

**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

NOVEMBER- 2024

© Indian Institute of Technology Delhi (IITD), New Delhi, 2024

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

by

ANKITA C. MAURYA

DEPARTMENT OF CHEMISTRY

Submitted

in fulfilment of the requirements of the degree of

Doctor of Philosophy

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

NOVEMBER- 2024

*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

Acknowledgement

I'm deeply grateful for the incredible journey of my PhD in science. Each step opened new ways of exploring and understanding the world's complexity. Every challenge, from the relentless pursuit of knowledge to the moments of success, shaped me into a stronger scholar. Along the way, collaborations flourished, ideas evolved, and valuable lessons were learned. Reflecting on this journey fills me with joy—not just for earning a degree, but for embarking on a life-changing adventure I'll always cherish. My heart is full of gratitude and happiness.

First and foremost, I express my deepest gratitude and reverence to my Ph.D. supervisor, **Prof. S.K. Khare**. Your guidance has been essential to my academic growth; you have given me the confidence to deal with problems and the courage to take on big study projects. Your helpful comments, criticism, and support have changed my study and personality, making me stronger and more determined. Your guidance goes beyond academics; you taught me important lessons about life and motivated me to do my best in everything I do. I am so thankful for your kindness, hard work, and confidence in my abilities; you have helped me reach my goals and be successful. This success is a tribute to your guidance, and I will always be grateful to you for how much you helped me grow as a person and in academics.

I want to express my heartfelt gratitude to my co-supervisor, **Prof. Soumik Siddhanta**, for his trust in me and invaluable support during my PhD journey. Your encouragement and expertise have played a pivotal role in shaping my research and academic development. I deeply appreciate your dedication, insightful feedback, and collaborative approach, which have been instrumental in achieving my research goals. Thank you for your unwavering support and belief in my abilities.

I am indebted to my SRC members, **Prof. Tanmay Dutta, Prof. Shashank Deep** and **Prof. Amita Gupta**, for critically assessing my work and providing their kind support, guidance and useful inputs throughout my doctoral tenure. I am equally thankful to **Prof. Siddharth Pandey**, Head, Department of Chemistry, **Prof. Narayanan D. Kurur, Prof. Anil J. Elias, Prof. Ashok K. Ganguli, Prof. Ravi Shankar** and **Prof. A. Ramanan**, previous Heads, Department of Chemistry for providing all the necessary.

I will be forever indebted to **Dr. Amrik Bhattacharya**; I cannot thank you enough for your steadfast support throughout my journey. Under your guidance, I learned the essence of real research. Completing my Ph.D. would have been impossible without your invaluable assistance. Your patience in listening to my concerns and professional and personal expert guidance have been remarkable. In my professional career, I couldn't have asked for a better mentor than you. Your calm attitude is admirable, and I aspire to imitate it to achieve even greater heights. Thank you for revealing the best aspects of the scientific world to me.

Dr. Shivani Chaturvedi, the senior post-doc of our lab, is one of the most amazing human beings I have ever met. She has been like an aura of light in our lab and always motivated me with encouraging words whenever I felt despondent. And most importantly, she taught me the value of faith. I would like to thank post-doc scholar **Dr Razi Ahmad** for teaching me that writing papers is not difficult once you start liking them. My time in the Enzyme and Microbial Biochemistry Lab was always enriched by the presence of other post-doc scholars like **Dr. Kumar Pranaw**; I thank you for helping me out in biodegradation studies and making me think for critical analysis. Their immense knowledge, scientific input and encouragement helped me overcome many experimental trouble-shooting and scientific failures. Indeed, their scientific rigour and cooperation are sincerely appreciated.

