Comprehensive Guide to Monitoring Marine Litter and Analysing Microplastics in Aquatic Ecosystems

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UNIVERSITY OF KERALA, INDIA

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by
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> Plastic waste is now found in the most remote areas of the planet. It kills marine life and is doing major harm to communities that depend on fishing and tourism."

António Guterres

FOREWORD

The increasing prevalence of marine litter poses an immediate threat to the ecological balance of our oceans and the interconnected web of marine life that relies on them for sustenance. In the expansive realm of marine debris, microplastics, the tiny particles that frequently underestimated in our daily lives, have surreptitiously permeated our oceans, rivers, streams, and extending their presence throughout the entire aquatic food web. As we grapple with the consequences of our dependence on plastic, understanding and addressing the issue of microplastics is a critical step towards a sustainable future.

The Department of Aquatic Biology & Fisheries at the University of Kerala boasts a distinguished legacy of marine research, dating back to the establishment of the Marine Biology Laboratory in 1938. Today, with the support of the European Union-funded Ecomarine Project and the establishment of the 'Marine Monitoring Lab' (MML), the department has reached significant milestones, elevating its marine research endeavors to unprecedented heights.

In light of the pivotal role the MML plays in monitoring marine debris, this book emerges as a vital cornerstone in expanding our collective understanding. The "Comprehensive Guide to Monitoring Marine Litter and Analyzing Microplastics in Aquatic Ecosystems" is an exquisite compendium, thoughtfully composed to illuminate the path for researchers, students, and environmentalists embarking on the journey to study and document marine debris and microplastic contamination in our precious aquatic realms.

Encompassing five comprehensive chapters, the book navigates through the positive and negative impacts of plastics, the sources and consequences of marine litter, the realm of microplastics, their repercussions on both aquatic ecosystems and human well-being, as well as the methodologies for monitoring and interpreting the data generated.

Its eloquent and structured presentation transforms it into an indispensable tool for individuals seeking to enrich their comprehension of marine litter and microplastics. I extend appreciation to the authors for their unwavering commitment and meticulous effort in creating this groundbreaking piece of work. I firmly believe that this book will serve as a catalyst for change – a resource that inspires individuals to reconsider their plastic consumption and prompts policymakers to enact meaningful regulations. The battle against microplastics is not an isolated endeavour; it is a collective responsibility that requires collaboration across borders, disciplines, and generations.

SENIOR PROFESSOR **DR. S. BIJOY NANDAN**
VICE CHANCELLOR
KANNUR UNIVERSITY
Date: 13-02-2024

PREFACE

We are honoured to present the "Comprehensive Guide to Monitoring Marine Litter and Analysing Microplastics in Aquatic Ecosystems," a culmination of our expertise developed through conducting marine debris surveys and microplastics analyses at the University of Kerala. This guide begins by providing an overview of plastics and their profound impacts on aquatic ecosystems. Subsequent sections delve into the various types of microplastics and their effects on a wide range of organisms and ecosystems. The chapter on marine debris survey methods offers insights into diverse survey techniques, with specific activities detailed extensively. The following chapter explores microplastic analysis, outlining collection methods for each taxon. Forms used for surveys and a photo guide for identifying common items in marine debris accompany this comprehensive resource. Recognizing the urgency of addressing these critical issues, we firmly believe that disseminating knowledge is a crucial step toward sustainable solutions.

The "Comprehensive Guide to Monitoring Marine Litter and Analysing Microplastics in Aquatic Ecosystems" goes beyond being a mere compilation of facts; it serves as a call to action. Our goal is not only to equip researchers, students, and environmental enthusiasts with the tools and methodologies for effective monitoring but also to instil a sense of responsibility and a collective commitment to preserving the health of our oceans.

In the subsequent chapters, we explore the complexities of marine debris, microplastics, their sources, impacts on aquatic ecosystems, and the methodologies for monitoring and analysing them. We hope this guide becomes a valuable reference, fostering a deeper understanding of the challenges we face and encouraging innovative approaches to mitigate the impacts of plastic pollution in our oceans.

We extend our gratitude to Project ECO MARINE (Constructing a comprehensive mechanism to preserve marine ecosystems and life from the adverse impacts of climate change and plastic debris disposal), co-funded by the Erasmus + program of the European Union, for their support in bringing out this publication. Special thanks go to Dr. Georgios Georgiou, Professor in the Department of Mathematics and Statistics and Director of the Oceanography Center at the University of Cyprus, the coordinator of the ECOMARINE project.

Appreciation is also expressed to Vice Chancellor Prof. (Dr.) Mohanan Kunnummal, Prof. (Dr.) K. S. Anil Kumar, Registrar (also the LEAR of Ecomarine project), syndicate members Prof. (Dr.) Gopchandran K. G., Prof. (Dr.) P.M. Radhamany, Adv. Muralidharan Pillai G., Dr. Shijukhan J.S., and Dr. Mini Dejo Kappen (Director, Planning and Development) for their encouragement and support. Thanks are due to Dr JK Patterson Edward, Director, Suganthi Devadason Marine Research Institute (SDMRI), Tuticorin, for supporting the training on microplastics, and the SDMRI faculty Dr Jamila Patterson, Dr RL Lajju, and Dr K. Immaculate Jeyasantha for their support during training. Special acknowledgment goes to Dr. Andy Booth, Chief Scientist and Research Manager, Observation and Ecosystem group, Trondheim, Trøndelag, Norway, whose training provided valuable insights enriching the contents of the book. Participants of the training also contributed inputs to enhance the quality of this publication.

As we embark on this journey together through the guide, we extend an invitation for you to join us in the collective effort to safeguard our aquatic environments. May this comprehensive resource spark curiosity, fuel meaningful discussions, and inspire tangible actions towards a future where our oceans thrive, free from the burdens of marine litter and microplastics.

Biju Kumar and **Suvarna Devi**

CONTENTS

1. PLASTICS: A DOUBLE-EDGED SWORD

1.1. An Omnipresent Material

Plastic, an omnipresent material deeply integrated into our daily lives, possesses remarkable attributes such as durability, versatility, lightness, and strength. It plays a pivotal role in various sectors including health, transportation, construction, sports, cosmetics, and preservation, making it an indispensable part of our existence. The inception of plastic dates back to 1856 when Alexander Parkes of Birmingham, UK, created the first plastic, named Parkesine, though it was notably unstable. During the Second World War, plastic production surged, marking the beginning of its mass production.

Despite its widespread use, the global recycling of plastic stands at 9%, with 12% being incinerated, and a staggering 79% accumulating in landfills, eventually leaching into our oceans each year, causing significant harm to biodiversity, the economy, and human health (Geyer et al., 2017). The substantial increase in plastic generation is closely associated with the expanding global population (Lusher et al., 2017). The alarming reality is reflected in an estimated 12 million tons of plastic entering the oceans annually, contributing to the 142 million tons of oceanic garbage and constituting 41% of marine debris (Horton, 2022).

Plastic pollution has emerged as a pervasive global challenge, casting detrimental effects on ecosystems, especially the marine environment and its biodiversity. The severity of this issue has escalated on a global scale, with plastic production projected to reach 450 million metric tons globally, doubling by 2045 (Geyer, 2020). Astonishingly, only 1% of oceanic plastic is found at the surface, while the majority settles on the ocean floor (Woodall et al., 2014). Land-based sources contribute 80% of marine litter, with the remaining fraction originating from fishing activities (Young, 2017).

The influx of improperly managed plastic waste into oceans occurs through various pathways, including inland streams, wastewater discharge, wind, and tides (Jambeck et al., 2015). Annually, approximately 14 million tons of plastic infiltrate the ocean, constituting up to 80% of all marine debris from surface waters to deep-sea sediments (IUCN, 2021). Recent findings reveal an astounding 170 trillion plastic particles adrift in global oceans, even infiltrating the deepest trenches, making them the ultimate repository for plastic waste due to the lack of movement elsewhere.

This ubiquity underscores the far-reaching impact of plastic pollution across all facets of the ecosystem. Asia stands out as a significant contributor to plastic production and marine litter, releasing an average of 58 million tons into the environment. Plastic production involves various polymers, with commonly used ones including high-density polyethylene (HDPE), low-density polyethylene (LDPE), polyvinyl chloride (PVC), polystyrene (PS), polypropylene (PP), and polyethylene terephthalate (PET) (Li et al., 2016). The use of chemical additives like bisphenol-A, phthalate plasticizers, and flame retardants, intended to enhance plastic durability and flexibility, poses risks as they may leach into the surrounding environment or directly into animal tissues.

Globally, there has been a substantial surge in plastic production, reaching 348 million tons in 2017 (Plastics Europe, 2019). Projections indicate that by 2025, the release of plastic will amount to 250 million tons and is expected to quadruple by 2050. In his book "Deep Future: The next 10,000 years of life on earth," Stager (2011) coined our current era as "The plasticene" due to the omnipresence of plastics in every corner of the world, from the Arctic to mountain lakes, deep-sea trenches, and even in the air. This pervasive presence poses a significant threat to our ecosystem, prompting heightened attention to microplastics due to their ubiquity even in the most remote places on Earth and concerns about their physiological and behavioral impacts on aquatic organisms and other biota.

Oceans possess an assimilative capacity to tolerate a certain extent of natural and man-made disturbances. However, when plastic reaches a critical threshold, it causes severe negative impacts. Plastics on the seafloor act as a barrier, hindering the exchange of gases between the seafloor and water, leading to hypoxia in aquatic organisms. Additionally, they can increase sediment permeability and reduce its heat-absorbing capacity, potentially altering the lives of many aquatic organisms. Plastics also trap sunlight, warming the surface and diminishing light penetration into deeper areas. Despite being considered inert, plastics contain a mixture of monomers, oligomers, dyes, and other chemical additives, making them chemically stable. These additives, including plasticizers, flame retardants, antioxidants, colorants, and UV stabilizers, pose risks as they may leach into the surrounding environment or directly into animal tissues (Rochman et al., 2019).

India faces a significant challenge of plastic pollution due to its growing plastic consumption, with per capita usage increasing from 700 grams to 2.5 kg over the last five years. Despite a per-person consumption of only 13.6 kg, mismanagement of plastics leads to the release of 40% of the produced waste into the environment. Annually, India generates 1.5 million tonnes of plastic waste, ranking among the top 10 plastic-producing countries. Unfortunately, only around 9% of the 7 billion tonnes of plastic generated in India had been recycled by 2022 (Tiwari et al., 2023). Approximately 5.5 million metric tonnes of plastic waste are reprocessed/recycled each year, with 60% being handled by the registered sector, 20% by the informal sector, and the remaining 10% at the household level (CSE 2020). The uncollected/littered 40% contributes to water and land pollution and drain clogging (CSE 2019a). In an effort to combat the issue, single-use plastic was banned on August 15, 2019, though the government encourages recycling over a complete ban due to potential economic disruptions (CSE, 2020). Climate change further complicates the problem, altering precipitation, temperature, and stratification patterns in water bodies, influencing the distribution patterns of plastic litter and releasing more chemicals into the aquatic environment (Welden and Lusher, 2017).

Recently, pyroplastics have been discovered, which are melted plastics that have lost their shape and color due to erosion by wind and water, associated with plastic pollution. They resemble stones with very smooth corners made of polyethylene, polypropylene, along with chromium. Another widely used plastic material is wrap, a thin transparent film used in grocery shops and households to wrap food items. It is challenging to recycle and is made with PVDC, PVC, and polyethylene. While the PVC and PVDC in wraps, when added in permissible concentrations, do not harm our food, burning or ending up in landfills releases a toxic chemical called dioxin. When these wraps reach the aquatic environment, bacteria and metals adsorb to their surface, posing harm to aquatic organisms when consumed. Nylon constitutes 60% of microplastics from fishing ropes, nets, toothbrush bristles, and similar products.

1.2. Advantage of Plastics

Plastics offer various advantages as a material, contributing to their widespread use in numerous applications. Some key advantages include:

Versatility: Plastics are highly versatile materials that can be moulded into a wide range of shapes and sizes. This flexibility makes them suitable for diverse applications, from packaging materials to medical devices.

Lightweight: Plastics are generally lightweight, making them an ideal choice for applications where weight is a critical factor. This characteristic feature is particularly beneficial in transportation, reducing fuel consumption and transportation costs.

Durability: Many plastics are durable and resistant to wear, corrosion, and chemicals. This durability extends the lifespan of products made from plastics, contributing to their longevity in various applications.

Cost-Effective: The production of plastics is often cost-effective, and their widespread availability makes them economical for use in various industries. This cost efficiency has led to the development of a wide range of affordable products.

Healthcare products: Plastics goods are indispensable in healthcare where nobody can replace them due to its low cost and various designs ranging from catheters, blood bags, organ transplants to stents; as they can be moulded and aids safety of the patients, protecting them from infection.

Insulation Properties: Plastics exhibit good insulation properties, both electrically and thermally which makes them suitable for use in electrical components, construction materials, and packaging that requires thermal insulation.

Hygiene and Safety: Plastics can be easily sanitized, making them suitable for applications where hygiene is crucial, such as in medical equipment and food packaging. Additionally, they are non-reactive with many substances, ensuring the safety of the materials they come into contact with.

Innovation and Design Freedom: Plastics provide designers and manufacturers with significant freedom in terms of design and innovation. The ability to create complex shapes and structures allows for innovative product design across various industries.

Recyclability: While the environmental impact of plastics is a concern, many types of plastics can be recycled. Advances in recycling technologies aim to minimize the environmental footprint of plastic products and promote a more circular economy.

Water and Chemical Resistance: Plastics can be engineered to resist water and chemicals, making them suitable for applications in which exposure to these elements is common. This property is valuable in packaging, agriculture, and construction.

While plastics offer numerous advantages, it is essential to balance their benefits with environmental considerations, such as proper waste management, recycling efforts, and the development of sustainable alternatives to address the challenges associated with plastic pollution.

1.3. Disadvantages of Plastics

Plastics, while versatile and widely used, come with several disadvantages, particularly concerning their environmental impact. Some key disadvantages of plastic materials include:

Environmental Pollution: One of the most significant drawbacks of plastics is their contribution to environmental pollution. Improper disposal and lack of effective recycling lead to the accumulation of plastic waste in landfills, oceans, and other ecosystems, causing harm to wildlife and marine life.

Non-Biodegradability: Most plastics are non-biodegradable, meaning they do not break down naturally over time. This characteristic leads to long-term environmental persistence, exacerbating the problem of plastic pollution.

Microplastic Pollution: Over time, larger plastic items can break down into smaller particles known as microplastics which can contaminate soil, water, and even air, posing potential threats to ecosystems and human health.

Resource Depletion: The production of plastics relies on non-renewable fossil fuels, such as oil and natural gas. This dependence contributes to resource depletion and reinforces the environmental impact associated with extracting and processing these resources.

Toxic Additives: Some plastics incorporate additives, such as plasticizers, flame retardants, and colorants, which can be toxic. Over time, these additives may leach out of the plastic and contaminate the surrounding environment, potentially causing harm to living organisms.

Greenhouse Gas Emissions: The production of plastics generates greenhouse gas emissions, contributing to climate change. The extraction, refining, and manufacturing processes involved in plastic production release carbon dioxide and other pollutants into the atmosphere.

Energy Intensive Production: The production of plastics is often energy-intensive, requiring significant amounts of energy for processes such as polymerization and moulding. This contributes to the overall carbon footprint associated with plastic manufacturing.

Limited Recycling Rates: While some plastics are recyclable, the actual recycling rates are often low. Challenges such as complex sorting processes, contamination of recyclables, and limited infrastructure hinder effective recycling efforts.

Single-Use Culture: The prevalence of single-use plastics, such as packaging and disposable items, contributes to the rapid generation of plastic waste. This “throwaway” culture exacerbates environmental issues associated with plastic pollution.

Harm to Wildlife: Animals can mistake plastic items for food or become entangled in plastic debris, leading to injury or death. The ingestion of plastics by marine life, in particular, poses a threat to ecosystems and biodiversity.

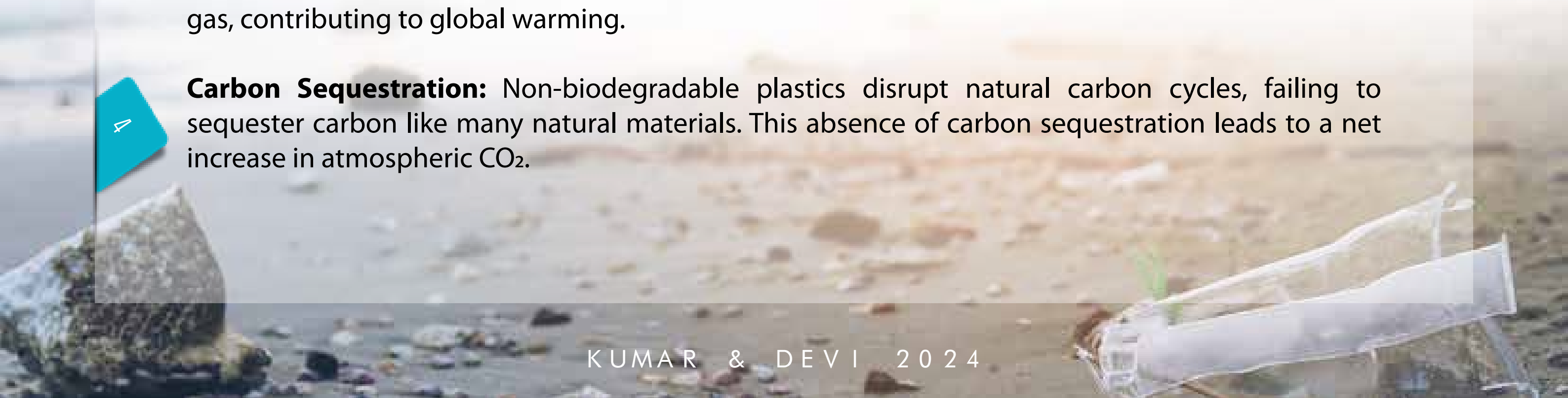
1.4. Climate Change and Plastics

A pervasive global concern, climate change manifests through observable phenomena such as rising sea levels, elevated temperatures, ocean acidification, and intensified extreme weather events, all expected to escalate (IPCC, 2021; Vicedo-Cabrera et al., 2021). Plastics, derived from fossil fuels and emitting greenhouse gases throughout their lifecycle, are integral to this climate change scenario (Zheng and Suh, 2019). This discussion delves into the multifaceted impacts of plastics on climate change.

Fossil Fuels and Production Process: Plastic production relies on petrochemicals, primarily sourced from fossil fuels. The extraction, refinement, and processing of these raw materials consume substantial energy and result in emissions, chiefly carbon dioxide (CO_2), a major climate change contributor.

Greenhouse Gas Emissions: Beyond CO_2 emissions from production, incinerating plastic waste releases CO_2 directly. Moreover, when plastics degrade, they emit methane, a potent greenhouse gas, contributing to global warming.

Carbon Sequestration: Non-biodegradable plastics disrupt natural carbon cycles, failing to sequester carbon like many natural materials. This absence of carbon sequestration leads to a net increase in atmospheric CO_2.



Disposal and Degradation: Plastics degrade slowly, releasing pollutants and greenhouse gases. Microplastics, during degradation, also emit greenhouse gases, exacerbating environmental concerns.

Impact on Ecosystems: Plastic pollution disrupts ecosystems in marine and natural habitats, indirectly influencing climate change by upsetting carbon sinks and potentially altering the carbon cycle.

Land Use Change: Plastic production and disposal necessitate land use changes, such as deforestation for oil extraction or landfill creation. These changes release carbon stored in vegetation and soils, contributing to climate change.

Carbon Footprint of Recycling and Waste Management: While recycling addresses environmental impact, it carries its own carbon footprint. Recycling processes, energy consumption, emissions, and transportation of recyclable materials contribute to the overall environmental cost.

Plastics are derived from naphtha, a substance based on crude oil, and ethane, sourced from liquid natural gas, augmented by various fossil fuel-based chemicals. Consequently, the manufacturing of plastic stands as a significant contributor to greenhouse gas emissions also. A recent investigation unearthed over 8,000 chemical additives utilized in plastic processing, with some exhibiting greenhouse gas potency a thousand times greater than carbon dioxide. Products like single-use packaging, plastic resins, foamed plastic insulation, bottles, and containers contribute substantially to global greenhouse gas emissions. The majority of plastic is not recyclable but can only be downgraded, often leading to incineration or utilization as fuel in waste-to-energy plants, colloquially termed chemical recycling. Despite the economic value of plastics being three to four times greater as fuel than as scrap, these recycling processes release elevated amounts of carbon dioxide into the atmosphere, intensifying the greenhouse effect.

It's crucial to note that the contribution of plastics to climate change varies based on type, production process, and disposal method. Plastics exert direct and indirect impacts due to their production, persistence, and disposal. Not all plastics are easily recyclable, complicating waste management. Mitigating the impact necessitates reducing plastic usage, transitioning to sustainable materials, and enhancing waste management and recycling practices. Innovations in material science, circular economy models, and policies promoting sustainable alternatives are crucial strategies explored by researchers and policymakers.

1.5. Chemicals in Plastics

When you come to think of the chemicals associated with plastics, during the production period, the polymerization reaction is usually incomplete which results in the production of several monomers like 1,3-butadiene, ethylene oxide and vinyl chloride, the phthalate plasticizers used and also those bound monomers from the plastics which is produced during biodegradation leaches into our environment and reach our water resources. Phthalates are also used as additives while making plastics to make it more flexible and prevent breakage (Oehlmann et al., 2009); hazardous chemicals in microplastics like bisphenol A (BPA) is also an additive used for softening acts as endocrine disruptors also reached the aquatic environment from packaging debris and untreated waste water (Sajiki and Yonekubo, 2003; Guerra et al., 2015). Presence of endocrine disruptors like nonylphenol was reported in Mackerals in Pacific Ocean.

