EVALUATION OF MICROPLASTIC POLLUTION IN THE INDIAN NORTHWEST COASTAL AREA: SEASONAL EFFECTS, CO-CONTAMINANTS, AND REMEDIATION

ANKITA C. MAURYA

DEPARTMENT OF CHEMISTRY

INDIAN INSTITUTE OF TECHNOLOGY DELHI

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by

ANKITA C. MAURYA

DEPARTMENT OF CHEMISTRY

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Dedicated to my parents and
my pet dog Boxer

CERTIFICATE

This is to certify that the thesis entitled "***Evaluation of microplastic pollution in the Indian northwest coastal area: seasonal effects, co-contaminants, and remediation***" being submitted by **MS. ANKITA CHANDRASHEKHER MAURYA** to the Indian Institute of Technology Delhi for the award of the degree of ***Doctor of Philosophy*** in Chemistry is a record of bonafide research work carried out by her. Ms. Ankita C. Maurya has worked under my guidance and supervision and has fulfilled the requirements for the thesis submission, which, to my knowledge, has reached the requisite standard.

The results contained in this dissertation have not been submitted in part or full to any other University or Institute for the award of any degree or diploma.

Date: 25th November 2024
Place: New Delhi

Dr. S. K. Khare
Professor of Biochemistry
Department of Chemistry
Indian Institute of Technology Delhi

Dr. Soumik Siddhanta
Assistant Professor of Biochemistry
Department of Chemistry
Indian Institute of Technology Delhi

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Ankita C. Maurya

New Delhi

Abstract

Microplastic (MP) pollution and associated co-contaminants pose a pervasive threat to ecosystems and human health. MPs, originating from various sources, accumulates in the environment, interacting with co-contaminants like persistent organic pollutants and heavy metals. These interactions aggravate ecological and health risks. Remediation strategies, including physical removal, chemical, and advanced filtration techniques, are being explored to mitigate MP pollution. However, the effectiveness of these methods remains variable, with challenges such as scale-up and cost. Simultaneously, research into the direct and indirect side effects of MPs on organisms and ecosystems underscores the urgent need for comprehensive management strategies to safeguard environmental integrity and public health.

The northwest coast of India, bordering the Arabian Sea, was selected to evaluate the MP abundance Despite increasing global awareness, seasonal dynamics of MP pollution in this region remain inadequately explored. This research represents the first comprehensive examination of how different seasons affect MP distribution, offering new insights into the temporal variations of MP contamination in the Indian northwest coastal area. Seashore sand samples were collected from Gorai Beach in different seasons. The collected MPs were dried, segregated, and evaluated based on their morphotype, size, color, and polymer type. A total of 1756.6, 7326.6, and 202 particles/Kg of sand were estimated in the pre-monsoon, monsoon and post-monsoon seasons, respectively. MPs types were further characterized by scanning electron microscopy (SEM) and atomic force microscopy (AFM), and MPs types were identified by Raman spectroscopy. Polypropylene (PP) type of plastic were found in dominance in the pre-monsoon and high-density polyethylene (HDPE) in monsoon and post-monsoon seasons. Along with low-

density polyethylene (LDPE), ethylvinyl acetate (EVA), polyvinyl acetate (PVA), polyvinyl chloride (PVC) was also observed. Maximum MPs was observed was pellet and blue colored type. Furthermore, the MP diversity was studied by employing the MP diversity integrated index, which suggests that most of the MP diversity was observed in the pre-monsoon period. The pollution load index employed an MP risk assessment, which presented a low degree of MP contamination. In contrast, the polymer hazard index was calculated as 21650.3 in post-monsoon, placing the area under the extreme danger category. It is evident from the data that the types of MP is more important than their number. Thus, MP morphotypes have importance in the adsorption of co-contaminants.

