



RESEARCH ARTICLE

Open Access



On the interaction of buoyant plastic debris and sea-surface layer organisms

Renjith VishnuRadhan^{1*} , Shagnika Das¹, Saumya Raj¹, Ashley Brereton^{2,3} and Luisa Galgani^{4,5}

Abstract

Surface ocean plastic and microplastic concentration have intensified in the past decade, bringing multiple potential adverse effects to ecosystems. This increased presence and related persistence of plastics in the marine environment pose questions about their interaction with sea-surface organisms, which are usually impacted by hazardous chemical leachates. Coastal regions, as entry pathways of most plastic litter through mismanaged plastic waste on land and river runoff, are zones of high plastic accumulation. The interactions of free-floating marine organisms and buoyant plastic debris (BPD) are identified as one of the issues of concern that would potentially harm future global biodiversity, needing immediate public attention and action. This article addresses emerging and underexplored ecological impacts of the plastic problem by focusing on the interaction of the sea surface layer pelagic community with BPD. The plastic litter and their macro and micro variants harbor organisms of diverse lineage, and this nursing stimulates direct behavioral and physiological changes that are able to alter the structure and the composition of a community. Such BPD-induced alteration impairs elementary traits of the most diverse group of bio-indicator and keystone organisms, such as buoyancy mechanisms and bio-physical coupling behaviors. Subsequently, such crucial impacts on remarkable eco-indicator organisms can potentially generate novel marine environmental challenges. Policy interventions on such ubiquitous nexus of BPD and sea-surface dwelling organisms that potentially disrupt crucial ecological indicators are necessary to tackle the associated social, environmental, and economic impacts.

Keywords Plastic pollution, Marine ecology, Evolution, Buoyant plastic debris, Sea-surface organisms

1 Introduction

Plastic materials are pervasive in every environmental compartment and matrices (Zalasiewicz et al. 2016). The anthropogenic production, usage, and mismanagement of plastic materials since 1950 have led to their leakage and accumulation in the Earth system in various forms and eventually manifested into a wicked environmental

problem. Coastal regions are the gateways of plastic input into the marine environment. The plastic pollutants and their root causes are difficult to tackle due to their intrinsic interactions with the prevailing socio-economic systems. Plastic is known to peril marine and freshwater ecosystems and is often identified as a planetary boundary threat (Villarrubia-Gómez et al. 2018; Borrelle et al. 2020). Buoyant plastic debris (BPD) is floating plastic materials that account for a significant portion of plastic pollution in aquatic environments (Sebille et al. 2015), and it is emerging as a tragedy of commons (Vince and Hardesty 2018). BPD is responsible for various ecological and biogeochemical implications ranging from species invasion to climate change (VishnuRadhan et al. 2019; Haram et al. 2023). Along with other organic drifting material, BPD is known to support a range of diverse taxa, such as barnacles, mollusks, decapods,

*Correspondence:

Renjith VishnuRadhan
renjithvr@amity.edu

¹ Centre for Marine Science and Technology, Amity Institute of Biotechnology, Amity University Uttar Pradesh, Noida 201301, India

² Lawrence Berkeley National Laboratory, 1 Cyclotron Rd, Berkeley, CA 94720, USA

³ Institute of Marine Sciences, University of California, Santa Cruz, CA, USA

⁴ Department of Biotechnology, Chemistry and Pharmacy, DBCF, University of Siena, Via Aldo Moro 2, 53100 Siena, Italy

⁵ National Biodiversity Future Center (NBFC), Palermo, Italy



and bryozoans, and they are often regarded as “floating islands” that can travel substantial distances (Jokiel 1990; Kiessling et al. 2015; Póvoa et al. 2021) and can support significant ecological shifts in the marine environment (Haram et al. 2021). Furthermore, among the wide range of organisms that harbor on these buoyant substrates, a considerable proportion of organisms are non-native and often increase the dominance of invasive species (Rech et al. 2018; García-Gómez et al. 2021; Chong et al. 2023), leading to colonization of organisms beyond their normal geographical limits (Zong 2021).

Currently, our understanding of BPD and its interaction with the marine ecological realm is uncharted beyond species invasion and substrate colonization of exotic species. BPD is not distributed equally throughout the oceans, and they tend to gather in specific regions known as “garbage patches” or “plastic gyres” which are areas of high surface accumulation of plastic and other marine debris (Ryan 2015; Lebreton 2022). Radical measures to tackle BPD, such as cleaning the ocean garbage patches, have led to ongoing controversies about altering the ambient ecosystem processes in the near-surface oceanic layers (Spencer et al. 2023). Marine debris is already known to alter the upper ocean physical processes (VishnuRadhan et al. 2019) and a recent study showed its effect on primary productivity and carbon chemistry (Kumar et al. 2024). Marine plastic litter substantially impacts biodiversity by inducing physical harm to larger organisms and enhancing the spread of non-native species and pathogens (Lincoln et al. 2022). Plastic waste and related chemicals have an impact on the marine food web, even though the effects of plastic trophic transfers are not fully known (Tuuri and Leterme 2023). Some recent investigations have highlighted the impacts of BPD on surface dwelling organism ecology (Egger et al. 2022; Lacerda et al. 2022), but to the best of our knowledge, there are no studies that have discussed the possible influence on adaptive traits of surface-dwelling organisms that use BPD as substrates during their life cycle.

In 2023, according to the consortium of “global biological conservation horizon scan of issues” the interactions of floating species and BPD are identified as one of the 15 concerns that need the immediate attention of societies worldwide to address (Sutherland et al. 2023). The vast amount of BPD currently in the ocean leads to its frequent interaction with sea surface layer communities, and there are substantial impacts and feedback due to this unexplored interaction. This article suggests that marine debris, particularly in dense concentrations like those of garbage patches, may alter the physical environment, posing considerable biological implications for communities that inhabit them through bio-physical coupling. This includes the gradual deterioration of adaptive

traits, which aid surface layer organisms in surviving the dynamic and changing ocean conditions, which have not yet been explored. Hence, this article aims to summarize the notions on the ecological and evolutionary implications of the interaction of living communities of the sea surface layer and BPD to generate stimulating discussions and research on the emerging BPD-organism nexus in the sea surface layer.

2 Persistence of BPD in the marine environment

The production of plastic began at the beginning of the 1900 s and was popularized after World War II as a globally widely used material in all society compartments, reaching an increased number of households. However, this large-scale production in the current scenario has become a threat to the ecosystems (Worm et al. 2017). Plastic materials have permeated the natural environment and pose serious ecological concerns (Li et al. 2021). Data suggest that the Great Pacific Garbage Patch (GPGP) alone is spread to an area of ~ 1.6 million km^2 of which plastics are the major marine litter covering a proportion of 99.9% of GPGP (Lebreton et al. 2018, 2024).

As shown in Fig. 1, the global plastic production (Fig. 1a) till 2015 was 8300 million metric tonnes (Mt), which is estimated to grow up to 12,000 (Mt) by 2050 (Geyer et al. 2017), of which 60% of all plastic produced is less dense than seawater (Lebreton et al. 2018). By 2015, a total of 6300 Mt of plastic waste was generated, with 2000 Mt still in use (Fig. 1b) (Geyer et al. 2017). From this 6300 Mt, 9% were recycled, 12% were incinerated, and 79% were discarded in the natural environment (Fig. 1c) (Geyer et al. 2017). Eight million tons of this 79% plastic litter end up in the ocean each year (Zong 2021), which leads to a 2.5% annual growth rate of garbage patches (Fig. 1d) (Leal Filho et al. 2021). Hence, from the previous reports, it is evident that plastic alone accounts for 60 to 80 percent of all marine litter (Zong 2021). All the cumulative factors lead to the total mass of BPD on the ocean surface being 2,33,400 tons, \sim two hundred times more than what is suspended in the water column (Harris et al. 2023). The specific surface degradation rates (Fig. 1e) for commonly used polymers like polypropylene (PP), low-density polyethylene (LDPE), and high-density polyethylene (HDPE) under normal conditions are 7.5, 15, and 4.3 $\mu\text{m}/\text{year}$, which is far less compared to the mass input rate (Chamas et al. 2020).

