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Marine plastic pollution in the Anthropocene: A linguistic toolkit for holistic understanding and action

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Abstract :

In the Anthropocene, the significant and pervasive human impact on Earth's ecosystems is manifested in myriad ways, with the ever-increasing presence of plastic pollution being a prime example. This paper presents a comprehensive exploration of the ubiquitous problem of marine plastic pollution in the Anthropocene, providing a vital lexicon for all stakeholders. This linguistic toolkit enables effective communication and mutual understanding among scientists, policymakers, activists, and the general public, fostering tailored and targeted approaches to address the various facets of plastic pollution. It further underscores the profound human impact on the environment to the extent that our plastic litter might symbolize the inception of a new geological epoch. However, these classifications, while mirroring our role in shaping the Earth, do not mitigate the urgent need to address plastic pollution. Rather, they serve as an urgent call to action, emphasizing the power we possess to solve the problem we have created. As we traverse this era full with plastic, our responsibility is to leverage this lexicon not only to comprehend the extent of the damage caused but also to ignite innovative solutions and foster resilience. Regardless of the nomenclature assigned to our era, our duty to safeguard the planet remains paramount.

Graphical abstract

Highlights

► The Anthropocene is characterized by the widespread use of plastics in our everyday lives. ► Integration of plastics and their impact on the natural environment. ► An in-depth review of the current lexicon related to plastic pollution. ► Effective communication and mutual understanding among stakeholders. ► Urgent need for global action to mitigate plastic pollution.

Keywords : Anthropocene, Litter, Plastics, Human impact, Ocean, Lexicon

INTRODUCTION

In the quest to chronicle and comprehend the shifts in the Earth's environment, science have coined a new term: the Anthropocene (Crutzen and Stoermer 2000; Waters and Turner 2022). This epoch, proposed as a successor to the Holocene (or a part of it), recognizes the overwhelming global impact of human activities on the Earth's ecosystems, climate, and biodiversity (Waters et al., 2016). It acknowledges the indelible imprint left by human civilization, with the most significant changes noted in the mid-20th century, the "Great Acceleration" (Zalasiewicz et al., 2019).

A defining characteristic of the Anthropocene is the proliferation of plastic pollution. Plastics, derived from petrochemicals, are durable, versatile, and inexpensive, making them an integral part of our modern life (Rangel-Buitrago et al., 2022). However, their resistance to natural degradation processes has caused a ubiquitous environmental crisis. An estimated 8.3 billion metric tons of plastic have been produced since the 1950s, with approximately 60% discarded in landfills or the natural environment (UNEP 2021). As plastics break down, they become microplastics and nanoplastics, which infiltrate terrestrial, freshwater, and marine habitats, disrupting ecosystems and threatening biodiversity (Williams and Rangel-Buitrago 2019 and 2022).

In grappling with this crisis, a unique challenge has been communication – conveying the extent, complexities, and implications of plastic pollution to diverse audiences. Herein lies the importance of an unification fo terms – a lexicon specifically designed to encapsulate and communicate the nuances of the Anthropocene's plastic problem.

The formulation of specialized terminology offers a systematic framework for academic inquiry, enabling greater methodological rigor and facilitating interdisciplinary synergy (Haram et al., 2020). Such lexicons not only enrich the precision of scientific discourse but also potentiate the translational efficacy of research into actionable policies by providing unequivocal nomenclature for intricate phenomena.

In the realm of public dissemination and education, a well-curated lexicon acts as an efficient vector for knowledge transmission. Terms such as 'carbon footprint' and 'blue economy' serve as salient examples, having transcended academic boundaries to become integrated into public discourse, thereby modulating awareness and catalyzing behavioral shifts (The Carbon Trust 2007).

As we proceed through the Anthropocene epoch, marked by heightened anthropogenic influence on Earth's geophysical systems, the exigency for a dedicated linguistic framework becomes paramount. This is particularly critical given the multidimensional impacts of plastic pollution, a global phenomenon that necessitates coordinated research and intervention strategies. A lexicon serves not merely as a semantic tool, it contributes to a predictive understanding of Earth systems alterations, a cornerstone for sustainable human-planet interactions, and thus represents a strategic asset in navigating the Anthropocene's complex terrains.

HISTORICAL PERSPECTIVE OF PLASTIC PROLIFERATION IN THE ANTHROPOCENE

Plastic, a creation of the 20th century, has reshaped humanity in ways that are both transformative and deeply problematic (Andrady 2022). The story of plastics in the Anthropocene is one of rapid growth and unchecked proliferation, paralleling the trajectory of human technological and industrial development.

The invention of Bakelite in 1907 marked the dawn of the age of synthetic plastics. However, it was in the aftermath of World War II that we truly entered the "Plastic Age". Aided by advancements in petrochemical technologies and the rising consumer culture, plastic production soared from 2.3 million tons in 1950 to almost 600 million tons by 2022 (Figure 1 - UNEP 2021). Today, it is hard to imagine a facet of human life untouched by plastic. From packaging and agriculture to healthcare and technology, plastic's versatility and low cost have embedded it in every corner of our modern world (Geyer 2020).

However, plastic's enduring legacy lies in its resistance to decay. While its durability is an asset during its usage, it becomes a curse once discarded. Traditional waste management strategies like landfilling and incineration pose environmental and health hazards. Further, the notion of "out of sight, out of mind" is flawed as plastics, when improperly disposed of, often end up infiltrating natural habitats, carried by wind currents or washed into water bodies.

The degradation process of plastics is slow and results in fragmentation rather than complete mineralization. Larger plastic debris breaks down into microplastics and nanoplastics, which are easily ingested by wildlife, leading to physical harm and toxicological effects (Derraik 2002). It is a pervasive issue, with studies finding plastics in the most remote locations – from the peaks of Mount Everest to the depths of the Mariana Trench (GRID-Arendal 2021).

The incessant increase in plastic production and the resultant disposal issue have far-reaching consequences. They disrupt ecosystems, threaten biodiversity, and have potential implications for human health (Gracia et al., 2018). Moreover, plastic production and waste management are intrinsically tied to climate change (Williams and Rangel-Buitrago 2022). As plastics are derived from fossil fuels, their production contributes to greenhouse gas emissions. Additionally, the mismanaged plastic waste in the environment can release greenhouse gases as they degrade (Lebreton and Andrady 2019).

The history of plastics proliferation in the Anthropocene is a cautionary tale of uncontrolled growth and the failure to fully understand and manage the lifecycle of a product. The impacts of this trend underline the need for drastic changes in how we produce, use, and dispose of plastics and also how we call this problem!

THE EMERGING LEXICON

The Basis

Coastal and marine environments frequently harbor a diverse array of debris materials, deposited through various mechanisms such as wind, waves, currents, and to a lesser extent, tidal forces. In the context of marine pollution, 'debris' refers to fragmented materials that have been either intentionally or unintentionally introduced into the marine ecosystem (Figure 2). These materials span a broad spectrum and their nature, origin, and impact can vary significantly based on environmental conditions and human activities. These debris materials can be categorized based on their specific sources:

Marine Wrack: Comprising organic, marine-origin items that are washed up, transported, and deposited in the marine environment. The constituents include a variety of marine autotrophs (micro and macro-algae and higher marine plants), animals, and/or their shells (Macreadie et al., 2017).

Terrestrial Debris: Organic, terrestrial-origin items, such as plants and animals, that naturally fall or are introduced into river basins. These materials often lodge in river channels before being transported and ultimately accumulating along beaches (Gracia et al., 2018; Grilliot et al., 2019).

Litter: Items manufactured and utilized by humans, which are either accidentally lost or deliberately discarded into the environment. These may also be indirectly introduced via rivers, sewage systems, storms, winds, waves, currents, or tides (UN, 2019; Williams and Rangel-Buitrago, 2019)."