The persistent and growing issue of MP pollution poses significant environmental and health risks, highlighting a crucial research gap in effective remediation strategies. Despite increasing awareness, traditional treatment methods often fall short in addressing the diverse and evolving nature of MP contamination, particularly at the nanoscale. Therefore, the study investigates the remediation of isolated MPs using iron oxide (Fe_3O_4) nanoparticles. Overall, 62% to 87% of the initial MP content was observed to be removed after 12 h of treatment with Fe_3O_4 nanoparticles. Further, the toxicity is enhanced when MPs are further degraded into nano-sized plastic particles termed nanoplastics (NPs). NPs are emerging contaminants, and their remediation is a challenge, as they escape most advanced treatment methods owing to their small size and mobility. Considering this, the present study for the first time, explores the potential of enzyme-induced calcite precipitation (EICP) technique in the remediation of polystyrene nanoparticles (PSNPs). A 96% removal of PSNPs was achieved as a calcite-PSNPs composite (precipitated product) within 0.5 h from an aqueous solution (pH 7.0) supplemented with 2% (w/v) urea, 76 U urease, and 50 mM $CaCl_2$. Electrostatic attraction between PSNPs and Ca^{2+} along with entrapment during precipitation of calcite resulted in PSNPs removal.

Scanning electron microscopy of the composite showed entrapment of NPs in calcite crystals. The X-ray diffractogram of calcite indicated a transition from crystalline to amorphous phase after PSNPs incorporation. Fourier-transform infrared spectroscopy and thermogravimetric analysis too confirmed the inclusion of PSNPs and consequent alteration in the structure of the calcite matrix. Optimum removal was detected at pH 7.0, and with the increase in precursors viz $CaCl_2$, enzyme, and PSNP levels, the precipitation of PSNPs increased. Moreover, calcite-PSNP interaction was stable, as there was no significant polymer release upon ultra-sonication of the composites. Overall, the study provides a feasible and newer approach to sequester NPs from the aqueous system using the naturally occurring EICP method. These innovative techniques offer promising, eco-friendly solutions for mitigating plastic pollution, providing a significant step toward safer water systems and environmental protection.

Following the assessment and remediation of MPs, there is a grave concern in co-contaminant presence. Studying these co-contaminants is essential as they can significantly amplify the environmental and health risks posed by MPs. Since HDPE and PP collected MPs during the monsoon season from Gorai beach were abundant, they were further characterized as associated contaminants. Metal absorbance was detected using Scanning Electron Microscopy with Energy Dispersive X-ray spectroscopy (SEM-EDX) mapping and Inductively Coupled Plasma Mass Spectrometry (ICP-MS). The presence of organic compounds (OCs) was analyzed using GC-MS. The MPs were found to be associated with metals viz. Ca, Fe, Mg, Mn, Cr, Zn, Cd and Ni. Among which the HDPE pellet morphotype exhibits a higher range of metal adsorption. Cr, Mn and Cd were present at concentrations of 127, 257 and 7 (ppb), which are 2.5, 5.1 and 1.4 times higher than the guideline value proposed by WHO. A total of 61 different OCs were associated

with MPs. PP pellets were found to contain triglycerides, fatty aldehydes, and alkaloids, along with HOCs. The HDPE pellets contained the highest amounts of hydrophobic organic compounds. It also contains environmentally hazardous compounds such as phthalates, alcohol and isocyanate. Among morphotypes, pellet forms of MPs were found to adsorb more contaminants. These co-contaminants infiltrate the study area through sewage runoff and shoreline debris deposition, subsequently interacting with MPs. This study underscores the importance of understanding co-contaminants associated with MPs, as their interactions with heavy metals and organic compounds can significantly elevate environmental and health risks. Given the hazardous nature of these contaminants, it is urgent to develop and implement effective remediation strategies to mitigate their environmental impact.