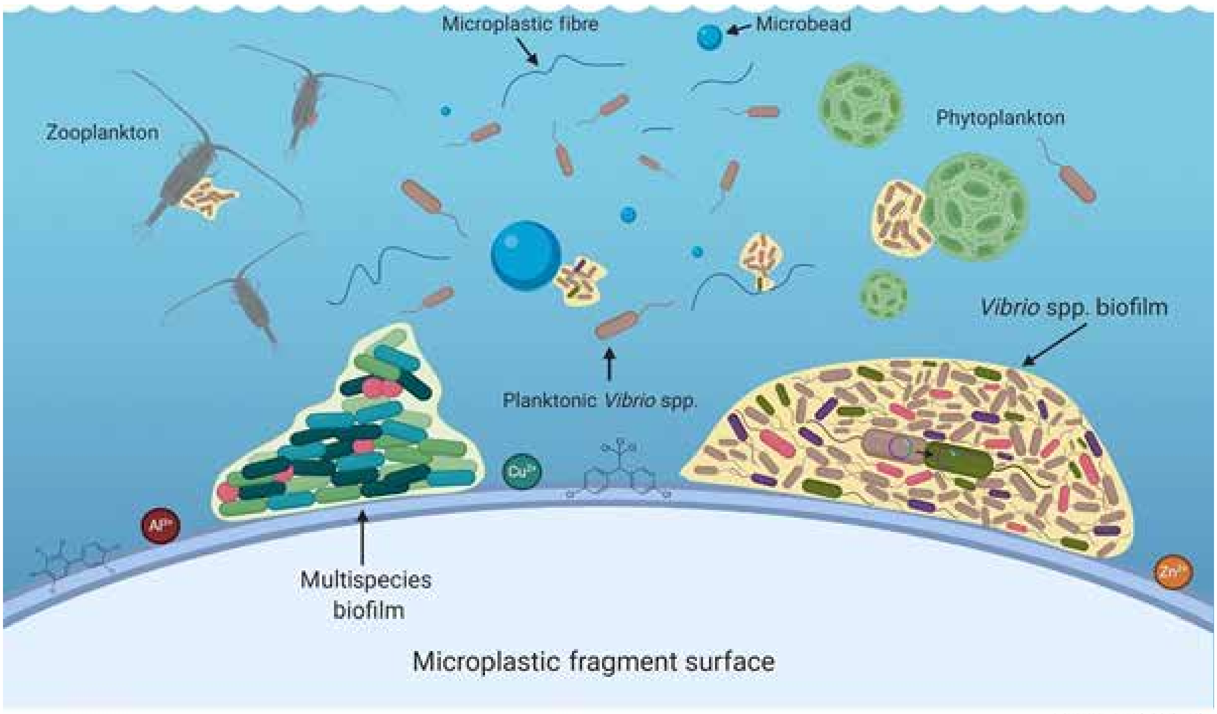
Other than this several other polymers which are used in manufacturing plastics as additives like colorants, fillers, stabilizers, and brominated flame retardants (BFR) are poisonous and are likely to increase the chemical and mechanical nature of the plastics. BFRs are more likely to leach out of the plastic particles. In addition to it, free floating pollutants like polychlorinated biphenyls

(PCBs), polycyclic aromatic hydrocarbons (PAHs), persistent organic pollutants (POP), DDT (Dichlorodiphenyltrichloroethane) and even heavy metals like cadmium, mercury and lead with long life span and can withstand environmental degradation may make way into the aquatic ecosystem also have a tendency to adsorb to the surface of microplastics. Leaching out of the chemicals in to the environment is dependent upon the polymer pore size and that of the noxious molecule.

1.6. Plastisphere

The plastisphere is a term used to describe the microbial communities that colonize plastic debris in the ocean. These communities can be found on all types of plastic, from large bottles and bags to tiny microplastics. It has been estimated that as many as 1.5 million plastic fragments are floating in every square kilometer of ocean. These marine microbes can be found on all types of plastic debris in the ocean, but they are especially adept at colonizing polyethylene, the most common type of plastic. The types of microbes found in the plastisphere vary depending on the location, the type of plastic, and the age of the debris.

Some common types of microbes found in the plastisphere include bacteria, algae, and fungi. The bacteria can take advantage of the organic matter that is often found on plastic debris, while the algae can use the sunlight to photosynthesize. The plastisphere is a relatively new ecosystem, and scientists are still learning about its impact on the environment. However, it is clear that the plastisphere can play a role in the spread of harmful bacteria and in the breakdown of plastic debris. Reports also indicate that the plastisphere can harbor ten times more bacteria than the surrounding seawater. This suggests that the plastisphere could be a source of harmful bacteria that could infect marine life.



Trends in Microbiology

Microbes interacting with the surface of plastics (Source: Bowley et al., 2021)

Various microbial communities, encompassing invasives, pathogens, and antibiotic-resistant genes (ARG), are recognized to inhabit microplastics (Oberbeckmann et al., 2018). These microbial colonies traverse long distances, reaching novel ecological niches, posing potential threats to human health and the environment. Microplastics not only facilitate the dissemination of bacteria, harmful algae, fungi, and invasive species to different regions but also play a significant role in their degradation. Studies indicate that microplastics have the capacity to adsorb antibiotics in aquatic environments, raising concerns about the potential spread of antibiotic-resistant microbes in aquatic ecosystems, impacting the global diversity and ecology of microbial communities.

The plastisphere, an intricate and relatively recent research area, is gaining rapid attention. Scientists are keen on understanding this ecosystem, as it could serve as a source of harmful bacteria affecting marine life. The pipes and surfaces that transport water foster the growth of both pathogenic and non-pathogenic microorganisms, forming biofilms. Microplastics, with their hydrophobic nonpolar surfaces, enhance microbial attachment, leading to biofilm formation. These microparticles, along with the chemicals they carry, can be transferred from prey to predators higher up in the food chain.

Exploring the plastisphere offers the potential for positive developments, such as aiding in the breakdown of plastic debris. It serves as a stark reminder of the environmental impact caused by human activities, presenting a challenge for scientists seeking to comprehend the effects of plastic pollution.

1.7. Plastics and Spread of Marine Species

Plastics play a significant role in the spread of marine species through various mechanisms, both intentional and unintentional. Here are some key ways in which plastics contribute to the dispersion of marine organisms:

Rafting and Floating Habitats: Plastics, particularly buoyant items like bottles, containers, and packaging materials, can serve as makeshift rafts or floating habitats. Marine organisms, such as algae, invertebrates, and even small fish, can attach themselves to these floating plastics, using them as a substrate to travel across oceans.

Invasive Species Transport: Plastics can transport invasive species to new regions. Organisms attached to or entangled in plastics may be carried far from their native habitats, introducing them to ecosystems where they can become invasive and disrupt local biodiversity.

Biofouling and Hitchhiking: The process of biofouling involves the accumulation of living organisms, including bacteria, algae, and small invertebrates, on the surfaces of submerged objects. Plastics, due to their smooth surfaces and durability, facilitate biofouling. Marine organisms can attach to plastics and hitch a ride across vast distances.

Microplastics as Transport Vectors: Microplastics, the tiny particles resulting from the breakdown of larger plastic items, can absorb and transport various contaminants and organisms. Marine species, including microbes, larvae, and small invertebrates, can adhere to microplastics and be transported over long distances before being released into new environments.

Floating Debris Accumulation: Plastics tend to accumulate in oceanic convergence zones (gyres), forming large floating debris patches. Marine organisms, especially those with a propensity for floating or clinging to surfaces, can become unintentionally associated with these plastic debris patches and be transported across oceanic expanses.

Transoceanic Transport : Plastics, especially larger items like buoys, fishing gear, and shipping containers, can drift across oceans and facilitate the transoceanic transport of marine species.

Artificial Marine Habitats: Sunken or submerged plastics can create artificial structures in the marine environment, providing shelter and habitat for various marine organisms.

Understanding the role of plastics in the spread of marine species is crucial for addressing the ecological and environmental implications associated with the unintentional human-mediated dispersal of organisms across oceans.

Spread of marine organisms through plastics

1.8. Single Use Plastics

Single-use plastics (SUPs) refer to plastic products that are designed to be used only once before they are discarded; these are ubiquitous in our daily lives, offer fleeting convenience but inflict lasting damage on the environment. SUPs, including plastic bags, straws, bottles, and utensils, are designed for momentary use and immediate disposal. Their affordability and perceived hygiene makes them attractive alternatives to reusable options.

However, this convenience comes at a steep price, one paid by future generations and the natural world. Every year, millions of tons of SUPs end up in landfills, oceans, and rivers, choking ecosystems and disrupting natural cycles. This plastic debris releases harmful chemicals into the environment, contaminating soil, water, and organisms.

Entanglement in plastic is a death sentence for countless marine animals. Sea turtles choke on plastic bags, birds build nests with deadly fragments, and fish ingest microplastics, unknowingly entering the food chain. Plastic debris disrupts habitats, smothers coral reefs, and alters delicate coastal ecosystems. Microplastics, reaching even the deepest oceans, are ingested by plankton, causing a ripple effect of contamination throughout the food web.

The disposable face masks (single use face masks) which are used by health care workers to prevent infectious diseases are also potential source of microplastics as they are made of polymers (Fadare and Okoffo, 2020). The outbreak of pandemic Covid 19 led to high demand of face masks using polymeric materials. Single use face masks are made of polymers such as polycarbonate, polyethylene, polystyrene, polypropelene, polyacrylonitrile, polyurethane and polyester consisting of three layers. The middle layer is most important which is made from micro and nano fibers where the melted polymer is made to pass through tiny nozzles with high-speed blowing gas. The face masks after using are thrown carelessly into both terrestrial as well as freshwater environment breakdown into microplastics under environmental conditions which could be new source of plastic pollution. One such report of face masks from ocean in Hong Kong (Bondaroff et al., 2020) stated that 1.56 billion masks are expected to enter our seas by 2020, resulting in between 4,680 and 6,240 metric tons of plastic pollution which might take up to 450 years to degrade, while also serving as a conduit of microplastic and severely impacting marine species and ecosystems, hence the presence of face masks in the ocean, is a serious concern and the populace should be sensitized to manage these litter while fighting against Covid-19.

Single use plastic items like bottle, shampoo bottle, bag, food packages, cutlery

2. PLASTICS IN AQUATIC ECOSYSTEMS

The prevalence of plastics in aquatic ecosystems is an escalating environmental issue with extensive consequences for marine life, ecosystems, and human welfare. Plastics have permeated rivers, lakes, oceans, and various water bodies, presenting a multitude of ecological challenges. Upon entering the aquatic environment, the destiny of microplastics is influenced by polymer density, dictating buoyancy, their location in the water, and their interactions with biota (Wright et al., 2013).

2.1. Rivers and Estuaries

Rivers and lakes, essential components of freshwater ecosystems, are confronting a silent intrusion – an influx of plastics and microplastics. These seemingly innocuous materials, once discarded, embark on a perilous journey, leaving a path of devastation in their wake. Rivers and streams serve as conduits for microplastics derived from terrestrial and agricultural runoff, atmospheric fallout, sewer outflows during heavy rains, and plastic manufacturing industries. This influx is transported into marine ecosystems via estuaries (Horton et al., 2017). Studies suggest that a significant portion of the estimated 8 million tons of plastic entering the oceans annually originates from rivers and lakes through littering, stormwater runoff, and wastewater discharges. However, not all plastic waste in rivers reaches the ocean. The majority of plastics found in both terrestrial and aquatic segments of river systems exhibit longevity, enduring for years, decades, or even centuries, with only a small fraction being released into the atmosphere. This perspective article introduces the concept of river systems functioning as plastic reservoirs. Plastics typically undergo mobilization, transport, and deposition within various river compartments (including riverbanks, floodplains, lakes, and estuaries) due to hydrometeorological factors such as wind, runoff, and river discharge. These plastic reservoirs primarily deplete during intense hydrological events, such as storms and floods. Research on retention mechanisms within different river compartments and their impact on the fate of accumulated plastics over varying timescales has been investigated by van Emmerik et al. (2022).

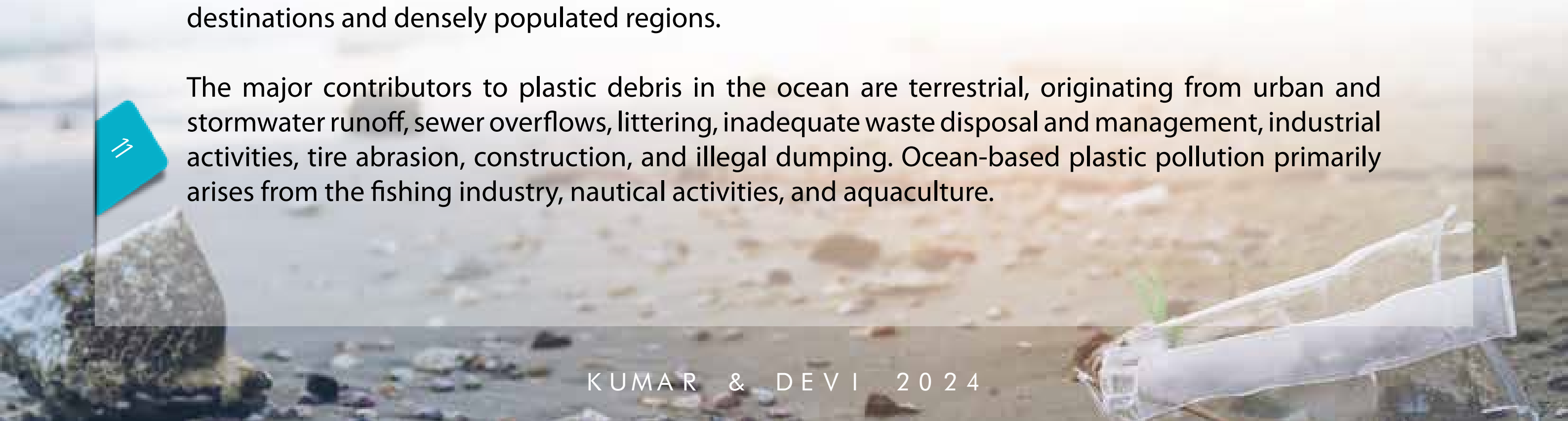
In natural or semi-natural habitats, Azevedo-Santos et al. (2021) observed evidence of plastic ingestion by 206 freshwater species, spanning a spectrum from invertebrates to mammals. Additionally, they documented consequences of synthetic polymers in freshwater environments, including the entanglement of diverse groups of creatures, such as birds. Estuaries serve as transitional ecosystems where microplastics flow from rivers into the marine ecosystem, providing habitat for estuarine and marine fauna, contributing food and shelter, and even operating as migration routes (Rodrigues et al., 2020).

2.2. Oceans

Since the 1970s, when plastics were first identified in the oceans (Carpenter et al., 1972), plastic pollution has evolved into a global environmental crisis. Quietly infiltrating our marine ecosystems, millions of tons of plastic debris wreak havoc each year, leaving behind a path of destruction.

On an annual basis, a minimum of 14 million tons of plastic makes its way into the ocean. Presently, plastic debris stands as the predominant type of litter in the ocean, constituting 80% of all marine debris discovered from surface waters to the depths of sea sediments (source: IUCN). This pervasive issue extends to shorelines on every continent, with higher concentrations near popular tourist destinations and densely populated regions.

The major contributors to plastic debris in the ocean are terrestrial, originating from urban and stormwater runoff, sewer overflows, littering, inadequate waste disposal and management, industrial activities, tire abrasion, construction, and illegal dumping. Ocean-based plastic pollution primarily arises from the fishing industry, nautical activities, and aquaculture.



Under the influence of solar UV radiation, wind, currents, and other natural factors, plastic undergoes degradation, breaking down into diminutive particles known as microplastics (particles smaller than 5 mm) or nanoplastics (particles smaller than 100 nm). The reduced size makes them easily ingestible by marine life, posing inadvertent threats to the ecosystem. In fact, only 1% of the visible plastic in the ocean comprises items like bottles and bags, while the remaining 99% consists of smaller plastic fragments found far below the surface. Plastic litter and microplastics can be transported within the ocean by currents, entering marine protected areas and even reaching the remote waters of the Southern Ocean.

The consequences of this plastic invasion are far-reaching and devastating. Plastic does not always float; it can also sink directly to the seafloor, become entangled in underwater avalanches, and mix with sediment flowing down submarine canyons. Plastic reaching the deep-sea can end up buried in seafloor sediments, particularly in areas that are hotspots for marine life. Entanglement in plastic debris is a frequent cause of death for various marine animals, from whales to dolphins. Sea turtles mistake plastic bags for food and choke on them. Birds inadvertently use deadly fragments in nest-building, dooming their young to a plastic tomb. Beyond the visible casualties, microplastics infiltrate the food chain, accumulating in the bodies of even the smallest creatures and eventually reaching our tables.

Microplastics in the deep-sea accumulate toxins on their surface. This toxin-covered plastic is then consumed by the smallest marine life, entering the food chain and being consumed by larger marine animals, ultimately posing a threat to human health.

Marine plastic pollution

- Over 400 million tons of plastic are produced every year for use in a wide variety of applications.
- At least 14 million tons of plastic end up in the ocean every year, and plastic makes up 80% of all marine debris found from surface waters to deep-sea sediments.
- Marine species ingest or are entangled by plastic debris, which causes severe injuries and death.
- Plastic pollution threatens food safety and quality, human health, coastal tourism, and contributes to climate change.
- There is an urgent need to explore new and existing legally binding agreements to address marine plastic pollution.

(Source: https://www.iucn.org/resources/issues-brief/marine-plastic-pollution)

2.3. River to the Oceans

Plastics and microplastics are transported from rivers to the sea through various mechanisms, including surface runoff during rainfall, watershed drainage, wind and aerial transport, tidal action in estuaries, and sediment transport. Studies indicate that an estimated 8 million tons of plastic enter the oceans annually, with a substantial portion making its way into rivers and lakes through littering, stormwater runoff, and wastewater discharges. Coastal erosion can expose and release buried plastics and microplastics from soil and sediments into the open sea. During heavy rainfall and flooding events, there is a rapid influx of microplastics from rivers and estuaries into the sea. Aquatic biota in rivers and estuaries can ingest microplastics, potentially being consumed by larger marine species and transported to the ocean. Coastal residents also contribute to plastic pollution through improper waste disposal and littering.

Wash-offs from industrial laundry and households produce microplastics that end up in the ocean (Magnuson et al., 2016). The loss rate of polymers from different fabric types varies, with the highest loss rate observed in polyester, acrylic, and polypropylene. Completely synthetic clothing tends to lose more polymers than cotton-synthetic blends, and woven polyester releases more microfibers than knit polyester. Therefore, synthetic industries are considered major sources of microplastics. Over time, garments release microfibers during wear and tear, with the release diminishing as the garment ages. The use of detergents during washing increases microfiber release, but the addition of conditioners may minimize this release. Top-loading washing machines release more microfibers than front loaders, contributing to microplastic release from domestic and industrial laundry.

Tires containing synthetic polymers erode during driving, releasing outer layers with synthetic polymers like styrene-butadiene rubber, natural rubber, various chemicals, accelerators, retarders, and additives. Truck tires (with 80% natural rubber) and car tires (with 15% natural rubber) are potential sources of microplastics. The quantity of microplastics released from tires depends on climate temperature, road surface, tire composition, driving style, and speed. Particles generated from tire abrasions and atmospheric fallout aggregate and can be carried by wind or washed into the ocean by rain.

Various processes, including the smoothing and shaping of building surfaces and machinery, release microplastics such as polystyrene, acrylic, polyester, polyallyl diglycol carbonate, urea, melamine, and phenol-formaldehyde into the environment. Paints and epoxies used for road painting leach into the soil and ultimately reach the ocean through weathering. Microbeads from cosmetic products used in hotels, hospitals, and households enter wastewater, contributing to ocean pollution. Urban areas produce city dust as a result of abrasion from various materials and buildings, adding to the production of microplastics. E-wastes also contribute significantly to the generation of microplastics.

2.4. Plastics in Fisheries and Aquaculture

To address the growing demand from an expanding global population, there has been a corresponding increase in the demand for fish. The growth of the aquaculture industry has prompted the integration of synthetic materials, employing various polymers within the culture system. While global estimates are not readily available, the entire fisheries sector significantly contributes to the dissemination of microplastics, with plastics playing a pivotal role from harvesting to packaging. Numerous fishing gears, including fish lines, trawls, dredges, floats, Fish Aggregating Devices (FADs), and antifouling paints on boats, are constructed from synthetic and semisynthetic polymers such as Polyethelene (PE), Polypropelene (PP), and Polyamide (PA) due to their cost-effectiveness, lightweight, and durability.

In aquaculture farms, plastics find applications in mesh screens, cages, buoys, drain pipes, containers, paddle wheel aerators, drums, pens, floats, plastic pond lining, and packaging for feed and seed.

Plastic polymers like PA, PP, and PE are commonly used in molluscan mariculture for ropes, mesh bags, crates, and spats. Plastic trays are even employed for cultivating oysters, with plastic mesh screens protecting them from predators. Crustaceans can be cultivated similarly, using cages and mesh screens, employing various plastic accessories. Fish processing units utilize plastic materials in insulated fish boxes, crates, conveyor belts, and packaging, leading to the gradual formation of microplastics over time. Fishmeal derived from larger fishes and shellfishes, which have ingested microplastics through trophic transfer, and fish feed prepared under unhygienic conditions pose a potential threat of microplastics to farmed fishes.