As a first step, it is important to define and differentiate between litter, rubbish, trash, garbage, and waste for a better understanding of plastic pollution. In the context of the Anthropocene, particularly in the study of plastic pollution, these terms gain added distinctions and significance. By defining and differentiating them, we can better understand the scale, nature, and implications of our waste generation habits and their impact on the planet.

Litter: This term typically refers to waste products that have been improperly disposed of in an outdoor setting, often in public places, rather than being disposed of in designated locations. Litter often includes items such as cigarette butts, used plastic bags, food wrappers, or beverage cans. It is closely associated with plastic pollution, as much of the litter we see in the environment, particularly in aquatic habitats, is composed of plastic.

Rubbish: This term is commonly used in British English in the same way "trash" is used in American English. It generally refers to dry waste materials that are discarded and unwanted. This can include items like paper, cardboard, and plastic packaging.

Trash: Similar to rubbish, trash generally refers to any discarded, rejected, or worthless material. It encompasses anything that is no longer needed or is not functioning. This is a broad term, and in the context of the Anthropocene, plastic trash is an important subcategory.

Garbage: Garbage usually refers to waste residue from household and kitchen waste. This can be both organic and inorganic, but in general, it is wet and decomposable. This term is less likely to be used in the context of plastic pollution, as most plastics are not decomposable and are not typically considered "garbage" in the traditional sense.

Waste: Waste is the broadest and most encompassing of these terms. It refers to any substance which is discarded after primary use, or is worthless, defective, and of no use. Waste can be categorized into different types such as solid waste, liquid waste, hazardous waste, organic waste, recyclable waste, and so on. "Plastic waste" refers specifically to plastic materials that are discarded after use or are offcuts from the plastic production process.

Understanding the origins of the Anthropocene

A **Geologic Era** is a significant division of geologic time, characterized by events that alter the Earth's surface and climate, and lead to the evolution and extinction of species (Elias 2018; Cohen et al., 2013). These eras represent broad spans of time and are further divided into periods, epochs, and ages for more detailed resolution. They mark substantial phases in Earth's 4.5 billion-year history, each distinguished by unique conditions and distinctive fossil records.

In this context, the proposed **Anthropocene**, though not officially recognized, represents as a profound shift in Earth's history. The term itself combines "anthropo-", meaning "human", with "-cene", the standard suffix for "epoch" in geological time (Zalasiewicz et al., 2008 and 2014). It was first proposed by ecologist Eugene F. Stoermer and popularized by atmospheric chemist Paul Crutzen in 2000. The Anthropocene represents the period when human activities started to significantly impact Earth's ecosystems on a global scale, marking a time when human activity, rather than natural processes, became the primary driver of geological and ecological changes (Rangel-Buitrago et al., 2022).

Plastic is now so ubiquitous in all world environments that its magnitude, distribution, and collateral effects have been suggested to indicate a new stage/age (or substage) within the Anthropocene: The **Plasticene** (Stager 2011; Corcoran et al., 2014; Haram et al., 2020; Rangel-Buitrago et al., 2022). This stage (or substage) was initiated when plastics began entering Earth's cycles due to their massive production and use (1950s), and since consists of increasing amounts of plastic as sedimentary materials (in all sizes, shapes, and compositions) deposited, buried, and now present as stratigraphic markers in deposits as well as rocks.

Despite the lack of official recognition, the terms Anthropocene and Plasticene encapsulates the significant influence of human activities on Earth's biophysical systems. It signifies a discernible shift from the relatively stable Holocene epoch to a period defined by human-induced environmental transformations. Various environmental indicators suggest the mid-20th century as a probable boundary between the Holocene and Anthropocene epochs. This period represents a divergence from the Holocene's comparative stability, giving way to pervasive, human-driven changes, particularly the spread and environmental impact of plastics.

Important terms

The widespread proliferation of plastics has given rise to unique new forms of pollution, necessitating the development of a new series of terms to encapsulate these phenomena accurately (Figure 1). Here we suggested a division of these terms based on five approaches. **General**, **Ecological**, **Geological**, **Oceanographic**, **Chemical, and Geopolitical.**

a) General

Plastics: The term "plastic" derives from the Greek word 'plastikos,' meaning 'able to be molded or shaped.' While often referred to as a single entity, plastic more accurately represents a vast category comprising hundreds of unique types (Andrady and Neal 2009). These belong to a broader group known as polymers, characterized by their long, chain-like molecular structures composed of recurring structural units. These large molecules typically possess considerable molecular weights in the range of 105–106 (g/mol).

Polymers, the fundamental building blocks of plastics, can originate from natural or synthetic sources. For instance, cellulose, silk, wool protein fibers, and starch are natural polymers. These polymers consist of long molecular chains assembled by linking smaller, repeating units in a chemical process called polymerization (Andrady 2022). The distinctive physical properties of plastics, such as their strength and flexibility, can be attributed to these lengthy, flexible, and intertwined molecular chains.

The term 'plastic' denote substances capable of being molded or shaped. Today, 'plastic' is a universal term representing many materials. Plastics permeate our daily lives. We encounter various types of plastic in everyday items like plastic bags, bottles, pens, pipes, and electrical devices. Despite their diverse nature, all these materials share one common trait: they consist of large chain-like molecules, termed macromolecules. These macromolecules are polymers, large molecules formed from smaller repeating units, or monomers, linked sequentially.

German chemist Hermann Staudinger first introduced the concept of macromolecules and their identification as polymers in the 1920s. The term 'polymer' derives from the Ancient Greek words 'poly' (meaning many) and 'meres' (representing parts). Every molecule within a polymer chain is considered a single unit, or a 'monomer,' with 'mono' indicating singularity. Monomers are small molecules capable of bonding to create long chains akin to individual pearls on a string (Young 1991).

The process of joining monomers to form a polymer is known as polymerization. For example, the polymerization of the monomer ethylene creates polyethylene, a standard plastic. Thus, a polyethylene plastic bag is essentially a tangled, unstructured mass of branched polymer chains, each composed of repeating ethylene monomers. These extensive molecular chains can be molded and shaped to produce solid items.

Plastic Pollution: This term refers broadly to the accumulation of plastic objects and particles in the Earth's environment that adversely affects wildlife, wildlife habitat, and humans (Williams and Rangel-Buitrago 2022). It often describes situations where large visible pieces of plastic, like bags or bottles, have been discarded improperly (Figure 1a). Plastic pollution covers a wide range of situations, from litter on our streets to waste aggregating in so-called 'garbage patches' in the oceans.

Plastic Contamination: This term is used to describe situations where plastics have been introduced into an environment or a process where they are unwelcome or harmful (Williams and Rangel-Buitrago 2022). It often refers to smaller, often microscopic particles, such as microplastics and nanoplastics, that can infiltrate various environments (e.g., water sources, soils, air), organisms, and even human food and water supplies. While plastic contamination is a form of plastic pollution, the term specifically underscores the infiltrative and pervasive nature of plastics, highlighting their ability to invade even seemingly pristine environments or to compromise processes and products that should be plastic-free.

Plastic Cycle: This term, first introduced by Bank and Hansson in 2019, refers to the continuous and complex movement of plastic materials between different abiotic (non-living) and biotic (living) ecosystem compartments, including humans. The term 'cycle' here extends beyond the mere movement of plastics. It encompasses their origin (including production and sources), evolution (changes in properties over time), interactions with other elements, impacts on ecosystems, and eventual accumulation or 'sinks' in the environment (Figure 3). This comprehensive term allows us to think about plastics not merely as static pollution but as dynamic materials that interact with our ecosystems in complex ways.

b) Ecological

Plastisphere: Is a term used to describe the unique ecosystems that form on the surface of floating plastic debris in the ocean (Zettler et al., 2013). Composed of a wide variety of organisms, including bacteria, algae, microorganisms, tiny invertebrates, and even fish, these communities can potentially impact the surrounding marine environment, including aiding the spread of harmful invasive species or pathogens (Figure 4).