Phthalates are commonly associated with MPs and are recognized as significant environmental pollutants due to their endocrine-disrupting properties. Terephthalic acid (TPA) are widely used plasticizer and monomer in the production of polyethylene terephthalate (PET) bottles, poses severe risks to both human health and the environment. Consequently, it is classified as a priority pollutant, necessitating stringent environmental control. Understanding and developing effective methods for TPA biodegradation are crucial for mitigating its environmental and health impacts. In the present work, the TPA biodegradation efficacy of the bacterium *Rhodococcus erythropolis* (MTCC 3951) was studied in mineral salt media with TPA as the sole carbon and energy source. *R. erythropolis* was observed to degrade 5 mM and 120 mM TPA within 10 h and 84 h of incubation, respectively. The degradation efficiency was further optimized by varying the culture conditions, and the following optimum conditions were obtained: inoculum size- 5% (v/v), temperature- 30 °C, agitation speed- 200 rpm, and pH- 8.0. The bacterium was found to use an ortho-cleavage pathway for TPA degradation determined based on

enzymatic and GC-MS studies. Moreover, during the degradation of TPA, the bacterium was observed to produce polyhydroxyalkanoate (PHA) - a biopolymer. Biodegradation of 120 mM TPA resulted in an accumulation of PHA. The PHA granules were visualized using fluorescence and transmission electron microscopy and were later characterized using FTIR spectroscopy. Furthermore, the robustness of the bacterium was demonstrated by its ability to degrade TPA in real industrial wastewater. Overall, *R. erythropolis* (MTCC 3951) hold the potential for controlling TPA pollution in the environment and vis-à-vis the production of PHA biopolymer.

The final section of the thesis addresses the need to enhance the stability and strength of *Rhodococcus erythropolis* MTCC 3951 during TPA degradation through effective cell immobilization. While immobilization techniques can significantly improve the efficiency and reusability of biocatalysts in bioremediation processes, there is a critical research gap in optimizing these techniques for bacterial stability and performance. Effective immobilization is crucial for maintaining bacterial activity over multiple degradation cycles, thereby enhancing the sustainability and cost-effectiveness of bioremediation strategies. In this study, various matrices were evaluated for immobilizing the bacterial cells, with Kappa carrageenan (KC) emerging as a promising material due to its ability to effectively entrap microbial cells. The concentration of KC was optimized to 4% for gelation with lesser cell leakage. However, conventional KC gel formation methods resulted in low mechanical strength, limiting stability and reusability. To overcome this, a cryofreezing technique was employed to enhance the mechanical strength of KC cryogels. These cryogels, formed through continuous freeze-thaw cycles, exhibited improved stability and structural integrity. The study evaluates the efficiency of KC cryogels in immobilizing *R. erythropolis* cells for TPA degradation through reusability of TPA biodegradation and characterization studies. Characterization

techniques, including Fourier-transform infrared spectroscopy (FTIR), thermal gravimetric analysis (TGA), and field emission scanning electron microscopy (FE-SEM) were employed to assess the structural properties of the KC cryogels. 5 freeze-thaw cycles were identified to be optimum for cryogel stability and exhibited maximum TPA degradation efficiency. The degradation cycle could be repeated up to 10 cycles. Thus, these studies highlight KC cryogels immobilized with *R. erythropolis* cells that are the potential for TPA remediation, aiding eco-friendly strategies to mitigate TPA pollution.

सार

माइक्रोप्लास्टिक (एमपी) प्रदूषण और संबंधित सह-प्रदूषक पारिस्थितिकी तंत्र और मानव स्वास्थ्य के लिए व्यापक खतरा पैदा करते हैं। विभिन्न स्रोतों से उत्पन्न होने वाले एमपी पर्यावरण में जमा हो जाते हैं, जो लगातार कार्बनिक प्रदूषकों और भारी धातुओं जैसे सह-प्रदूषकों के साथ परस्पर क्रिया करते हैं। ये परस्पर क्रियाएँ पारिस्थितिकी और स्वास्थ्य जोखिमों को बढ़ाती हैं। एमपी प्रदूषण को कम करने के लिए भौतिक निष्कासन, रासायनिक और उन्नत निस्पंदन तकनीकों सहित उपचार रणनीतियों की खोज की जा रही है। हालाँकि, इन विधियों की प्रभावशीलता परिवर्तनशील बनी हुई है, जिसमें स्केल-अप और लागत जैसी चुनौतियाँ हैं। साथ ही, जीवों और पारिस्थितिकी तंत्रों पर एमपी के प्रत्यक्ष और अप्रत्यक्ष दुष्प्रभावों पर शोध पर्यावरण अखंडता और सार्वजनिक स्वास्थ्य की सुरक्षा के लिए व्यापक प्रबंधन रणनीतियों की तत्काल आवश्यकता को रेखांकित करता है।