Plastic can persist in the environment as long as it does not degrade. The major ocean plastic degradation mechanism is photooxidative degradation (Gewert et al. 2015). The degradation rates in marine environments are low because of lower ambient temperatures. It is estimated that HDPE bottles in the marine environment take 116 years to degrade (Chamas et al. 2020). The majority of

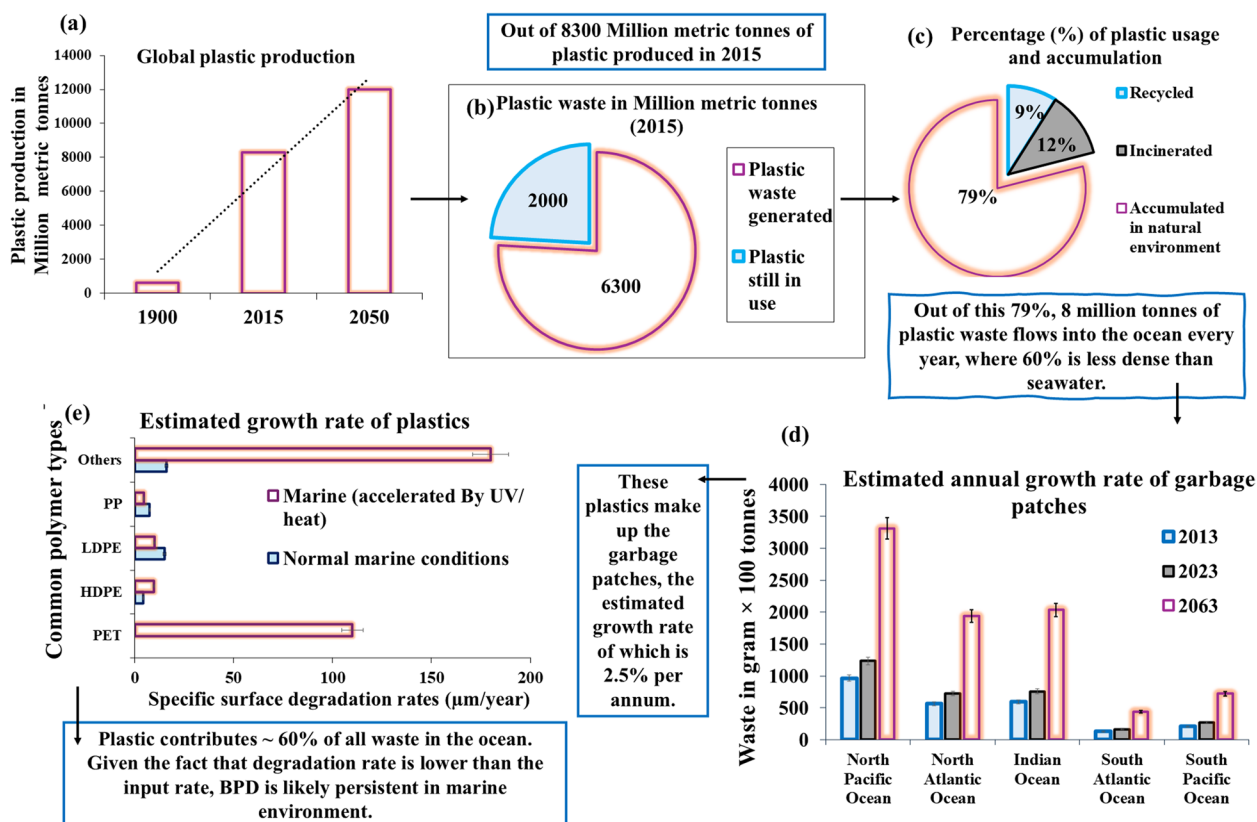


Fig. 1 A comprehensive diagram of the persistence of buoyant plastics in the marine environment. **a, b** and **c** (Geyer et al. 2017) put forth the global plastic production, its usage, and the percentage entering the natural environment. **d** shows the current annual growth rate of garbage patches due to mass plastic input (Leal Filho et al. 2021), and **e** shows the rate of degradation of plastic, which is far lower than the input rate (Chamas et al. 2020)

marine plastics are composed of polyethylene (PE) and PP (Egger et al. 2021), which have a degradation rate between 10 to 100 µm/year (Chamas et al. 2020). However, plastic degradation rates might be inaccurate as they have only been comprehensively studied in laboratories under high temperatures, conditions that are far from natural and ambient temperature profiles. The polymer degradation by ultraviolet rays depends on short wavelengths with strong oxidizing conditions, which is rarely achieved in ambient conditions. This makes the actual degradation rates in the marine environment much lower than the experimentally determined ones (Gewert et al. 2015). Hence, plastic is persistent in the marine environment (Worm et al. 2017), given the current increasing inputs that show a positive relation with abundance of ocean surface-dwelling invertebrates (Chong et al. 2023; Kiessling et al. 2015). This denotes the increasing amount of floating anthropogenic litter that is a habitat for a wide range of surface-dwelling organisms, mostly invertebrates (Kiessling et al. 2015). It highlights the potential of garbage patches to support floating organisms, such as neustons (Chong et al. 2023), microorganisms, seaweeds,

and invertebrates, further drawing attention to marine rafting dispersal (Kiessling et al. 2015).

3 BPD- Sea Surface layer organism nexus

BPD has many well-known impacts on marine organisms, ranging from ghost fishing to blocking sunlight on the sea surface (Royer et al. 2023; Jambeck and Walker-Franklin 2023). The top few millimetres of the ocean surface, where properties are most altered relative to deeper water, are often referred to as the sea surface microlayer, and marine neuston inhabits the sea surface microlayer (Soloviev and Lukas 2013). Persistence, buoyancy, and variety in terms of the chemical composition of BPD facilitate their colonization by macro and microorganisms potentially invasive, thus acting as a vector for their transport across different marine areas (García-Gómez et al. 2021). The impact of BPD on the surface layers of the ocean has gained recent attention (VishnuRadhan et al. 2019; Galgani and Loiselle 2019; George and Fabre 2021). Such an interaction with surface-associated pelagic communities is an emerging topic, and the influence of BPD on the structure and dynamics of these

communities is not well understood. Many organisms inhabit the ocean surface layer, such as barnacles, cnidarians, snails, nudibranchs, and their larval stages (Banse 1975). Many organisms living on the sea surface layer use natural buoyancy mechanisms to stay afloat on the ocean surface, though the mechanisms differ across species. A significant proportion of recorded rafters are facultative rafters, while confined to a floating object, these organisms become dispersed from their usual habitats. However, some organisms are obligate rafters, spending their whole life cycle on a raft (Thiel and Gutow 2005). Many floating animals use gas-trapping mechanisms to remain at the surface (Anthony et al. 2024). They also harness opportunistic floating substrates to support and complete their life cycle. Historically, they depend on floating organic substrates of terrestrial origin or marine macroalgae such as seaweed (Kiessling et al. 2015).