I would like to thank my super seniors, **Dr. Anshu Gupta, Dr. Ruchi Gaur, Dr. Ram Karan** and **Dr. Chetna Joshi, Dr. Arvind Sinha, Dr. Rajeshwari Sinha** and **Dr. R. Hemamalini**, who left the lab long before I joined, but helped me with their guidance and kind support whenever needed. From the outset, **Dr. Sumit Kumar** has been mentor to me. I take this opportunity to thank him for sharing his immense scientific knowledge and for being someone who can solve all your problems. I am thankful to them for helping me plan experiments, develop essential biochemistry concepts, and inspire me with her indomitable spirit and perfect sincerity. **Dr. Ayesha Sadaf**, your knowledge, hard work and meticulous experimentation have motivated me. **Dr. Jasneet Grewal**, the precious things I learned from you are grit, determination, and patience. I thank my senior, **Dr. Shubhrima Ghosh**, for constantly making me believe that you can manage your hobbies and Ph.D. together. I am proud of your enthusiasm towards science and dance. **Dr. Neerja Yadav**, thank you for being there for me with your warmth, optimism, and creativity. I learned never to give up so easily from you. I am thankful to **Dr. Syeda Warisul Fatima** for infusing her infectious enthusiasm in the lab and **Dr. Shahenvaz Alam** for the light and hearty moments, along with sharing my love for food! You are my favourite senior, and I will always admire you.

Ms. Huma Fatima, I appreciate you keeping the lab in a harmonious and stress-free environment. **Ms. Sukriti Srivastava**, you are the best listener one can have. You both are my dearest friend that one can ask in a unknown place. **Ms Simran Kaur**, you are like a sister having the same mental disorder. I adore you a lot. And I thank **Mr. Nitin, Ms. Nikky Goel, Ms. Pooja, Ms. Deeksha Gopaliya, Ms. Saniya Zaidi, Mr. Bibhuti Das** for your support. And **Ms. Tanisha** for being an enthusiastic junior and jolly person. Each of you is like a spark, ready to light up the sky! The memories we created together will be cherished forever. I thank all M. Tech and M. Sc. Students: **Mr. Varun Vij** (who worked extensively

on the microplastic with me), **Ms. Bhoomika**, **Ms. Heena**, **Mr. Sarthak**, **Ms. Hinadri** for participating in all lab activities and creating a lively lab atmosphere.

I am delighted to acknowledge the care and support provided by my dear friends who bailed me out in difficult times and who made my stay at IITD worthwhile: **Mr. Vikas Dixit**, for helping me with my NMR studies and preparing me for every presentation. You are a good friend I can take away from IIT and **Ms Swati Singh**, my ex-roommate, and **Ms Rajat Joshi**. Talking to you both has always calmed me.

Lastly, my thesis would not have been completed without the help of my dear family members and relatives, who made all my efforts worth the struggle. Words are insufficient to express my gratitude to my loving parents for their unwavering support and belief in me. My mother, **Ms. Vandana Maurya**, is my silent support. In the course of my Ph.D, she would be forever concerned about my health and my sleep routines! She can never see me upset; I always liked her whenever she said, It is just a PhD, not a life; buckle up! I am indebted to my father, **Mr. Chandrashekher Maurya**, who constantly worried about my academic stability and mental health. Whenever he felt I was drowning in emotions and I may give up, he talked for hours, telling me all the motivating stories. I owe him for making me survive my 5 years in Ph.D. I can never forget my pet dog **Boxer**; he was the reason I got calmer watching his videos far away from home. He was like my little brother. He is the best thing that happened in my life. You will always be missed. Rest in peace my furry friend.

I thank my dearest childhood friends, **Mr. Bhagyesh Wagh**, **Mr. Virag Sane**, **Mr. Nikhil Vishwakarma** and **Ms. Roopali Sharma**. Thank you for constantly listening to my Ph.D. problems. I am very grateful for having friends like them and for making me laugh on calls during my worst breakdowns. Also, I am grateful to my brother, **Mr. Tushaar Maurya**, for

giving me the mental strength to fight the inner looser and for teaching me about faith. He was always the first to call whenever I felt clueless.

Lastly, I would like to thank a special person, **Mr. Vikash Mishra**. He supported me as a friend, parent, and competitor. He walked me through difficulties and brought the best out of me. He took care of me in sickness. I will be in great debt to you.

I will always be grateful to all those whose names might not have been mentioned here but have inspired me to complete this PhD journey.