अरब सागर की सीमा से लगे भारत के उत्तर-पश्चिमी तट को एमपी की प्रचुरता का मूल्यांकन करने के लिए चुना गया था। एमपी वितरण पर विभिन्न मौसमों के प्रभावों पर जोर देने वाला यह पहला अध्ययन है। एकत्र किए गए एमपी को सुखाया गया, अलग किया गया और उनके आकार, रंग और बहुलक प्रकार के आधार पर मूल्यांकन किया गया। प्री-मानसून, मानसून और पोस्ट-मानसून सीज़न में क्रमशः कुल 1756.6, 7326.6 और 202 कण/किलोग्राम रेत का अनुमान लगाया गया, जिसमें प्री-मानसून में पॉलीप्रोपाइलीन (पीपी) प्रकार के प्लास्टिक और मानसून और पोस्ट-मानसून सीज़न में उच्च घनत्व वाले पॉलीथीन (एचडीपीई) की प्रधानता थी। कम घनत्व वाले पॉलीथीन (एलडीपीई) के साथ इसके अलावा, एमपी विविधता का अध्ययन एमपी विविधता एकीकृत सूचकांक का उपयोग करके किया गया था, जो बताता है कि अधिकांश एमपी विविधता मानसून-पूर्व अवधि में देखी गई थी। प्रदूषण भार सूचकांक ने एमपी जोखिम मूल्यांकन का उपयोग किया, जिसने एमपी संदूषण की कम डिग्री प्रस्तुत की। इसके विपरीत, पॉलिमर खतरा सूचकांक की गणना मानसून के बाद 21650.3 के रूप में की गई, जिसने क्षेत्र

को अत्यधिक खतरे की श्रेणी में रखा। डेटा से यह स्पष्ट है कि एमपी के प्रकार उनकी संख्या से अधिक महत्वपूर्ण हैं। इस प्रकार, एमपी मॉर्फोटाइप्स का सह-संदूषकों के अवशोषण में महत्व है।

एम.पी. के अत्यधिक प्रदूषण को देखते हुए, आयरन ऑक्साइड (Fe_3O_4) नैनोकणों का उपयोग करके इन पृथक एम.पी. को ठीक करने का प्रयास किया गया। कुल मिलाकर, Fe_3O_4 नैनोकणों के साथ 12 घंटे के उपचार के बाद प्रारंभिक एम.पी. सामग्री का 62% से 87% हटा दिया गया। इसके अलावा, विषाक्तता तब बढ़ जाती है जब एम.पी. को नैनो-आकार के प्लास्टिक कणों में विघटित किया जाता है जिन्हें नैनोप्लास्टिक (एन.पी.) कहा जाता है। एन.पी. उभरते हुए संदूषक हैं, और उनका उपचार एक चुनौती है, क्योंकि वे अपने छोटे आकार और गतिशीलता के कारण अधिकांश उन्नत उपचार विधियों से बच जाते हैं। इसे ध्यान में रखते हुए, वर्तमान अध्ययन पहली बार पॉलीस्टाइनिन नैनोकणों (PSNPs) के उपचार में एंजाइम-प्रेरित कैल्साइट अवक्षेपण (EICP) तकनीक की क्षमता का पता लगाता है। 2% (w/v) यूरिया, 76 यू यूरिएज और 50 mM CaCl2 से पूरक जलीय घोल (pH 7.0) से 0.5 घंटे के भीतर कैल्साइट-PSNPs कम्पोजिट (अवक्षेपित उत्पाद) के रूप में PSNPs का 96% निष्कासन प्राप्त किया गया। PSNPs और Ca^{2+} के बीच इलेक्ट्रोस्टैटिक आकर्षण और कैल्साइट के अवक्षेपण के दौरान फंसने के परिणामस्वरूप PSNPs का निष्कासन हुआ। कम्पोजिट की स्कैनिंग इलेक्ट्रॉन माइक्रोस्कोपी ने कैल्साइट क्रिस्टल में NPs के फंसने को दिखाया। कैल्साइट के एक्स-रे डिफ्रैक्टोग्राम ने PSNPs के समावेश के बाद क्रिस्टलीय से अनाकार अवस्था में संक्रमण का संकेत दिया। फूरियर-ट्रांसफॉर्म इंफ्रारेड स्पेक्ट्रोस्कोपी और थर्मोग्रैविमेट्रिक विश्लेषण ने भी PSNPs के समावेश और कैल्साइट मैट्रिक्स की संरचना में परिणामी परिवर्तन की पुष्टि की। pH 7.0 पर इष्टतम निष्कासन का पता चला, और पूर्ववर्ती जैसे CaCl2, एंजाइम और PSNP स्तरों में वृद्धि के साथ, PSNPs का अवक्षेपण बढ़ गया। इसके अलावा, कैल्साइट-पीएसएनपी इंटरैक्शन स्थिर था, क्योंकि कंपोजिट के अल्ट्रा-सोनिकेशन पर कोई महत्वपूर्ण पॉलिमर रिलीज नहीं हुआ था। कुल मिलाकर, यह अध्ययन प्राकृतिक रूप से होने वाली ईआईसीपी विधि

