbonyl, carboxyl and ester functional groups, these activities decrease their hydrophobicity. Fungi show different varieties they show the wide distribution and high reproductive ability [53]. *Penicillium simplicissimum* YK have the capacity to degrade PE [54]. Fungi can change the morphology and internal properties of microplastics [49]. In a study by Volke-Sepúlveda [55], thermo-oxidized at 80 °C, 15 days, lowdensity polyethylene (TO-LDPE) mineralization mediated by *Aspergillus niger* and *Penicillium pinophilum* was also evaluated. Fungi can also degrade hydrolyzable plastics [49].

Bacterial consortium

The bacterial consortium is very effective in microplastic degradation. A combination of different bacteria can eliminate the effect of toxic metabolites formed during bacterial microplastic degradation Compared with pure bacterial cultures. This is due to the toxic metabolite produced by one microorganism being used by the other one as a substrate [56]. In the study of Park and Kim, 2019, the degradation of PE microplastics by a mesophilic bacterial consortium was obtained. The two types of bacterial species *Bacillus sp*. and *Paenibacillus sp*. combained to form a consortium effective for the degradation of microplastics [58]. The earthworm *Lumbricus terrestris* has the capacity to degrade the microplastic LDPE. The earthworm decreases its particle size by decaying MPs in the gut of the worm [33]. Microbes isolated from the gut of the larvae of *Plodia interpunctella* (mealmoth) can partially biodegrade PE [52].

Biofilm

The colonization of the microorganism forms biofilms. Biofilm contains microorganisms, organic, inorganic particles, cell secretions, etc [59].

Biofilms can damage the structure and function of MPs in diverse ways. Some of the activities by the biofilms are it mask surface properties, improving degrading additives, secreting degrading enzymes and releasing metabolic byproducts [60]. MIcroplstics can immobilize the biofilms that are effective for the MPs degradation [61].

Degradation

There are many factors that affect the biodegradation of polymers. What is the type of organisms involve in the degradation process, characteristics of polymer and nature of pretreatment involved in the degradation. Mobility of polymer, groups arrangement in polymers, crystallinity, molecular weight, the type of functional groups present and substituents present in its structure and are the polymer characteristics that influence its degradation [62]. The first step involved in the degradation process is the breakdown in to small monomers. Small- sized monomers can only enter into the cellular membranes so there is a need for depolymerazation. If it is small monomers only can enter into cell for microbial degradation within the cell. In microbial degradation depolymerization of microplastics occurs by the microorganisms and enzymes, it involves hydrolysis. Hydrolysis is a very important reaction in the degradation of microorganisms. Microplastic hydrolysis is the opposite to oxidative degradation. In the hydrolysis process, the enzymes first bind into the microplastics and catalyze the hydrolytic cleavage. Microplastic degradation can be intracellular or extracellular. In the intracellular degradation hydrolysis of endogenous carbon occurs. In extracellular degradation use of exogenous carbon source occurs. Extracellular enzymes break down the microplastics into small monomers. The process is called depolymerization. After depolymerization mineralization occurs, the monomers are mineralized into CO_2, H_2O or CH_4 and these are further used as energy sources [63].

Conclusion

Mangroves create unique ecological environments. It is the most productive ecosystem. Due to the anthropogenic activities, mangrove ecosystems are in threat. Mangroves are such an ecosystem that favors the growth of lots of microorganisms like bacteria, fungi and microalgae, etc. Mangrove ecosystem is the main attraction for contaminants like microplastics (MPs). The conservation of mangrove ecosystem is essential for total equilibrium. Many studies show that microbial degradation of microplastic. Mangroves favors the microbial degradation of microplastics. It will result in toxic- free removal of MPs from the environment.