A handwritten signature in dark ink, appearing to read 'Ankita', with a stylized flourish underneath.

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 CaCl_2 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 CaCl_2 , 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 गोरार्ड 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 अर्थात् 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 छरों में एचओसी के साथ-साथ ट्राइग्लिसराइड्स, फैटी एल्डीहाइड और एल्कलॉइड पाए गए। एचडीपीई छरों 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 छरों 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, टैरेफ्थैलिक 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

रोडोकोक्स 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 (KC) 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 KC की सांद्रता को 4% तक अनुकूलित किया गया था। हालांकि, पारंपरिक KC जेल निर्माण विधियों के परिणामस्वरूप कम यांत्रिक शक्ति, सीमित स्थिरता और पुनः प्रयोज्यता हुई। इसे दूर करने के लिए, KC 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 पुनः 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।

Table of Content

Certificate		i
Acknowledgment		ii
Abstract		vii
Table of Content		xviii
List of Figures		xxv
List of Tables		xxxiii
List of Abbreviations		xxxv
CHAPTER 1	INTRODUCTION	1-62
1.1	Rationale of the work	1
1.2	Objectives	6
1.3	Scope of the thesis	6
1.4	Review of literature	11
1.4.1	Plastic pollution	11
1.4.2	Plastic Waste Management	11
1.4.3	Macroplastics to microplastics	12
1.4.4	MP pollution in the environment	13
1.4.5	Harmful effects of MP in the aquatic system	14
1.4.6	Harmful effects on human life	15
1.4.7	Methods for MPs assessment	16
1.4.7.1	Sample collection and separation	17
	Water sample collection	17
	Sand and sediment sample collection	17
1.4.7.2	Pre-treatment of sand and sediment samples	18
1.4.7.3	Characterization of MPs	19
1.4.7.4	Methods used for quantification and detection of MP	20
1.4.8	Methods for MP removal from the environment	32
1.4.8.1	Adsorption method	32
1.4.8.2	Membrane filtration method	33
1.4.8.3	Chemical induced coagulation-flocculation-sedimentation (CFS) method	33

1.4.8.4	Bioremediation of MPs	34
1.4.9	Association of co-contaminants with MPs	36
1.4.9.1	Inorganic co-contaminants	37
1.4.9.2	Organic co-contaminants	38
1.4.10	Plasticizers: An organic co-contaminant	40
1.4.11	Phthalates: A class of plasticizers	41
1.4.12	Different methods to remediate phthalates	43
1.4.13	Terephthalic acid: An emerging organic pollutant	45
1.4.14	Applications of TPA	46
1.4.15	Analyzing global TPA demand	48
1.4.16	Harmful effects of TPA	48
1.4.17	Remediation of TPA	49
1.4.18	Pathway followed by microorganisms during TPA biodegradation	50
1.4.19	Biopolymer formation following TPA degradation	52
1.4.20	Immobilization of microbial cells	53
1.4.21	Innovation methods for immobilization of microbial cells	61
CHAPTER 2	EVALUATION OF MICROPLASTICS IN BEACH SEDIMENTS FROM THE NORTHWEST COAST OF INDIA: ABUNDANCE, DISTRIBUTION, POLYMER TYPE AND RISK ASSESSMENT	63-96
2.1	Introduction	63-66
2.2	Materials and methods	67-75
2.2.1	Area of study	67
2.2.2	Sampling and Separation of MPs from sand sample	68
2.2.3	Pre-treatment of sand samples containing MPs	69
2.2.4	Abundance of MPs	71
2.2.5	Identification of MP using Raman spectroscopy	71
2.2.6	Surface morphology analysis	72
2.2.6.1	Scanning Electron Microscopy (SEM) analysis	72
2.2.6.2	Atomic force microscopy (AFM) analysis	72
2.2.7	Microplastic diversity index and risk assessment	73
2.2.7.1	MPs Diversity Integrated Index (MPDII)	73