In recent decades, the amount of sturdy and persistent BPD has exponentially increased and is further expected to rise (Geyer et al. 2017), leading to a vast availability of colony-supporting substrates for floating species in the marine ecosystem. The availability of durable substrates enables marine hitchhiking and rafting, transporting species across boundaries (García-Gómez et al. 2021). Since plastic substrates are durable, there is no need for the colonizing organisms to switch and occasionally find new substrates. This can stimulate a thriving sea surface community that depends exclusively on BPD substrates. However, there is a contrasting side to this process. The sea-surface microlayer also has a high concentration of other pollutants (Wurl and Obbard 2004; Liss and Duce 2009) that, together with BPD and BPD-derived leachates or BPD-adsorbed chemicals, can be harmful to invertebrates and their larvae, while it may instead stimulate other communities of organisms, such as the metabolism of heterotrophic bacterial communities (Romera-Castillo et al. 2018; Sheridan et al. 2022). However, no verified comprehensive studies currently address the issue regarding such BPD-invertebrate interactions, although these processes can drive ecological and evolutionary changes in the sea surface layer ecosystem.

Phenotypic or adaptive plasticity among organisms is an evolutionary adaptation to unique environmental variations leading to diverse ecological implications. A wide range of behavioural, morphological, physiological, biochemical, chemical, or life history traits of marine organisms has been shown to be phenotypically plastic resulting from responses to the environment during the organism's lifetime or across generations ((Padilla and Savedo 2013). The processes that underline phenotypic plasticity frequently entail modifications in gene expression brought on by external stimuli. These modifications may impact several biological processes, resulting

in distinct phenotypic manifestations (Wray 2013). The plasticity is evolutionarily significant as it facilitates the evolution of new traits by providing a buffer against environmental variability (Longa 2021). Phenotypic plasticity is abundant in nature and plays a major role in marine biological invasions (Smith 2009). Morphological plasticity, which is a subset of phenotypic plasticity (West-Eberhard 1989), is most common in marine invertebrates, and they are one of the most comprehensive examples of organisms exhibiting phenotypic plasticity among other organisms, which goes through a succession of developmental and ontogenetic stages during their lifetimes. (Padilla and Savedo 2013). For example, the cosmopolitan marine free-living ciliates *Glauconema* spp., undergo significant phenotypic changes in terms of body shape in response to food shortages (Pan et al. 2024), and colonial invertebrates such as corals exhibit morphological plasticity (Sánchez et al. 2007; Million et al. 2022). There are other types of plasticity, such as tubificid oligochaetes in the Foundry Cove, New York. These invertebrates developed cadmium resistance because of a battery factory dumping 50 tonnes of cadmium and nickel hydride into the waters. This resistance was lost by 2002, after the clean-up (Levinton et al. 2003). There is evidence that natural populations often experience the weakening or removal of a source of selection, which is critical in maintaining one or more traits, known as "relaxed selections" (Lahti et al. 2009). Cave-dwelling fish exhibit relaxed selection on vision-related traits (Wilkins 2020), similar to deep-sea organisms (Poulson 2001). The natural buoyancy mechanism is an adaptive trait (Dobzhansky 1956) essential for the survival of the floating marine species, where they have various strategies, such as maintaining low-density substances and body fluids, gas chambers, and hydrodynamic shapes that allow them to stay suspended in the water column for longer time (Molloy and Cowling 1999). These adaptive traits help them maintain low energy expenditure and increased survival, and they can occur under the above-discussed plasticity and relaxed selection mechanisms.

There is a possibility that the buoyancy mechanism of floating organisms can dwindle with time due to the increased reliance on BPD. In addition, bio-physical coupling, induced by turbulence, can influence the recruitment of early life stages of floating invertebrates that utilize BPD as a substrate. The role of evolution in ecological processes is expected to be significant for traits that change rapidly, which strongly influences ecological interactions (Carroll et al. 2007). Ecologically significant evolutionary change increasingly occurs over short timescales of tens of generations or fewer (Alexander et al. 2017). This phenomenon and the short life span of floating species can prompt a higher probability

Table 1 Organism Interactions with BPD on the ocean's surface across the globe

Sl. no	Phylum	Species	BPD-Organisms interaction	Region	Reference
1	Bryozoa	Microporella	Long-distance transport, invasive potential	Sicily	(Rosso et al. 2025)
2	Chordata	<i>Didemnum vexillum</i>	Rafting	Europe	(González-Ortegón et al. 2024)
3	Chordata	<i>Abudefduf vaigiensis</i> , <i>Histrio histrio</i> , <i>Oplegnathus punctatus</i> , and <i>Petrosciartes spp.</i>	Long-distance species dispersal	Western and Eastern Pacific Ocean	(Benadon et al. 2024)
4	Cnidaria	<i>Tubastraea spp.</i>	Dispersal	South America and Caribbean coasts	(Soares et al. 2023)
5	Arthropoda	<i>Semibalanus balanoides</i>	Rafting	Long Island Sound, USA	(Brandler and Carlton 2023)
6	Mollusca	<i>Umbonium vestiarium</i>	Fouling, Colonization, Transportation	Tamil Nadu Coast, India	(Kannan et al. 2023)
7	Cnidaria	<i>Nanomia Bijuga</i>	Bio-invasion, Species Introduction, Ingestion	South Brazil	(Lacerda et al. 2022)
8	Cnidaria	<i>Porpita</i>	Transportation, Rafting	North Atlantic	(Chong et al. 2023)
9	Arthropoda	<i>Halobates spp.</i>	Substrate	Eastern North Pacific Ocean	(Egger et al. 2021)
10	Mollusca	<i>Saccostrea cucullata</i>	Rafting	Persian Gulf	(Shabani et al. 2019)
11	Chordata	<i>Ciona intestinalis</i>	Substrate	Bahía La Herradura, Chile	(Bravo et al. 2011)
12	Annelida	<i>Hydroides elegans</i>	Rafting	New Zealand	(Thiel and Gutow 2005)
13	Arthropoda	<i>Idotea metallica</i>	Fouling	Ligurian Sea, Western Mediterranean	(Aliani and Molcard 2003)
14	Annelida	<i>Spirorbis corrugatus</i>	Fouling	Western Atlantic and the Southern Pacific	(Winston et al. 1997)

of rapidly altering their buoyancy-related traits. Any changes in the ecological characteristics of these organisms, for example, the natural buoyancy mechanism and the associated bio-physical coupling, presumably can have far-reaching consequences for marine ecosystems and trophic structures. Recent studies show that floating animal species evolved from epibiotic and rafting ancestors (Anthony et al. 2024). Given their known interactions with marine organisms, BPD can be a potential driver of evolutionary changes that can lead to changes in the marine ecosystem, inducing altered ecosystem services that can pose a wide range of impacts on the marine environment and human societies. The evolutionary changes in plastisphere communities can be studied and documented with metagenomics approaches or eDNA. Besides all these, marine invertebrate species also function as bioindicators for various anthropogenic and natural pollutants. This scenario is not ideal, as the bioindicator invertebrate, in the prolonged presence of BPD, can alter its eco-indicative traits, creating ambiguity in monitoring and assessing the environmental impacts and developing management strategies when confronted with environmental pollutants. Table 1 lists various organisms belonging to different phyla that live on marine surface waters and interact with BPD, based on the available but limited literature on the subject. For example, the cnidarian *Nanomia bijuga*, which is bio-invasive in South Brazil, the arthropods *Idotea metallica*, which fouls the BPD

surface in the Mediterranean, organisms showing rafting behaviors like *Hydroides elegans*, an annelid found in the surface waters of New Zealand. Thiel and Gutow (2005) was followed to deduce the list of marine organisms that are rafters. Invertebrates from most marine phyla are rafting organisms, and bryozoans, crustaceans, and gastropods were the most common taxa observed in rafting (Subías-Baratau et al. 2022). The dominant ones are grazing/boring and suspension-feeding organisms, which occurred on all floating substrata, and the selected references represent these classes of organisms.