References

1. Strong AB. Plastics: materials and processing3rd ed. Pearson Prentice Hall, Upper Saddle River, NJ, 2006.
2. Rivard C, Moens L, Roberts K, Brigham J, Kelley S. Starch esters as biodegradable plastics: Effects of ester group chain length and degree of substitution on anaerobic biodegradation. Enzyme and Microbial Technology. 1995;17(9):848-852.
3. Scalenghe R. Resource or waste? A perspective of plastics degradation in soil with a focus on end-of-life options. Heliyon. 2018;4(12):e00-941.
4. Andrady AL. Microplastics in the marine environment. Marine pollution bulletin. 2011;62(8):1596-1605.
5. Mason SA, Garneau D, Sutton R, Chu Y, Ehmann K, Barnes J, *et al*. Microplastic pollution is widely detected in US municipal wastewater treatment plant effluent. Environmental pollution. 2016;218:1045-1054.
6. Lusher A. Microplastics in the Marine Environment: Distribution, Interactions and Effects. Mar. Anthropog Litter, 2015, 245-307.
7. Gong J, Kong T, Li Y, Li Q, Li Z, Zhang J. Biodegradation of microplastic derived from poly (ethylene terephthalate) with bacterial whole-cell biocatalysts. Polymers. 2018;10(12):13-26.
8. Cole M, Lindeque P, Fileman E, Halsband C, Goodhead R, Moger J, *et al*. Microplastic ingestion by zooplankton. Environ. Sci. Technol. 2013;47:6646-6655.
9. Ma J, Zhao J, Zhu Z, Li L, Yu F. Effect of microplastic size on the adsorption behavior and mechanism of triclosan on polyvinyl chloride. Environmental Pollution. 2019;254:113-104.
10. Bayen S. Occurrence, bioavailability and toxic effects of trace metals and organic contaminants in mangrove ecosystems: a review. Environ. Int. 2012;48:84-101. https:// doi.org/10.1016/j.envint.2012.07.008.
11. Dittmar T, Hertkorn N, Kattner G, Lara RJ. Mangroves, a major source of dissolved organic carbon to the oceans. Global biogeochemical cycles, 2006, 20(1).
12. Martin C, Almahasheer H, Duarte CM. Mangrove forests as traps for marine litter. Environmental Pollution. 2019;247:499-508.
13. Glass JE, Swift G. Agricultural and synthetic polymers, Biodegradation and Utilization, ACS Symposium Series 433. American Chemical Society, Washington, 1989.

14. Rutkowska M, Heimowska A, Krasowska K, Janik H. Biodegradability of polyethylene starch blends in Sea Water. Pol. J Environ. Stud. 2002;11:267-274.

15. Scott G. Polymers in modern life. In: Polymers and the Environment. The Royal Society of Chemistry, Cambridge, UK, 1999.

16. Alauddin M, Choudkury IA, Baradie MA, Hashmi MSJ. Plastics and their machining: a review. Materials Processing Technology. 1995;54:40-46.

17. Avella M, Bonadies E, Martuscelli E, Rimedio R. European current standardization for plastic packaging recoverable through composting and biodegradation. Polymer Testing. 2001;20:517-521.

18. https://www.britannica.com/technology/microplastic

19. McDevitt JP, Criddle CS, Morse M, Hale RC, Bott CB, Rochman CM. Addressing the issue of microplastics in the wake of the microbead-free waters act-a new standard can facilitate improved policy. Environ. Sci. Technol. 2017;51(12):6611-6617.

20. Li WC. The occurrence, fate and effects of microplastics in the marine environment. In Microplastic Contamination in Aquatic Environments Elsevier, 2018, 133-173.

21. Gregory MR, Andrady AL. Plastic in the marine environment. In: Andrady AL, editor. Plastics and the environment. New York (NY): John Wiley, 2003, 379-401.

22. Zitko V, Hanlon M. Another source of pollution by plastics: skin cleansers with plastic scrubbers. Marine Pollution Bulletin 22, 41-42. Cole M *et al*. Marine Pollution Bulletin 62 1991, 2011, 2588-25972597.

23. Derraik JGB. The pollution of the marine environment by plastic debris: are view. Marine Pollution Bulletin. 2002;44:842-852.

24. Gregory MR. Plastic ‘scrubbers’ in hand cleansers: a further (and minor) source for marine pollution identified. Marine Pollution Bulletin. 1996;32:867-871.

25. Ryan PG, Moore CJ, Van Franeker JA, Moloney CL. Monitoring the abundance of plastic debris in the marine environment. Philosophical Transactions of the Royal Society B, 2009.

26. Browne MA, Galloway T, Thompson R. Microplastic-an emerging contaminant of potential concern? Integrated Environmental Assessment and Management. 2007;3:559-56.