का उपयोग करके जलीय प्रणाली से एनपी को अलग करने के लिए एक व्यवहार्य और नया दृष्टिकोण प्रदान करता है।

एम.पी. के आकलन और उपचार के बाद, सह-प्रदूषक उपस्थिति में गंभीर चिंता है। चूंकि गोराई समुद्र तट से मानसून के मौसम के दौरान एचडीपीई और पीपी एकत्रित एम.पी. प्रचुर मात्रा में थे, इसलिए उन्हें संबद्ध प्रदूषक के रूप में आगे चिह्नित किया गया था। एसईएम-ईडीएक्स मैपिंग और आईसीपी-एमएस का उपयोग करके धातु अवशोषण का पता लगाया गया था। जीसी-एमएस का उपयोग करके कार्बनिक यौगिकों (ओसी) की उपस्थिति का विश्लेषण किया गया था। एम.पी. धातुओं के साथ संबद्ध पाए गए अर्थात सीए, फ़े, एमजी, एमएन, सीआर, जेडएन, सीडी और नी। जिनमें से एचडीपीई गोली मोर्फोटाइप धातु अवशोषण की एक उच्च श्रेणी प्रदर्शित करता है। सीआर, एमएन और सीडी 127, 257 और 7 (पीपीबी) की सांद्रता में मौजूद थे, पीपी छर्रों में एचओसी के साथ-साथ ट्राइग्लिसराइड्स, फैटी एल्डीहाइड और एल्कलॉइड पाए गए। एचडीपीई छर्रों में सबसे अधिक मात्रा में हाइड्रोफोबिक कार्बनिक यौगिक पाए गए। इसमें पर्यावरण के लिए खतरनाक यौगिक जैसे कि थैलेट्स, अल्कोहल और आइसोसाइनेट भी शामिल हैं। मॉर्फोटाइप्स में, एमपी के छर्रों के रूप में अधिक संदूषक पाए गए। ये सह-संदूषक सीवेज अपवाह और तटरेखा मलबे के जमाव के माध्यम से अध्ययन क्षेत्र में घुसपैठ करते हैं, बाद में एमपी के साथ बातचीत करते हैं।

थैलेट को एम.पी.एस. से जुड़ा पाया गया। एक गिरावट अध्ययन किया गया। इसलिए, टेरेफ्थैलिक एसिड (टीपीए) थैलेट में से एक है और एक एंडोक्राइन डिसरप्टर है जिसका व्यापक रूप से प्लास्टिसाइज़र के रूप में और पीईटी बोतलों के निर्माण में मोनोमर के रूप में उपयोग किया जाता है। हालांकि, मनुष्यों और पर्यावरण पर विभिन्न हानिकारक प्रभावों के कारण, इसे अब एक प्राथमिक प्रदूषक के रूप में पहचाना जाता है जिसका पर्यावरण स्तर नियंत्रित करने की आवश्यकता है। वर्तमान कार्य में, बैक्टीरिया