Abandoned, lost, or discarded fishing gears (ALDFG) contribute significantly to marine litter. Ghost fishing, resulting from illegal, unreported, and overcrowded fisheries, pollutes the food web with plastics. Norway is the sole country systematically addressing lost fishing gear. Synthetic nylon fishing nets degrade slowly, drifting through water over long distances and causing harm to sea birds, turtles, and dolphins. Efforts are being made by Korean and Norwegian institutions to develop biodegradable gill nets to minimize the risk of ghost fishing and reduce plastic pollution. Marine isopods contribute to microplastics by burrowing into expanded polystyrene floats on fishing docks and aquaculture equipment, releasing countless microplastics. Anticorrosive paints used on ship hulls and on-deck equipment, containing plastics like polyurethane (PU), vinyls, and epoxy, are directly released into the sea. Recreational fisheries, including scuba diving, hook and line fishing, and underwater diving, also contributes to microplastic pollution. Efforts toward responsible fisheries management and the development of biodegradable alternatives aim to mitigate the environmental impact of plastics in aquatic ecosystems.

2.5. Plastic Management and Sustainable Development Goals

Plastic management plays a crucial role in achieving several of the 17 Sustainable Development Goals (SDGs) outlined by the United Nations. The impact of plastic pollution on the aquatic environment, human health, and socioeconomic aspects underscores the need for comprehensive strategies to manage plastic waste sustainably.

SDG 3: Good Health and Well-Being: Plastic pollution has implications for human health, with microplastics entering food chains and water sources. Responsible plastic management helps mitigate health risks, aligning with the goal of ensuring good health and well-being.

SDG 6: Clean Water and Sanitation: Plastic waste contaminates water sources, affecting the availability of clean water. Effective plastic management initiatives, including reducing plastic usage and improving waste management systems, contribute to achieving clean water and sanitation goals.

SDG 7: Affordable and Clean Energy: The production of plastic relies on energy resources. Sustainable plastic management, including recycling and reduced production, contributes to more efficient resource use and aligns with the goal of affordable and clean energy.

SDG 9: Industry, Innovation, and Infrastructure: Sustainable plastic management requires innovation in materials, recycling technologies, and waste management infrastructure. Addressing plastic pollution fosters industry innovation and supports sustainable infrastructure development.

SDG 12: Responsible Consumption and Production: Plastic management contributes to responsible consumption and production by promoting the reduction, recycling, and proper disposal of plastic products. Initiatives such as circular economy models and sustainable packaging design aim to minimize the environmental footprint of plastic consumption.

SDG 13: Climate Action: Plastic production and disposal contribute to greenhouse gas emissions.

Sustainable plastic management, including recycling and reducing plastic production, aligns with efforts to address climate change and reduce overall environmental impact.

SDG 14: Life Below Water: Plastic pollution poses a significant threat to marine life and ecosystems. Effective plastic management, including measures to reduce plastic input into oceans, can help preserve marine biodiversity and ecosystems, aligning with the objectives of SDGs.

SDG 17: Partnerships for the Goals: Addressing plastic pollution requires collaborative efforts. Partnerships between governments, industries, NGOs, and communities are essential for implementing effective plastic management strategies and achieving the broader sustainable development goals.

Effective plastic management is intertwined with various Sustainable Development Goals, reflecting the interconnectedness of environmental, social, and economic aspects. Sustainable solutions to plastic pollution contribute to a more resilient and equitable future for people and the planet.

3. PLASTICS AND MICROPLASTICS

Microplastics are tiny particles of plastic that are less than 5 millimeters in size. They can be either intentionally manufactured at a microscopic scale or can result from the breakdown of larger plastic items. The presence of microplastics in the environment has raised concerns due to their widespread distribution and potential impacts on ecosystems and human health.

3.1. Types of Microplastics

There are two primary sources of microplastics:

3.1.1. Primary Microplastics

Microbeads: These are small plastic particles intentionally manufactured for use in various personal care and cosmetic products, such as exfoliating scrubs and toothpaste. Microbeads are designed to be small and abrasive, contributing to their microscopic size.

Microfibers: These are tiny synthetic fibers shed from clothing made of materials like polyester, nylon, and acrylic during washing and use. Microfibers are a major source of microplastics in aquatic environments.

3.1.2. Secondary Microplastics

Fragmentation: Larger plastic items, such as bottles, bags, and packaging materials, degrade over time due to exposure to sunlight (UV radiation), wind, and wave action. This process, known as fragmentation, breaks down the plastics into smaller and smaller particles, eventually forming microplastics.

Abrasion: Plastic particles on roads, in landfills, and in the environment can undergo mechanical abrasion, breaking into smaller fragments. This process is common with materials like car tires, which release microplastics into the environment as they wear down on the road.

The breakdown of plastics into microplastics occurs through physical, chemical, and biological processes. Over time, exposure to environmental conditions, such as sunlight, heat, and mechanical stress, causes the polymer chains in plastic to break apart. This fragmentation results in the formation of smaller plastic particles.

Additionally, biological processes, such as microbial degradation and biofouling, can contribute to the breakdown of plastics into microplastics. Microorganisms may colonize the surface of plastic items, leading to degradation and fragmentation.

Microplastics are considered as indicators of hydrophobic organic chemicals which help in bioaccumulating them in aquatic organisms is still a hot topic for debate. The general cut-off size for microplastics accepted frequently is less than 5mm in size. To unify the dimensions of microplastics we follow the suggested size definitions by Hartmann et al. (2019. Categories of microplastics include fiber, foam, pellets or nurdles, beads, film and fragments which come in a variety of shapes and colours (Rochman et al. 2019). Fibres are mainly contributed by the textile industry, laundry, upholstery, carpets; microbeads from cosmetics, toothpastes and foam arise from insulation and packaging material.

Table1. Classification of plastic litter

Terminology	Size range
Megaplastics	> 1m
Macroplastics	20 to 1 m
Mesoplastics	0.5 – ≤ 20 cm
Microplastics	1 µm – ≤5 mm
Nanoplastics	1nm – ≤ 1 µm

Tires made from rubber are also considered as synthetic plastics, when recycled are shredded into small fragments and its abrasion while used in vehicles can be the source for microplastics; hence the wear and tear of these tires result in microparticles to move from land to air and finally moved by wind and rain to water resources nearby and ultimately end up with oceans. Global percentage of contribution of microplastics minus city dust: textiles in India and South East Asia (15.9%), tires in North America (11 5%), tires in Europe and Central Asia (10.3%) and textiles in China (10.3%) (Boucher and Friot, 2017).

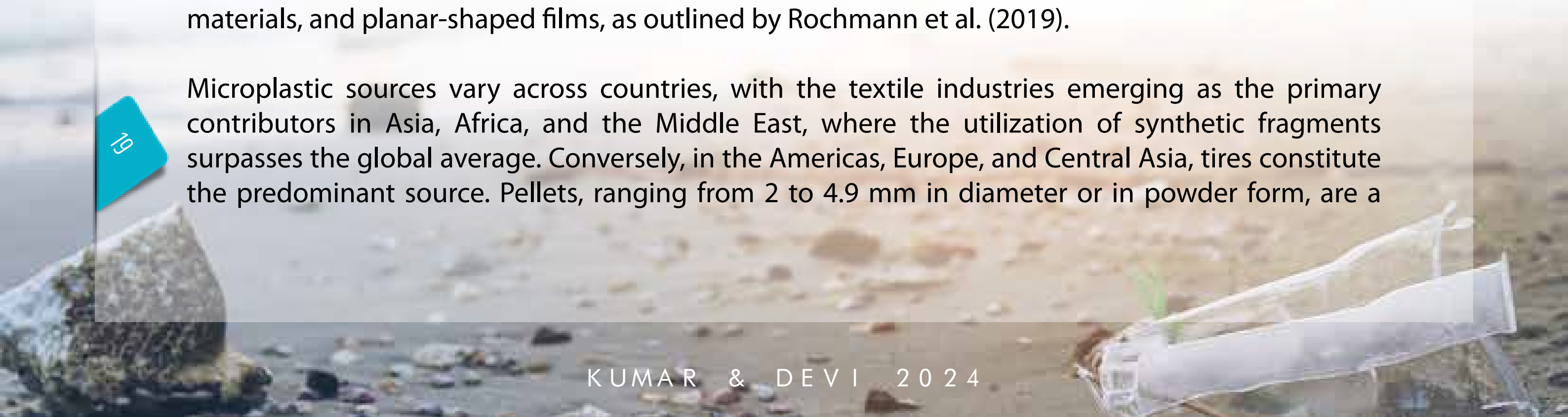
3.2. Source of Microplastics

Microplastics in our environment originate from both primary and secondary sources, as highlighted by Andrady (2011). Primary microplastics, produced for industrial purposes, are directly introduced into the environment. The majority of these particles result from unintentional losses during land-based activities, such as tire erosion and the laundering of synthetic textiles. Additionally, intentional losses occur through personal care products like body scrubbers, shower gels, creams, and cleansers, which contain abrasive scrubbers. Accidental losses during the transportation of raw materials from processing plants can also contribute to primary microplastics. These particles may ultimately reach the ocean through road runoff and wind action. Nurdles, the precursors of plastics, represent another source of primary microplastics entering the environment through careless transportation and handling, leading marine organisms to mistakenly consume them due to their shape and color.

On the other hand, secondary microplastics result from the fragmentation of plastic products through processes like photodegradation and weathering. They enter the aquatic ecosystem through various routes, including wastewater, agricultural runoff, abrasion, and UV light penetration. Ghost fishing, an example of secondary plastic, contributes significantly less to the microplastic problem compared to primary sources, as highlighted by Circular Ocean (2015) and Macfadyen et al. (2009). Further degradation to monomers is facilitated by microorganisms, although certain plastics, such as aromatic polyesters, may resist this process.

Microplastics exhibit diverse shapes and morphologies, ranging from long and thin fibers to plain and irregular forms. Categories include irregularly shaped fragments, fiber bundles, fibers from clothing and upholstery, beads from personal care products, pellets from feedstock, foam from insulation materials, and planar-shaped films, as outlined by Rochmann et al. (2019).

Microplastic sources vary across countries, with the textile industries emerging as the primary contributors in Asia, Africa, and the Middle East, where the utilization of synthetic fragments surpasses the global average. Conversely, in the Americas, Europe, and Central Asia, tires constitute the predominant source. Pellets, ranging from 2 to 4.9 mm in diameter or in powder form, are a



noteworthy form of microplastics that escape into the environment during manufacturing, processing, or transportation of products.

The pathways through which microplastics infiltrate freshwater include drainage systems, effluent discharge, wind dispersal, and occasional intentional dumping. In marine environments, fishing activities, tourism, aquaculture, and the discharge of industrial wastewater during packaging contribute to the presence of microplastics. Studies on microplastics in aquatic ecosystems have demonstrated significant variations in their load before and after rain and storms, highlighting these weather events as substantial contributors.

Microplastics can be categorized as sinking or floating types. Floating types include polyethylene (from plastic bags), expanded polypropylene (caps, ropes), and polystyrene (floats, cups). Sinking types encompass polystyrene (containers), polyvinyl chloride (film, pipes), polyamide (ropes, gear), polyethylene terephthalate (bottles), polyester resin and fibers (textiles), polyurethane (pillows, mattresses), and cellulose acetate (found in cigarette filters). Fragments are characterized by jagged particles, films by thin and flimsy material, foams by spongy particles resulting from the degradation of large plastic debris, and pellets by smooth, rounded particles derived from microbeads in consumer products or plastic precursors. Fibers, whether natural (cotton, wool) or synthetic (polyester), are thin fibrous particles originating from textiles, cigarette filters, and fishing gears.

3.3. Nanoplastics

Nanoplastic particles (NP) exhibit sizes ranging from 0.001 µm to 0.1 µm, surpassing the harmful impact of microplastics. They result from the further degradation of microplastics and enter the food web through small organisms such as algae, diatoms, bacteria, and other filter-feeding aquatic organisms. Due to their expansive surface area, NP have the ability to accumulate more toxic materials. Despite their increased potential for biological impact on biota, our understanding of nanoplastics remains limited.

Polymeric nanoparticles, including nanospheres and nanocapsules, are utilized in various medical applications and are considered safe as they are biodegradable and do not persist in the environment for extended periods. Detecting nanoplastics involves the use of techniques such as UV-VIS spectrometry, electron microscopy, field flow fractionation (FFF), and dynamic light scattering (DLS). Nanoparticles can induce cellular dysfunction and traverse lipid membranes. Study by Zhu et al (2021) has shown that nanopolystyrene particles can traverse the aquatic food chain, moving from green algae to water fleas and eventually to carp and other fishes, impacting lipid metabolism and inducing erratic behaviour. This underscores the potential ecological consequences of nanoplastic exposure in aquatic ecosystems.

3.4. Major Impacts of Microplastics

The increasing prevalence and accumulation of microplastics have become a cause for concern due to their persistent nature and their ability to attract organic pollutants (Karbalaei, 2018). Recognizing plastic debris in the ocean as an emerging environmental issue, the United Nations Environment Programme (UNEP) highlighted the significance of addressing this problem in 2011. Microplastics, along with the associated chemicals, pose significant threats to both humans and other organisms (Brown et al., 2001; Browne et al., 2013; GESAMP, 2016; Rochman et al., 2015). Notably, the textile industry releases an average of approximately 1900 microplastic fibers from synthetic materials during a single washing cycle (Brown et al., 2011). As global efforts to recycle plastic continue, it becomes crucial to develop mitigation strategies targeting the life expectancy of microplastics.

Microplastics are found ubiquitously across various environments, including freshwater (Eerkes-Medrano et al., 2015), marine ecosystems (Andrady, 2011), terrestrial realms (soil and sludge) (Zubris et al., 2005), and even in dust and air (Dris et al., 2017). Humans are exposed to microplastics through air, water, and food (Wright, 2017). Surprisingly, even sea salt has been found to be contaminated with microplastics like nylon, polyethylene, and polypropylene (Selvam et al., 2020).

The transport pathway of microplastics is complex, involving physical, chemical, and biological processes. The physical properties of plastics, such as size, shape, buoyancy, and density, vary significantly and influence their transport behavior. Microplastics with greater density settle to the sediment, neutrally buoyant particles remain suspended in the medium, and those with a density lesser than seawater float on the surface. In aquatic environments, the transport of floating microplastics is influenced by wind and circulating currents, while suspended microplastics are vertically distributed in the upper water column due to wind action and turbulent mixing forces.

When considering sinking microplastics with high density, both the density of the particle and the shape of the polymer are taken into account. Low-density particles, such as polyethylene and polypropylene, enhance biofouling, causing them to sink rather than float. This explains the occurrence of these particles in sediments. Additionally, the settling of low-density particles is facilitated by their incorporation into organic aggregates. Research conducted by Long et al. (2015) has demonstrated that microbeads incorporated into diatoms sink at a much faster rate.

3.5. Impacts on Land

Research on the impacts of microplastics on terrestrial environments is relatively scarce and often overlooked. However, it is a crucial area that demands immediate attention, considering it is the primary source of plastics, with manufacturing facilities situated on land. Plastic pellets, produced initially, may inadvertently spill onto the land during transportation. The breakdown of plastic materials in landfills contributes to the formation of microplastics. Sewage sludge from wastewater treatment plants, encompassing both industrial and domestic sewage systems, releases microplastics directly into agricultural soil, posing potential health risks from items like tampon applicators, condoms, and diapers. The fate of microplastics depends on their size and the efficacy of water treatment; some may enter the sea, while others end up in sludge spread on arable land. Surprisingly, studies indicate that agricultural fields may accumulate more microplastics than ocean basins (Nizzetto et al., 2016). Plastic waste infiltrates the land through air and irrigation practices contaminated with microplastics. However, land-based debris degrades more rapidly due to exposure to sunlight and oxygen (Andrady, 2011). The use of plastic mulch for weed suppression and sewage sludge for soil fertilization contributes to the presence of micro/nano plastics in the soil. Microplastics have been reported in flowers (Liebeeit et al., 2014), and these may enter various insects (Riudavets et al., 2007), including mosquitoes (Al-Jaibachi, 2018). Reports of contaminated honey highlight the need for attention, as the presence of microplastics in honey challenges conventional perceptions of natural honey (Oliveira et al., 2019). Very small microbeads, resembling pollen grains, can disrupt plant pollination, potentially impacting the ecosystem negatively. Microplastics have infiltrated various aspects of our daily lives, contaminating the water we drink, the fish we consume, and the air we breathe. Plastic debris from landfills reaches the land through atmospheric fallout, with synthetic fibers comprising a significant portion (Dris et al., 2016). Additionally, microplastic particles, owing to their hydrophobic nature, attract persistent organic pollutants (POPs) such as polychlorinated biphenyls, polycyclic aromatic hydrocarbons, and organochlorine pesticides. Wetlands, marshy plains, and floodplains also act as reservoirs for microplastics during flooding events.

3.6. Impacts on Water

Encountering a pond, canal, stream, river, estuary, or ocean without anthropogenic debris is a rare occurrence. Rivers and streams play a vital role in transporting microplastics from land to the ocean. Although the impact of microplastics in freshwater ecosystems is relatively limited (Duis and Coors, 2016), certain rivers are colloquially known as "plastic rivers" due to their substantial contributions of

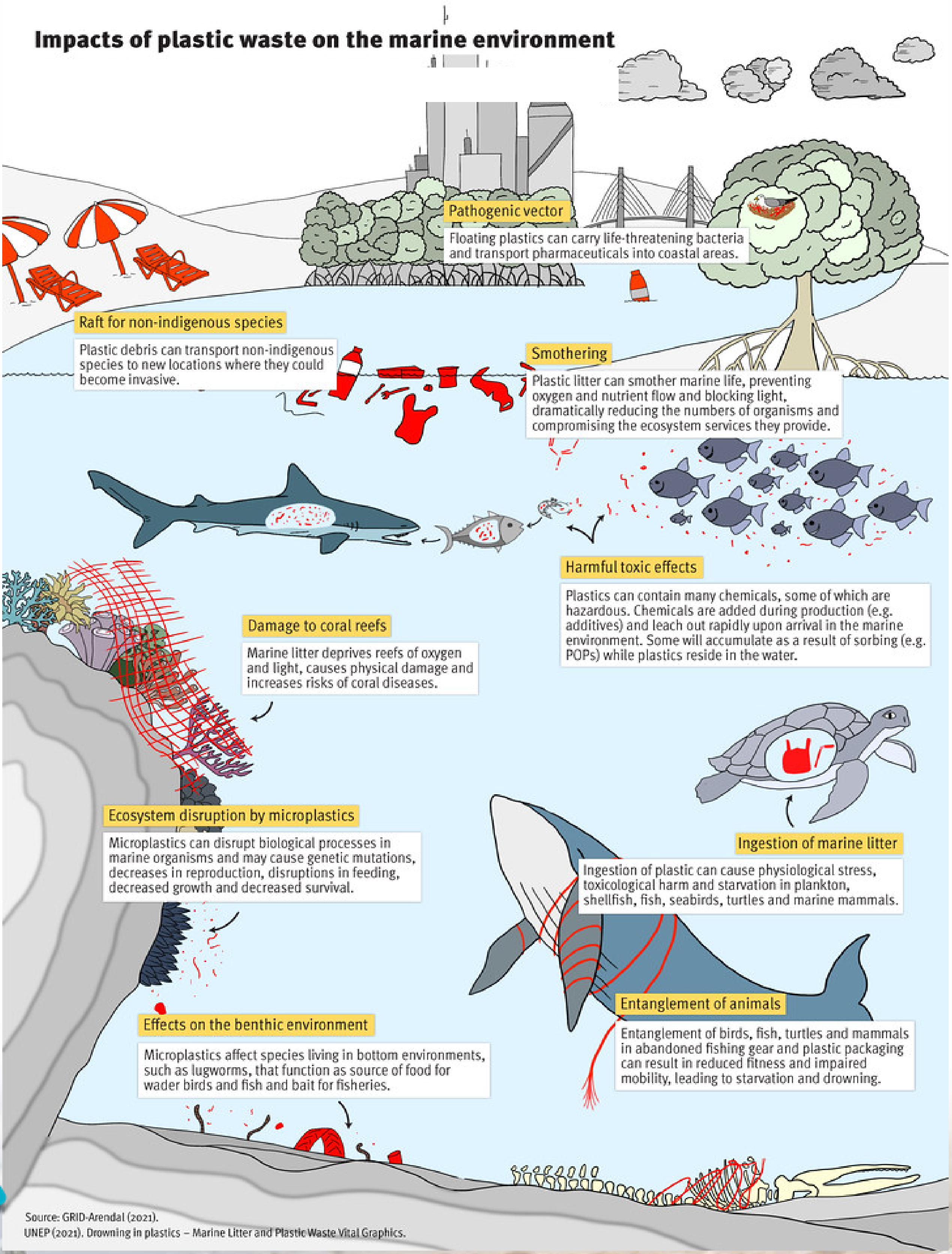
plastic debris to the sea. Globally, riverine plastic emissions into the ocean range between 0.8 to 2.7 million metric tons (theoceancleanup.com). The discharge of untreated sewage waste into ponds, lakes, and rivers, especially during rainfall, significantly contributes to the presence of microplastics. In these water bodies, longer and denser microplastics may either float or settle to the bottom, incorporating into the sediment and acting as a sink area for these particles. Groundwater studies consistently show low concentrations of microplastics, likely due to the overlying strata acting as a sieve (Marsden et al., 2019). Lakes and dams can also accumulate microplastics and serve as sinks due to limited water movement. Various freshwater biotas, particularly fish, have been studied as important groups ingesting microplastics.

In marine environments, plastic enters through leaching, littering, industrial leakages, and drainage. Fishing activities, including fishing vessels with nets, crates, cruise ships, and leisure boats, significantly contribute to plastic litter. The Food and Agriculture Organization (FAO, 2017) emphasizes the role of plastics in fisheries and aquaculture, where items like ropes, netting, boat paints, and antifouling paints become sources of microplastics when they break after extended use. Ship hull maintenance, involving cleaning and repainting, releases old plastic abrasive powder and paint flakes with a variety of polymer bases into the environment. Approximately 70% of commercial ships are dismantled and recycled, requiring the removal of toxic substances, including oil. The density of spilled plastic determines its fate—denser plastics sink to the bottom, while lighter ones float and move with water currents, occasionally washing ashore or traveling greater distances. Plastic undergoes fragmentation into tiny microplastics when exposed to wave action and sunlight, found in surface and deep waters, and even within sediment, posing a threat to ecosystems. Unlike natural flotsam such as kelp, plastics, despite exposure to wave action and UV radiation, remain buoyant for extended periods and can travel significant distances (Barnes and Milner, 2005). Wind, surface currents, turbulence from tidal and wave action, dredging, sea storms, and deep-sea trawlers all play roles in transporting plastics. Researchers worldwide turned their attention to studying plastic contamination following Moore's discovery of plastic debris in the North Pacific Ocean.