2.2.7.2	Pollution load index (PLI)	73
2.2.7.3	Polymer hazard index (PHI)	74
2.2.8	Quality control and contamination	74
2.2.9	Statistical analysis	74
2.3	Results and discussion	75-94
2.3.1	Microplastic distribution	75
2.3.2	Physical characteristics of MPs	78
2.3.2.1	Morphotypes	78
2.3.2.2	Size	80
2.3.2.3	Color	81
2.3.3	Chemical Characterization of MPs	83
2.3.4	Surface characterization of the MPs	88
2.3.4.1	SEM analysis	88
2.3.4.2	AFM analysis	89
2.3.5	Microplastic diversity index and risk assessment in different seasons	91
2.4.	Conclusion	94- 96
CHAPTER 3	REMEDIATION OF MICROPLASTICS AND NANOPLASTICS THROUGH MAGNETIC NANOPARTICLES AND ENZYMATIC PROCESS	97- 123
3.1	Introduction	97-100
3.2	Materials and Methods	101-105
3.2.1	Materials	101
3.2.2	Remediation of microplastics using magnetic iron nanoparticles	101
3.2.3	Remediation of PSNPs	101
3.2.4	NP quantification	102
3.2.5	Characterization of the precipitate after NP removal	103
3.2.5.1	Field emission scanning electron (FESEM) analysis	103
3.2.5.2	X-ray diffraction (XRD) analysis	103
3.2.5.3	Fourier transform infrared spectroscopy (FTIR) spectroscopy	104
3.2.5.4	Thermogravimetric analysis (TGA)	104

3.2.6.	Effect of different reaction conditions on the removal of PSNPs	104
3.2.6.1	Varying enzyme and CaCl ₂ levels	104
3.2.6.2	Varying PSNP concentrations and pH	105
3.2.7	Stability of calcite-PSNPs composite	105
3.2.8	Statistical analysis	105
3.3	Results and Discussion	106-122
3.3.1	Remediation of MPs	106
3.3.2	PSNPs standardization	108
3.3.3	PSNP removal using co-precipitation	108
3.3.4	Characterization of calcite/calcite-PSNPs composite	111
3.3.4.1	FESEM analysis	111
3.3.4.2	FTIR spectroscopy analysis	112
3.3.4.3	XRD analysis	113
3.3.4.4	TGA	115
3.3.5	Effect of varying reaction conditions on the removal of PSNPs	116
3.4	Conclusions	122-123
CHAPTER 4	ASSESSMENT OF MICROPLASTICS ASSOCIATED CO-CONTAMINANT: HEAVY METALS AND ORGANIC POLLUTANTS	124-155
4.1	Introduction	124-126
4.2	Materials and Methods	126- 128
4.2.1	MP collection	126
4.2.2	Metal estimation by field emission scanning electron microscopy with energy dispersive X-ray	126
4.2.3	Metal extraction and analysis by inductively coupled plasma mass spectrometry (ICP-MS)	126
4.2.4	Extraction of organic compounds (OCs)	127
4.2.5	OC analysis using gas chromatography mass spectroscopy (GC-MS)	127
4.3	Results and Discussion	128-154
4.3.1	FESEM-EDX analysis	128

4.3.2	Metals extracted from different morphotypes of MP	134
4.3.3	OCs extracted from different morphotypes of MP	138
4.3.4	Common OCs among morphotypes of MP	150
4.4	Conclusion	154-155
CHAPTER 5	BIODEGRADATION OF CO-CONTAMINANT TEREPHTHALIC ACID USING <i>RHODOCOCCLUS ERYTHROPOLIS</i> MTCC 3951 CELLS WITH SIMULTANEOUS PRODUCTION OF POLYHYDROXYALKANOATES	156- 188
5.1	Introduction	156-158
5.2	Materials and Methods	158-165
5.2.1	Materials	158
5.2.2	Microorganism	158
5.2.3	Media and culture conditions	158
5.2.4	Cell viability assay	159
5.2.5	Effect of varying culture conditions on TPA degradation	159
5.2.6	Effect of varying TPA concentrations on the degradation of TPA	160
5.2.7	Cell surface hydrophobicity of <i>R. erythropolis</i> MTCC 3951	160
5.2.8	Identification of the TPA biodegradation pathway	161
5.2.8.1	Enzymatic assay	161
5.2.8.2	Identification of intermediate metabolites using GC-MS	162
5.2.9	Quantification of TPA	162
5.2.10	TPA removal from industrial wastewater	163
5.2.11	Polyhydroxyalkanoate (PHA) production	163
5.2.12	Extraction of PHA	164
5.2.13	PHA characterization	165
5.2.13.1	Nile red staining	165
5.2.13.2	Confocal scanning laser microscopy (CLSM)	165
5.2.13.3	FTIR spectroscopy	165
5.3	Results and Discussion	166-187
5.3.1	Presence of TPA and quantification	166
5.3.2	Growth and TPA degradation	167