रोडोकॉकस एरिथ्रोपोलिस (एमटीसीसी 3951) की टीपीए बायोडिग्रेडेशन प्रभावकारिता का अध्ययन टीपीए को एकमात्र कार्बन और ऊर्जा स्रोत के रूप में खनिज नमक मीडिया में किया गया था। आर. एरिथ्रोपोलिस को क्रमशः 10 घंटे और 84 घंटे के ऊष्मायन के भीतर 5 मिमी और 120 मिमी टीपीए को विघटित करते हुए देखा गया। संस्कृति की स्थितियों में बदलाव करके विघटन दक्षता को और भी बेहतर बनाया गया, और निम्नलिखित इष्टतम स्थितियाँ प्राप्त की गईं: इनोकुलम का आकार- 5% (v/v), तापमान- 30 °C, हलचल की गति- 200 rpm, और pH- 8.0. जीवाणु को TPA विघटन के लिए ऑर्थो-क्लीवेज मार्ग का उपयोग करते हुए पाया गया, जो एंजाइमेटिक और GC-MS अध्ययनों के आधार पर निर्धारित किया गया था। इसके अलावा, TPA के विघटन के दौरान, जीवाणु को पॉलीहाइड्रॉक्सीएल्कानोएट (PHA) - एक बायोपॉलिमर का उत्पादन करते हुए देखा गया। 120 mM TPA के जैव विघटन के परिणामस्वरूप PHA का संचय हुआ। PHA कणिकाओं को प्रतिदीप्ति और संचरण इलेक्ट्रॉन माइक्रोस्कोपी का उपयोग करके देखा गया और बाद में FTIR स्पेक्ट्रोस्कोपी का उपयोग करके उनकी विशेषताएँ निर्धारित की गईं। इसके अलावा, जीवाणु की मजबूती वास्तविक औद्योगिक अपशिष्ट जल में TPA को विघटित करने की इसकी क्षमता से प्रदर्शित हुई। कुल मिलाकर, आर. एरिथ्रोपोलिस (एमटीसीसी 3951) में पर्यावरण में टीपीए प्रदूषण को नियंत्रित करने और पीएचए बायोपॉलिमर के उत्पादन की क्षमता है।

थीसिस के अंतिम भाग में TPA विघटन के दौरान आर. एरिथ्रोपोलिस MTCC 3951 की शक्ति/स्थिरता में वृद्धि को शामिल किया गया है। जीवाणु कोशिकाओं को विभिन्न मैट्रिक्स में स्थिर किया गया था, जिनमें से कप्पा कैरेजेनान (κC) सूक्ष्मजीव कोशिकाओं को प्रभावी ढंग से फंसाने की अपनी क्षमता के कारण एक आशाजनक स्थिरीकरण प्रदान करता है। कम सेल रिसाव के साथ जेलेशन के लिए κC की सांद्रता को 4% तक अनुकूलित किया गया था। हालांकि, पारंपरिक κC जेल निर्माण विधियों के परिणामस्वरूप कम यांत्रिक शक्ति, सीमित स्थिरता और पुन: प्रयोज्यता हुई। इसे दूर करने के लिए, κC क्रायोजेल की यांत्रिक शक्ति को बढ़ाने के लिए क्रायोफ्रीजिंग तकनीक का उपयोग किया गया था। निरंतर फ्रीज-थॉ