Microplastics pose a threat to marine life across various levels, affecting organisms from microscopic zooplankton to mammals and causing enduring impacts on the environment. These particles are not only indigestible but also carry toxicity for the organisms consuming them. Globally, over 690 species of marine biota have been affected by plastic, including 40% of sea birds, 50% of mammals, and all turtle species that ingest plastics (Gall and Thompson, 2015; Kuhn et al., 2015). Reports of microplastic ingestion by marine fishes have also been documented in India (Kripa, 2018; Mandal et al., 2023; Keerthika et al., 2023; Harikrishnan et al., 2023). Filter-feeding organisms like clams and mussels, while filtering substantial amounts of water, inadvertently intake microplastics. The impact of these microplastics extends beyond the individual organism, affecting bacteria and viruses and modifying population structures, thereby influencing ecosystem dynamics (Wright et al., 2013a, b). Bacteria colonizing microplastics differ from those in adjacent areas (Zettler et al., 2013; Harrison, 2012). The term 'platisphere,' as defined by Zettler et al. (2013), refers to floating plastics or those in the water column or at the bottom, serving as new food sources or habitats for marine organisms.

Chemicals associated with ingested microplastics are transferred through the food chain, causing inflammation and damage to gut tissues (Auta et al., 2017). Polymers commonly contain additives like biocides and plasticizers, which aggregate microbial pathogens (Kirstein et al., 2016) and toxic persistent organic pollutants (POPs) such as DDT, DDE (a metabolite of DDT), and polycyclic aromatic hydrocarbons (PAHs) (Rios et al., 2007). Plasticizers, used to enhance plastic stability and flexibility, along with dyes, lubricants, and anti-adhesives, form a cocktail of contaminants within the polymer, posing risks to living beings.

Microplastics also have the capability to adsorb endocrine-disrupting chemicals (EDCs) like BPA, phthalates, and heavy metals, disrupting normal hormone function and leading to various health issues. Some chemicals in plastics may even contribute to cancer or birth defects. Pellets can accumulate PCBs and DDEs from marine water, and when mistaken for food by fishes and birds, these particles enter the food chain and eventually reach humans. Virgin plastics have been reported to adsorb metals such as aluminum, copper, iron, zinc, and lead from marine water. Experimental evidence with European sea bass exposed to microplastics and mercury demonstrates the considerable negative impact of heavy metals in the aquatic environment enhanced by microplastics.



Impacts of plastic waste on the marine environment

Pathogenic vector

Floating plastics can carry life-threatening bacteria and transport pharmaceuticals into coastal areas.

Raft for non-indigenous species

Plastic debris can transport non-indigenous species to new locations where they could become invasive.

Smothering

Plastic litter can smother marine life, preventing oxygen and nutrient flow and blocking light, dramatically reducing the numbers of organisms and compromising the ecosystem services they provide.

Harmful toxic effects

Plastics can contain many chemicals, some of which are hazardous. Chemicals are added during production (e.g. additives) and leach out rapidly upon arrival in the marine environment. Some will accumulate as a result of sorbing (e.g. POPs) while plastics reside in the water.

Damage to coral reefs

Marine litter deprives reefs of oxygen and light, causes physical damage and increases risks of coral diseases.

Ecosystem disruption by microplastics

Microplastics can disrupt biological processes in marine organisms and may cause genetic mutations, decreases in reproduction, disruptions in feeding, decreased growth and decreased survival.

Ingestion of marine litter

Ingestion of plastic can cause physiological stress, toxicological harm and starvation in plankton, shellfish, fish, seabirds, turtles and marine mammals.

Entanglement of animals

Entanglement of birds, fish, turtles and mammals in abandoned fishing gear and plastic packaging can result in reduced fitness and impaired mobility, leading to starvation and drowning.

Effects on the benthic environment

Microplastics affect species living in bottom environments, such as lugworms, that function as source of food for wader birds and fish and bait for fisheries.

Source: GRID-Arendal (2021).
UNEP (2021). Drowning in plastics – Marine Litter and Plastic Waste Vital Graphics.

Impacts of plastic waste on marine environment (Source: GRID-Arendal, 2021)

Barnes (2002) assessed the colonization of stranded plastic debris on Antarctic and Arctic islands, determining that plastic littering due to anthropogenic activities is more than twice the likelihood of biota assembly. This may pose a threat to the dispersal of invasive aliens, thereby endangering fragile coastal areas (Barnes, 2002; Barnes & Milner, 2005; Gregory, 2009). The microplastic particles from these building wastes act as substrates for the attachment of hydroids and jellyfish medusa, promoting their flourishing.

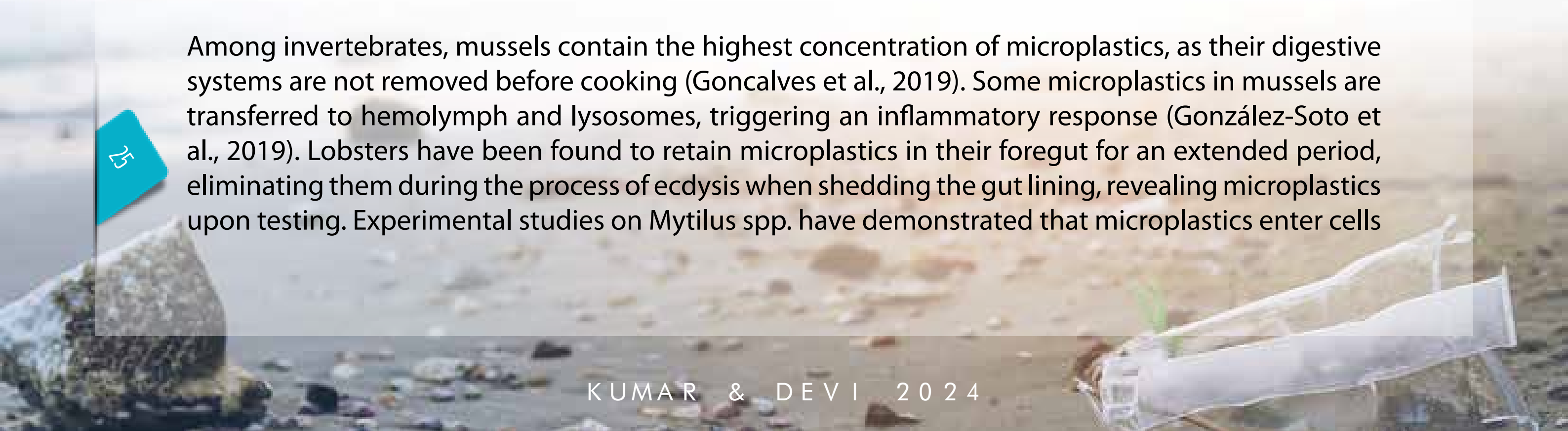
In addition to ingestion of microplastics by biota, there is a considerable potential for the transportation of these substances. Animals feeding on microplastics may excrete them elsewhere, leading to microplastic pollution in new locations. In some instances, these animals also act as vectors, transporting microplastics through the food web (Lusher et al., 2016). Marine microplastics are known to impact the growth and photosynthesis of phytoplankton, exert toxic effects on zooplankton, and pose a threat to ocean carbon sequestration by affecting the marine biological pump and microbial carbon pump (Shen et al., 2020). Floating particles, resembling floating seaweed, contribute to genetic mixing among populations, potentially serving as refuges and feeding grounds for other aquatic animals (Rothäusler et al., 2012; Vandendriessche et al., 2007).

Coastal, intertidal, and offshore sediments worldwide are recognized for containing variable levels of microplastics. Biofilms on microplastics exhibit uniqueness compared to their surrounding environment, providing a substratum for bacterial growth rich in carbohydrates and proteins. The surfaces of microplastics attract various bacterial species, increasing the potential for the spread of harmful pathogens (Vethaak and Leslie, 2016). Pathogenic Vibrio species such as *V. alginolyticus*, *V. coralliilyticus*, *V. fluvialis*, *V. harveyi*, *V. parahaemolyticus*, and *V. splendidus* have been detected on microplastics, enhancing the transport of these microorganisms. Microorganisms on microplastics increase their density, sinking to the bottom and enriching the sediment with them. Generally, sediments from deeper areas exhibit higher microplastic concentrations than littoral zones and water. However, obtaining sediment samples from deeper ocean areas poses challenges, resulting in limited data availability on such sediments.

The FAO provides a comprehensive overview of microplastics in fisheries and aquaculture (Lusher et al., 2017). Various marine organisms, such as zooplanktons, sea birds, whales, deep-sea organisms (Auta et al., 2017), mussels, oysters (Van Cauwenberghe and Janssen, 2014; De Witte et al., 2014; Mathalon and Hill, 2014), lobsters (Murray and Cowie, 2011), and fishes (Lusher et al., 2013; Rochman et al., 2015), have been analyzed for stomach contents, revealing the presence of microplastic particles. Microplastics can enter aquatic organisms either directly from the environment or indirectly through trophic transfer from prey. In some instances, microplastics may be taken up through the gills, or they may adhere to the legs, setae, antennae, or antennules of invertebrates (Cole et al., 2015; Paul-Pont et al., 2016).

Planktivores directly consume microplastics from the natural environment, while fishes may ingest them via trophic transfer or accidental ingestion. Non-selective organisms consume whatever is readily available, even if it is a microplastic, whereas selective feeders rely on factors such as color and particle size. If a microplastic is covered with biofilm, mimicking the properties of organic matter, even a selective feeder may consume it without recognizing its true nature. When an organism consumes another organism that has ingested microplastics, there is potential for the bioaccumulation of persistent pollutants.

Among invertebrates, mussels contain the highest concentration of microplastics, as their digestive systems are not removed before cooking (Goncalves et al., 2019). Some microplastics in mussels are transferred to hemolymph and lysosomes, triggering an inflammatory response (González-Soto et al., 2019). Lobsters have been found to retain microplastics in their foregut for an extended period, eliminating them during the process of ecdysis when shedding the gut lining, revealing microplastics upon testing. Experimental studies on Mytilus spp. have demonstrated that microplastics enter cells



and tissues, exerting toxic effects at these levels, including the molecular level (Paul-Pont et al., 2016).

Zooplankton, pivotal to the marine food chain, face detrimental effects from microplastics as they ingest these minute particles. The concentration of microplastics escalates up the food chain, impacting various marine organisms. Shockingly, reports reveal wild coral Astrangia poculata opting for microplastics with no nutritional value over shrimp eggs, eventually ceasing to consume shrimp eggs altogether (Rotjan et al., 2019).

Studies from Britain indicate the presence of microplastics in the gut contents of wild cetaceans and seals. Dolphins and seals, as apex predators with extended lifespans, are considered indicators of marine ecosystems but accumulate pollutants such as plastics and toxins, which can block their guts and reduce long-term survival (Werner et al., 2016). Even fishes in the Amazon have been found to be contaminated with microplastics. Deep-sea sediments near the ice edge of the Greenland Sea contain substantial amounts of microplastics (Bergmann et al., 2017), and research indicates that sea ice serves as a temporary sink and transport mechanism for microplastics.

While the partial effects of microplastics on organisms can be observed in the field, a comprehensive understanding can only be gained through laboratory experiments. Exposure to microplastics leads to physical damages and toxic effects in organisms. Instances of microplastic adherence to algae reducing algal photosynthesis (Bhattacharya et al., 2010), diminished algal consumption by zooplankton (Cole et al., 2013), and decreased sediment uptake with polystyrene in lungworms (Besseling et al., 2012) have been documented. Chemical transference from microplastics has been observed in lungworms, resulting in the reduction of various biological functions (Browne et al., 2013).

Marine organisms, including non-filter feeding ones, can ingest microplastics through their exposed gills. Studies have shown reduced reproductive capacity and larval growth in oysters fed with microplastics (Sussarellu et al., 2016). Mussels lose their grip when encountering microplastics, making it difficult to reproduce, leading to reduced yield as they are washed ashore by tides. Sea cucumbers exposed to PVC (pellets, fragments) and nylon fragments for four hours consumed more plastic particles than sand grains due to their larger surface area and smooth surface.

Experimental studies have demonstrated various adverse effects, including starvation, disrupted energy reserve metabolism, reduced performance in prey capture in fishes, altered swimming and feeding behavior, weight loss, and energy depletion (Watts et al., 2015; Cole et al., 2013; Wright et al., 2013; Auta et al., 2017). In many cases, ingested microplastics are translocated within organs, tissues, and body fluids, triggering immune responses, granuloma formation (Tang and Eaton, 1995), particle toxicity, inflammation, and fibrosis (von Moos et al., 2012; Höher et al., 2012). Daphnids have shown translocation of micro and nanoplastics in lipid droplets and embryos, while mollusks have exhibited detection of microplastics in the haemolymph.

The translocation of microplastics within cells and organelles depends on various factors, including size, distribution, shape, density, polymer properties, exposure duration, the ability to absorb contaminants, and the biology of the organism. Persistent organic pollutants, such as DDT, accumulate in organism tissues, undergoing biomagnification as they ascend the food chain, ultimately impacting higher trophic levels, including humans (Teuten et al., 2009). Experimental studies on mussels exposed to primary HDPE microplastics smaller than 0-80 µm have demonstrated absorption into the digestive vacuole (von Moos et al., 2012). The accumulation of microplastics in lysosomes has led to the lysis of cellular membranes, releasing enzymes into the cytoplasm, resulting in apoptosis and immune reactions (Höher et al., 2012).

Various researchers have reported microplastics with low concentrations of metals. Metals exhibit a greater affinity for adherence to microplastics than new plastics, and the release of these metals from microparticles is higher in the acidic conditions of organisms' guts. Experimental studies on fishes exposed to microplastics have reported severe inflammation, tissue damage, and necrosis of gastrointestinal tissue in juvenile sea bass, thickening of the mucosal epithelial layer in juvenile silver barb, and damage to the epithelial layer of the gut in zebrafish when exposed to PVC and polystyrene spheres. PCBs have been linked to masculinization in polar bears and immediate abortions in seal populations. Therefore, microplastics have the potential to impact growth rates, reproduction, and mortality, ultimately altering population dynamics and affecting profitability and efficiency in the aquaculture sector.

In discussions of toxicity, the size and shape of microplastics are crucial considerations. Smaller particles pose greater toxicity to organisms (Shen et al., 2019; Gonçalves and Bebiano, 2021). Microplastics with a larger surface area have an enhanced capacity to adsorb contaminants, heightening toxicity. On the other hand, smaller microplastics, if retained in the body for an extended period, elevate the risk of potential harm. Smaller microplastics can easily traverse biological membranes, such as the villi of the gut, and irregular fragments and fibers can persist in the gut for longer durations, intensifying toxicity. The aggregation of nanoplastics based on surface charge is linked to toxicity, given the existence of positively and negatively charged nanoparticles. Positively charged particles form smaller aggregates, while negatively charged particles form larger aggregates. This emphasizes the significance of particle-biota interactions as a crucial driver of bioavailability and its associated adverse effects. Experiments by Dawson et al. (2018) illustrated the ingestion of microplastics by Antarctic Krill (*Euphausia superba*), with subsequent identification of much smaller-sized particles in its tissues and fecal matter. This indicates the degradation of microplastics to nanoplastics, allowing them to reach various tissues that were initially inaccessible during consumption.

Certain microplastics, such as microbeads, are intentionally added to products like cosmetics, toothpaste, and household cleaning items, serving as abrasives or scrubbers. Nanoparticles are also manufactured for applications like paints, adhesives, drug delivery vehicles, and electronics (Kolemanns et al., 2015). Microplastics and nanoparticles are employed in inhalable and ingestible medicines for drug delivery to humans and other organisms, as they can easily traverse the lungs or gut and enter the circulatory system (Dalmon et al., 1995; Corbanie et al., 2006). The retention rate of microplastics in body tissues is not well-established, and those excreted end up in sewage water. Non-biodegradable microbeads in face wash and toothpaste are washed down drains, reaching aquatic bodies and contaminating them through waterways (Miraj et al., 2019; McDevitt et al., 2017). Zebrafish exposed to polystyrene microbeads for a week accumulated microplastics in the gut, gills, and liver, resulting in inflammation and lipid accumulation in the liver. Currently, eight countries have banned microbeads. Despite microbeads appearing in personal products 50 years ago, consumer awareness regarding their harmful effects remains limited.

3.7. Socio-economic Impacts

Improper plastic disposal, as emphasized by Hartley et al. (2013), not only diminishes the visual appeal of coastal areas but also discourages tourists, resulting in economic losses for countries (Anderson and Brown, 1984; Ballance et al., 2000; Tudor and Williams, 2006; WHO, 2003). The costs linked with beach clean-ups are substantial, imposing an additional burden on the economy. Furthermore, plastic pollution poses a threat to marine vessels, with ship and trawler engines and propellers susceptible to damage, incurring extra repair expenses and contributing to ghost fishing—a global issue that contaminates the food web with plastics.

Ghost gear, often a consequence of illegal and unreported fishing practices, is a prevalent problem, with Norway being the sole country systematically addressing lost or discarded fishing gear. Slowly degrading synthetic nylon fishing nets pose threats to sea birds, turtles, and dolphins, emphasizing the need for sustainable solutions. To mitigate the risks of ghost fishing, collaborative efforts between Korean and Norwegian institutions aim to develop biodegradable gill nets for responsible fisheries management, thereby reducing plastic pollution.

The impact of microplastics goes beyond physical harm to aquatic organisms. Microplastics can carry pathogenic microbes and invasive aliens, disrupting native crustacean and fin fish populations. Increased energy expenditure in foraging, driven by the need to avoid microplastics, diverts energy away from growth and reproduction in aquatic organisms, delaying their attainment of harvestable sizes and diminishing profits in the fisheries sector. European consumers face concerns on annual consumption of microplastics through seafood, as documented by Van Cauwenberghe and Janssen (2014) and Catarino et al. (2018).

Birds, especially petrels and albatrosses relying on their sense of smell for food acquisition, ingest more plastics due to the olfactory resemblance of algae-covered microplastics to zooplankton. Consequently, microplastics pose a threat to both ecosystems and the economic services they provide, introducing financial and economic risks.

Tourism, a crucial source of income for countries, faces negative consequences from marine litter. Activities such as whale watching, scuba diving, and sport fishing are adversely affected by the presence of marine litter, deterring tourists and leading to revenue and job losses. Marine litter, particularly plastics, adversely affects the aesthetic value and beauty of beaches and shorelines, necessitating costly clean-up programs in developed countries, reaching up to $24 million annually and posing a significant burden to authorities.

Marine litter can have significant economic impacts on the fisheries sector. While it is challenging to provide precise global figures, the loss in the fisheries sector due to marine litter can be attributed to several factors:

Gear Damage: Marine litter, especially plastic debris, can damage fishing gear and equipment which leads to increased maintenance costs and, in some cases, the need to replace gear, which can be expensive.

Reduced Catch Efficiency: Fishing in areas with a high concentration of marine litter, such as discarded fishing nets or debris, can result in reduced catch efficiency. These obstacles make it difficult to set and retrieve nets and traps, reducing the overall catch. Decrease in catch in fisheries and increased costs for cleanup of fishing gear due to marine litter was reported in Scottish marine vessels. Ingestion of microplastics by commercially valuable species can also have economic loss that can negatively impact the fishing industry as well.

Contamination of Catch: Marine litter can introduce pollutants into the marine environment, some of which may be absorbed by fish and other seafood. This contamination can result in reduced market value for the catch and potential health risks to consumers.

Navigation and Safety Costs: Marine debris, especially where concentration of debris is high, can pose navigation hazards for fishing vessels. This can lead to increased fuel consumption, longer travel times, and heightened safety risks.

Cleanup Costs: Fisheries may incur costs related to the removal of marine litter from fishing grounds, as well as from the harbors and ports where vessels are docked for which cleanup efforts are necessary to maintain operational safety and efficiency.

Reduced Tourism and Market Access: Coastal communities reliant on fishing and tourism may experience economic losses due to the negative impact of marine litter can significantly detract from the aesthetics and attractiveness of these areas, affecting tourism and related income streams.

Public Perception and Consumer Preferences: As consumers become more aware of environmental issues, they may favor sustainably caught seafood over products associated with areas heavily affected by marine litter. This can influence market demand and prices for fish and seafood.

Lost Fishing Time: Fishermen may spend extra time and resources disentangling gear from marine litter, which reduces the time available for productive fishing and leads to income loss. Lost or abandoned fishing gear, known as ghost gear, continues to catch fish and other marine life, leading to economic losses for the fishing industry.

Disruption of Fish Habitats: Marine litter can cause habitat destruction in critical fishery areas, impacting the breeding, feeding, and migration patterns of fish populations. Loss or alteration of these habitats can reduce fish stocks, affecting the long-term sustainability of fisheries.

Health Risks to Fish and Seafood Consumers: Marine litter, particularly plastic debris, can break down into microplastics, which can be ingested by fish. This ingestion poses health risks for fish populations and, subsequently, for seafood consumers, potentially leading to concerns about food safety.

Regulatory Compliance and Certification: International standards and certifications often require adherence to environmental regulations, including maintaining clean and sustainable fishing practices. The presence of marine litter could impact compliance, making it harder for fishing operations to meet these standards.