Plasticivores: These are organisms that consume and break down plastics (Hohn 2011). Recent research has discovered certain bacteria, fungi, and even mealworms capable of digesting certain types of plastic, transforming them into usable organic matter.

Biofilms: A biofilm comprises one or more types of microorganisms that can grow on various surfaces, including plastics (Hidalgo Ruz et al., 2018). The formation of biofilms on plastic surfaces in the marine environment can influence the buoyancy, movement, and degradation of plastic debris.

Epiplastic: Coined by Reisser et al. (2014), this term refers to life forms living on floating plastic. It was initially used to denote periphyton colonization of plastic surfaces in experimental mesocosms (Blumenshine et al., 1997).

Plasticized: Introduced by Eriksen (2014) and later used by UNEP (2016), this term metaphorically represents the shaping of the environment by the proliferation of plastic pollution. Derived from "plasticize" (v.), which means "to make plastic or moldable, especially by the addition of a plasticizer".

Bioaccumulation: accumulation of plastic particles within an organism over time (Thompson et al., 2004). These particles can be ingested directly or can enter the organism through other means (such as absorption through the skin). Over time, these particles can accumulate in the organism and can lead to various health effects.

Trophic transfer: the process by which plastic particles (especially microplastics) are passed up the food chain (Bergmann et al., 2017). For example, a small fish might ingest microplastics. Then, a larger fish eats the smaller fish, and the microplastics are transferred to the larger fish. This process can lead to an accumulation of plastics in top predators, including humans. It is especially concerning because plastics can carry other pollutants, which also get transferred and may have harmful effects.

c) Geological

Plastic Geological Cycle: Introduced by Rangel-Buitrago et al. (2022) it can be defined as an expanded version of the Plastic Cycle that includes not only the production, use, and disposal of plastic materials, but also their ongoing transformation and persistence within the Earth's geology (Figure 5). This concept recognizes that plastics have entered the geologic record and will continue to evolve and impact our planet on a geological timescale. This cycle begins with the extraction of raw materials and proceeds through transportation, design and production, and use of plastic items. However, unlike the traditional view of the plastic life cycle, which ends with disposal, the Plastic Geological Cycle sees disposal as merely a stage in an ongoing process. Post-disposal, plastics undergo various transformations through physical, chemical, and biological processes. They can break down into microplastics and nanoplastics, infiltrate various ecosystems, and even integrate with geological materials to form novel entities like plastiglomerates. Moreover, these transformed plastic materials can move between different abiotic and biotic compartments of ecosystems, just like other geological materials. The concept of the Plastic Geological Cycle underscores the long-term, persistent impacts of plastic pollution that extend far beyond the human timescale.

Rocks with plastics: In the context of the Plasticene stage, these are coherent aggregates composed of one or more minerals along with plastic materials. These aggregates form recognizable and mappable volumes and have necessitated an update to traditional geological definitions of rocks. Traditionally, rocks were aggregates of naturally occurring, inorganic, crystalline solids (minerals) with definite physical and chemical properties (Rangel-Buitrago et al. 2022 and Rangel-Buitrago and Neal 2023).

Despite their unique characteristics, the formation of these rocks is closely tied to processes that form clastic sedimentary rocks. This involves weathering (in the case of rocks) and degradation (in the case of plastics), which are processes that result in the physical disintegration and chemical decomposition of pre-existing igneous, metamorphic, sedimentary rocks, and plastic litter Rangel-Buitrago et al. (2023) . The end product of weathering and degradation includes solid particles and ions in solution which become the raw material for new types of sedimentary rocks.

Transportation of these new materials from their sites of origin to locations where they accumulate can be facilitated by different mediums such as rivers, oceans, winds, and rain-runoff. The deposition of these solid particles usually happens when the energy of the transporting medium is insufficient to carry on the process. Deposition can also occur when there are changes in temperature or chemistry that cause material to precipitate and crystallize, sometimes trapping plastic particles, or when organisms remove dissolved materials to construct shells (Rangel-Buitrago et al. 2022 and Rangel-Buitrago and Neal 2023).

Given the variation in how products of rock weathering and plastic degradation are transported, deposited, and turned into solid rock, three categories of plastic sedimentary rocks can be recognized (**Table 1**).

- **Detriplastic Rocks:** These rocks are a combination of various sized and shaped plastics with solid particles (gravel, sand, silt, and clay) that are derived from pre-existing rocks via mechanical and chemical weathering (Rangel-Buitrago et al. 2022). The primary example of this type of rock is Plastiglomerates (Corcoran et al., 2014). Plastiglomerates consist of rock fragments, sand grains, plastic debris, and organic materials held together by a plastic matrix. This category is further divided into two types based on how plastic is incorporated: i) the plastic is melted on the surface, or ii) the plastic acts as a binding matrix or cement for the rocks, shells, or woody debris.
- **Bioplastic Rocks:** These rocks form when plastics are combined with organisms that accumulate and then compress and cement together after dying. Examples include Antropoquinas (Fernandiño et al. 2020), which contain anthropogenic items cemented with biogenic and siliciclastic material. Another example is the "plastic peat" found in Mausund and Froan islands, Norway, composed of up to 72% of medium-density polyethylene, polypropylene, and polystyrene (Cyvin et al. 2021).

- **Chemiplastic Rocks:** Chemiplastic rocks are created by chemical precipitation, which starts when water traveling through a rock containing plastics dissolves some of the minerals. This process carries away the plastics and dissolved minerals from their source (Iñiguez et al., 2017). The plastic is eventually redeposited along with the precipitation of the solutes when the water evaporates, resulting in plastic being incorporated into evaporite deposits.

Igneous-Associated Rocks with Plastic: These are rocks where plastic materials are incorporated into igneous processes (Rangel-Buitrago et al. 2022). Most often, these occur in low-temperature igneous processes where plastics can be preserved. Plastics can be buried by cooled volcanic ash, potentially leading to partial melting and the formation of an intergranular matrix. An example could be a plastirhyolite, where the plastic material becomes part of the igneous rock structure. In certain conditions, even if plastic melts and vaporizes under the heat of lava flows, there is a potential for a cavity (or mold) to be left behind that retains the shape of the original plastic object. These cavities can be seen as a form of fossil or artifact of the plastic object.

Pyroplastics: Described as amorphous matrices consisting of angular to weathered-rounded clasts generated from burning plastics (Turner et al. 2019; Ehlers and Ellrich, 2020). They usually have cracks, fractures, pits, cavities, and smooth surfaces (Figure 6). Notably, pyroplastics are positively buoyant in seawater. They've been reported in several countries including England, Scotland, Ireland, Spain, Canada, Italy, Peru, Japan, Portugal, Colombia and Brazil.

Plasticrusts: Initially reported in Portugal, plasticrusts are pieces of plastics of varying shapes and sizes embedded in porous rocks, often in intertidal regions (Gestoso et al. 2019). The formation process is related to molding and even melting plastic particles over the porous surfaces of bedrock after being transported and deposited by waves, currents, tides, and wind (Ehlers and Ellrich 2020; De la Torre et al., 2021). Plasticrusts have also been found in Italy, Colombia and Peru.