5.3.3	Optimization of culture conditions	169
5.3.4	Degradation of varying TPA concentrations under optimum conditions	173
5.3.5	Cell surface hydrophobicity of <i>R. erythropolis</i> MTCC 3951	175
5.3.6	Identification of the TPA biodegradation pathway	177
5.3.6.1	P34O enzyme activity	177
5.3.6.2	Identification of intermediate metabolites using GC-MS	180
5.3.7	TPA removal from industrial wastewater	182
5.3.8	PHA production and characterization	183
5.3.9	Characterization of PHA	184
5.3.9.1	Nile red assay	184
5.3.9.2	CLSM analysis	185
5.3.9.3	FTIR spectroscopy analysis	186
5.4	Conclusion	187-188
CHAPTER 6	DEVELOPMENT OF TEREPHTHALIC ACID BIOREMEDIATION PROCESS BY USING IMMOBILIZED R. ERYTHROPOIESIS CELLS	189-210
6.1	Introduction	189-191
6.2	Materials and Methods	191-196
6.2.1	Materials and microorganism	191
6.2.2	TPA degradation medium	191
6.2.3	Free cell preparation	191
6.2.4	Immobilization of bacterial cells	192
6.2.4.1	Calcium alginate entrapment	192
6.2.4.2	Polyvinyl alcohol (PVA) cryogels entrapment	192
6.2.4.3	Agar and agarose entrapment	193
6.2.4.4	Kappa carrageenan (KC) entrapment	193
6.2.5	KC cryobeads preparation	194
6.2.6	Reusability of the immobilized cells on KC cryobeads	194
6.2.7	CLSM for cell viability	194
6.2.8	Characterization of cryobeads	195
6.2.8.1	FTIR spectroscopy	195

6.2.8.2	TGA	195
6.2.8.3	FESEM analysis	195
6.2.9	Quantification of TPA using HPLC	196
6.2.10	Statistical study	196
6.3	Results and Discussion	196-210
6.3.1	Screening of suitable matrix for immobilization of <i>R. erythropolis</i> cells for TPA degradation	196
6.3.2	TPA degradation by free and immobilized cells	198
6.3.3	Effect of KC concentration on TPA degradation	199
6.3.4	Reusability of KC cryobeads	201
6.3.5	Cell viability	205
6.3.6	Structural characterization of KC cryobeads	206
6.3.6.1	FTIR spectroscopy analysis	206
6.3.6.2	TGA	207
6.3.6.3	FESEM analysis	208
6.4	Conclusions	210
SUMMARY OF THE THESIS		211
FUTURE PERSPECTIVES		215
APPENDIX		218
REFERENCES		220
LIST OF PUBLICATIONS		292
BIO-DATA		294