It is crucial to recognize that the economic repercussions of marine litter on the fisheries sector can vary regionally, contingent on factors such as the extent of the litter issue, the nature of fishing practices, and the specific species targeted. Furthermore, the indirect and prolonged consequences, including harm to marine ecosystems and fisheries resources, may be challenging to quantify but hold implications for the overall sustainability of the industry.

Efforts to alleviate the impact of marine litter on the fisheries sector encompass diverse measures. These include routine clean-up operations to clear fishing grounds of marine litter, education and training initiatives for fishermen regarding the consequences of marine litter, advocacy for responsible waste management practices, promotion of sustainable fishing methods, reduction of plastic waste at its source, development of fishing gear and techniques to minimize interactions with and entanglement in marine litter, implementation and enforcement of regulations to decrease marine litter, and enhancement of waste management and recycling systems. Tackling marine litter necessitates a comprehensive approach involving governments, industries, communities, and individuals to mitigate its impact on fisheries and the broader marine ecosystem.

Complying with European Union fishing fleet standards, the estimated net loss of income attributable to marine litter is approximately $81.7 million (€74.6 million) annually (ARCADIS, 2014). Conversely, instances of jellyfish (*Nemopilem anomurai*) outbreaks in Korean waters have been linked to increased floating plastic debris, identified through DNA barcoding of extracts from microplastics and these outbreaks have led to significant losses in the fisheries sector (Yoon et al., 2014).

3.8. Microplastics and Human Health

Despite the widespread awareness among researchers, the public, government entities, and the media regarding the potential threats posed by microplastics, resolving the plastic problem remains challenging due to its incomplete and contradictory nature. Microplastics have been identified as causing physical harm, gastrointestinal blockages, and respiratory issues in various organisms (Guzzetti et al., 2018). The World Health Organization (WHO, 2019) emphasizes the omnipresence of microplastics in the environment, highlighting the disturbances caused by both micro and nano plastics and their implications for human health. Extensive studies by Campanale et al. (2020) have investigated the hazardous chemical substances associated with plastic products and their impact on

human health. These substances enter the human system through contaminated food consumption and inhalation. Notably, everyday consumables like salt, sugar, beer, alcohol, and drinking water have been found to contain micro and nano plastics, raising concerns.

In considering the link between microplastics and human health, the size of microparticles is crucial. Microplastics smaller than 20 µm can penetrate various human organs, with those at 10 µm having accessibility to every organ, crossing cell membranes, the blood-brain barrier, placenta, liver, kidney, spleen, muscles, and even sperm. Factors such as length, size, shape, concentration, and chemical properties further contribute to their impact. Various techniques involving pH variations, aging particles, hydrophobic interactions, and polymer composition are implicated in the adsorption of chemicals to these microplastics.

Despite a significant gap in understanding the toxicity caused by microplastics in humans and limited information (Galloway, 2015; Lusher et al., 2017), studies suggest that microplastics entering the human body through seafood consumption pose a threat (Van Cauwenberghe and Janssen, 2014), particularly in the case of individuals consuming bivalves, mollusks, and sea cucumbers, including the gut (GESAMP, 2015), with increased risk for those who consume these items along with the gut (Beaumont et al., 2019). In regions like Lakshadweep, where seafood is a primary dietary source and per capita fish consumption is high (20,000 MT in 2020, Statista.com), the impact of microplastics on human health is a pressing concern.

Once ingested, microplastics can migrate from the gut to the lymphatic system and enter the circulatory system (Hussain et al., 2001). Particles smaller than 2.5 µm, entering the gut through endocytosis of M cells in Peyer's patches, can lead to inflammation in the intestinal lumen and subsequently the circulatory system. Evidence of microplastics in human feces, mainly polyethylene (PE) and polypropylene (PP), further supports their presence in the human gut (Schwabl et al., 2019). Airborne microplastics can cause respiratory disorders, cytotoxicity pneumonia, allergic alveolitis, and inflammation. The thin tissue barrier in the human lung, less than 1 µm, facilitates the entry of nanoparticles into the bloodstream. Individuals working in the textile industry, in direct contact with nylon, polyester, and acrylic fibers, may experience similar conditions. Additionally, the size of microfibers poses a challenge, as smaller particles are difficult to remove from macrophages in the lungs. Notably, plastic feeding bottles used for babies release millions of microplastics when vigorously shaken (Li et al., 2020), highlighting concerns about exposure in early life.

The likelihood of microplastics (MPs) manifesting through the skin during scrubbing and cleaning is low, as particles smaller than 100 nm face difficulty in penetrating the corneous layer of the skin. However, the entry of nanoparticles is still possible. The rising concern about persistent pollutants in seafood arises from the transfer of these compounds from the environment to aquatic organisms and subsequently onto our plates. While studies have indicated higher levels of Persistent Bioaccumulative Toxicants (PBTs) in individuals consuming more fish, it is not universally consistent, as the dietary intake of contaminants and additives through MPs is negligible (Lusher et al., 2017). To safeguard seafood resources and reduce plastic pollution, proactive measures can be taken on our part.

Nevertheless, the fate of nano and microplastics, particularly whether MPs degrade into nanoparticles in the gastrointestinal (GI) tract and whether they are excreted, remains unstudied. Consequently, conclusions about their potential harmful effects in humans are challenging to draw (Lusher, 2017). A prudent method to minimize MP contamination in seafood is to remove the GI tract before consumption, as most MPs tend to accumulate in the gastrointestinal tract.

Experiments involving nano-sized polystyrene particles (240 nm diameter) and microplastics have revealed their ability to traverse the human placenta (Wick et al., 2011; Ragusa et al., 2021). However, when microplastics shrink below a quarter of a millimeter, harmful effects become evident as these particles interact with cells and tissues (Berntsen et al., 2010; Fröhlich et al., 2009). Subsequently, they are taken up by lysosomes, vacuoles, circulatory systems, lymph (Hussain et al., 2001), and even placental tissue, as mentioned earlier. Implants like polyethylene (PE) and polymethylmethacrylate (PMMA), used in contact lenses, bone cements, and dental restorations, may induce particle-induced osteolysis upon degradation within the body (Martinez et al., 1998; Petit et al., 2002; Nich et al., 2011).

Various chemicals or additives used in everyday plastic products pose risks to human health, causing cancer, reproductive issues, DNA mutations, and hormonal disruption. Phthalates and Bisphenol A (BPA), brominated flame retardants found in food packaging, are particularly harmful. BPA-based plastics, used in high-temperature food packaging and microwave ovens, exhibit decreased stability and leach into landfills, serving as endocrine-disrupting chemicals (EDCs). EDCs may mimic natural hormones, alter their action, and disrupt metabolism, potentially leading to cancers, genital deformities, infertility, obesity, asthma, and autism. Phthalates have been found in human breast milk, blood, and urine, necessitating analysis for microplastic presence, given that phthalates are used to soften plastic products. Some phthalates are restricted in childcare articles by European legislation. Heavy metals (cadmium, chromium, calcium, lead, titanium) in plastics, used as additives in flame retardants, colorants, pigments, and stabilizers, can cause toxicity in humans depending on concentration, exposure duration, age, and sex.

Stabilizers play a crucial role in enhancing the durability of plastics by enabling them to withstand high temperatures, UV radiation, and various environmental factors that might otherwise compromise their longevity. Biocides such as arsenic, antimony, and tin are also employed as additives in polymers to deter microbial attacks. However, the use of heavy metals in plastics introduces a risk of toxicity, causing harm to cells and tissues and contributing to various diseases in humans. Certain heavy metals, including lead, mercury, antimony, barium, arsenic, cadmium, copper, cobalt, and others, exhibit estrogenic properties, displaying a high affinity for estrogen receptors and potentially leading to breast cancer.

Numerous studies have highlighted the strong adsorption affinity of nanoplastics to lead, particularly when exposed to UV oxidation under specific environmental conditions. Copper and zinc are released from antifouling paints, and PVC and PS have been found to adsorb these metals. Titanium dioxide, present in many plastic products, induces cytotoxicity in the epithelium of the lungs and colon. Lead, on the other hand, modifies genes regulating tumors, resulting in adverse effects on the central nervous system, including convulsions, coma, and even death. Mercury adversely affects both the central nervous system and kidneys, causing various toxic effects in humans.

Flame retardants, crucial for preventing fires, fall into two categories: reactive and additive flame retardants. Reactive flame retardants are covalently linked to polymers, making them less likely to escape into the environment unless burned or degraded. In contrast, additive flame retardants are dissolved in materials, increasing the likelihood of leaching from products. Approximately 70 flame retardants in the brominated flame retardant (BFR) category, used as additives in plastics, can disrupt the immune system, liver metabolism, and oxidative stress in fish. Through the food chain, these effects may extend to humans, causing various toxic outcomes.

Monomers of plastics, such as styrene and vinyl chloride, pose threats to human health. Styrene exhibits properties similar to estrogen, while vinyl chloride is both a genotoxin and a mutagen. Considering these factors, microplastics emerge as a potential global health threat.

3.9. Are there any Biodegradable Plastics?

Biodegradable plastics offer a glimmer of hope in the battle against plastic pollution, envisioning a world where plastics naturally decompose without posing a threat to our planet. In simple terms, biodegradable plastics are designed to break down into harmless substances like water, carbon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dioxide, and compost under specific conditions, mimicking the decomposition process of organic matter through the action of microorganisms. The biodegradable plastics include aliphatic polyesters, bacterial polymers, and bio-derived polymers.

However, many plastic products labeled as biodegradable do not live up to this promise. The major disadvantages of this include limited availability, higher cost, and some may require specific conditions for degradation. Some disintegrate into smaller pieces while retaining their original polymer properties. Biodegradable options known for reducing ecological footprints, such as aliphatic polyesters, bacterial polymers, and bio-derived polymers, are often more expensive. Commodity plastics, prized for their durability, prioritize strength over degradability, and the endurance of biodegradable plastics may not always meet these criteria. Exposure to UVB radiation or bacterial activity can make biodegradable plastics brittle, causing them to degrade into smaller fragments. These plastics are produced from renewable raw materials or petrochemicals, including soybeans, switchgrass, sugar cane, and corn. While some undergo degradation into water, carbon dioxide, and organic matter through microbial action, achieving complete biodegradation often requires exposure to temperatures exceeding 50°C for an extended period, making it impractical in normal environmental conditions.

Biodegradation in marine environments is particularly challenging, as plastics in these settings may become covered with sand or biofilm, reducing their degradability. Complete biodegradation, resulting in water, carbon dioxide, and methane, is achievable only in industrial composters requiring a temperature of 70°C, a process termed mineralization (Andrady, 1994). While some plastics labeled as 'biodegradable' break down more easily, their limited uses and higher costs compared to conventional plastics must be considered. Additionally, oxo and photo-biodegradable plastics exist, degrading faster into smaller fragments.

While biodegradable plastics represent a positive stride toward a more sustainable future, they are not a universal solution. Acknowledging their limitations and investing in research, infrastructure, and consumer education can help harness their potential to reduce plastic pollution and contribute to a cleaner world.

3.10. Alternatives for Plastics

Numerous alternatives to traditional plastics are being explored and implemented to address environmental concerns associated with plastic pollution which also include biodegradable plastics. The others alternatives are listed below:

Compostable Plastics: Plastics that can break down into compost, providing a nutrient-rich material for soil.
Types: Polylactic Acid (PLA) is a common compostable plastic.
Pros: Breaks down into non-toxic components, suitable for certain composting facilities.
Cons: Requires specific composting conditions, may not degrade in traditional landfill environments.
Plant-Based Plastics: Plastics derived from renewable plant sources such as corn, sugarcane, or cellulose.
Types: PLA is a common plant-based plastic.
Pros: Reduces reliance on fossil fuels, lower carbon footprint.
Cons: May still require industrial composting facilities for proper disposal.
Edible Packaging: Packaging made from edible materials, often used for single-use items.
Types: Edible films made from seaweed, starch, or proteins.
Pros: Eliminates packaging waste, safe for consumption.
Cons: Limited to certain applications, may impact taste or texture.
Paper and Cardboard: Description: Traditional materials like paper and cardboard are being reintroduced as alternatives to single-use plastics.

Pros: Biodegradable, recyclable, and widely available.
Cons: Limited durability in certain applications.
Glass: Glass is a durable and recyclable material often used for packaging.
Pros: Infinitely recyclable, does not leach harmful substances.
Cons: Heavier and more fragile than plastic, energy-intensive manufacturing.
Metal: Metals such as aluminum and stainless steel are used for durable and recyclable packaging.
Pros: Highly recyclable, long lifespan.
Cons: Energy-intensive production, heavier than plastic.
Silicone: Silicone is a flexible and durable material used for various products, including food storage.
Pros: Reusable, durable, and heat-resistant.
Cons: Derived from non-renewable resources, limited recyclability.
Mushroom Packaging: Packaging made from mycelium, the root structure of fungi.
Pros: Biodegradable, lightweight, and customizable.
Cons: Limited scalability, currently higher cost.
Recycled Plastics: They are materials that have undergone a process of reprocessing and reclamation, typically after being used in their original form. Using recycled plastics reduces the demand for new plastic production.
Pros: Reduces dependence on virgin plastics, lowers energy consumption.
Cons: May have limitations in terms of quality and application.
Bio-Based Plastics: Plastics made from renewable resources, including agricultural products.
Types: Polyethylene derived from sugarcane (bio-PE), for example.
Pros: Utilizes renewable resources, lower carbon footprint.
Cons: Limited availability, competition with food crops.

It's important to note that each alternative has its own set of advantages and challenges. The adoption and success of these alternatives depend on factors such as cost, scalability, functionality, and the overall environmental impact throughout their life cycle. Additionally, a combination of approaches, along with improved waste management practices and recycling efforts, is likely needed to address the complex issue of plastic pollution effectively.

Additionally, the following concepts may also be tried for reducing consumption of plastics:

Reduce your overall consumption: The best way to reduce plastic pollution is to simply use less plastic in the first place. This means carrying a reusable water bottle and shopping bags, avoiding single-use plastics, and buying products with minimal packaging.

Support sustainable businesses: Look for companies that are committed to using recycled materials, reducing their packaging, and developing sustainable alternatives to plastic.

Advocate for change: Let your voice be heard by supporting policies that reduce plastic pollution and encourage the development of sustainable alternatives.
By making small changes in our everyday lives, we can all help to reduce our reliance on plastic and create a more sustainable future.

3.11. Mitigation and Remediation Strategies

Mitigating and remediating plastic pollution requires a multifaceted approach involving various strategies across different stages of the plastic life cycle. Few strategies are outlined here, and there is ample scope for innovation in this field.

Reduce and Reuse

Consumer Education: Raise awareness about the environmental impact of single-use plastics and promote behavioral changes, such as using reusable bags, bottles, and containers.

Plastic-Free Initiatives: Encourage businesses to adopt plastic-free practices and promote alternatives.

Reorient and Diversify
This refers to shifting the market towards sustainable alternatives, which will require a shift in the way products and packaging are produced, consumer demand, regulatory frameworks and costs.

Recycling
Improved Recycling Infrastructure: Invest in efficient and widespread recycling facilities and systems, making it easier for consumers to recycle plastic products.
Extended Producer Responsibility (EPR): Shift the responsibility for recycling and waste management to the producers, encouraging them to design more recyclable products.

Innovation in Packaging
Alternative Materials: Develop and promote the use of alternative, eco-friendly materials for packaging.
Design for Recycling: Encourage the industry to design packaging with recyclability in mind.

Clean-Up and Collection
Ocean and Beach Clean-Up Programs: Organize and support initiatives that focus on cleaning up plastic waste from oceans and beaches.
River and Waterway Management: Implement strategies to prevent plastic from entering water bodies, including the installation of litter traps and river clean-up programs.

Waste Management
Improved Waste Collection and Disposal: Strengthen waste management systems, particularly in developing countries, to reduce the likelihood of plastics entering the environment.
Landfill Management: Implement advanced landfill technologies to prevent leachate and emissions from landfill sites.

Microplastic Management
Wastewater Treatment: Upgrade wastewater treatment plants to capture and filter out microplastics before they enter water bodies.
Textile Industry Regulations: Regulate and encourage the textile industry to reduce microfiber shedding during production and use.

Policy and Legislation
Single-Use Plastics Bans: Enforce or encourage bans on certain single-use plastic items, such as bags, straws, and utensils.
Plastic Packaging Regulations: Implement and strengthen regulations regarding the use and disposal of plastic packaging.

Research and Monitoring
Plastic Monitoring Programs: Establish monitoring programs to track the distribution and accumulation of plastic waste in the environment.
Research on Alternatives: Invest in research to develop and assess the environmental impact of alternative materials and technologies.

International Collaboration
Global Agreements: Promote international cooperation to address plastic pollution through agreements and initiatives.
Information Sharing: Share best practices, research findings, and technologies globally to enhance collective efforts.

Public and Private Partnerships
Collaboration with NGOs: Work with non-governmental organizations (NGOs) and private companies to implement plastic reduction initiatives and clean-up campaigns.
Corporate Responsibility: Encourage companies to adopt sustainable practices and reduce their plastic footprint.

Circular Economy Practices
Closed-Loop Systems: Promote the adoption of circular economy principles, encouraging the recycling and reuse of plastics within closed-loop systems.
Implementing these strategies requires a collaborative effort from governments, businesses, communities, and individuals. Combining regulatory measures with educational campaigns and technological innovations will contribute to a more effective and sustainable reduction of plastic pollution.

3.12. International Treaties

It is imperative to maintain and enhance the current international legal frameworks aimed at tackling the issue of marine plastic pollution. The three most significant ones are the 1978 Protocol to the International Convention for the Prevention of Pollution from Ships (MARPOL), the 1996 Protocol to the London Convention (the London Protocol), and the 1972 Convention on the Prevention of Marine Pollution by Dumping Wastes and Other Matter (the London Convention).

Heads of State, Ministers of environment and other representatives from UN Member States endorsed a historic resolution at the UN Environment Assembly (UNEA-5) in March 2022 at Nairobi to **End Plastic Pollution** and forge an **International legally binding agreement** by 2024. The resolution addresses the full lifecycle of plastic, including its production, design and disposal.

It is expected to present a legally binding instrument by 2024, which would reflect diverse alternatives to address the full lifecycle of plastics, the design of reusable and recyclable products and materials, and the need for enhanced international collaboration to facilitate access to technology, capacity building and scientific and technical cooperation. Few thrust areas in this treat would be the following, according to the United Nations Development Programme:

Life cycle approach: The draft included proposed provisions covering all stages of the plastic value chain, from primary plastic polymers to waste management. While member states unanimously agreed that we are facing a global plastic pollution crisis, and the actions needed to be taken to tackle plastic pollution with a life cycle approach, they disagreed about where the life cycle should start.

The key issue is whether to reduce or restrict the production of primary plastics. Some member states consider that the plastics life cycle starts with the production of primary plastics. Capping the plastics polymer production can stop plastic pollution at its source. Others argue that plastics have played an important economic role, and that the treaty should not restrict plastics polymer production but focus on fighting pollution.

Product design: The Zero Draft of the Plastics Treaty promotes better product design to reduce plastic use and improve recycling.

Forty percent of plastics are used for packaging. Can we think of better design to reduce excessive packaging? Can we replace packaging with local, ecological materials? How can we reduce single use plastics?

One critical obstacle to plastic recycling is the large number of types and compositions of plastics. There are tens of thousands of chemicals and additives, making them difficult to separate, consolidate and process. Given the difficulty and high cost of collection and separation, there is a need to limit the types of additives and plastics.

Extended producers' responsibility: Member states generally agree on the principle of polluters paying, and the Zero Draft includes a provision on extended producers' responsibility (EPR) "to establish and operate ERP systems to encourage increased recyclability, promote higher recycling rates, and enhance the accountability of producers and importers for safe and environmentally sound management, of plastics and plastic products throughout their life cycle and across international supply chains".

Producers have the best knowledge, capacity and technical expertise to make the most use of post-consumer products for reuse, recycling or disposal. They are also best positioned to produce environmentally sustainable products. Policies and economic and social incentives need to be developed to make producers more responsible for the environmental costs of their products, incentivizing change at the design stage.

The Zero Draft includes a provision to establish and operate the EPR to promote increased recyclability, and higher recycling rates, and enhance the accountability of producers and importers for safe and environmentally sound management of plastics and plastic products throughout their life cycle and across international supply chains.

3.13. Role of Academic and Research Community

The academic and research community plays a crucial role in addressing plastic pollution and formulating effective management strategies. Their contributions span a wide range of activities, from understanding the sources and impacts of plastic pollution to developing innovative solutions. In countries like India, the academic and research community has to diversify the research arenas to consolidate the data and to frame effective and regionally suitable management measures. Few of the knowledge gap areas are listed below:

Understanding Sources and Pathways

Surveillance and Monitoring: Scientists conduct research to monitor and analyze the distribution, concentration, and sources of plastic pollution in different environments, including oceans, rivers, lakes, and terrestrial ecosystems.

Identifying Sources: Research helps identify the primary sources of plastic pollution, such as mismanaged waste, industrial discharges, and microplastic shedding from various products.

Impact Assessment

Ecological Impact Studies: Researchers assess the ecological impact of plastic pollution on marine life, terrestrial ecosystems, and human health.

Food Chain Dynamics: Understanding how plastics move through food chains and potentially impact different species is a critical area of research.

Plastic Characterization

Chemical Composition: Research focuses on the chemical composition of different types of plastics, including additives and potential contaminants, to better understand their environmental behavior.
Microplastics Research: Investigating the sources, transport, and effects of microplastics is crucial, considering their widespread presence in ecosystems.

Innovative Technologies

Biodegradable and Sustainable Materials: Scientists research and develop alternative materials that are biodegradable, sustainable, and have reduced environmental impacts compared to traditional plastics.

Advanced Recycling Technologies: Exploring and improving recycling technologies for different types of plastics is vital for creating a circular economy.

Behavioral Studies

Consumer Behavior Research: Understanding consumer behavior towards plastic use and waste management helps in designing effective awareness and education campaigns.