Biofouled plastics: Pieces of plastic that have been colonized by biological organisms, typically in a water environment. This is a particular concern in marine and freshwater ecosystems where plastic pollution can serve as a substrate for a variety of organisms including bacteria, algae, barnacles, mussels, oysters, polychaetes, and more. The process of biofouling begins almost immediately upon the plastic entering the water. Microscopic organisms, such as bacteria and diatoms, are usually the first to colonize the surface, forming a layer known as a biofilm. This provides a base for larger organisms like barnacles, mussels, and oysters to attach. Examples of this are Plastisessils, as defined by Ellrich et al. (2023).

Plastitar: This term describes an agglomerate of tar and plastics (mainly microplastics), which are amalgamated and attached to a rock surface (Dominguez-Hernandez et al. 2022). The mix may also include small pieces of wood, glass, rocks, and sediments. This element was first reported in the Canary Islands, Spain (Dominguez-Hernandez et al. 2022).

Plasticlasts: As defined by Avelar et al. (2022), plasticlasts are remnants resulting from the weathering, erosion, and transport of former plastic forms such as plastiglomerates and pyroplastics. This term applies to all mechanically transported plastic fragments or clasts, which may eventually become lithified.

Anthrosols - Plastisols: These are entirely human-made soils, comprised of litter items like glass, plastics, and rubber (Anthrosol), or solely plastics (Plastisol). These litter-derived soil layers can mix with the O Horizon (organic matter) and/or the A Horizon (mineral matter and humus) of soil profiles. Because these layers contain dateable materials, they can provide relative dating information for all layers above (younger than the litter items) and all layers below (older than the litter items).

Technofossils: First defined by Zalasiewicz et al. (2014), technofossils are remnants, impressions, or traces of manufactured technologies or artifacts preserved in rock. This term encompasses a wide range of objects, from early human tools to modern-day items such as cans, bottles, or plastic toys.

Urban Fossils: Introduced by Cirilli and Delfino (2016), urban fossils are traces or remnants of human activity left in an urban environment. These primarily include plastics embedded in asphalt, concrete, and tar, which increase their potential for preservation and incorporation into rock strata.

d) Chemical

Bioplastics: plastics derived from renewable sources, such as plants, and are designed to biodegrade (Andrady 2011). However, many require specific conditions to break down and can still persist in the environment and potentially cause harm to wildlife.

Microplastics and Nanoplastics: Microplastics are minuscule plastic fragments less than 5mm long (Figure 7)., harmful to our oceanic and aquatic life (Andrady 2022). Nanoplastics are even smaller, less than 100 nanometers in size, and their impacts on ecosystems are still largely unknown (Andrady 2011).

Microfibers: a type of microplastic that come from synthetic clothing, like those made from polyester or nylon. When these garments are washed, tiny fibres shed and can make their way into water systems and eventually, oceans.

Microbeads: a kind of microplastic that are used in cosmetics, toothpaste and other personal care items for their abrasive properties (Barboza and Gimenez 2015). They are typically smaller than 1mm and are not filtered out during sewage treatment, making their way into rivers and oceans.

Nurdles: Pre-production plastic pellets used in the plastic manufacturing industry. They often end up as pollutants in marine environments (Coe and Rogers 1997).

Plastic Confetti: This term is sometimes used for accumulations of colorful plastic fragments on beaches or in the ocean (Moore and Phillips, 2011).

Plasticizers: additives that increase the plasticity or decrease the viscosity of a material (Frias and Nash 2019). Plasticizers are commonly added to polymers such as plastics and PVC to increase their flexibility, workability, and durability. However, some plasticizers can leach out of products and enter the environment, and some have been found to have adverse health effects.

Bisphenol A (BPA): BPA is a chemical used to make certain types of plastic (Andrady 2022). It is used in a variety of consumer products, including water bottles, sports equipment, CDs and DVDs. BPA can leach out of these products, especially when they are heated. Some research has shown that BPA can affect reproduction and development in animals by mimicking the hormone estrogen.

Phthalates: These are a group of chemicals used in hundreds of products, such as toys, vinyl flooring, and wall covering, detergents, lubricating oils, food packaging, pharmaceuticals, blood bags and tubing, and personal care products, such as nail polish, hair sprays, aftershave lotions, soaps, shampoos, perfumes, and other fragrance preparations (Andrady 2022). Phthalates are used in a variety of consumer products to soften and increase the flexibility of plastics and vinyl. Some phthalates can disrupt the endocrine system, and there is an ongoing debate about their safety.

e) Oceanographic

Windrow: This term refers to the aggregations of various materials, including plastics, seafoam, seaweeds, plankton, and woody debris, appearing on the ocean surface (Cozar et al 2014). A "windrow" is an aggregation of floating refuse in the submesoscale domain (less than 10 km horizontally), irrespective of the force causing the surface convergence, such as wind, tides, or density-driven currents.

Plastic Litter Blooms: This term is used when longshore current patterns combined with extreme runoff lead to the significant mobilization of plastic litter and woody debris (Figure 8 -Rangel-Buitrago et al., 2017).

Plastic Smog: This term is employed to describe the ubiquitous distribution of microplastics and nanoplastics in the air, akin to the dispersal of tiny particles in atmospheric smog (Van sebille et al., 2020).

Plastic Soup: This is a term used to define regions of the ocean where plastic debris has gathered in high concentrations, often due to ocean currents and winds (Suaria et al., 2016).

Gyre: A gyre refers to a significant system of circulating ocean currents, primarily those associated with substantial wind movements (Brach et al., 2018). Gyres result from the Coriolis effect, planetary vorticity, and horizontal and vertical friction, which dictate the circulatory patterns from the wind curl (torque). The world's oceans feature five primary gyres - the North Atlantic, South Atlantic, North Pacific, South Pacific, and the Indian Ocean Gyres. These gyres are crucial in the context of plastic pollution because they tend to accumulate plastic debris. Plastics entering the ocean from rivers, direct dumping, or other sources can be ensnared by these gyre currents.

Plastic Litter Patch: This term pertains to an area where plastic has accumulated in the environment, most commonly associated with marine settings (Brach et al., 2018). Specific examples include the notorious "garbage patches" in the world's oceans. Among the most famous plastic litter patches is the Great Pacific Garbage Patch, a vast area in the North Pacific Ocean where gyre currents have concentrated plastic waste. Similar patches are also found in the Atlantic and Indian Oceans.

f) Geopolitical

Plastic Exporting Countries: These are countries that manufacture and export a large quantity of plastic waste, such as the United States, Japan, Germany, and the United Kingdom. This term often refers to the global flow of plastic waste, especially when it comes to waste shipped from wealthier nations to developing countries (Williams et al., 2005).

Plastic Importing Countries: Countries that import significant quantities of plastic waste, often for recycling purposes. However, some of these nations, like Malaysia, Vietnam, and the Philippines, have faced issues with the mismanagement of these wastes, leading to environmental pollution. In many cases, these countries have started to push back and ban the import of foreign plastic waste (Williams et al., 2005).

Plastic Ban Policies: Refers to governmental policies and regulations aimed at restricting or banning the production, sale, and use of certain plastic items, most commonly single-use plastics like bags, straws, and cutlery (Williams and Rangel-Buitrago 2019 and 2022). These policies aim to reduce plastic waste and pollution.

Extended Producer Responsibility (EPR): EPR is a policy approach under which producers are given significant responsibility—financial and/or physical—for the treatment or disposal of post-consumer products (Viera et al., 2020). In the context of plastics, this means that the manufacturers of plastic products are held responsible for the waste generated by their products, encouraging them to design more sustainable products and packaging (Williams and Rangel-Buitrago 2019).

Circular Economy: A system of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing, and recycling existing materials and products as long as possible (Schröder and Raes 2021; Tudor and Williams 2021). In this context, the value of the products, materials, and resources is maintained in the economy for as long as possible, minimizing the generation of waste. In terms of plastics, this can mean designing products to be more easily recycled, encouraging the reuse of plastic items, and increasing the rate of plastic recycling.