चक्रों के माध्यम से बनाए गए इन क्रायोजेल ने बेहतर स्थिरता और संरचनात्मक अखंडता का प्रदर्शन किया। अध्ययन TPA जैव अपघटन और लक्षण वर्णन अध्ययनों की पुन: प्रयोज्यता के माध्यम से R. एरिथ्रोपोलिस कोशिकाओं को TPA अपघटन के लिए स्थिर करने में KC क्रायोजेल की दक्षता का मूल्यांकन करता है। KC क्रायोजेल के संरचनात्मक गुणों का आकलन करने के लिए फूरियर-ट्रांसफॉर्म इंफ्रारेड स्पेक्ट्रोस्कोपी (FTIR), थर्मल ग्रेविमेट्रिक एनालिसिस (TGA), और फील्ड एमिशन स्कैनिंग इलेक्ट्रॉन माइक्रोस्कोपी (FE-SEM) सहित विशेषता तकनीकों का उपयोग किया गया। क्रायोजेल स्थिरता के लिए 5 फ्रीज-थॉ चक्रों को इष्टतम माना गया और अधिकतम TPA क्षरण दक्षता प्रदर्शित की गई। क्षरण चक्र को 10 चक्रों तक दोहराया जा सकता है। इस प्रकार, ये अध्ययन आर. एरिथ्रोपोलिस कोशिकाओं के साथ स्थिर किए गए KC क्रायोजेल को उजागर करते हैं जो TPA उपचार की क्षमता रखते हैं, जो TPA प्रदूषण को कम करने के लिए पर्यावरण-अनुकूल रणनीतियों में सहायता करते हैं।

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LIST OF ABBREVIATIONS

OECD	Organization for Economic Cooperation and Development
MP	Microplastic
NP	Nanoplastic
TPA	Terephthalic acid
CTPA	Crude terephthalic acid
KC	Kappa Carrageenan
PHA	Polyhydroxyalkanoate
PAE	Phthalic acid esters
UNEP	United Nations Environment Programme
UV	Ultraviolet
mm	millimeter
GI	Gastrointestinal
DNA	Deoxyribonucleic acid
FTIR	Fourier transform infrared spectroscopy
XRD	X-ray diffraction
HPLC	High performance liquid chromatography
SEM	Scanning electron microscopy
FESEM-EDX	Field emission scanning electron microscopy with energy dispersive X-ray
ICP-MS	Inductively coupled plasma-mass spectrometry
GC-MS	Gas chromatography-mass spectrometry
AFM	Atomic force microscopy
TGA	Thermogravimetric analysis
WPO	Wet peroxide oxidation

HDPE	High- density polyethylene
LDPE	Low- density polyethylene
PP	Polypropylene
PVC	Polyvinyl chloride
EVA	Ethyl vinyl acetate
PVA	Polyvinyl acetate
PI	Polyisoprene
PMMA	Polymethyl methacrylate
PET	Polyethylene terephthalate
PUR	Polyurethan
CP	Cellophane
AR	Alkyd resin
RA	Rayon
PBA	Polybutadiene acrylonitrile
CA	Cellulose acetate
EA	Ethyl acrylate
PTFE	Polytetrafluorethylene
ABS	Acrylonitrile butadiene styrene
PDMS	Polydimethylsiloxane
PAA	Polyacrylic acid
MPDII	Microplastic Diversity Integrated Index
DMP	MP diversity
DMPS	MP diversity of size
DMPC	MP diversity of color
DMPM	MP diversity of morphotype

DMPP	MP diversity of polymer ttype
PLI	Polymer Load Index
PHI	Polymer Hazard Index
CFi	Concentration factor
EICP	Enzyme-induced calcite precipitation
PS	Polystyrene
PSNPs	Polystyrene nanoplastics
POP	Persistent organic pollutants
OC	Organic compounds
HM	Heavy metals
OP	Organic pollutants
HOC	Hydrocarbon organic compound
PFAS	Polyfluoroalkyl substance
COD	Chemical Oxygen demad
CLSM	Confocal laser scanning microscopic
MATH	Microbial adhesion to hydrocarbon
P45O	Protocatechuate 4,5-dioxygenase
P34O	Protocatechuate 3,4-dioxygenase
ECF	Extracellular fraction
ICF	Intracellular fraction
MF	Membrane fraction
PCA	Protocatechuic acid
OD	Optical density
PVA	Polyvinyl alcohol