4 Marine invertebrates as bioindicators: the repercussions of BPD-organism nexus

Marine surface layer communities play a vital role in open ocean epipelagic food webs and represent a significant food source for varied marine organisms. They are also an essential source of biomass in pelagic ecosystems, and their interactions with BPD are still not known (Maximenko et al. 2021). Many invertebrate species such as macro crustaceans (Das et al. 2020) and crabs, (Capparelli et al. 2022), decapods (Das et al. 2023), cladocerans (Lee et al. 2021), mollusks (Chang and Wang 2024) and as well as polychaetas (Malzahn et al. 2024) are bioindicator that bioaccumulate toxicants from a diverse range of marine pollutants such as trace metals, organic pollutants, microplastics, petroleum hydrocarbons and endocrine disruptors (Bryan and Darracott 1979; Mason

2001; Lourenco et al. 2019; Parolini et al. 2023) manifesting their traits (Cima et al. 1998; Botté et al. 2022). Recent studies show that in marine ecosystems, the ecological niche factor has greater relevance in bioaccumulation than the habitat (dos Santos Lima et al. 2023). Furthermore, ecological niche factors include the life history, trophic position, various abiotic factors, and geographic range of the organism (Das et al. 2022). The BPD-organism nexus can create varying changes in the ecological niche factor, potentially affecting the bioaccumulating capacity. Currently, there are no notions on the directions of these impacts, and feedback will either be beneficial or harmful. Further, many invertebrate species are indicators of marine plastic pollution (Bonanno and Orlando-Bonaca 2018). The adaptation and evolutionary changes of sea surface-dwelling species are also relevant concerning the competitive exclusion principle (den Boer 1986), stating that two species competing for the same limited resource cannot coexist at constant population values. This is a highly relevant dimension considering the fact that many sea-surface-dwelling organisms are essential components of marine trophic structure (Helm 2021). BPD also harbors various chemical compounds and toxic additives, which are persistent, mobile, highly polar, environmentally stable sub-groups with various uses in plastic products (Fries and Sühling 2023). Research regarding plastic leachate impacts on marine organisms is still at its very early beginning and is suffering from both relatively severe conceptual and methodological gaps, which are likely to hamper our ability to understand the actual ecological effect of this new type of pollution (Delaeter et al. 2022). In addition to the direct impacts of leachates on invertebrate communities, the BPD-associated plastisphere microbiome also interacts with the hazardous plastic leachates (Li et al. 2024), and the effects on sea-surface layer marine invertebrates are not well known. The interaction with BPD can alter the capacity of invertebrate species to bioaccumulate toxic chemicals, and evolutionary changes in the organisms can bring forth changes in the assimilating capacity of toxic compounds. Hence, The BPD-organism nexus creates unforeseen challenges in the current marine environmental impact assessment arena, transforming the issue into a complex ecological problem that calls for further studies.

5 BPD in the marine environment: Progression of a complex problem

Marine plastic pollution is a complex issue, and BPD processes in the marine system are complex, with various closed circles of causal relationships within a system or feedback mechanisms. We depict these evolving BPD-marine ecosystem nexuses with a causal loop diagram (CLD) (Fig. 2). CLDs visually represent key

components and their interactions that can help decipher complex systems and their dynamics (Richardson 1986). A closed loop of causal relationships between variables defines a feedback mechanism. There are balancing loops that dampen or stabilize behavior and reinforcing loops that amplify or intensify it. Changes within a system are amplified or reinforced by reinforcing feedback mechanisms.

In contrast to balancing feedback, reinforcing feedback mechanisms cause exponential growth or decline by pushing the system farther from its starting point. The purpose of balancing feedback mechanisms is to keep a system stable or in equilibrium. Balanced feedback mechanisms counteract deviations or changes in any part of the system and return it to its initial state. Figure 2 shows that plastic pollution issues are mostly comprised of reinforcing loops, manifesting the whole issue into a wicked environmental problem with no single, standard solution. A significant contributor is inefficient waste management systems across the globe, which is a causative factor for the leakage of plastic pollutants into the environmental compartments. This results in various reinforcing feedback mechanisms, some emerging and underexplored, pushing the system to a destabilizing state. The CLD shows that the BPD can instigate far-reaching marine ecosystem implications through emerging evolutionary pathways. Comprehending these feedback mechanisms facilitates the identification of possible intervention strategies and aids in understanding the evolution of complex systems over time. Balancing and reinforcing loops can create robust structures within the system, which may have unexpected consequences when policies and interventions are implemented. The undesirable consequences can be tackled by evidence-based policy instruments, legally binding agreements, and international cooperation. Besides, socio-economic factors are deeply intertwined with issues of plastic pollution. Comprehensively, addressing one loop at a time utilizing holistic approaches involving three pillars of sustainability, social-economic-environmental, can ensure a stable planetary health scenario in the future.

6 The need for BPD-specific policy interventions

Considering the production and consumption of plastic in recent decades (Walker and Fequet 2023) and the influx of plastic waste into the global ocean (Zhang et al. 2023), BPD has fairly reached a crucial stage in which organisms are so adapted to having these substrates that they would not do otherwise and are evolving. There can be a couple of exemplary effects that may significantly alter marine food webs. At the same time, we more or less know the approximate number of plastics that float (Eriksen et al. 2014, Oberbeckmann et al., 2020; Eriksen