Plastic Leakage: This term is often used in the context of plastic waste management. It refers to the escape of plastic waste from collection and disposal systems into the environment, where it can cause significant damage, especially in aquatic ecosystems (Ocean Conservancy 2021).

Plastic Footprint: An estimate of the total amount of plastic a person, organization, or country uses and discards over a certain period, often calculated on an annual basis (Williams and Rangel-Buitrago 2019 and 2022). It is a measure of the impact that one's lifestyle or operations have on plastic pollution.

CHALLENGES AND COMPLEXITIES IN MANAGING MARINE PLASTIC POLLUTION IN THE ANTHROPOCENE: A MULTIDIMENSIONAL PERSPECTIVE

The Anthropocene context demands innovative, adaptive, and integrative strategies to effectively manage the growing marine plastic pollution crisis. However, the management of marine plastic litter in the Anthropocene era entails complex challenges:

Environmental Dynamics: Anthropocene-induced escalation in plastic production and dissemination complicates ecological risk assessment and strategic planning. Urgent, adaptive interventions are required to mitigate ecological alterations.

Socioeconomic Strain: Rising plastic consumption and poor waste management exacerbate socioeconomic stressors on coastal zones, disproportionately affecting vulnerable communities, especially in developing nations.

Technological Constraints: Existing technologies for plastic waste monitoring and mitigation remain limited, ranging from suboptimal recycling solutions to inadequate remote sensing for marine litter tracking.

Knowledge Deficits and Uncertainty: Significant gaps in understanding the long-term ecological impacts of microplastics render risk assessment and strategic planning challenging.

Transboundary Regulatory Complexity: Disparate legal frameworks across jurisdictions create barriers to international cooperation for marine litter management.

Environmental Justice: Equitable distribution of environmental burdens and benefits linked to plastic waste is essential. This is particularly crucial for marginalized populations that bear disproportionate environmental impact.

Stakeholder Tension: Conflicting interests among stakeholders, such as industries opposed to production restrictions, can hinder consensus on effective waste management.

Resource Limitations: Adequate funding and resources for research, cleanup, and public awareness initiatives are often lacking, particularly in resource-constrained settings.

Legal Inadequacies: Existing laws often lack the rigor to effectively manage plastic waste, with exemptions and loopholes undermining legislative intent.

Political Volatility: Political instability can disrupt continuity in strategies aimed at plastic waste management.

Inertia to Change: Economic concerns or ignorance of the gravity of plastic pollution can result in resistance to change in plastic production and consumption habits.

INTEGRATED MANAGEMENT OF MARINE PLASTIC POLLUTION IN THE ANTHROPOCENE: A MULTI-STAKEHOLDER APPROACH

In the Anthropocene epoch, coastal and marine ecosystems confront unique challenges from plastic pollution, warranting the adoption of precautionary and integrated management principles. These principles advocate a multi-dimensional approach that incorporates scientific, sociocultural, legal, and institutional considerations. The complexity of managing plastic pollution is magnified by the diversity of its sources and the uncertainty of Anthropocene changes, necessitating proactive environmental stewardship (Williams and Micallef, 2009). Mitigating plastic pollution in this era involves:

- Life-Cycle Approach: Examining the environmental and social repercussions at every stage of plastic's life cycle, from production to disposal.
- Interdisciplinary Collaboration: Utilizing expertise from marine biology, ecology, social sciences, economics, and law to address knowledge gaps and offer holistic solutions.
- Adaptive Management: Implementing dynamic strategies that adapt to the rapidly evolving conditions characteristic of the Anthropocene.

- Stakeholder Inclusion: Ensuring the active participation of all stakeholders, including local communities, indigenous people, and governmental agencies, for successful strategy implementation.
- Policy Coordination: Harmonizing sectoral policies and international cooperation to offer a unified response to plastic pollution.
- Sustainable Financing: Leveraging multiple funding sources, including government budgets, international aid, and private sector investments.
- Resilience Enhancement: Boosting the resilience of coastal systems through habitat conservation, sustainable resource use, and community-led initiatives.
- Capacity Building: Educating stakeholders through various programs to strengthen plastic pollution control efforts.
- Technological Advancements: Employing modern technologies for monitoring and management, such as remote sensing and GIS.
- Policy Reforms: Updating regulatory frameworks to facilitate adaptive and integrated plastic waste management.
- Ecosystem-Based Management: Adopting comprehensive strategies like marine protected areas and integrated basins management.
- Research and Development: Fostering continual research to adapt to Anthropocene shifts and improve waste management strategies.

In the Anthropocene context, an integrated approach to plastic pollution management should be broad, inclusive, and proactive, including long-term perspectives, adaptive management, and stakeholder collaboration. Overall, the shift towards integrated management of plastic pollution in the Anthropocene will likely be incremental, with medium- to long-term outcomes.

A linguistic tool aimed at addressing marine plastic pollution in the Anthropocene serves as an instrumental mechanism for harmonizing communication and action across multiple stakeholders, including researchers, policymakers, activists, and the public. Below are key ways in which such a lexicon can advance marine plastic litter pollution management:

- Standardization of Terminology: The lexicon provides a standardized set of terms and definitions that allows for a consistent understanding of the issue across disciplines and sectors. This standardization is vital for data collection, interpretation, and comparison.
- Facilitation of Interdisciplinary Research: By offering a common linguistic framework, the tool eases cross-disciplinary dialogue and collaboration, essential for addressing the multifaceted problem of marine plastic pollution, which intersects with oceanography, ecology, material science, and social science.
- Policy Formulation and Implementation: The precise definitions and terms in the lexicon enable policymakers to construct regulations and guidelines that are both specific and comprehensive. This clarity streamlines legislative processes and minimizes ambiguity in regulatory compliance.
- Stakeholder Engagement: A standardized lexicon facilitates clearer communication between different stakeholders, making consultations and collaborations more effective. It can serve as a mediation tool to resolve conflicting interests, such as between industry advocates and environmental organizations.

- Public Awareness and Education: The lexicon, once disseminated, enables a higher level of public discourse. Clear, accessible terminology can be incorporated into educational materials, raising public awareness and potentially leading to behavior change.
- International Collaboration: Marine plastic pollution is a transboundary issue. A universally accepted lexicon aids in international cooperation and treaty formulation, ensuring that global efforts are synergistic and effective.
- Adaptive Management: The lexicon can be dynamic, updated based on scientific advances and changing societal needs. This adaptability is crucial for the management of a rapidly evolving issue like marine plastic pollution in the Anthropocene epoch.
- Risk Assessment and Prioritization: A standardized terminology allows for a systematic evaluation of the risks associated with different types of plastic pollution (e.g., microplastics vs. macroplastics), facilitating the prioritization of management efforts.
- Monitoring and Evaluation: With standardized terms, metrics for monitoring the effectiveness of pollution management strategies can be clearly defined and universally applied, facilitating longitudinal studies and impact assessments.

- Resource Allocation: A common understanding among stakeholders allows for more effective allocation of resources, whether it be for research, cleanup efforts, or preventive measures.

HOW AND WHERE TO USE?

Utilizing a linguistic tool as a management instrument for marine plastic pollution involves several strategic steps. These steps are designed to integrate the lexicon into decision-making processes, stakeholder engagement, and policy implementation. The following lines resumes how to employ it:

Integration into Research Protocols: Embed the standardized terminology into research methodologies and data collection instruments. This ensures that empirical studies across different disciplines speak the same language, enabling cross-validation and meta-analyses.

Policy Document Drafting: Use the lexicon as the reference for drafting policy documents, reports, and guidelines (i.e. UNEPor OSPAR guideliness). This ensures clarity and precision in language, eliminating ambiguities that could hinder implementation.