Policy Impact Analysis: Researchers assess the impact of existing policies and regulations on plastic use and disposal, providing insights for policy improvements.

Remediation and Cleanup

Innovative Cleanup Technologies: Research contributes to the development of innovative technologies for removing existing plastic pollution from oceans, rivers, and other ecosystems.

Efficacy of Cleanup Measures: Evaluating the effectiveness of cleanup efforts is essential for refining strategies and optimizing resource allocation.

Policy Recommendations

Scientific Input for Legislation: Researchers provide scientific evidence and recommendations to policymakers for developing and implementing effective regulations to curb plastic pollution.

Life Cycle Assessments: Conducting life cycle assessments helps in understanding the environmental impact of different types of plastics and guiding policy decisions.

International Collaboration

Data Sharing and Collaboration: The global nature of plastic pollution requires collaboration among scientists and researchers worldwide to share data, methodologies, and findings.

Global Research Initiatives: Participating in or leading global research initiatives enhances the collective understanding of plastic pollution and facilitates coordinated efforts.

Public Awareness and Education

Communication of Findings: Scientists have a role in effectively communicating their research findings to the public, policymakers, and industry stakeholders.

Education Programs: Engaging in educational programs helps raise awareness about the environmental impacts of plastic pollution and encourages sustainable practices.

Long-Term Monitoring

Sustainability Assessments: Implementing long-term monitoring programs helps assess the effectiveness of management strategies and measure progress in reducing plastic pollution over time.

In short, the research and science community is instrumental in providing the knowledge base, innovative solutions, and policy guidance necessary for effectively addressing plastic pollution and implementing sustainable management practices. Collaboration among scientists, policymakers, industry, and the public is essential for comprehensive and impactful efforts.

4. METHODS

The escalation of plastic production globally has resulted in widespread environmental repercussions, particularly in marine environment. Understanding the journey of plastics from land to ocean is crucial for devising effective mitigation strategies. Plastics enter marine environments through diverse pathways. Runoff from urban areas, rivers, and streams serves as a primary conduit, carrying accumulated plastics from land to the ocean. Coastal regions, often characterized by human activities and inadequate waste management, contribute substantially to this transport.

Wind transport, particularly in the form of microplastics, further extends the reach of plastic debris from land to sea. The majority of plastic in our oceans originates on land; by weight, rivers or coastlines carry between 70% and 80% of all plastic pollution into the ocean (Li et al., 2016). The remaining 20% to 30% originate from marine resources, including fishing nets, lines, ropes, and derelict boats (Lebreton et al., 2018). Given that Asia is home to about 60 % of global population, 81% of ocean plastics are emitted from Asia, and India is one of the top countries in Asia contributing to marine plastic pollution. With rather inadequate waste management systems, coastal cities in middle-income countries are the world's plastic emissions hotspots.

Mechanical forces, such as wind and water currents, play a pivotal role in the transport of plastics. Surface runoff facilitates the transfer of larger plastic items, while wind-driven dispersion is instrumental in the transport of smaller particles. Coastal erosion and storm events exacerbate the transportation process, amplifying the influx of plastics into marine ecosystems.

Various factors influence the journey of plastics from land to ocean. Geographical features, climate patterns, and human population density contribute to the distribution and concentration of plastic pollution. Inadequate waste management practices, especially in rapidly developing regions, aggravate the problem, emphasizing the need for global cooperation in addressing this environmental challenge.

4.1. Marine Debris

Marine debris or litter is any persistent solid material that is generated or processed by people and subsequently discarded, disposed of, or abandoned in the coastal or maritime environment, comprising mostly of various sorts of garbage and waste that wind up in oceans, seas, and other bodies of water. Marine debris can originate from both land-based (such as coastal areas, rivers, and metropolitan areas) and ocean-based (such as fishing, shipping, and offshore businesses) activities. Marine litter poses various significant issues for ecosystems, including threat to marine biodiversity, disruptions in ecosystem services, ecosystem degradation, ecological imbalances due to the introduction of invasive species, chemical pollution, as well as economic consequences for coastal communities reliant on tourism, fishing, and other marine-related industries. Shoreline assessments and beach clean-ups are critical components in addressing these issues.

Environmental Impact: Marine litter has a detrimental impact on ecosystems, as it can harm and kill marine life through ingestion and entanglement. It disrupts food chains and habitats, contributing to ecosystem imbalances and loss of biodiversity.

Human Health: Microplastics, which originate from larger plastic items that break down over time, can enter the human food chain through seafood consumption. Monitoring marine litter helps assess potential health risks associated with the ingestion of these pollutants.

Economic Consequences: Marine litter poses economic challenges for industries such as fishing, tourism, and shipping. Cleanup efforts and damage caused by litter can lead to substantial economic losses.

Aesthetic and Tourism Value: Litter can mar the beauty of coastlines and beaches, impacting tourism and recreation. Coastal communities often rely on tourism for their economic well-being.

Water Quality: Litter and pollutants leach into the water, affecting water quality. Monitoring is essential to track contamination levels and protect drinking water sources.

4.2. Why Marine Debris Survey (MDS)?

Conducting a marine debris survey is crucial for several reasons:
Assessing the extent of the problem: Shoreline surveys help in understanding the quantity, distribution, and types of marine debris present in a particular area. This information is vital for assessing the overall scale and impact of the issue. It allows researchers and policymakers to quantify the problem and develop effective strategies for mitigation.

Identifying pollution sources: By examining the composition and characteristics of the debris found on shorelines, it becomes possible to identify potential sources of pollution. This knowledge is crucial for implementing targeted measures to reduce or eliminate these sources, such as improving waste management practices or addressing specific industries responsible for the majority of marine debris.

Understanding ecological impacts: Marine debris can have severe ecological consequences. By surveying shorelines, scientists can assess the impact of debris on local ecosystems, including wildlife, habitats, and coastal vegetation. This information helps in evaluating the magnitude of ecological damage and formulating conservation plans accordingly.

Guiding clean-up efforts: Shoreline surveys provide valuable data for planning and executing clean-up operations. By identifying areas with high concentrations of marine debris, authorities can prioritize clean-up efforts in those locations, ensuring that limited resources are allocated effectively.

Monitoring progress and evaluating interventions: Regular shoreline surveys allow for the monitoring of long-term trends and the evaluation of the effectiveness of interventions aimed at reducing marine debris. By conducting surveys at regular intervals, changes in the amount and types of debris can be tracked, helping to measure the success of cleanup initiatives and policy interventions over time.

Raising awareness and advocacy: The data collected from shoreline surveys can be used to raise public awareness about the issue of marine debris. The visual representation of the problem and its local impacts can help engage communities, stakeholders, and policymakers, leading to increased support for measures to address marine debris pollution.

In short, the data generated through proper shoreline surveys in various regions will help developing a stronger monitoring network that support collecting robust data and science based policies. This shall help to evaluate the efficiency of existing polices to prevent marine debris, and create public awareness and engagement on the topic. Further, regular surveys will provide overview on spatial and temporal changes in debris in a particular geographic region. Further, this will help addressing local issues in a decentralised manner and to introduce the methods of survey based on local scenarios. Here we follow the Marine debris monitoring and shoreline survey guide of NOAA (Burgess et al., 2021).

4.3. Things to Remember Before Survey

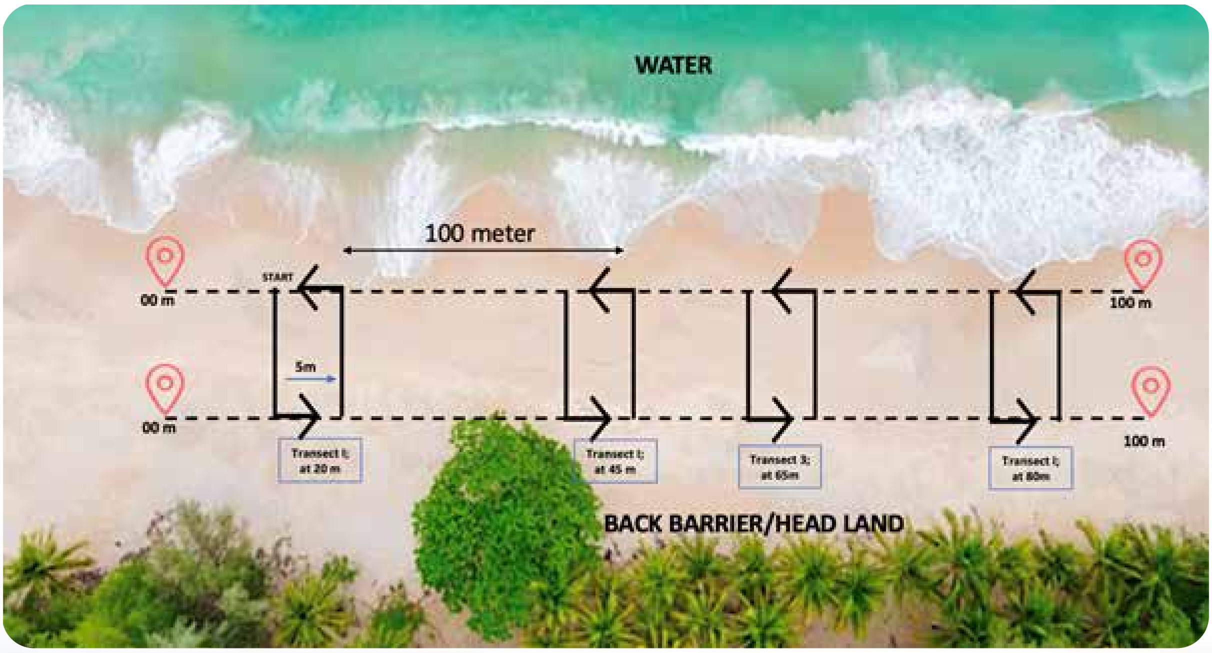
Camera/cell phone: To take photos of debris, the site, survey activities
GPS unit: To record GPS points of the survey site; you can also use mobile apps such as GPS Logger and Geo Tracker)
Tape: To measure the full 100-meter site length after establishment of the site.
Transect markers: To mark the beginning of each transect. Flags can be put up to mark the edges of the transect.
Datasheets: Survey sheet, copies of the Transect Survey Form.
Pencil: To write on datasheets (avoid pen as it may blot)
Containers: To collect debris items inside or outside the 100-meter transect.
Gloves: To keep your hands clean and protected
Weighing machine: To weigh the debris collected
Forms: Site Characterization Form, Transect Survey Form

4.4. Methods

4.4.1. How to select a site for survey?

This process should be done before the survey. Better to select a 100 meter shoreline as the site of your survey. The characteristics of the shore sites should be the following wherever possible (Fig. 1).

- The site should have direct access, without any hindrances for entry or survey.
- The area should be within a continuous section of shoreline, at least 100 meters in length parallel to the water, not interrupted by water (wave) or headland.
- Mark the end of the 100 meter area with a permanent landmark at the start or end to help
- Identify and return to the exact location over time



During each survey, four random transects are searched. In this example, transect 20, 45, 65 and 80 are shown. The team can select any transect. In each transect the path for walk along the perimeter of each transect is shown, from water front to back barrier and back.

4.5. Activity 1

4.5.1. Survey Site Characterization

Before beginning data collection, complete the Shoreline Site Characterization Form (Appendix 1). The purpose is essentially to describe the site characteristics. This will also help to repeat the surveys and to document the characteristic features of the area that ultimately influence the debris loading in the site.

This can be done by the coordinator of the program.

4.6. Activity 2

4.6.1. Transect Survey

Identify a team leader for each 100 meter zone. The team leader may mark the 100 meter area and randomly select the transect zone and mark them using flags or marks in beach using a stick.

Before the start of the survey, each team (in a 100 meter area) may assemble one copy of the Survey Coversheet and at least four copies of the Transect Survey Form. At site, label the sheet with details of district, beach, geocoordinates, segment (eg. I for first 100 meter, II for second 100 meter etc), transect numbers (eg. In each 100 meter, four transects at any 5 meter gap, eg. 0m, 5m, 15m, 25m, etc).
Each transect is 5 meters long parallel to the water. (Remember, there are possibilities of 20 transect within each 100-meter site, and you can select any random four). The transects can be numbered in five metre increments along the 100-meter site they begin (0, 5, 10, 15, 20, 25,……95, 100) (See Figure).

We require **four random transects in each 100 meter you survey.** The beach clean-up team may cover a total of 500 or 1000 meter area, depending on the situation of the beach.

There may be two members for each transect, one taking photos and identifying the items/using mobile app (Marine Debris Tracker of NOAA, downloaded from https://play.google.com/store/apps/details?id=edu.uga.engr.geolog.marinedebristrack&hl=en&gl=US), and the second person marking items in survey sheet.

Before survey, mark the beginning of each transect area with a flag or a mark. Take the GPS reading (you can use mobile apps for this purpose). Measure five meter rectangular transect area with a tape, parallel to the water (See Fig. 4).

4.6.2. How to search?

- Search from the water edge to the head land on the surface of the site and back. Do not dig for debris during the search.
- Walk along the edge of the transect and scan for debris within half of the transect (adistance of 2.5 meters to the center of the transect from where you are).
- Enter the transect only to collect debris for disposal.
- Walk along the entire perimeter of the transect and record items.
- Record these debris item counts in the main beach section on the back side of the Transect Survey Form.

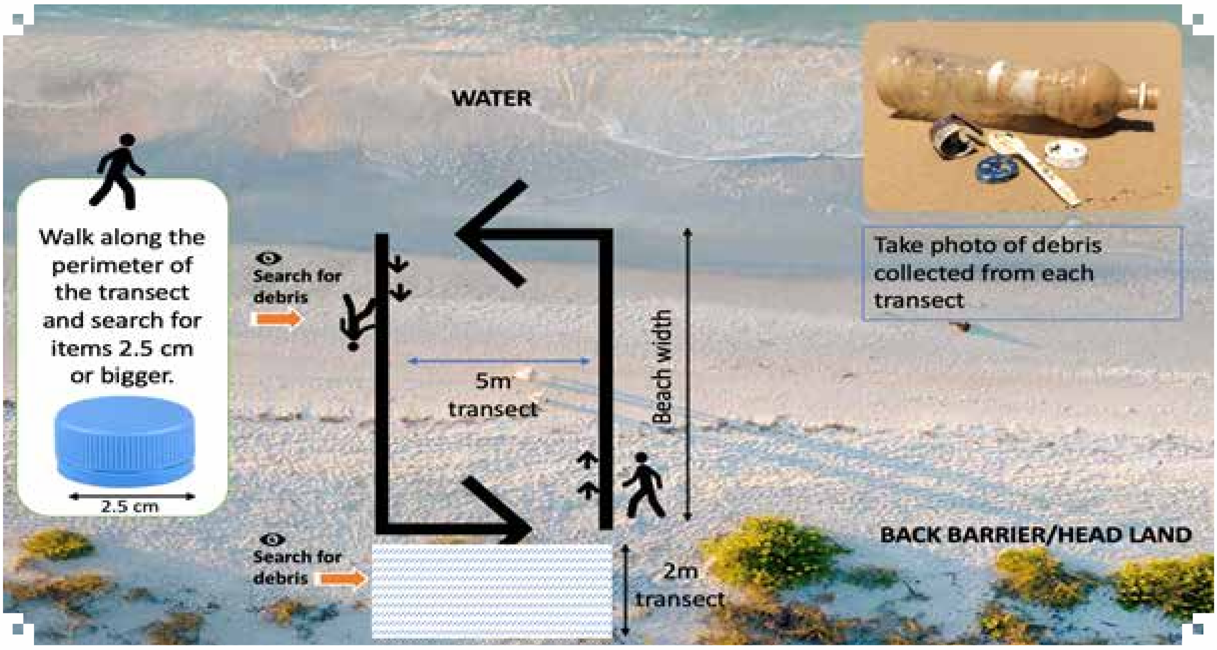
4.7. Activity 3

4.7.1. Survey the back barrier

If the site has a back barrier that can be surveyed (including back wall, dune, or vegetation), measure and search a distance of two meters into the back barrier. Stand at the edge looking into the back barrier, do not enter sensitive vegetation or unstable surfaces (Fig. 5). Record these counts in the back barrier section of the item counts side of the Transect Survey Form **(Appendix 2).**

4.7.2. Complete Transect Survey Forms

Complete both sides of the Transect Survey Form before proceeding to the next transect. This datasheet documents the conditions of the transect and quantifies debris loads by material and type. Look at **Appendix 3** of field guide to confirm the items.



First search for items in the beach by walking the perimeter of the transect (5 m width). Then search the back barrier (2 m length) just behind each transect. Record item counts in the main beach and back barrier sections of the Transect Survey Form.

4.8. Activity 4

Each team in a transect may collect all debris located within the transect, spread them in beach and take a photo using mobile and WhatsApp the picture with a message of transect zone and transect number to the coordinator.

The group leader may also take photos of the wide angle and close up image of the marine debris in the beach and WhatsApp the picture with a message of beach name to the coordinator.
Hand over the survey sheet to the group leader, and the group leaders may hand over this to the coordinator from University of Kerala.

4.8.1. What to Count?

- Only record items that measure at least 2.5 centimeters, or 1 inch (roughly the size of a bottle cap), in the longest dimension. Items smaller than 2.5 centimeters should not be counted, but their abundance can be documented with photos or notes. This is because on average, people can find most items that are 2.5 centimeters or larger within a 5 meter transect, but smaller items are less likely to be detected.
- If you have any doubt in identifying the item, do not enter, take the photo and send the photo to the coordinator.
- The debris items, for convenience are grouped under the following major seven categories:

(See Appendix 3)

i. **PLASTICS:** (Film, foam, bag, beverage bottle, caps, cups, food wrappers, straws, utensils, rings, cigar tips, lighters, buoys, fishing nets/lines, plastic balloons, personal care products (such as containers of cosmetics and oil, tooth paste, brush etc), syringe, toys and other plastics (any plastic items larger than 2.5 cm, which is unidentifiable and not in the categories above)

ii. **METAL:** (Metal fragments, aerosol cans, Aluminium/tin cans, other metal items (any fragments of metals above 2.5 cm, not in above categories and unidentified)

iii. **GLASS:** (Glass fragments, Beverage bottles, jars, other glass (any fragments of glass above 2.5 cm, not in above categories and unidentified)

iv. **RUBBER:** (Rubber fragments, latex balloons, flip flops or slippers, latex gloves, tires, other rubber (any fragments of rubber above 2.5 cm, not in above categories and unidentified)

v. **PROCESSED WOOD:** Cardboard cartons, wood in buildings, paper and card board, paper bags, other processed wood (any fragments of processed wood above 2.5 cm, not in above categories and unidentified)

vi. **FABRIC:** Fabric fragments, clothes and shoes, face masks, gloves (non-rubber), rope and nets (natural fibre such as coir), towels and kerchiefs, other fabric items (any fragments of processed wood above 2.5 cm, not in above categories and unidentified)

vii. **OTHER:** If the primary material type could not be identified or is not listed above, count the item as Other. It may include concrete pieces, plaster, fire crackers, a belt with leather and metal, etc.

4.9. Activity 5

4.9.1. Marine debris collection, delivery and group photo

Collect all the debris from the transect zones and the entire stretch of beach where the survey was undertaken. Sort plastics items separately wash them in sea water in gunny bags to remove the dirt and hand it over to the local body. The other debris items may be kept in sacs given and handed over. Before handing over the debris, the group leader will assist in weighing the total quantity of debris collected and its characterisation.

The group leader can arrange the volunteers for a group photo. The photo may be shared with all the volunteers and the coordinator.

4.10. Safety Instructions

Check local tide tables (if applicable) and plan to arrive during a low or outgoing tide. This provides a means of standardization and will avoid the tide encroaching on your activities.
Dress for the weather (rain coat during rainy days, cotton shirts during summer etc).

5. MICROPLASTIC ANALYSIS

Various sampling techniques have been employed for the water, sediment and biota samples for freshwater and marine habitats. Unless you standardize the techniques, one cannot proceed with further research as it may hamper your result. Samples can be collected from various sources like water, gut contents, tissue, sediments, effluents, sludge etc. Due to their lesser concentrations in various environments, sampling usually requires large volumes. Several researchers adopt different methods as a result; it is often difficult to compare the results of other work done. MPs occur in water columns and sediments at different depths hence locality of sampling is very important; also replicates should be taken in order to avoid errors, hence a minimum of three replicates are essential for the study.

5.1. Water

Samples from water can be taken manta/bongo/plankton nets of variable mesh sizes (preferably 300 µm) coupled with flowmeter which can be towed from freshwater, brackishwater as well as marine habitats. The volume of the samples filtered can be recorded with flowmeter at the open end of the net and microplastics can be calculated (items/gram) per unit water volume. Tidal actions, wind and current also influence the amount of water passing through the net, hence for water sampling calm water is preferred. Further, visual analysis can be made and large sized particles can be sieved out and digesting the organic matter if any using acid/alkali and later density separation with NaCl or ZnCl.

5.1.1. Collection of samples

Seawater (0–1 m depth) samples of 5 litres will be obtained using manta trawl nets of mesh size 330 µm; with a flowmeter (Hydro-Bios, Germany) fixed on the mouth of the net to calculate the filtered volume for sampling period of 30 min and GPS was recorded for each survey. The nets will be flushed with deionised water from top to bottom prior to the sampling. The material at the bottom of the net will be transferred into pre-cleaned 1L glass bottles and were washed with deionised water at least three times to the same bottle from each sampling location and sealed.