27. Horton AA, Barnes DK. Microplastic pollution in a rapidly changing world: implications for remote and vulnerable marine ecosystems. Science of the Total Environment. 2020;738:140-349.
28. Ziajahromi S, Neale PA, Leusch FD. Wastewater treatment plant effluent as a source of micro-plastics: review of the fate, chemical interactions and potential risks to aquatic organisms. Water Sci. Technol. 2016;74:2253-2269.
29. Cole M, Lindeque P, Fileman E, Halsband C, Galloway TS. The impact of polystyrene microplastics on feeding, function and fecundity in the marine copepod Calanus helgolandicus. Environmental science & technology. 2015;49(2):1130-1137.
30. Kirstein IV, Wichels A, Gullans E, Krohne G, Gerdts G. The plastisphere-uncovering tightly attached plastic “specific” microorganisms. PLoS One. 2019;14(4):e021-5859.
31. Courtene-Jones W, Quinn B, Ewins C, Gary SF, Narayanaswamy BE. Consistent microplastic ingestion by deep-sea invertebrates over the last four decades (1976-2015), a study from the North East Atlantic. Environmental Pollution. 2019;244:503-512.
32. Horton AA, Svendsen C, Williams RJ, Spurgeon DJ, Lahive E. Large microplastic particles in sediments of tributaries of the River Thames, UK-Abundance, sources and methods for effective quantification. Mar. Pollut. Bull. 2017;114:218-226.
33. Huerta Lwanga E, Gertsen H, Gooren H, Peters P, Salanki T, Van der Ploeg M, *et al*., Microplastics in the terrestrial ecosystem: implications for *Lumbricus terrestris* (Oligochaeta, Lumbricidae). Environ. Sci. Technol. 2016;50:2685-2691.
34. Rodriguez-Seijo A, Lourenco J, Rocha-Santos TA, Da Costa J, Duarte AC, Vala H, *et al*., Histopathological and molecular effects of microplastics in Eisenia andrei Bouché. Environ. Pollut. 2017;220:495-50.
35. Kiyama Y, Miyahara K, Ohshima Y. Active uptake of artificial particles in the nematode *Caenorhabditis elegans*. J Exp. Biol. 2012;215:1178-1183.
36. Kulkarni R, Deobagkar D, Zinjarde S. Metals in mangrove ecosystems and associated biota: a global perspective. Ecotoxicology and environmental safety. 2018;153:215-228.

37. Owuor MA, Icely J, Newton A. Community perceptions of the status and threats facing mangroves of Mida Creek, Kenya: implications for community based management. Ocean & Coastal Management. 2019;175:172-179.

38. Norris BK, Mullarney JC, Bryan KR, Henderson SM. The effect of pneumatophore density on turbulence: a field study in a Sonneratia-dominated mangrove forest, Vietnam. Continental Shelf Research. 2017;147:114-127.

39. Martin C, Corona E, Mahadik GA, Duarte CM. Adhesion to coral surface as a potential sink for marine microplastics. Environmental Pollution. 2019;255:113-281.

40. Tata T, Belabed BE, Bououdina M, Bellucci S. Occurrence and characterization of surface sediment microplastics and litter from North African coasts of Mediterranean Sea: Preliminary research and first evidence. Science of the total environment. 2020;713:136-664.

41. Deng H, He J, Feng D, Zhao Y, Sun W, Yu H, *et al*. Microplastics pollution in mangrove ecosystems: A critical review of current knowledge and future directions. Science of the Total Environment. 2021;753:142-041.

42. Wang T, Hu M, Song L, Yu J, Liu R, Wang S, *et al*. Coastal zone use influences the spatial distribution of microplastics in Hangzhou Bay, China. Environmental Pollution. 2020;266:115-137.

43. Ivar do Sul JA, Costa MF, Silva-Cavalcanti JS, Araújo MCB, Plastic debris retention and exportation by a mangrove forest patch. Mar. Pollut. Bull. 2014;78:252-257.

44. Aujoulat F, Roger F, Bourdier A, Lotthé A, Lamy B, Marchandin H, *et al*. From environment to man: genome evolution and adaptation of human opportunistic bacterial pathogens. Genes. 2012;3(2):191-232.