Training and Capacity Building: Train researchers, policymakers, and enforcers in the use of the lexicon. Webinars, workshops, and educational modules can be designed for different stakeholder groups.

Public Communication: Include terms from the lexicon in public awareness campaigns, educational programs, and outreach material. The consistent use of terminology helps educate the public and foster a unified understanding of the issue.

Stakeholder Consultations: During multi-stakeholder meetings use the lexicon as a foundational reference. This ensures that all parties are on the same page, facilitating effective dialogue and negotiation.

International Diplomacy: Advocate for the adoption of the lexicon in international forums. Standardized language aids in the drafting of international treaties and agreements, enabling cooperative action on a global scale.

Monitoring and Evaluation Metrics: Utilize the lexicon to define key performance indicators (KPIs) for evaluating the effectiveness of plastic pollution management strategies. This allows for objective assessment and comparability across different regions or projects.

Conflict Resolution: Use the lexicon as a neutral tool for resolving disputes or misunderstandings among stakeholders. Since the terminology is standardized, it helps to remove subjectivity from debates, streamlining the resolution process.

Adaptive Strategy Formulation: the presented lexicon is not closed, continuously update the lexicon to incorporate new scientific findings or societal shifts. This living document can then be used to adapt management strategies accordingly.

Resource Allocation: The lexicon can be used to precisely define the scope and objectives of projects, allowing for targeted resource allocation. This ensures that funding and efforts are directed where they are most needed and most effective.

Legal Enforcement: Employ the lexicon terms in legal frameworks to ensure that regulations are clear, enforceable, and universally understood. This helps in reducing loopholes and ambiguities in the law.

Reporting and Documentation: Standardize all forms of reporting and documentation using terms from the lexicon. This ensures that data collected from different sources can be aggregated and analyzed collectively, contributing to a broader understanding of the issue.

By systematically incorporating a dedicated lexicon into these management processes, a unified, effective, and adaptive approach to marine plastic pollution can be achieved. This contributes to more sustainable and impactful interventions in the Anthropocene.

FINAL REMARKS

A lexicon, or a set of terms and their meanings, is crucial in understanding a specific field of study or issue. In this case, the lexicon related to plastic pollution provides important terminology for discussing and understanding the nuances of the problem. Here are several ways this lexicon can help different stakeholders:

- **Scientists:** A clear lexicon helps scientists communicate their research findings more effectively, both within the scientific community and with the public. It ensures that everyone is using the same terminology, which reduces confusion and facilitates collaboration. Additionally, as new forms of pollution and their impacts are discovered, new terms will be added to the lexicon, driving further research.
- **Policymakers:** A defined lexicon provides policymakers with the necessary language to create legislation and policies that address specific aspects of the plastic pollution problem.

For example, understanding the difference between 'microplastics' and 'macroplastics' can help policymakers tailor regulations to target the sources of these different types of pollution.

- **Activists:** For activists, this lexicon provides a clear language to articulate the plastic pollution problem and its implications to the public and policymakers. The lexicon can also help in creating focused campaigns to target specific sources of pollution (e.g., 'nurdles' or 'microbeads').
- **Public:** For the general public, this lexicon enhances their understanding of the issue, enabling them to make more informed choices and support policies that address the plastic pollution problem. It can also encourage behavioral changes such as reducing single-use plastics or participating in clean-up efforts targeting certain types of pollution (e.g., 'plastic litter patches').

This lexicon might shape future research, policy-making, and activism by providing a more detailed understanding of the different facets of plastic pollution. It allows for more specific and targeted approaches to address the issue. For example, research could focus on the impact of specific types of pollution like 'microplastics' on marine life. Policymakers could then use this research to create regulations targeting the sources of these microplastics. Activists could use these policies and research to educate the public and rally support for changes in production and consumption behaviors.

Overall, a robust and evolving lexicon is essential in tackling complex environmental issues such as plastic pollution. It provides a common language for different stakeholders to understand, communicate, and address the problem effectively.

Classifications, while instrumental in helping us make sense of our world, are human constructs and thus artificial (Elias, 2018). This means that they are subjective and shaped by human understanding and interpretation. However, the naming or classification we provide for our current geological era won't change the profound and lasting impact of plastic pollution on our environment. Plastic litter, a ubiquitous problem today, will persist regardless of the nomenclature we adopt to describe our time.

Establishing a name for our current geological period or designing a universal rock-classification scheme doesn't alter the urgent necessity for us to address the issue of plastic pollution. Whether we call our time the Anthropocene, Plastocene, or any other term, the core message is that we need to act now to mitigate, and eventually eliminate, the devastating impacts of plastic use and litter on our planet.

In fact, the extent and rate at which we're changing Earth through our actions, especially in terms of plastic pollution, is comparable, if not more substantial, than many natural changes that the planet has undergone throughout its geological history. We've created, utilized, and discarded so much plastic waste that this litter has become a global marker, potentially characterizing the start of a new epoch.

These man-made imprints might be more prevalent and long-lasting than even some natural event markers. For example, the boundary delineating the Triassic-Jurassic Extinction, a significant event that wiped out about 80% of Earth's species 201.3 million years ago, might be less extensive than the impacts of plastics today. Paraphrasing Winston Churchill, we might say that the Pleistocene, the geological epoch that ended 11,700 years ago, doesn't mark the end, but perhaps the beginning of the end. The persistent issue of plastic pollution that we're facing today could indeed be a signal of a new geological era shaped by human impacts - one that's characterized by the remnants of our pervasive use of plastic.

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Table 1. Nomenclature to define rocks by mineral composition along with included plastics (Rangel-Buitrago et al., 2022). The three Plastic Rock divisions show subclasses using standard sedimentary rock-type names.

COMPOSITION	TEXTURE	NAME	
Plastics with rock fragments, quartz, feldspar grains and clay minerals.	Mostly angular and/or subangular gravel with plastics	Plastibreccia	**Detriplastic rocks**
	Mostly subround and/or well-rounded gravel with plastics	Plastiglomerate	
	Mostly quartz sand with plastics	Quartz plastisandstone	
	Mostly feldspar sand with plastics	Plastiarkose	
	Mostly rock fragments with plastics	Lithic plastisandstone	
	Sand is mixed with mud and plastics	Plastiwacke	
	Mostly silt with plastics	Plastisiltone	
	Mostly Clay with plastics (fissile – shale; blocks-clay)	Plastishale	
		Plasticlaystone	
Plastics with plants fragments and /or charcoal	Plastics inside a porous brown rock with visible plat fragments	Plastipeat	**Bioplastic rocks**
	Plastics inside a dull, dark brown, brittle, organic-rich rock	Plastilignite	
	Plastics inside a black, layered, brittle coal rock.	Plasticoal	
Plastics with shells/coral fragments and calcareous items	Plastics with a mostly gravel-sized shells or coral fragments	Anthropoquinas	
	Plastics with a mostly sandy-sized shells or coral fragments	Plasticalcarenite	
	Plastics with microscopic shells of calcareous phytoplankton	Plastichalk	
Plastics with specific calcite or aragonite fabrics	Plastics with calcareous oolite (spherical) grains	Plasticoolitic limestones	**Chemiplastic rocks**
	Plastics with masses of visible crystals of $CaCo_3$as in cave and spring deposits	Plastitravertine	
Plastics in salt deposits (e.g,,halite; gypsum)	Plastics combined with visible cubic crystals of NaCl or other precipitated salts	Plastihalite	

Figure 1. Global Plastic production between 1950-2022. Source: UNEP 2021.