5.1.2. Materials required

- 30% hydrogen peroxide (H_2O_2)
- Technical grade (>98%) Sodium chloride (NaCl) of density 1.2 gm/ml is prepared
- Glass filter paper of pore size- 1.2 µm

5.1.3. Sample preparation

The seawater samples in the glass bottle were poured over a metallic sieve with pore diameters of 4.75 mm and transferred to clean beakers. To the subsamples of 100 ml, 30 ml of 30 % H_2O_2 was added to the beaker, and kept in oven at 60 °C for 48 h to digest the organic contents. The liquid in the beaker was transferred to a glass beaker for density separation by adding 1.2gm/ml NaCl (Quinn et al., 2016). The beaker was washed repeatedly with saturated NaCl to ensure thorough transportation of the particles to the density separator and was allowed to settle overnight. A filter paper of 1.2 µm was used to filter the supernatant. The MPs in the filter paper will be carefully taken using metal forceps and then subjected to the hot needle test (Devriese et al., 2015) for the initial confirmation step, and the MPs were characterized based on their size, shape and colour Li et al. (2015).

5.2. Biota

Here the tissue, the digestive tract, the faecal matter or even carcasses of seals, sea birds, cetaceans or any other animal can be used for analysis.

5.2.1. Collection of samples

Trawl nets and gill nets are employed for fish and shellfish, handpicking from substratum, chiselling with knife is also done, they can also be procured from market as soon as they are caught. One must be very careful while handling biota so as not to cause any stress or disturbance to the biota as they may egest or regurgitate MPs. For smaller invertebrates like zooplanktons may be collected using plankton nets. Sea grass and algae can be collected by diving.

5.2.1.1. Algae and sea grass

Blades of algae and sea grass were collected and brought to the laboratory site were carefully taken out, measured and weighed and are used for microplastic analysis.

5.2.1.2. Zooplanktons

Since they are small in size whole organism is used for MP analysis. Zooplanktons were thoroughly rinsed with deionised water to remove any adhering MPs if any from their body and then undergo usual digestion protocols.

5.2.1.3. Shellfish

The total length, width and muscle tissue and weight of the alimentary canal and gills of shellfishes are noted, which are analysed for MPs.

5.2.1.4. Sea cucumber

They are suspension feeders or deposit feeders usually found in organic-rich sediment regions that may absorb microplastics (Mohsen et al. 2019). The specimens procured are thoroughly rinsed with deionised water and its intestine and oral tentacles are subjected to digestion.

5.2.1.5. Fish

The total length, sex, weight of the biota and other tissues or body parts are determined. Gastroinstestinal tract, muscle tissues, gills, liver and kidney can be used for microplastic analysis.

5.2.1.6. Sea birds

The entire alimentary canal, muscle tissues and hepatopancreas of the birds can be analysed for MPs, and its weight noted.

5.2.2. Sample preparation

Samples of biota procured from various sites are washed in deionised water to remove debris and kept in glass boxes and then placed in an ice box and taken to the laboratory for further analysis. The biota will be photographed, identified, labelled, weighed and measured to the nearest centimetre.
The fish and shellfish will be dissected and GI tract will be taken out and measured to nearest millimetre, weighed and the concerned body part is frozen, dried or sometimes even kept in formalin until further analysis. The shellfish will be photographed, identified, measured and weighed to the nearest millimetre; gills and abdomen of shell fish were taken separately and kept in glass bottles and labelled. The portion taken for study is wholly digested with acid, alkali, oxidizing agents or enzyme depending upon the biota (Lusher et al., 2017). To the samples will be added 10 % KOH and kept at 60^{0}C for 48 hours for digestion (Dehaut et al., 2016). After complete digestion, the samples were processed using a vacuum pressure pump using filter paper of 1.2µm; later, filter paper is air

Microplastics harm freshwater fauna

dried, and MPs were detected under a stereo zoom microscope and image is captured with Leica Application Suit software.

5.2.2.1. Sediments

Here size of the particle and organic matter is more important. When collecting sediments from the beach, high tide line where floatsam aggregate is the most frequently sampled area.

5.2.2.1.1. Collection of samples

A preferred area is sampled using quadrats. Sediments from different depth can be sampled as we can know the concentrations of MPs at multiple depths as varying depth may carry different amount of MPs. Van Veen grabs are also used to collect sediment samples from shallow waters to deep sea (Vianello et al., 2013; Van Cauwenberge et al., 2013a; Lusher and and Mendoza-Hill, 2017). Sediments are obtained from the bottom using Van Veen grab sampler (area 0.1m2) and GPS will be recorded for each survey from the beach (hightide line and above hightide line). Depth core must be in between 4–5 cm deep so that we can to assess the standing stock of microplastics in marine sediments (Martin et al., 2017). From a single sample, several subsamples will be made and analyzed for data. For superficial sediments grabbers or box corers could also be used. All the samples should be kept in glass bottles to prevent contamination. The collected samples can be sieved with a mesh size of 4.75 mm, to remove larger particles, later samples are frozen at -200C or dried until further analysis.

5.2.2.1.2. Materials required

30% Hydrogen peroxide (H_2O_2); technical grade (>98%) Sodium chloride (NaCl) of density 1.2 gm/ml; glass filter paper of pore size: 1.2µm

5.2.2.1.3. Sample preparation

The sediment samples taken in a glass beaker and covered with petri dish is dried in an oven at 60^0C for 24 hrs and later each subsample will be suspended in deionized water and digested using of 30% H_2O_2 and kept for 72 hrs at 40^0C to digest the organic materials. Further 1.2gm/ml of NaCl is added to the samples for density separation and stirred using a glass stirrer for 15 mins. After 24 hrs, the supernatant was filtered using a vacuum pump with a filter paper of pore size 1.2 µm. The MPs of size <5000 µm thus obtained in the filter paper will be kept in a petri dish and examined under stereo zoom microscope (Leica EZ4 D) and its length and diameter measured as well as photographed. The method of extracting microplastics from effluents and sludges is similar to that of water and sediments.

5.2.2.2. Seagrass/algae

5.2.2.2.1. Materials required: Glass vial, scalpel

5.2.2.2.2. Sample Collection

Seagrass/algal samples were procured by using a quadrant of 1 m^2 and taken every 10 m across 100 m transect line with replicates (n=20) (Jones et al., 2020). Sampling site was recorded using GPS. Thus, approximate sea grass abundance was made, so that we can recognize the association between MP load and sea grass coverage. Seagrass blades were removed from both sides of transect from every 10 m, hence a total of sea grass blades 60 numbers were taken and were kept in zip-lock pouches which were thoroughly rinsed with deionised water separately. Within the quadrat, the percentage cover of seagrass was determined by visual estimation using existing Seagrass-Watch percentage cover recommendations (McKenzie et al., 2001). The height of the seagrass was determined by measuring five seagrass shoots inside each quadrat from the base of the shoot to the tip of the leaf (without considering the highest shoots) and calculating an average height.

5.2.2.2.3. Sample preparation

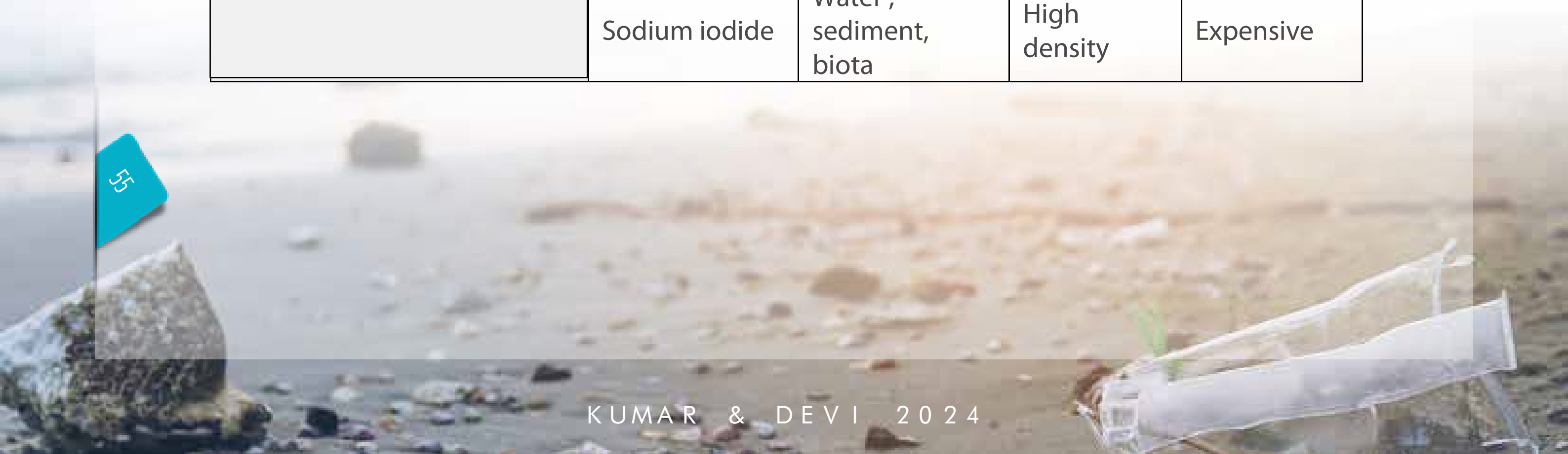
In the laboratory, the sea grass samples were kept in a clean petri dish using a sterile steel forceps and washed with 35 ml of deionised water and length of the blade was measured. They are transferred to a sterile 50 ml centrifuge tube and vigorously shaken for 30s. The samples were then transferred to a steel tray and each blade is scraped with the blunt end of the scalpel in order to separate MPs if any. Finally, the blades are rinsed with deionised water which is also added to the scraped particles and stored in petri dishes for vacuum filtration.

5.3. Digestion of the samples using different reagents

The organic materials in the samples can be digested by acid, alkali or oxidizer by adding common solvents like H_2O_2, KOH, NaOH, HNO_3 and $HClO_4$ or with a combination of these solvents. Digestion with HNO_3 destroys most of the organic matter when compared to HCl, H_2O_2 and NaOH and HCl the weakest (Table 2). Acid or enzymatic digestion is more acceptable for nanoplastics. In case of alkali, KOH is a better choice for MP digestion as they are resistant to most of the polymers when compared to NaOH. The use of H_2O_2 is advisable only in lesser percentage as the plastic becomes thinner. Also, some of the plastic polymers like polyoxymethylene, polyamide polycarbonate etc react with strong acidic or alkaline solutions; hence the more favorable approach is the enzymatic digestion put forth by Cole et al. (2014) using proteinase-K. Different eznymes like chitinase, lipase, amylase and proteinase which are not poisonous can also be used for digestion as the organic matter will get degraded at its maximum. But they are expensive and effort needed is more.

Table 2. Comparison of different methods of sample preparation

Methods		Materials Used	Performed on	Pros	Cons
Organic digestion	Acid digestion	HNO_3, HCl	Water, sediment and biota	Most organics destroyed	Incomplete digestion in HNO_3
	Alkaline digestion	NaOH, KOH	Water , sediment and biota	Most organics destroyed	Polymers like PET, PVC etc gets degraded in case of NaOH
	Enzymatic degradation	Cellulose, lipase, chitinase, protease, proteinase-K	Water , sediment, biota	Most organics destroyed	Expensive, time-consuming enzyme specific for samples
	Oxidising digestion	H_2O_2	Water , sediment, biota	Most organics destroyed	Some polymers affected
Density separation		Sodium chloride	Water , sediment, biota	Cheap, no toxic effects	All polymer types not identified
		Sodium tungstate	Water , sediment, biota	Cost effective, high density	
		Sodium polytungstate	Water , sediment, biota	High density	Expensive
		Potassium formate	Water , sediment, biota	Cost effective, high density	Hygroscopic
		Zinc chloride	Water , sediment, biota	Not expensive, high density	High density
		Sodium iodide	Water , sediment, biota	High density	Expensive



5.4. Methods of Microplastics Analysis

Until far, the sampling and preparation of samples has varied greatly between laboratories. Standard methods for microplastic analysis are still being developed, and a variety of methodologies are presently utilized to identify microplastics (Renner et al., 2018). This uneven profusion of approaches makes it difficult to compare microplastic studies and in appraising its significance and hazards.

5.4.1. Density separation

Sometimes even after digestion, some of the organic matter still remains, which can be separated through density separation. Here the sample is mixed with highly concentrated or saturated salt solution and shaken thoroughly. Most of the plastics have low density, hence float on the surface and can be separated using a funnel and filter paper. NaCl, NaI, ZnCl2, (K(HCOO)) and filtered canola oil are similar substances with high density which can be employed for density separation. This technique is mostly adapted for MPs in sediment samples.

The particles obtained by these treatments need not always be microplastics, hence hot needling technique can be adopted for confirmation of plastic particles. Several organic and inorganic adherants as well as biofilms have to be getting rid of from its surface which will interfere with sophisticated instrument analysis reading.

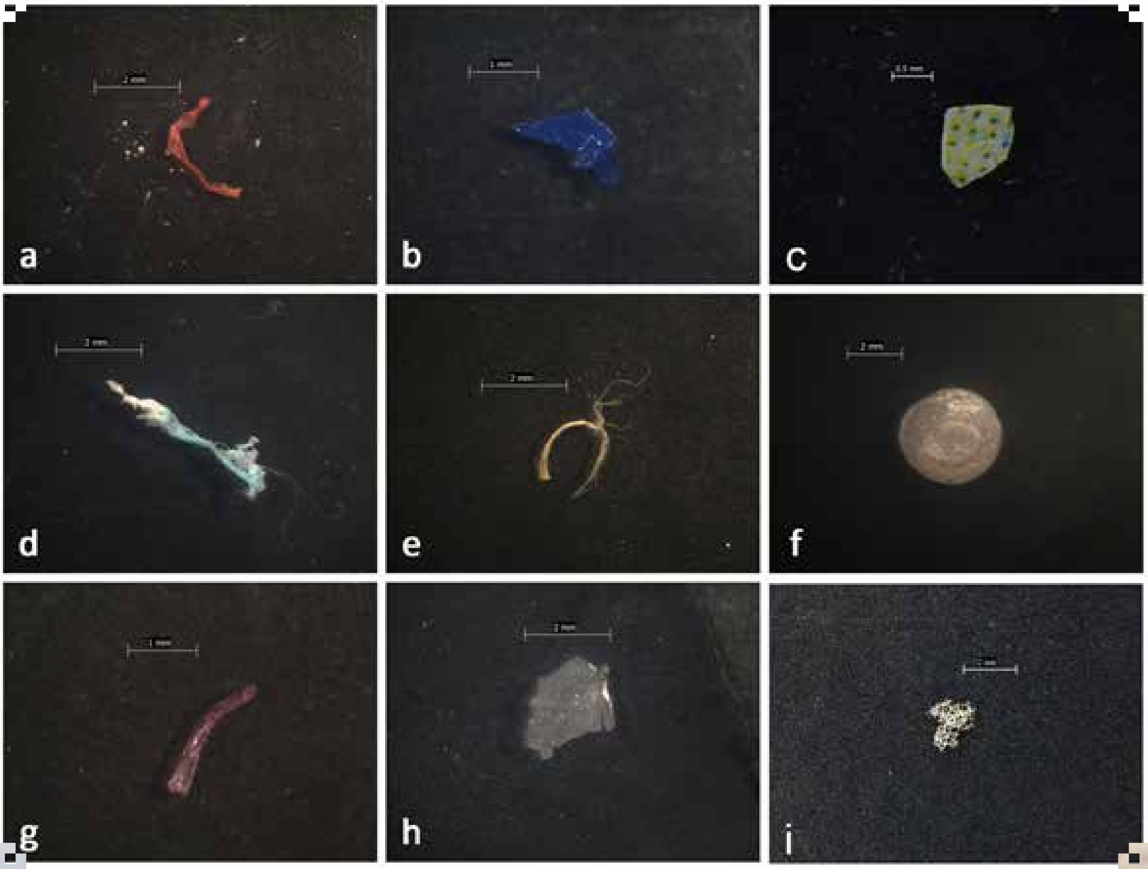
Soon after this process, visual sorting is done under stereozoom dissection microscope, the number, colour and morphology of MPs are noted. Later, microplastics can be determined by their characteristics, polymer composition and density, by spectroscopic, chemical or thermoanalytical approaches.

5.4.2. Separation of microplastics from samples

The samples collected always contain organic and inorganic matter which needs to be eliminated prior identifying the plastic polymer. So, after digestion and density separation, the supernatant is vacuum pumped and filtered using a whatmann filter paper of pore size 1.2µm. The filter paper is dried in an oven and examined under a stereozoom microscope and MPs were recovered with the help of metal forceps and placed in silicon glass slides and covered with cover glass and kept in slide box for further analysis. Different polymers have different densities; the density of PET and PVC ranges between 0.8- 1.4 g cm^{-3}. Density separation can be done with solutions of Zinc, calcium or strontium chloride, NaCl and sodium polytungstate of varying densities, out of which zinc chloride is the most recommended one because of various reasons.

Like we mentioned earlier in the book, MPs can be classified based on their shape. Wide spectra of colours are also reported in MPs which can be furthur examined for the colourants and the chemicals added to it.

Separation of microplastic techniques- a: Digestion of samples; b: Filtration of digested samples; c: filtrate enclosed in petri dish; d: detecting and sorting microplastics through Leica S9i stereozoom microscope



Microplastics: a to c - film; d, e- fiber; f - pellet; g, h - fragment; i- foam

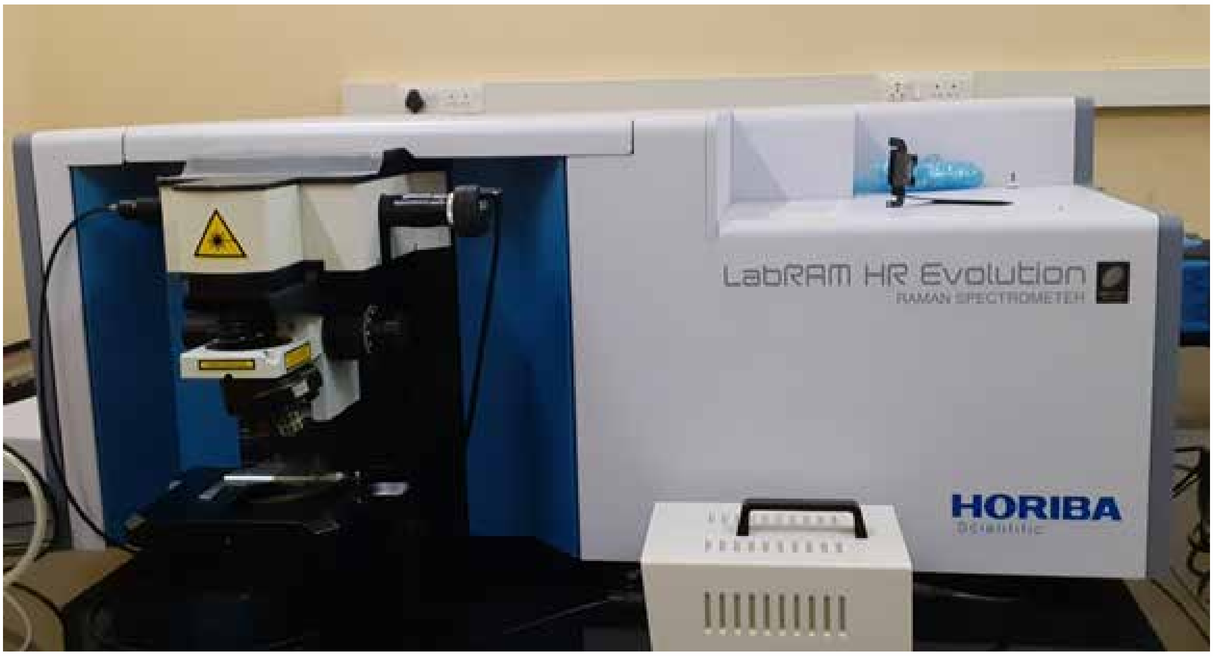
5.4.3. Identification of microplastics by chemical composition

The characterisation of the emerging environmental contaminants MP is a more complex process comprising different methods. One such method is C:H:N analysis, in which the samples are placed in distilled water based on their density, ethanol or concentrated calcium or strontium chloride is added till they become buoyant and the density evaluated by weighing certain volume of the solution. Polymers coming under different group have particular elemental composition with which we can identify the plastic origin by further undergoing C:H:N analysis. Hence by doing this analysis one can compare the densities and C:H:N ratios of the samples and can conclude whether the material is plastic or not and it could be allocated into a particular group of polymers. This method does not undergo any chemical analysis, consumes time and not appropriate for smaller particle.

Common technique adopted by researchers globally include two techniques namely, Raman and Fourier transform infrared (FTIR) spectroscopy. Spectroscopy is used to identify the chemical structure of polymers by comparing their emission spectra or absorption spectra with the reference spectra. FTIR works on the principle of attenuated total reflectance (ATR-FTIR). The most reliable and commonly used is the infrared (IR) or the Fourier transform infrared spectroscopy (FTIR) which identifies particles of size ranges 10-20µm. Any dirt in the sample may give improper result. When a sample is subjected to infrared radiation, it excites the molecular vibrations of the sample which is dependent upon the composition and molecular structure of the sample. The energy produced as a result of this radiation in turn excites a particular vibration which is absorbed to a certain extent that helps in measuring the characteristic IR spectra. Plastic polymers have IR spectra with clear bands which are specific and considered as a very good feature of this technique. The advantage of FTIR when compared to Raman is that large particles can be identified and its disadvantage is if you try to measure the IR spectra of very small plastic particle of irregular size, then the reflectance mode may yield spectra which are unable to interpret as a result of refractive error and the transmittance mode requires IR transparent filters due to its total absorption capacity.