45. Luigi M, Gaetano DM, Vivia B, Angelina LG. Biodegradative potential and characterization of psychrotolerant polychlorinated biphenyldegrading marine bacteria isolated from a coastal station in the Terra Nova Bay (Ross Sea, Antarctica). Mar. Pollut. Bull. 2007;54:1754-1761.

46. Qi Y, Yang X, Pelaez AM, Lwanga EH, Beriot N, Gertsen H, *et al*. Macro-and micro-plastics in soil-plant system: effects of plastic mulch film residues on wheat (*Triticum aestivum*) growth. Science of the Total Environment. 2018;645:1048-1056.

47. Shah AA, Hasan F, Hameed A, Ahmed S. Biological degradation of plastics: a comprehensive review. Biotechnology advances. 2008;26(3):246-265.

48. Ammala A, Bateman S, Dean K, *et al*. An overview of degradable and biodegradable polyolefns. Progress in Polymer Science. 2011;36:1015-1049.

49. Yuan J, Ma J, Sun Y. Microbial degradation and other environmental aspects of microplastics/plastics. Science of the Total environment. 2020;715:136-968.

50. Bakir A, Rowland SJ, Thompson RC. Enhanced desorption of persistent organic pollutants from microplastics under simulated physiological conditions. Environ. Pollut. 2014;185:16-23.

51. Auta HS, Emenike CU, Jayanthi B, Fauziah SH. Growth kinetics and biodeterioration of polypropylene microplastics by *Bacillus* sp. and *Rhodococcus* sp. isolated from mangrove sediment. Mar. Pollut. Bull. 2018;127:15-21.

52. Yang J, Yang Y, Wu WM, Zhao J, Jiang L. Evidence of polyethylene biodegradation by bacterial strains from the guts of plastic-eating waxworms. Environ. Sci. Technol. 2014;48:13776-13784.

53. Chen Y, Stemple B, Kumar M, Wei N. Cell surface display fungal laccase as a renewable biocatalyst for degradation of persistent micropollutants bisphenol A and sulfamethoxazole. Environ. Sci. Technol. 2016;50:8799-8808.

54. Yamada-Onodera K, Mukumoto H, Katsuyaya Y, Saiganji A, Tani Y. Degradation of polyethylene by a fungus, Penicillium simplicissimum YK. Polym. Degrad. Stab. 2001;72:323-327.

55. Volke-Sepúlveda T, Saucedo-Castañeda G, Gutiérrez-Rojas M, Manzur A, Favela Torres E. Thermally treated low density polyethylene biodegradation by *Penicillium pinophilum* and Aspergillus niger. J Appl. Polym. Sci. 2002;83:305-314.

56. Singh L, Wahid ZA. Methods for enhancing bio-hydrogen production from biological process: a review. J Ind. Eng. Chem. 2015;21:70-80.

57. Park SY, Kim CG. Biodegradation of micro-polyethylene particles by bacterial colonization of a mixed microbial consortium isolated from a landfill site. Chemosphere. 2019;222:527-533.

58. Tsiota P, Karkanorachaki K, Syranidou E, Franchini M, Kalogerakis N. Microbial degradation of HDPE secondary microplastics: preliminary results. Proceedings of the International Conference on Microplastic Pollution in the Mediterranean Sea, 2018, 181-188.

59. Flemming HC. Relevance of Biofilms for the Biodeterioration of Surfaces of Polymeric Materials, 1997.

60. Miao L, Wang P, Hou J, Yao Y, Liu Z, Liu S, *et al*. Distinct community structure and microbial functions of biofilms colonizing microplastics. Science of the Total Environment. 2019;650:2395-2402.

61. Galloway TS, Cole M, Lewis C, Interactions of microplastic debris throughout the marine ecosystem. Nat. Ecol. 2017;1:116.

62. Artham T, Doble M. Biodegradation of Aliphatic and Aromatic Polycarbonates. Macromol Bio Sci. 2008 Jan;8(1):14-24.

63. Gu JD. Microbiological deterioration and degradation of synthetic polymeric materials: recent research advances. Int. Biodeterior. Biodegradation. 2003;52:69-91.