LIST OF FIGURES

Figure No.	Descriptions	Page No.
Fig 1.1	Graphical representation of the scope of work	5
Fig 1.2	Sources of primary and secondary MPs	13
Fig 1.3	The size difference between MPs and NPs	20
Fig 1.4	MPs Studies undertaken in coastal areas around the world	21
Fig 1.5	Secondary pollutants arising from plastic pollution	40
Fig 1.6	Classification of plasticizers and types of phthalates	42
Fig 1.7	Production of TPA from p-xylene	46
Fig 1.8	Applications of TPA	47
Fig 1.9	Catabolic pathway of TPA biodegradation	51
Fig 1.10	Different techniques used for immobilization of microbial cells	54
Fig 2.1	Map of the location and details of the sampling sites from where the sediments were collected. The sampling station represents the coast (a) Gorai Beach in Mumbai along the northwest coast of India, (b) the seashore sediment sampling collection area, and (c) a polluted location near the study area	67
Fig 2.2	Sample collection: (a) A quadrant of 50 cm transect along the broad shoreline of the Gorai beach; (b) sand sample collected in steel jar	68
Fig 2.3	Sample processing: (a) Dried sand sample at 65 °C in an oven, (b) Samples separation using sieves of mesh size 5 mm (top) to 0.3 mm (bottom)	69

Fig 2.4	Steps in isolation and separation of MPs from the collected environmental sample (a) Wet peroxidation method by using 30% H ₂ O ₂ with 0.05 M Fe (II) solution followed by; (b) density gradient separation by using NaCl; (c) Isolated MPs stored in glass Petri plates	70
Fig 2.5	Morphotype characteristics of MPs collected from northwest coast of India during pre-monsoon (May), monsoon (August) and post-monsoon (November)	79
Fig 2.6	Different sizes of MPs collected from northwest coast of India during pre-monsoon (May), monsoon (August) and post-monsoon (November)	80
Fig 2.7	Physical characteristics based on morphotype with colors of MPs collected in different seasons from the northwest coast of India	81
Fig 2.8	One-way ANOVA significance analysis of the morphotypes with color observed in different seasons	82
Fig 2.9	Chemical and structural characterization of collected MPs using Raman spectroscopy	84
Fig 2.10	Abundance of polymer types among the collected MPs in different seasons	85
Fig 2.11	Abundance of polymer types among the collected MPs in different seasons (a) polymer types and morphotypes, and (b) polymer types and their different sizes of MPs collected during different seasons	86, 87

Fig 2.12	Surface characterization of MPs using scanning electron microscopy (SEM). SEM micrographs of collected aged MP particles. An arrow showing (a, b, c) tearing and fragmentation on the film; (d, e, f) grooves and holes on the pellets; and (g, h, i) fractured edges on the threads	89
Fig 2.13	The surface characterization/topography of the collected MPs using AFM. The 3D and 2D AFM images of the film (a, b), pellet (c, d) and thread (e, f)	90
Fig 2.14	Diversity index (DI) and microplastic diversity integrated index (MPDII) of MPs collected from the northwest coast of the Arabian Sea in a different season	91
Fig 3.1	A graphical illustration of effective remediation of NPs using UCIP method	100
Fig 3.2	Removal of different MPs (a) HDPE and (b) PP by applying magnetic force	107
Fig 3.3	Absorbance spectra at varying wavelengths for PSNPs quantification	108
Fig 3.4	Absorbance spectra of PSNPs using urease-mediated calcite precipitation	110
Fig 3.5	Field emission scanning electron micrographs of (a) calcite (formed after urease-induced calcite precipitation- Mag 3KX, Scale 5 μ m) (b) PSNPs (Mag 50KX, Scale 500 nm) (c) & (d) calcite-PSNPs composites (formed after urease-induced calcite precipitation-Mag 50 KX, Scale 500 nm)	111

Fig 3.6	FTIR spectra of calcite and calcite-PSNPs composite formed using UICP	112
Fig 3.7	XRD spectra of (a) calcite and (b) calcite-PSNPs composites formed using UICP	114
Fig 3.8	TGA plots of (a) calcite and (b) calcite-PSNPs composites formed using UICP	115, 116
Fig 3.9	Effect of varying (a) urease and (b) CaCl_2 levels on removal PSNPs	117
Fig 3.10	Effect of (a) higher and (b) lower concentrations of PSNPs	118
Fig 3.11	Effect of initial pH on removal of PSNPs	119
Fig 4.1	(a) FESEM image of HDPE film, (b) element spectrum of HDPE film, (c-k).elemental mappings on the surface of HDPE film	129
Fig 4.2	(a) FESEM image of HDPE pellet, (b) element spectrum of HDPE pellet, (c-k).elemental mappings on the surface of the HDPE pellet	130
Fig 4.3	(a) FESEM image of HDPE thread, (b) element spectrum of HDPE thread, (c-k).elemental mappings on the surface of the HDPE thread	131
Fig 4.4	(a) FESEM image of PP film, (b) element spectrum of PP film, (c-k).elemental mappings on the surface of PP film	132
Fig 4.5	(a) FESEM image of PP pellet, (b) element spectrum of PP pellet, (c-k).elemental mappings on the surface of PP pellet	133
Fig 4.6	Concentration of selected metals extracted from MPs of monsoon season	135