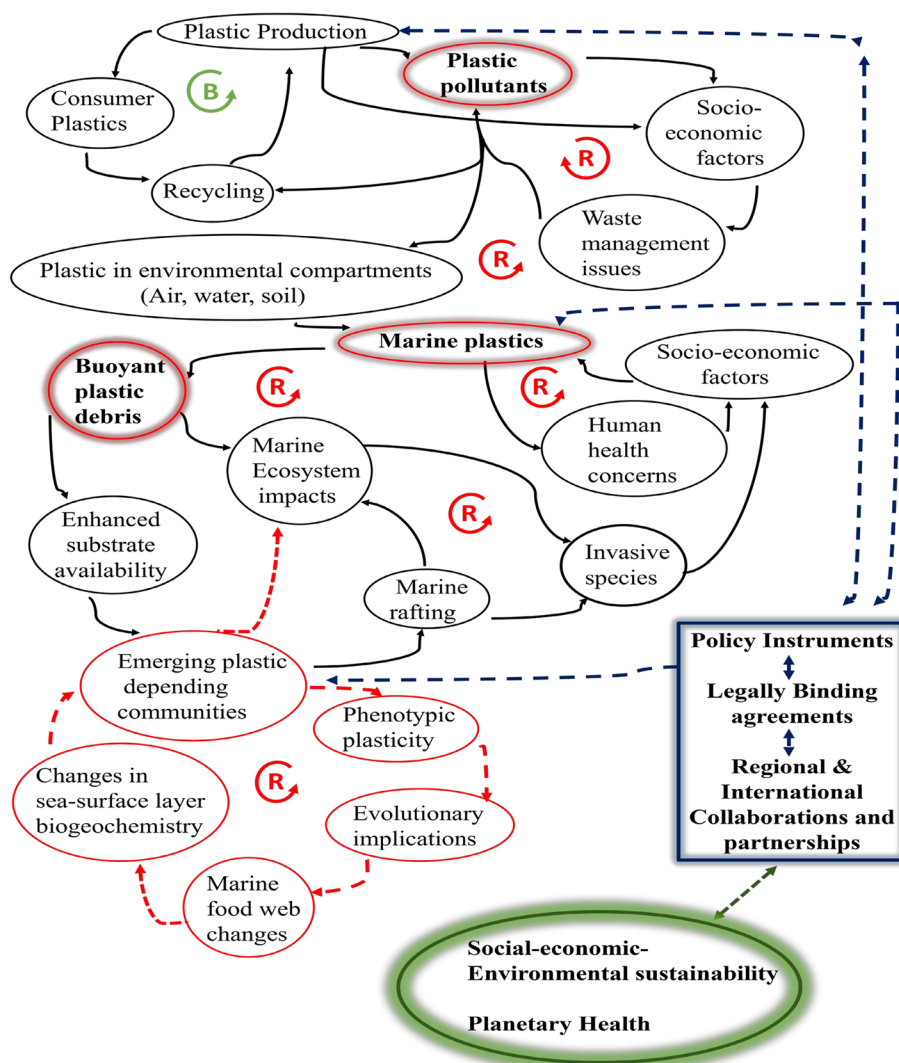


Fig. 2 CLD showing various processes in the plastic-marine environmental system. Blue arrows connect the relations and known feedback mechanisms, and red dashed arrows connect the less-known components of BPD-marine ecosystem interactions. Black color and arrows depict the policy component in the system. Green color depicts the three necessary conditions (social, economic, environmental) for sustainability, and the overall outcomes of policy interventions B and R represent the balancing and reinforcing loops, respectively

et al. 2023). An estimate of the numerical budget for the percentage of organisms that rely on these substrates and inhabit the sea-surface microlayer could be one way to quantify the emerging effects of BPD. Further, various ongoing ocean clean-up ventures should be carried out cautiously, given the diversity of sea-surface dwelling organisms. International partnerships and legally binding agreements that address the entire life cycle of plastics, from the extraction of raw materials to legacy plastic pollution, are necessary to tackle its social, environmental, and economic impacts pragmatically (Simon et al. 2021) and should consider the BPD-organism interactions and their associated bio-physical coupling.

Regional, local, and national initiatives are required to curb the problems associated with BPD (Rahman et al. 2023). BPD can be reduced by preventing plastic from entering the oceans through the transformation of the ways plastics are used and recycled. Once in the ocean, BPD should be tackled via clean-ups or monitoring systems (Beukering 2018). Individuals can avoid daily single-use plastic items like disposable water bottles, cutlery, bags, and wrappings, which are less buoyant than sea water, contributing a major portion of BPD (Rahman et al. 2023). Community education, providing households with recycling bins, and targeting specific waste streams can reduce the plastic landing on the shores of the ocean

(Willis et al. 2022). There are currently fewer studies focused on reducing the marine floating litter and their emerging impacts, which paves the way for future studies targeted toward BPD abatement.

A combination of regulations, incentives, and initiatives for reducing plastic waste production, promoting recycling and circular economy, technologically mediated land-based waste management systems, using bio-sourced and eco-friendly materials, and increasing awareness among citizens regarding plastic use and its responsible disposal are just a few of the concrete efforts that must be made to address the BPD scenario in the marine environment including the associated emerging marine ecological and evolutionary issues. There is an immense gap regarding our understanding of the BPD-marine ecosystem nexus, and it warrants holistic approaches and evidence-based actions. BPD-specific partnership, cooperation, and funding for innovation and research projects to create plastic-like materials, advance recycling techniques, and find solutions to address marine plastic pollution are needs of the hour. These will enhance the success rates of our shared goals dedicated to tackling various emerging planetary boundary bottlenecks, attaining sustainability, and fulfilling one health initiative.

7 Conclusion

The surface layer pelagic communities face various issues, from habitat destruction due to fishing activities to marine pollution. The surge in BPD in the ocean is a lifeline for these pelagic communities, which can aid in their adaptive evolution. Our evolutionary history shows that species often evolve and adapt to the most available resources, and the fittest ones continue to thrive and extend their geographical limits. This can bring unforeseen consequences to the ambient marine ecosystem processes.

Having discussed the impact of BPD on floating organisms and its possible evolutionary implication, it should be noted that BPD undergoes biofouling. Biofouling is the undesirable adhesion and collection of organisms on the surface of BPD (Hussein 2023). The organisms like algae, bacteria, barnacles, mollusca, and polychaetes, make up the biofouling community in the ocean, with major substrates being polystyrene (PS) and polypropylene (PP) (Subías-Baratau et al. 2022). Our current understanding indicates that biofouling increases the specific density of BPD, allowing it to sink (Kaiser et al. 2017). But this can be the other way around, depending on the type of plastic. The deterioration of the structural stability of BPD may pave the way for the trapping of air molecules, rendering it more buoyant. This dimension has not been explored yet. A recent study showed plastic litter sunk by

biofouling recovers buoyancy due to benthic predation (Pinochet et al. 2024). The ecosystem implications of this newly proposed process are yet to be understood. The current understanding of sea-surface dwelling organisms and their bio-physical coupling is limited, which warrants holistic approaches to understanding these significant members of the marine food web. Further, the BPD-surface layer organism nexus has the potential to postulate many emerging challenges in the near future, in addition to the existing wicked problems related to marine plastic pollution.

Acknowledgements

We would like to extend our gratitude to all the affiliated institutions for the encouragement and facilities given for carrying out this study. Luisa Galgani was supported by the Italian Ministry of University and Research funded by the European Union – NextGenerationEU, project code CN_00000033, CUP B63 C22000650007, project title “National Biodiversity Future Center – NBFC”. Shagnika Das acknowledges the Direction Generale Delegation Relations Internationales of the University of Lille, France and the Laboratory of Oceanology and Geosciences (LOG, CNRS) for hosting her as an invited visiting researcher and lecturer.

Authors' contributions

Conceptualization, R.V.R.; methodology, R.V.R., and S.D.; Validation: R.V.R., S.D., A.B., and LG; formal analysis, R.V.R., S.D. and S.R.; investigation, R.V.R., S.D., S.R., A.B., and LG; data curation, R.V.R., S.D. and S.R.; writing-original draft preparation, R.V.R.; writing-review and editing, R.V.R., S.D., S.R., A.B., and LG; supervision, R.V.R. All authors have read and agreed to submitted version of the manuscript.

Funding

This study received no funding from any agency.

Data availability

Data will be available under request.

Declarations

Competing interests

The authors have no competing interests.