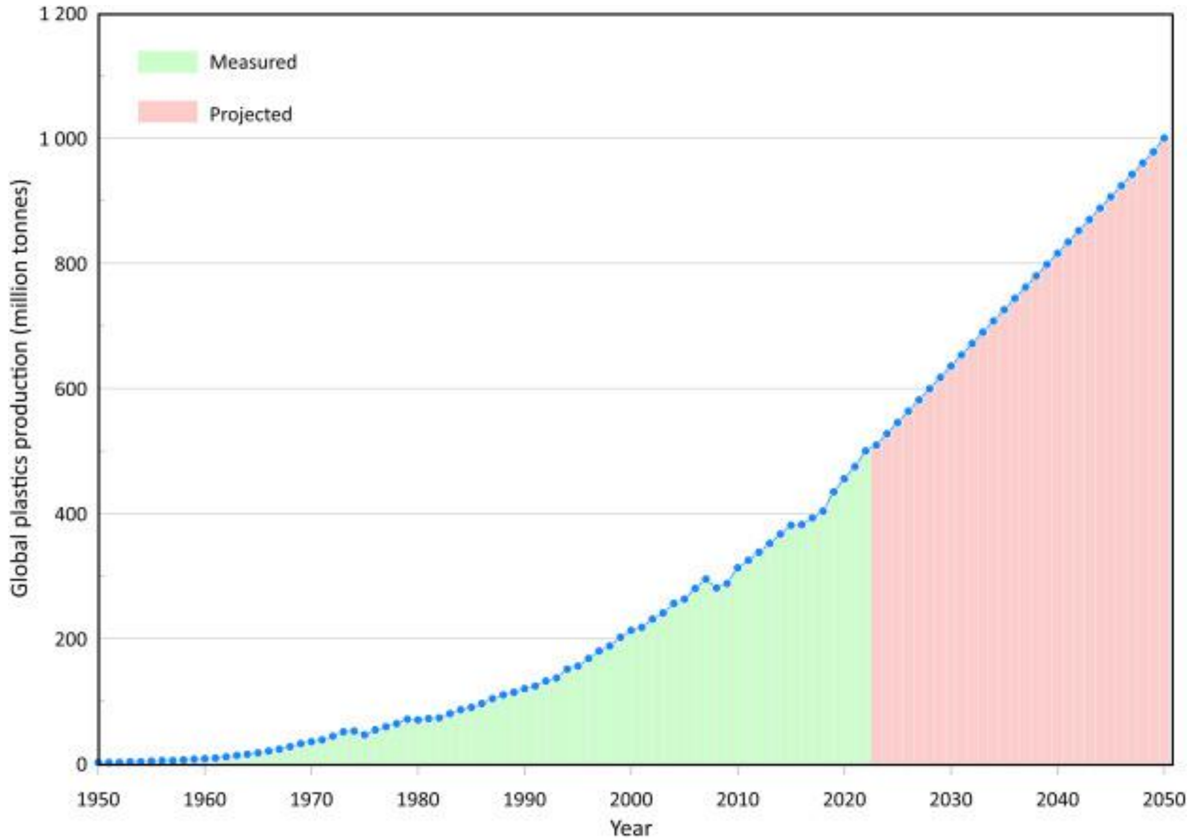

Figure 2. Examples of debris materials, deposited through various mechanisms such as wind, waves, currents, and to a lesser extent, tidal forces. a) Marine Wrack, b) Terrestrial Debris, c) Litter.

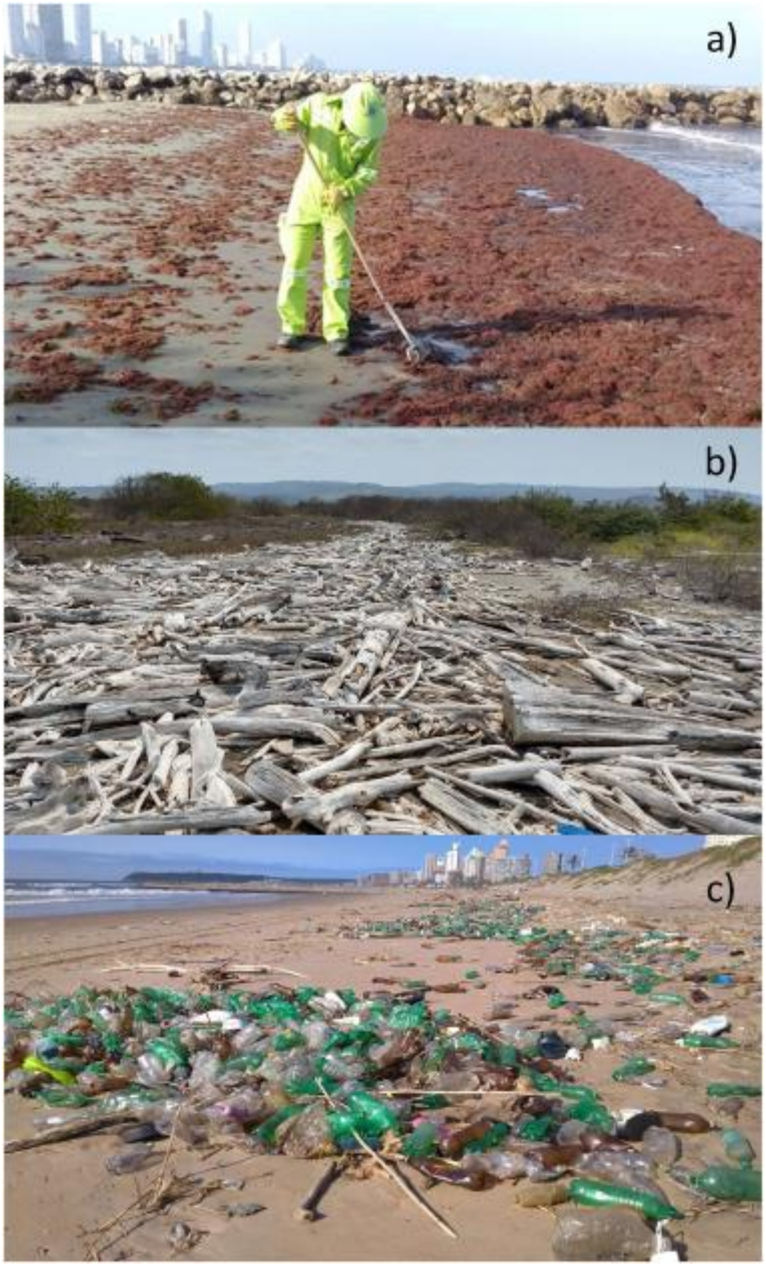

Figure 3. The life cycle of plastics. This cycle is composed of Extraction and Conversion, Transport, Production, Distribution, Use and Disposal. Plastics can escape into the environment at every stage of their life cycle.

Figure 4. Example of Plastisphere. Organisms (i.e., shells) on the surface of a plastic buoy found in the Caribbean Sea.

Figure 5. The Plastic Geological Cycle. This cycle follows the processes from extraction through production/use to the transformation of plastics into various new forms or pollution.