Fig 4.7	Concentration of heavy metals extracted from MPs of monsoon season (a) heavy metals, and (b) heavy metals in trace amounts	136, 137
Fig 4.8	One-way ANOVA significance analysis of the metals associated with different polymer types	138
Fig 4.9	GC-MS analysis of OCs extracted from (a) control, (b) HDPE pellets, (c)HDPE threads, (d) PP films, and (e) PP pellets	139
Fig 4.10	(a-d) Relative concentrations of OCs extracted from different polymer and morphotype types of monsoon samples	148
Fig 4.11	One-way ANOVA significance analysis of the polymer types adsorbing different OCs	149
Fig 4.12	Venn diagram showing compounds present among different polymer types with respect to morphotypes	150
Fig 5.1	Schematic representation of PHA extraction from bacterial cells using NaOCl-chloroform extraction method	164
Fig 5.2	HPLC chromatogram of pure TPA	166
Fig 5.3	Growth and TPA degradation profile of <i>R. erythropolis</i> MTCC 3951	167
Fig 5.4	Confocal laser scanning microscopy (CLSM) of <i>R. erythropolis</i> MTCC 3951. (a) live cells of <i>R. erythropolis</i> MTCC 3951 from fresh mother culture and (b) dead cells after 16 h of growth in 5 mM TPA-containing mineral media (pH 7.0)	168
Fig 5.5 (a)	Effect of inoculum size on TPA degradation by <i>R. erythropolis</i> MTCC 3951	169
Fig 5.5 (b)	Effect of pH on TPA degradation by <i>R. erythropolis</i> MTCC 3951	170

Fig 5.5 (c)	Effect of temperature on TPA degradation by <i>R. erythropolis</i> MTCC 3951	171
Fig 5.5 (d)	Effect of agitation speed on TPA degradation by <i>R. erythropolis</i> MTCC 3951	172
Fig 5.6	Effect of varying TPA concentrations on degradation of TPA	173
Fig 5.7 (a)	Decrease in turbidity of the aqueous suspension of <i>R. erythropolis</i> caused by adhesion of cells to n-octane maintained in the interface region	175
Fig 5.7 (b)	Hydrophobicity of the <i>R. erythropolis</i> MTCC 3951 was determined by MATH test in reference to TPA degradation	176
Fig 5.8	Catabolic degradation pathway of TPA	178
Fig 5.9	Protocatechuate 3,4- dioxygenase activity in three fractions of cell	179
Fig 5.10	Time course changes in protocatechuate 3,4-dioxygenase activity during degradation of TPA	180
Fig 5.11	GC-MS spectrum of TPA degradation metabolite/product	181
Fig 5.12	Removal of TPA from industrial wastewater using <i>R. erythropolis</i> MTCC 3951	182
Fig 5.13	PHA production by <i>R. erythropolis</i> MTCC 3951 during TPA degradation. (a) TEM micrographs showing no accumulation of PHA granules (control: without TPA), (b) cells after 24h TPA incubation, (c) cells after complete degradation of 120 mM of TPA in 84h, and (d) a single cell TEM micrograph showing accumulations of PHA granules after 84h of incubation	183