Received: 12 October 2024 Revised: 23 February 2025 Accepted: 21 March 2025

Published online: 29 April 2025

References

- Alexander TJ, Vonlanthen P, Seehausen O (2017) Does eutrophication-driven evolution change aquatic ecosystems? *Philos Trans R Soc Lond B Biol Sci* 372(1712):20160041
- Aliani S, Molcard A (2003) Hitch-hiking on floating marine debris: macrobenthic species in the Western Mediterranean Sea. In *Migrations and Dispersal of Marine Organisms: Proceedings of the 37 th European Marine Biology Symposium held in Reykjavik, Iceland, 5–9 August 2002* (pp. 59–67). Springer Netherlands
- Anthony CJ, Bentlage B, Helm RR (2024) Animal evolution at the ocean's water-air interface. *Curr Biol* 34(1):196–203
- Banse K (1975) Pleuston and neuston: on the categories of organisms in the uppermost pelagial *Int Rev gesamten Hydrobiol* 60(4):439–447
- Benadon C, Zabin CJ, Haram L, Carlton JT, Maximenko N, Nelson P, Crowley M, Ruiz GM (2024) Marine debris facilitates the long-distance dispersal of fish species. *Mar Biol* 171(2):43

- Beukering PV (2018) Marine litter: how to monitor, reduce and prevent ocean debris. Focus on plastics and microplastics
- Bonanno G, Orlando-Bonaca M (2018) Perspectives on using marine species as bioindicators of plastic pollution. *Mar Pollut Bull* 137:209–221
- Borrelle SB, Ringma J, Law KL, Monnahan CC, Lebreton L, McGivern A, Murphy E, Jambeck J, Leonard GH, Hilleary MA, Eriksen M (2020) Predicted growth in plastic waste exceeds efforts to mitigate plastic pollution. *Science* 369(6510):1515–1518
- Botté A, Seguin C, Nahrgang J, Zaidi M, Guery J, Leignel V (2022) Lead in the Marine Environment: Concentrations and Effects on Invertebrates *Ecotoxicol* 1:1–4
- Brandler KG, Carlton JT (2023) First report of marine debris as a species dispersal vector in the temperate Northwest Atlantic. *Mar Pollut Bull* 188:114631
- Bravo M, Astudillo JC, Lancellotti D, Luna-Jorquera G, Valdivia N, Thiel M (2011) Rafting on abiotic substrata: properties of floating items and their influence on community succession. *Mar Ecol Prog Ser* 439:1–7
- Bryan GW, Darracott A (1979) Bioaccumulation of marine pollutants. *Philos Trans R Soc Lond B Biol Sci* 286(1015):483–505
- Capparelli MV, Gómez-Ponce MA, Borges-Ramírez MM, Rendón-von Osten J, Celis-Hernández O, Briceño-Vera AE, ... Moulatlet GM (2022) Ecological traits influence the bioaccumulation of microplastics in commercially important estuarine crabs from the southeastern Gulf of Mexico *Mar Pollut Bull* 183:114088
- Carroll SP, Hendry AP, Reznick DN, Fox CW (2007) Evolution on Ecological Time-Scales *Funct Ecol* 21(3):387–393
- Chamas A, Moon H, Zheng J, Qiu Y, Tabassum T, Jang JH, Abu-Omar M, Scott SL, Suh S (2020) Degradation Rates of Plastics in the Environment *ACS Sustain Chem Eng* 8(9):3494–3511
- Chang X, Wang WX (2024) In vivo bioaccumulation and responses of hemocytes of mussels *Perna viridis* to microplastics and nanoplastics exposure. *J Hazard Mater* 480:135939
- Chong F, Spencer M, Maximenko N, Hafner J, McWhirter AC, Helm RR (2023) High concentrations of floating neustonic life in the plastic-rich North Pacific Garbage Patch *Plos Biol* 4:21(5):e3001646
- Cima F, Marin M, Da Ros L, Ballarin L (1998) Marine invertebrates as bioindicators of organotin contaminants: immuno- and embryotoxicity. *Ann Chim* 88:517–527
- Das S, Aria A, Cheng JO, Souissi S, Hwang JS, Ko FC (2020) Occurrence and Distribution of Anthropogenic Persistent Organic Pollutants in Coastal Sediments and Mud Shrimps from the Wetland of Central Taiwan *PloS* 15(1):e0227367
- Das S, Ouddane B, Souissi S (2022) Responses of the copepod *Eurytemora affinis* to trace metal exposure: A candidate for sentinel to marine sediment resuspension effects. *Mar Pollut Bull* 181:113854
- Das S, Souissi A, Ouddane B, Hwang JS, Souissi S (2023) Trace Metals Exposure in Three Different Coastal Compartments Show Specific Morphological and Reproductive Traits across Generations in a Sentinel Copepod *Sci Total Environ* 10(859):160378
- Delaeter C, Spilmont N, Bouchet VM, Seuront L (2022) Plastic Leachates: Bridging the Gap between a Conspicuous Pollution and Its Pernicious Effects on Marine Life *Sci Total Environ* 20(826):154091
- den Boer PJ (1986) The present status of the competitive exclusion principle. *Trends Ecol Evol* 1(1):25–28
- Dobzhansky T (1956) What is an adaptive trait? *Am Nat* 90(855):337–347
- dos Santos Lima G, Menegario AA, Suarez CA, Kamazuka SH, Gemeiner H, Sánchez-Sarmiento AM, Ferioli RB, Barreto AS (2023) Pelagic and estuarine birds as sentinels of metal (loid)s in the South Atlantic Ocean: Ecological niches as main factors acting on bioaccumulation *Environ Pollut* 326:121452
- Egger M, Quiros L, Leone G, Ferrari F, Boerger CM, Tishler M (2021) Relative Abundance of Floating Plastic Debris and Neuston in the Eastern North Pacific Ocean *Front Mar Sci* 8:626026
- Egger M, Schilt B, Wolter H, Mani T, de Vries R, Zettler E, Niemann H (2022) Pelagic distribution of plastic debris (> 500 µm) and marine organisms in the upper layer of the North Atlantic Ocean *Sci Rep* 2(1):13465
- Eriksen M, Lebreton LC, Carson HS, Thiel M, Moore CJ, Borero JC, Galgani F, Ryan PG, Reisser J (2014) Plastic pollution in the world's oceans: more than 5 trillion plastic pieces weighing over 250,000 tons afloat at sea *PloS* 9(12):e111913
- Eriksen M, Cowger W, Erdle LM, Coffin S, Villarrubia-Gómez P, Moore CJ, ... & Wilcox C (2023) A growing plastic smog, now estimated to be over 170 trillion plastic particles afloat in the world's oceans—Urgent solutions required *PloS* 18(3):e0281596
- Fries E, Sühning R (2023) The unusual suspects: Screening for persistent, mobile, and toxic plastic additives in plastic leachates *Environ Pollut* 335:122263
- Galgani L, Loiselle SA (2019) Plastic Accumulation in the Sea Surface Micro-layer: an Experiment-Based Perspective for Future Studies *Geosci* 9(2):66
- García-Gómez JC, Garrigós M, Garrigós J (2021) Plastic as a vector of dispersion for marine species with invasive potential. A Review *Front Ecol Evol* 9:629756
- George M, Fabre P (2021) Floating Plastics in Oceans: A Matter of Size *Curr Opin Green Sustain Chem* 32:100543
- Gewert B, Plassmann MM, MacLeod M (2015) Pathways for Degradation of Plastic Polymers Floating in the Marine Environment *Environ Sci Process Impacts* 17(9):1513–1521
- Geyer R, Jambeck JR, Law KL (2017) Production, use, and fate of all plastics ever made. *Sci Adv* 3(7):e1700782
- González-Ortegón E, Demmer J, Robins P, Jenkins S (2024) Floating plastics as a potential dispersal vector for rafting marine non-native species. *Mar Pollut Bull* 207:116919
- Haram LE, Carlton JT, Centurioni L, Crowley M, Hafner J, Maximenko N, Murray CC, Shcherbina AY, Hormann V, Wright C, Ruiz GM (2021) Emergence of a Neopelagic Community through the Establishment of Coastal Species on the High Seas *Nat Commun* 12(1):6885
- Haram LE, Carlton JT, Centurioni L, Choong H, Cornwell B, Crowley M, Egger M, Hafner J, Hormann V, Lebreton L, Maximenko N (2023) Extent and Reproduction of Coastal Species on Plastic Debris in the North Pacific Subtropical Gyre *Nat Ecol Evol* 7(5):687–697
- Harris PT, Maes T, Raubenheimer K, Walsh JP (2023) A Marine Plastic Cloud-Global Mass Balance Assessment of Oceanic Plastic Pollution *Cont Shelf Res* 255:104947
- Helm RR (2021) The mysterious ecosystem at the ocean's surface. *PLoS Biol* 19(4):e3001046
- Hussein A (2023) Chapter 10—Biofouling. In: Hussein A (ed) *Essentials of Flow Assurance Solids in Oil and Gas Operations*. Gulf Professional Publishing, pp 449–483
- Jambeck JR, Walker-Franklin I (2023) The impacts of plastics' life cycle. *One Earth* 6(6):600–606
- Jokiel PL (1990) Long-distance dispersal by rafting: reemergence of an old hypothesis. *Endeavour* 14(2):66–73
- Kaiser D, Kowalski N, Waniek JJ (2017) Effects of Biofouling on the Sinking Behavior of Microplastics *Environ Res Lett* 12(12):124003
- Kannan G, Mghili B, Di Martino E, Sanchez-Vidal A, Figuerola B (2023) Increasing risk of invasions by organisms on marine debris in the Southeast coast of India. *Mar Pollut Bull* 195:115469
- Kiessling T, Gutow L, Thiel M (2015) Marine litter as habitat and dispersal vector. *Marine Anthropogenic Litter* 2015:141–181
- Kumar BSK, Chari NV, Reddy KK, Cheriyan E, Sherin CK, Rao DB, Elangovan SS, Reddy B, Gupta GV (2024) Natural Light Driven Plastic Leaching Effects on Carbon Chemistry in the Tropical Coastal Waters of Eastern Arabian Sea: an Experimental Study *Environ Pollut* 362:124948
- Lacerda AL, Taylor JD, dS Rodrigues L, Kessler F, Secchi E, Proietti MC (2022) Floating plastics and their associated biota in the Western South Atlantic *Sci Total Environ* 805:150186
- Lahti DC, Johnson NA, Ajie BC, Otto SP, Hendry AP, Blumstein DT, Coss RG, Donohue K, Foster SA (2009) Relaxed selection in the wild. *Trends Ecol Evol* 24(9):487–496
- Leal Filho W, Hunt J, Kovaleva M (2021) Garbage Patches and Their Environmental Implications in a Plastisphere *J Mar Sci Eng* 9(11):1289
- Lebreton L (2022) The status and fate of oceanic garbage patches. *Nat Rev Earth Environ* 3(11):730–732
- Lebreton L, Slat B, Ferrari F, Sainte-Rose B, Aitken J, Marthouse R, Hajbane S, Cunsolo S, Schwarz A, Levivier A, Noble K (2018) Evidence that the