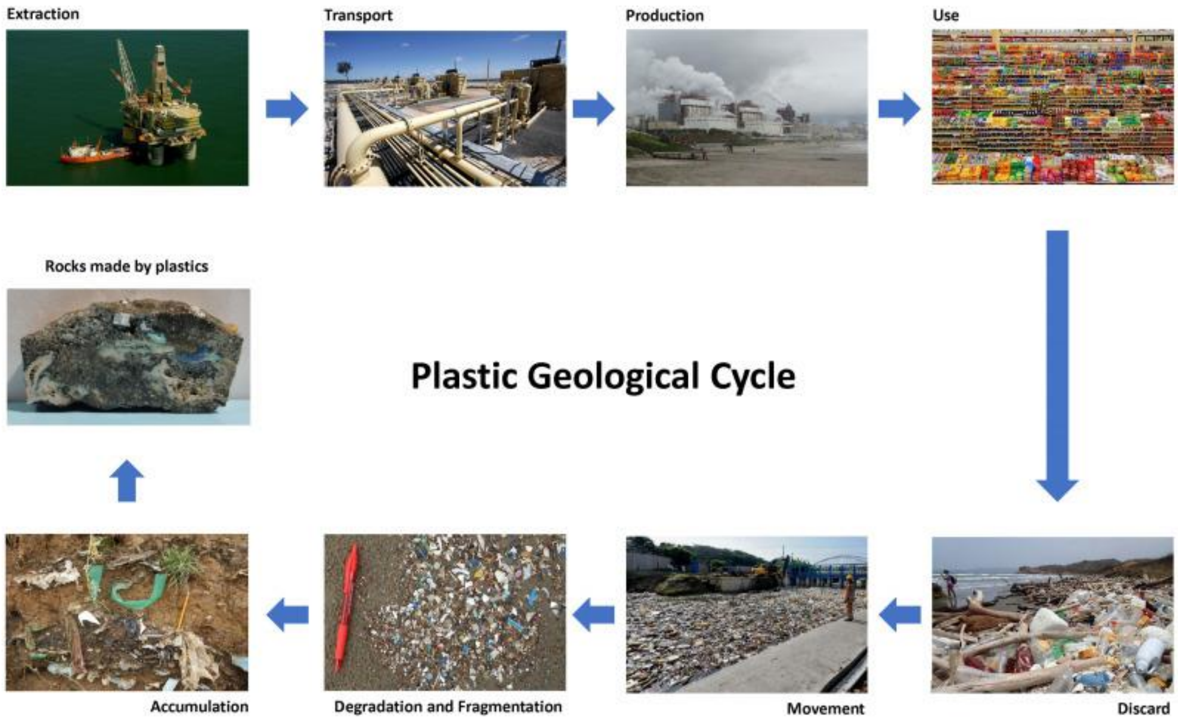

Figure 6. Example of two Pyroplastics. Amorphous matrices consisting of angular to weathered-rounded clasts generated from burning plastics. Pyroplastics are positively buoyant in seawater.

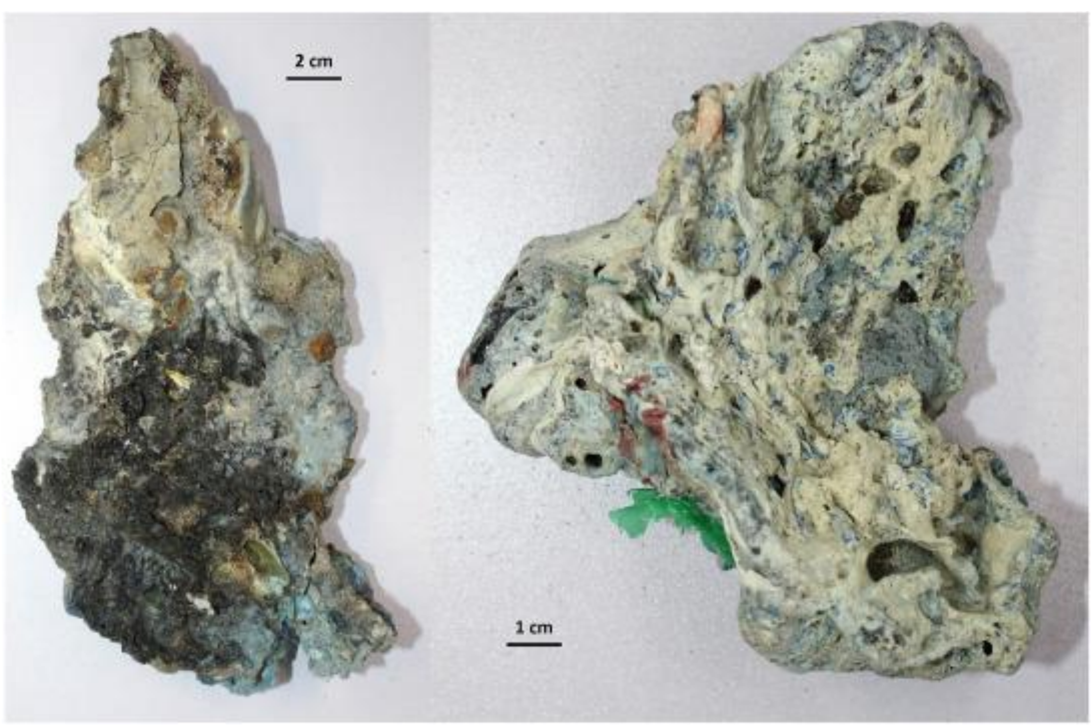

Figure 7. Example of microplastics. Microplastics are minuscule plastic fragments less than 5mm.

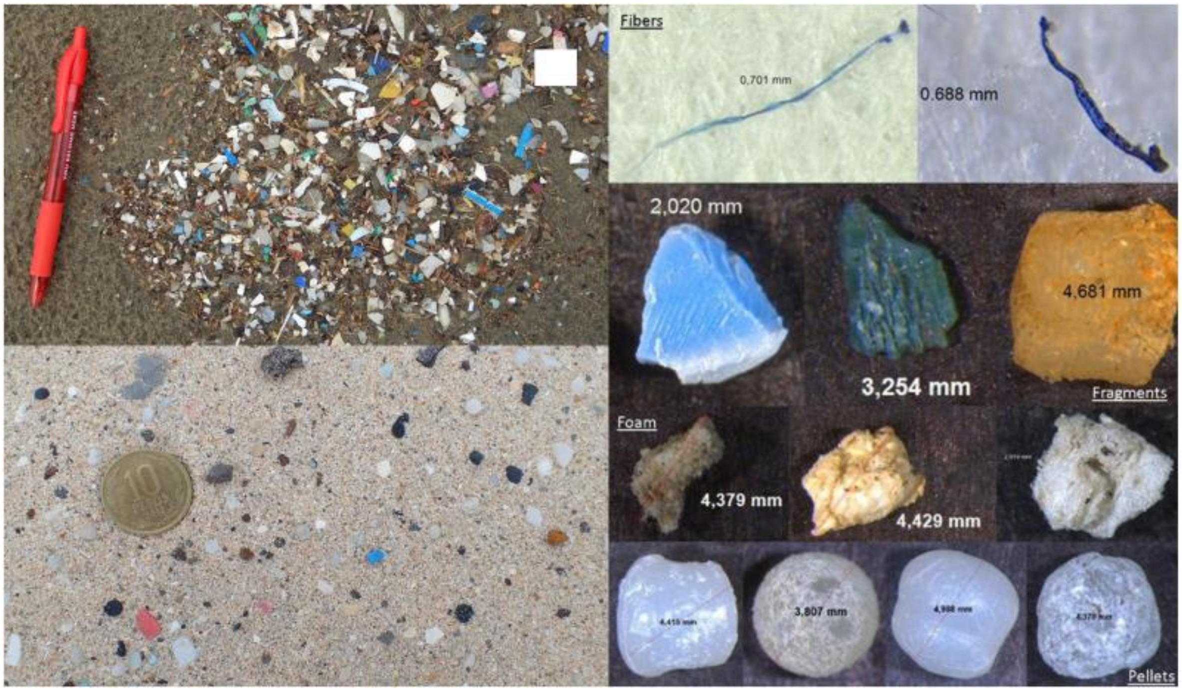

Figure 8. Example of a Plastic Litter Blooms in the Caribbean coast of Colombia. Extreme runoff combined with longshore current patterns lead to the significant mobilization of plastic litter and woody debris.