Fig 5.14	Nile red-staining of PHA containing <i>R. erythropolis</i> MTCC 3951 cells	184
Fig 5.15	CLSM images showing the accumulation of PHA in <i>R. erythropolis</i> MTCC 3951. (a, c) Red fluorescence showing the accumulation of PHA and (b) differential interference contrast	185
Fig 5.16	FTIR spectra of purified PHA extracted from <i>R. erythropolis</i> MTCC 3951	186
Fig 6.1	TPA degradation by free and immobilized cells of <i>R. erythropolis</i> MTCC 3951 on different matrices (agar, agarose and KC)	198
Fig 6.2	(a) The extent of cell leakage (CFU/mL) from cryogel beads of varying KC concentrations (b) Effect of various concentrations of KC on TPA degradation	200
Fig 6.3	Reusability analysis of <i>R. erythropolis</i> immobilized on KC cryobeads of varying freeze-thaw cycle treatment, (a) Set 1: only KCl, no freeze-thaw treatment, (b) Set 2: KCl + 3 cycles of freeze-thaw treatment, (c) Set 3: KCl + 5 cycles of freeze-thaw treatment (d) Set 4: KCl + 7cycles of freeze-thaw treatment	201-203
Fig 6.4	CLSM image showing live and dead cells of immobilized <i>R. erythropolis</i> MTCC 3951 extracted from KC cryobeads obtained after cycle 10 of TPA degradation. (a) Live cells are stained with Syto 9 dye (scale bar, 5 μ m), and (b) dead cells are stained red with propidium iodide (scale bar, 10 μ m)	205

Fig 6.5	FTIR spectra of KC cryobeads treated with several freeze-thaw cycles (set 2- 4) and control (set 1) untreated	206
Fig 6.6	TGA curve of KC cryobeads treated with several freeze-thaw cycles (set 2-4) and control (set 1) untreated	207
Fig 6.7	FESEM microscopic images of KC cryobeads, (a, b) set 1: only KCl, no freeze-thaw, (c, d) set 2: KCl + with freeze-thaw incubation for 3 times, (e, f) set 3: KCl + freeze-thaw incubation for 5 times, (g, h) set 4: KCl + freeze-thaw incubation for 7 times	209
Fig A1	Calibration curve for quantification of PSNPs (260 nm)	218
Fig A2	Standard curve of TPA for the estimation of residual TPA	218
Fig A3	Standard curve of protocatechuic acid (PCA) for the estimation of P34O enzyme activity	219

LIST OF TABLES

Table No.	Descriptions	Page No.
Table 1.1	MP pollution in ocean seashore sand, sediments and water samples across the world	23
Table 1.2	Microorganisms used for biodegradation of different types of phthalates	43
Table 1.3	Various matrices used for immobilizing microbial cells for bioremediation of toxicants	55
Table 2.1	MP pollution in seashore sediments across the coast of India	76
Table 2.2	ANOVA test of MP different colors and morphotypes observed in different seasons	82
Table 2.3	Ecological risk assessment in sediment samples across the coast of India	93
Table 3.1	Effect of varying concentrations of Iron nanoparticles on the extent of MPs removal	106
Table 3.2	Various techniques for remediation of PSNPs and their remediation efficiency	121
Table 4.1	Metals present on the surface of MP samples based on their polymer and morphotypes	134
Table 4.2	One-way ANOVA test of metals extracted from different morphotypes of MPs	138
Table 4.3	OCs extracted from different polymer and morphotypes of MPs	140
Table 4.4	Hazardous OCs associated with HDPE pellets	147

Table 4.5	One-way ANOVA test of OCs extracted from of different polymers and morphotypes of MPs	149
Table 4.6	Common OCs extracted from different polymers and morphotypes of MPs	151
Table 5.1	Biodegradation of TPA using various bacterial species	174
Table 6.1	Screening of matrices for immobilization of <i>R. erythropolis</i> MTCC 3951 cells	197
Table 6.2	Estimation of bacterial cell leakage (CFU/mL) in various sets of freeze-thaw treatment of cryobeads after first cycle of TPA degradation	204

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
P450	Protocatechuate 4,5-dioxygenase
P340	Protocatechuate 3,4-dioxygenase
ECF	Extracellular fraction
ICF	Intracellular fraction
MF	Membrane fraction
PCA	Protocatechuic acid
OD	Optical density
PVA	Polyvinyl alcohol