- Great Pacific Garbage Patch is rapidly accumulating plastic. *Sci Rep* 8(1):1–5
- Lebreton L, de Vries R, Pham Y, Wolter H, van Vulpem M, Puskic P, Egger M (2024) Seven Years into the North Pacific Garbage Patch: Legacy Plastic Fragments Rising Disproportionally Faster than Larger Floating Objects *Environ Res Lett* 19(12):124054
- Lee Y, Yoon DS, Lee YH, Kwak Ji, An YJ, Lee JS, Park JC (2021) Combined exposure to microplastics and zinc produces sex-specific responses in the water flea *Daphnia magna*. *J Hazard Mater* 420:126652
- Levinton JS, Suatoni E, Wallace W, Junkins R, Kelaher B, Allen BJ (2003) Rapid Loss of Genetically Based Resistance to Metals after the Clean-up of a Superfund Site *Proc Natl Acad Sci* 100(17):9889–9891
- Li P, Wang X, Su M, Zou X, Duan L, Zhang H (2021) Characteristics of plastic pollution in the environment: a review. *Bull Environ Contam Toxicol* 107:577–584
- Li C, Gillings MR, Zhang C, Chen Q, Zhu D, Wang J, Zhao K, Xu Q, Leung PH, Li X, Liu J (2024) Ecology and risks of the global plastisphere as a newly expanding microbial habitat. *Innovation* 5(1):100543
- Lincoln S, Andrews B, Birchenough SN, Chowdhury P, Engelhard GH, Harrod O, Pinnegar JK, Townhill BL (2022) Marine Litter and Climate Change: Inextricably Connected Threats to the World's Oceans *Sci Total Environ* 837:155709
- Liss PS, Duce RA (2009) *The Sea Surface and Global Change*. Univ, Cambridge
- Longa VM (2021) in Shackelford TK, Weekes-Shackelford VA (Eds.) *Encyclopedia of evolutionary psychological science*. Cham: Springer International Publishing
- Lourenço RA, Magalhães CA, Taniguchi S, Siqueira SG, Jacobucci GB, Leite FP, Bicego MC (2019) Evaluation of macroalgae and amphipods as bioindicators of petroleum hydrocarbons input into the marine environment. *Mar Pollut Bull* 145:564–568
- Malzahn, A. M., Sele, V., Belghit, I., Tibon, J., Nilsen, H., Sindre, H., ... & Hagemann, A. (2024). Transfer and bioaccumulation of chemical and biological contaminants in the marine polychaete *Hediste diversicolor* (OF müller 1776) when reared on salmon aquaculture sludge. *Journal of Environmental Management*, 367, 122073.
- Mason RP (2001) The bioaccumulation of mercury, methylmercury and other toxic elements into pelagic and benthic organisms *Coastal and Estuarine Risk Assessment*, CRC/Lewis Publ 127–149
- Maximenko N, Palacz AP, Biermann L, Carlton J, Centurioni L, Crowley M, Hafner J, Haram L, Helm RR, Hormann V, Murray C (2021) An integrated observing system for monitoring marine debris and biodiversity. *Oceanography* 34(4):52–59
- Million WC, Ruggeri M, O'Donnell S, Bartels E, Conn T, Krediet CJ, Kenkel CD (2022) Evidence for adaptive morphological plasticity in the Caribbean coral. *Acropora Cervicornis Proc Natl Acad Sci* 119(49):e2203925119
- Molloy PJ, Cowling MJ (1999) Buoyancy Mechanisms of Marine Organisms: Lessons from Nature *Underw Technol* 24(2):41–49
- Oberbeckmann S, Labrenz M (2020) Marine microbial assemblages on microplastics: diversity, adaptation, and role in degradation *Annu Rev Mar Sci* 12(1):209–232
- Padilla DK, Savedo MM (2013) A systematic review of phenotypic plasticity in marine invertebrate and plant systems. *Adv Mar Biol* 65:67–94
- Pan J, Wang Y, Li C, Zhang S, Ye Z, Ni J, Li H, Li Y, Yue H, Ruan C, Zhao D (2024) Molecular basis of phenotypic plasticity in a marine ciliate *ISME J* 18(1)
- Parolini M, Stucchi M, Ambrosini R, Romano A (2023) A Global Perspective on Microplastic Bioaccumulation in Marine Organisms *Ecol Indic* 149:110179
- Pinochet J, Thiel M, Urbina M (2024) How Plastic Litter Sunk by Biofouling Recovers Buoyancy-the Role of Benthic Predation *Sci Total Environ* 952:175910
- Poulson TL (2001) Adaptations of cave fishes with some comparisons to deep-sea fishes. *Environ Biol Fishes* 62:345–364
- Póvoa AA, Skinner LF, de Araújo FV (2021) Fouling organisms in marine litter (rafting on abiotic substrates): a global review of literature *Mar Pollut Bull* 166:112189
- Rahman MA, Mojumdar S, Rahman SA, Marimuthu K (2023) Plastic pollutions in the ocean: their sources, causes, effects and control measures *J Biol Sci* 6(1):37–52
- Rech S, Salmina S, Pichs YJ, García-Vázquez E (2018) Dispersal of alien invasive species on anthropogenic litter from European mariculture areas. *Mar Pollut Bull* 131:10–16
- Richardson GP (1986) Problems with Causal-Loop Diagrams *Syst Dynam Rev* 2(2):158–170
- Romera-Castillo C, Pinto M, Langer TM, Álvarez-Salgado XA, Herndl GJ (2018) Dissolved organic carbon leaching from plastics stimulates microbial activity in the ocean *Nat Commun*:9(1), 1430
- Rosso A, Di Martino EM, Siddiolo C (2025) Going west: the spread of non-native *Microporella* (Bryozoa) species on drift plastic debris *Mediterr Mar Sci* 26(1):71–89
- Royer SJ, Corniuk RN, McWhirter A, Lynch IV HW, Pollock K, O'Brien K, Escalle L, Stevens KA, Moreno G, Lynch JM (2023) Large floating abandoned, lost or discarded fishing gear (ALDFG) is frequent marine pollution in the Hawaiian Islands and Palmyra Atoll *Mar Pollut Bull* 196:115585
- Ryan PG (2015) A Brief History of Marine Litter Research. In: Bergmann M, Gutow L, Klages M (eds) *Marine Anthropogenic Litter*. Springer International Publishing, pp 1–25
- Sánchez JA, Aguilar C, Dorado D, Manrique N (2007) Phenotypic plasticity and morphological integration in a marine modular invertebrate. *BMC Evol Biol* 7:1–9
- Shabani F, Nasrolahi A, Thiel M (2019) Assemblage of encrusting organisms on floating anthropogenic debris along the northern coast of the Persian Gulf. *Environ Pollut* 254:112979
- Sheridan EA, Fonville JA, Cottingham S, Zhang Y, Dittmar T, Aldridge DC, Tanentzap AJ (2022) Plastic Pollution Fosters More Microbial Growth in Lakes than Natural Organic Matter *Nat Commun* 13(1):4175
- Simon N, Raubenheimer K, Urho N, Unger S, Azoulay D, Farrelly T, Sousa J, van Asselt H, Carlini G, Sekomo C, Schulte ML (2021) A binding global agreement to address the life cycle of plastics. *Science* 373(6550):43–47
- Smith LD (2009) The role of phenotypic plasticity in marine biological invasions. In *Biological invasions in marine ecosystems: ecological, management, and geographic perspectives* (pp. 177–202). Berlin, Heidelberg: Springer Berlin Heidelberg
- Soares MO, Garcia TM, Giarrizzo T, Martinelli Filho JE, Tavares TC, Ziveri P, ... & Teixeira C EP (2023) Marine debris provide long-distance pathways for spreading invasive corals *Sci Total Environ* 900:165637
- Soloviev A, Lukas R (2013) *The near-surface layer of the ocean: structure, dynamics and applications* (Vol. 48). Springer Science & Business Media
- Spencer M, Culhane F, Chong F, Powell MO, Holst RJ, Helm R (2023) Estimating the Impact of New High Seas Activities on the Environment: the Effects of Ocean-Surface Macroplastic Removal on Sea Surface Ecosystems *PeerJ* 11:e15021
- Subías-Barata A, Sanchez-Vidal A, Di Martino E, Figuerola B (2022) Marine biofouling organisms on beached, buoyant and benthic plastic debris in the Catalan Sea *Mar Pollut Bull* 175:113405
- Sutherland WJ, Bennett C, Brotherton PN, Butterworth HM, Clout MN, Côté IM, Dinsdale J, Esmail N, Fleishman E, Gaston KJ, Herbert-Read JE (2023) A global biological conservation horizon scan of issues for 2023 *Trends Ecol Evol* 38(1):96–107
- Thiel M, Gutow L (2005) The ecology of rafting in the marine environment. II. The rafting organisms and community *Oceanography and marine biology* 2005 Jun 24 (pp. 289–428). CRC Press
- Tuuri EM, Leterme SC (2023) How plastic debris and associated chemicals impact the marine food web: A review. *Environ Pollut* 321:121156
- Van Sebille E, Wilcox C, Lebreton L, Maximenko N, Hardesty BD, Van Franeker JA, Eriksen M, Siegel D, Galgani F, Law KL (2015) A Global Inventory of Small Floating Plastic Debris *Environ Res Lett* 10(12):124006
- Villarrubia-Gómez P, Cornell SE, Fabres J (2018) Marine plastic pollution as a planetary boundary threat – The drifting piece in the sustainability puzzle *Mar Policy* 96:213–220
- Vince J, Hardesty BD (2018) Governance Solutions to the Tragedy of the Commons That Marine Plastics Have Become *Front Mar Sci* 5:214
- VishnuRadhan R, Eldho TI, David TD (2019) Can plastics affect near surface layer ocean processes and climate? *Mar Pollut Bull* 140:274–280
- Walker TR, Fequet L (2023) Current trends of unsustainable plastic production and micro (nano) plastic pollution *TrAC Trends Anal Chem* 160:116984
- West-Eberhard MJ (1989) Phenotypic plasticity and the origins of diversity *Annu Rev Ecol Syst* 249–78
- Wilkins H (2020) The role of selection in the evolution of blindness in cave fish. *Biol J Linn Soc* 130(3):421–432
- Willis K, Hardesty BD, Vince J, Wilcox C (2022) Local waste management successfully reduces coastal plastic pollution *One. Earth* 5(6):666–76