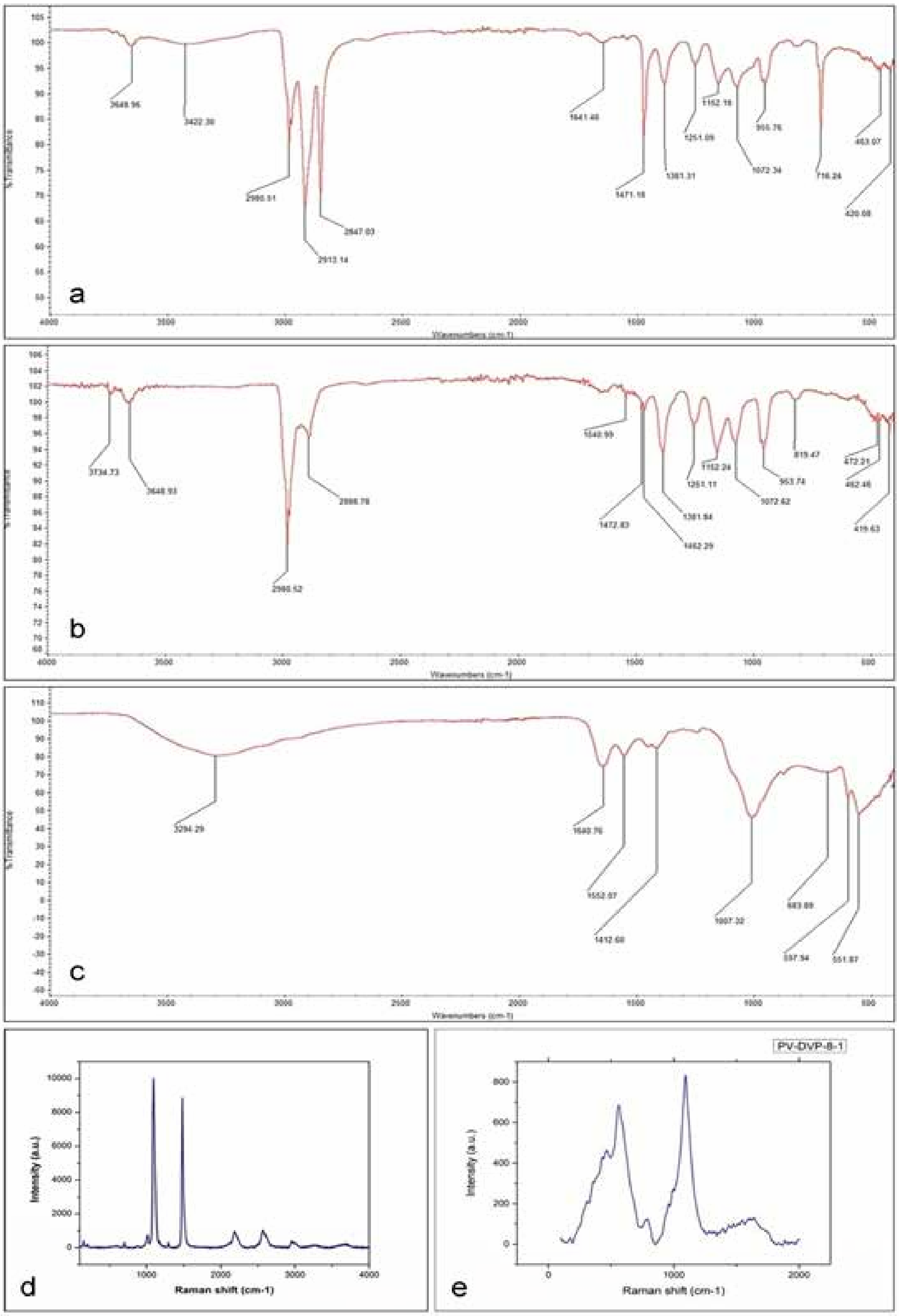
Nicolet iS50 ATR-FTIR Spectroscopy (Thermo Fischer)

Raman spectroscopy which works on interference helps in identification of the particles of much smaller size; within 1-20 µm. Molecular vibration is inactive here. Here the sample undergoes irradiation with monochromatic laser source ranging from wavelengths from 500-800 nm. As a result of this there will be difference in the frequency of the backscattered light of the atoms and molecules of the samples which can be detected as Raman shift and can be read as Raman spectra. Thus, by comparing with a reference spectrum we can identify the plastic polymers. In micro-Raman spectroscopy particle size below 1µm can be identified. To detect the polymer particles in the biological tissues, Raman spectroscopy can be integrated with con focal laser-scanning microscopy. Raman spectra of fluorescent samples when excited by laser cannot be generated which is its disadvantage. Thus, in order to measure fluorescent samples, they should be purified for the correct identification of the polymer. Even though FTIR and Raman spectroscopy are expensive, they are considered as supporting techniques as they can provide reliable results, hence used as diagnostic tools.



Raman Spectrometer (HORIBA Scientific)

Even the degradation products of polymers and the chemical composition of the microplastics can be identified with thermoanalytical methods where the samples are pyrolysed under inert conditions. Pyrolysis-gas chromatography (GC) when combined with mass spectroscopy (MS) yields specific pyrograms which helps in identifying the polymer type. For this method microplastics are extracted from the sediment samples and sorted out and then the polymer is identified by comparing the degradation products with respective pyrograms in the reference pyrograms of known virgin polymer samples. The only drawback of this method is that the microparticles have to be kept in the pyrolysis tube manually and that too of a certain minimum size. Only one particle can be run at a time, hence large number of samples cannot be run simultaneously.



ATR-FTIR spectra of plastic polymers: Polyethylene (PE), Polypropyene (PP), Nylon 6, Polyvinylchloride (PVC), Polyethylene terephthalate (PET), Polystyrene (PS). Source: Devi et al., 2024

Although scanning electron microscopy is also used for identification of microparticles using surface morphology, it is not very common. SEM coupled with EDS can distinguish MPs from fish scales and other substances. For NPs; SEM, TEM, Confocal laser scanning microscopy (CLSM) as well as other electron microscopy techniques are employed. Even then, identifying NPs from fish matrix is very difficult as they have similar densities and chemical composition. Another emerging method is that of pyrolysis GC-MS in which the chemical composition of microplastics by thermal decomposition is done and the gaseous products are also analysed. Each of the above suggested methods have their own size limits.

SEM EDX (Carl Zeiss Evo-18)


Pepsodent

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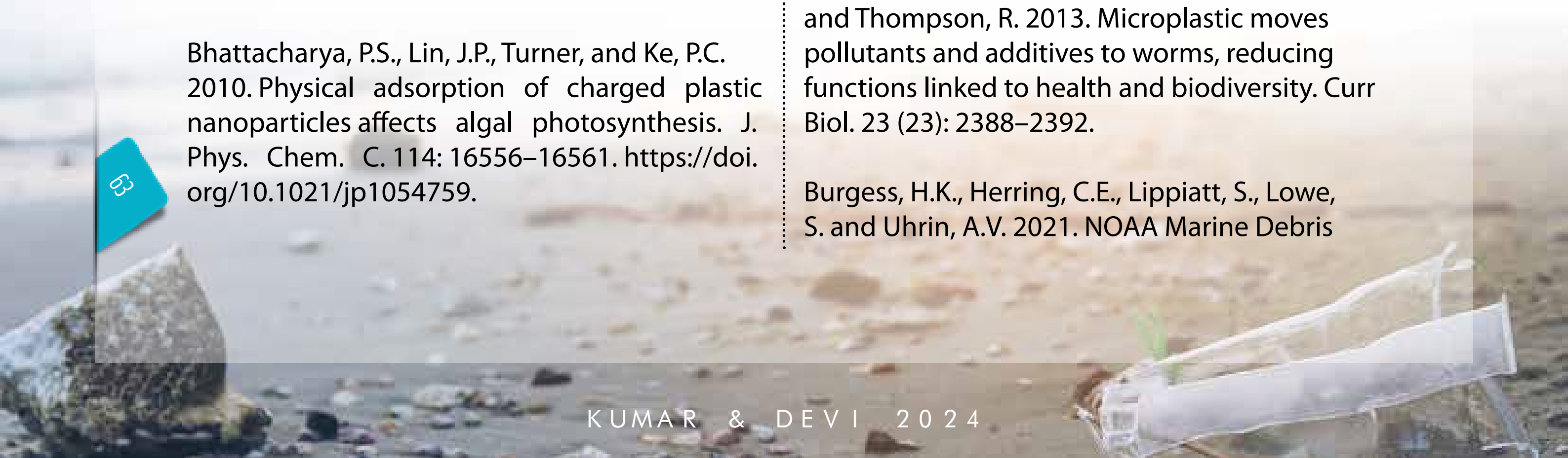

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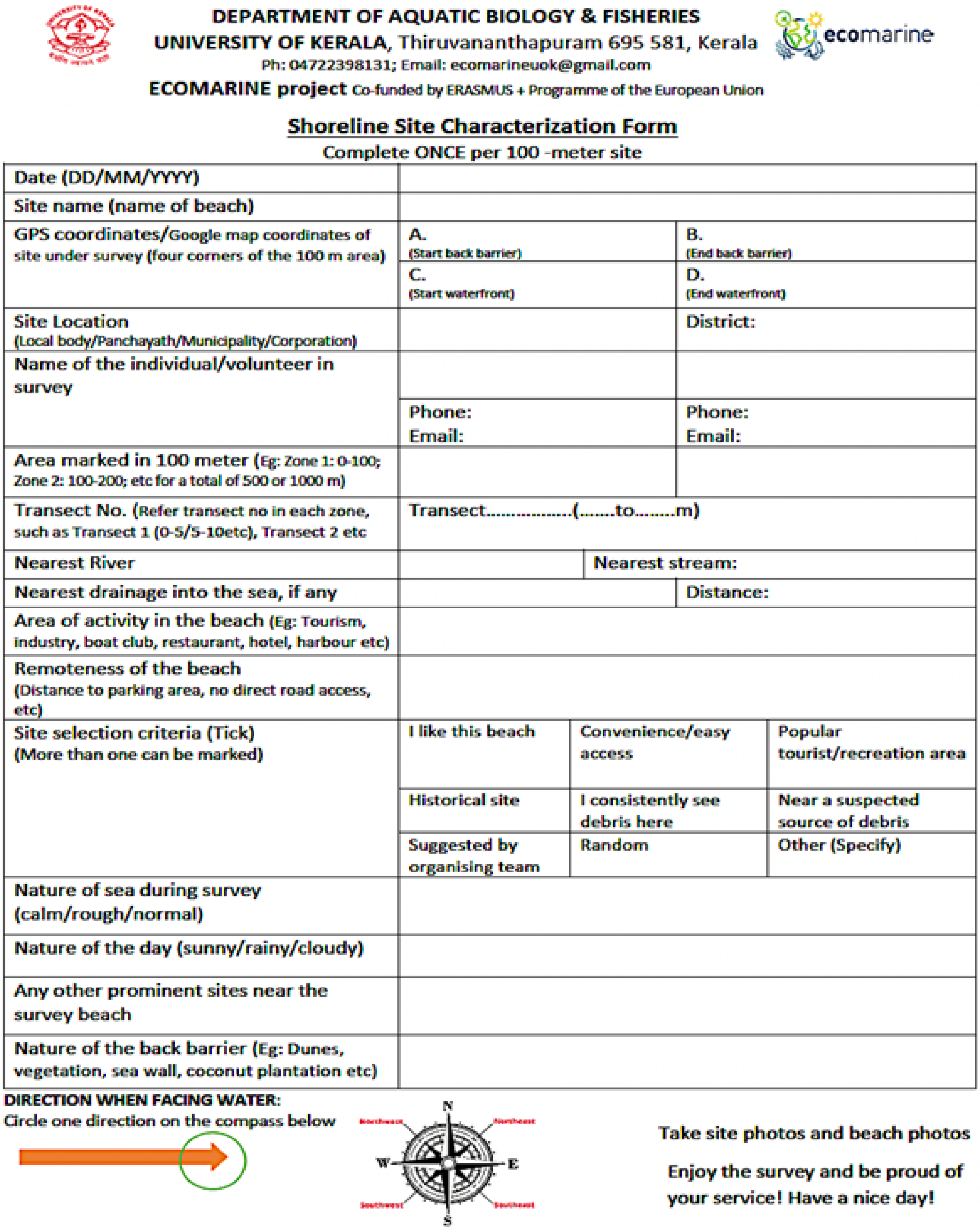
APPENDICES

Appendix 1
Site Characterization Form



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Shoreline Site Characterization Form

Complete ONCE per 100 -meter site

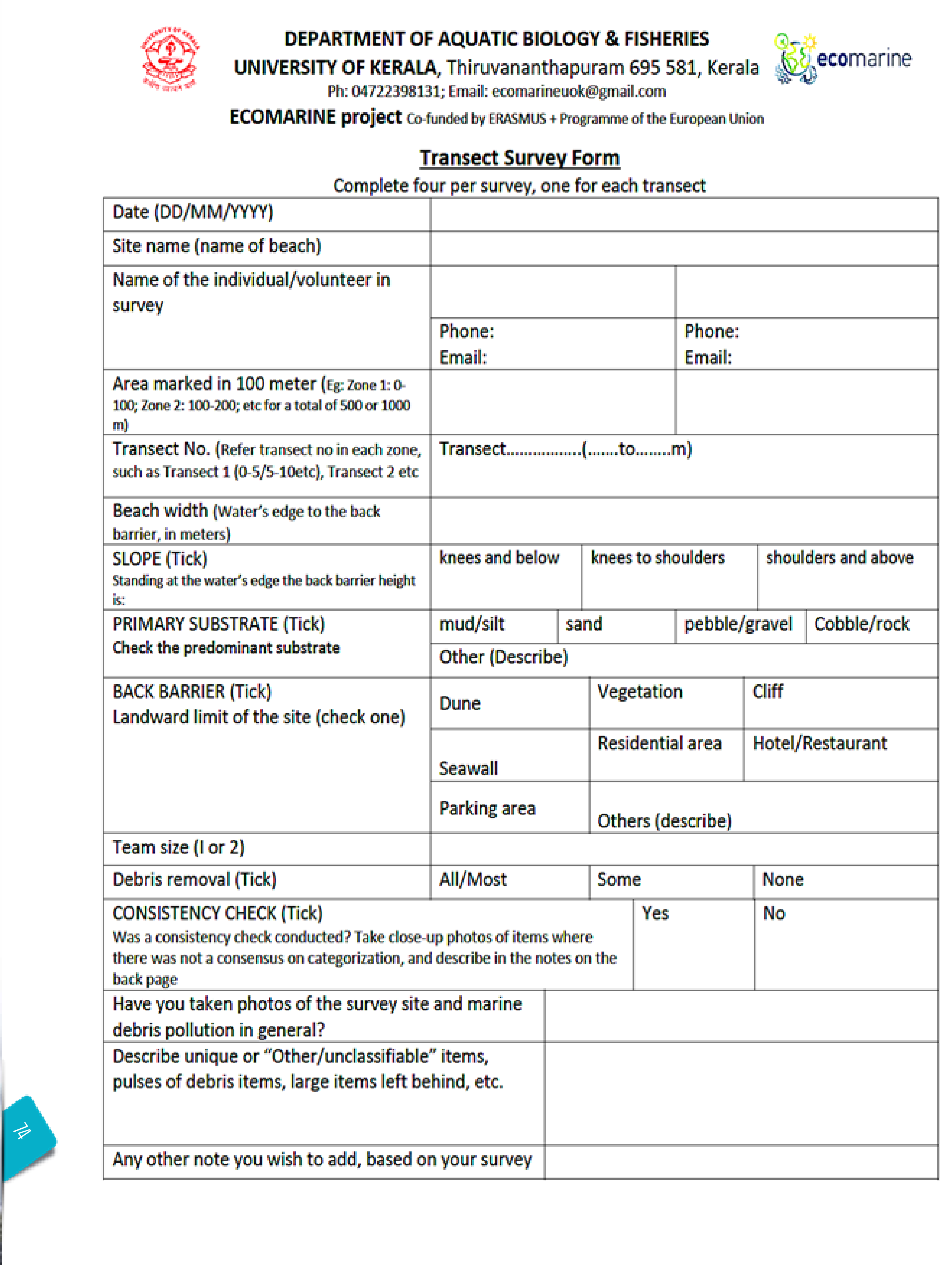
Date (DD/MM/YYYY)			
Site name (name of beach)			
GPS coordinates/Google map coordinates of site under survey (four corners of the 100 m area)	A. (Start back barrier)	B. (End back barrier)	
	C. (Start waterfront)	D. (End waterfront)	
Site Location (Local body/Panchayath/Municipality/Corporation)		District:	
Name of the individual/volunteer in survey			
	Phone: Email:	Phone: Email:	
Area marked in 100 meter (Eg: Zone 1: 0-100; Zone 2: 100-200; etc for a total of 500 or 1000 m)			
Transect No. (Refer transect no in each zone, such as Transect 1 (0-5/5-10etc), Transect 2 etc	Transect.................(.......to........m)		
Nearest River		Nearest stream:	
Nearest drainage into the sea, if any		Distance:	
Area of activity in the beach (Eg: Tourism, industry, boat club, restaurant, hotel, harbour etc)			
Remoteness of the beach (Distance to parking area, no direct road access, etc)			
Site selection criteria (Tick) (More than one can be marked)	I like this beach	Convenience/easy access	Popular tourist/recreation area
	Historical site	I consistently see debris here	Near a suspected source of debris
	Suggested by organising team	Random	Other (Specify)
Nature of sea during survey (calm/rough/normal)			
Nature of the day (sunny/rainy/cloudy)			
Any other prominent sites near the survey beach			
Nature of the back barrier (Eg: Dunes, vegetation, sea wall, coconut plantation etc)			

DIRECTION WHEN FACING WATER:
Circle one direction on the compass below

Take site photos and beach photos

Enjoy the survey and be proud of your service! Have a nice day!

Appendix 2
Transect Survey Form



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Transect Survey Form

Complete four per survey, one for each transect

Date (DD/MM/YYYY)				
Site name (name of beach)				
Name of the individual/volunteer in survey				
	Phone: Email:		Phone: Email:	
Area marked in 100 meter (Eg: Zone 1: 0-100; Zone 2: 100-200; etc for a total of 500 or 1000 m)				
Transect No. (Refer transect no in each zone, such as Transect 1 (0-5/5-10etc), Transect 2 etc	Transect................(.......to........m)			
Beach width (Water's edge to the back barrier, in meters)				
SLOPE (Tick) Standing at the water's edge the back barrier height is:	knees and below	knees to shoulders	shoulders and above	
PRIMARY SUBSTRATE (Tick) Check the predominant substrate	mud/silt	sand	pebble/gravel	Cobble/rock
	Other (Describe)			
BACK BARRIER (Tick) Landward limit of the site (check one)	Dune	Vegetation	Cliff	
	Seawall	Residential area	Hotel/Restaurant	
	Parking area	Others (describe)		
Team size (I or 2)				
Debris removal (Tick)	All/Most	Some	None	
CONSISTENCY CHECK (Tick) Was a consistency check conducted? Take close-up photos of items where there was not a consensus on categorization, and describe in the notes on the back page	Yes	No		
Have you taken photos of the survey site and marine debris pollution in general?				
Describe unique or "Other/unclassifiable" items, pulses of debris items, large items left behind, etc.				
Any other note you wish to add, based on your survey				

ITEM COUNTS (2.5 centimeters or larger) **SEARCH TIME: .... to...**

PLASTIC	**Main beach**	**Barrier**	**METAL**	**Main beach**	**Barrier**
Film			Metal fragments		
Foam			Aerosol cans		
Other hard fragments			Aluminium/tin cans		
Bags			Other metal		
Beverage bottles			**GLASS**	**Main beach**	**Barrier**
Bottle or container caps			Glass fragments		
Cups (incl. polystyrene/foam)			Beverage bottles		
Food wrappers			Jars		
Other jugs & containers			Other glass		
Straws			**RUBBER**	**Main beach**	**Barrier**
Utensils			Rubber fragments		
Cigar tips/ Cigarettes			Balloons (Rubber)		
Disposable lighters			Flip flops/Slippers		
Buoys & floats			Gloves (rubber)		
Fishing lines/nets			Tires		
Balloons (plastic)			Other rubber		
Personal care products			**PROCESSED WOOD**	**Main beach**	**Barrier**
Other plastics			Cardboard cartons		
FABRIC	**Main beach**	**Barrier**	Building waste		
Fabric fragments			Paper & cardboard		
Clothing & shoes			Paper bags		
Face masks			Other processed wood		
Gloves (non-rubber)			**OTHER ITEMS**	**Main beach**	**Barrier**
Rope & nets (natural fiber)					
Towels & rags					
Other fabric					

Appendix 3

Marine Debris Categorization Guide

1. PLASTICS


Form fragment


Bag


Cap


Cup


Food wrap


Straw


Utensil


Ring


Cigarette tip


Cigarette lighter


Buoys item


Fishing nets

Personal care product

Hard fragment

Beverage bottle

Container cap

Container

Rope

Plastic toy

Plastic balloon

Tooth paste

Syringe

2. METALS


Metal fragment


Metal can


Aerosol can

3. GLASS


Glass fragments


Beverage bottle


Glass bulb

4. RUBBER


Tube


Latex glove


Latex Balloon


Flip flop


Other rubber

5. PROCESSED WOOD

Cardboard carton

Paper

Paper bag

6. FABRIC

Fabric fragment

Clothing

Face mask

Cloth bag

Rope (natural fiber)

Other fabric

7. OTHER ITEMS

Battery fragment

Leather item

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"Comprehensive Guide to Monitoring Marine Litter and Analysing Microplastics in Aquatic Ecosystems" serves as an indispensable resource that unravels the pervasive issue of plastics and their profound impacts on aquatic ecosystems, especially our oceans. From an introduction to marine microplastics and their detrimental effects on a wide range of organisms to an in-depth exploration of marine debris survey methods, this guide is a treasure trove of knowledge for researchers, civil society organisations, and volunteers alike.

Discover diverse survey techniques, meticulously detailed activities, and essential methodologies for analysing microplastics across various marine taxa. Each chapter is crafted to enhance your understanding and effectiveness in cataloguing and tackling marine litter. The guide also includes forms for surveys and a comprehensive photo guide to identifying common marine debris items, making it an invaluable tool for beach clean-ups and research initiatives.

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