- Winston JE, Gregory MR, Stevens LM (1997) Encrusters, epibionts, and other biota associated with pelagic plastics: a review of biogeographical, environmental, and conservation issues. *Marine debris: Sources, impacts, and solutions* 81–97
- Worm B, Lotze HK, Jubinville I, Wilcox C, Jambeck J (2017) Plastic as a Persistent Marine Pollutant *Annu Rev Environ Resour* 42(1):1–26
- Wray GA (2013) Genomics and the Evolution of Phenotypic Traits *Annu Rev Ecol Evol* 44(1):51–72
- Wurl O, Obbard JP (2004) A review of pollutants in the sea-surface microlayer (SML): a unique habitat for marine organisms. *Mar Pollut Bull* 48(11–12):1016–1030
- Zalasiewicz J, Waters CN, Do Sul JA, Corcoran PL, Barnosky AD, Cearreta A, Edgeworth M, Gałuszka A, Jeandel C, Leinfelder R, McNeill JR (2016) The Geological Cycle of Plastics and Their Use as a Stratigraphic Indicator of the Anthropocene *Anthropocene* 13:4–17
- Zhang Y, Wu P, Xu R, Wang X, Lei L, Schartup AT, Peng Y, Pang Q, Wang X, Mai L, Wang R (2023) Plastic Waste Discharge to the Global Ocean Constrained by Seawater Observations *Nat Comm* 14(1):1372
- Zong H (2021) A Correlation Analysis between Global Plastic Production and Floating Macro-and Micro Plastic Waste in the Ocean *Int J Stud Res* 3(6):51–55