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Plastics in the Anthropocene: A multifaceted approach to marine pollution management

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Abstract :

The Anthropocene, defined by human-induced environmental transformations, presents a critical challenge: plastic pollution. This complex problem, particularly prominent in coastal and marine environments, requires integrated and adaptive responses. This opinion paper examines global efforts across policy interventions, scientific innovations, and public education, highlighting both advancements and hurdles in managing this problem. These include enforcement limitations in policy implementation, scalability and cost issues in scientific innovations, and challenges in effecting large-scale behavioral change through public education. The complexities inherent in managing plastic litter in coastal and marine environments are further discussed, emphasizing the necessity for an integrated approach. This approach involves interdisciplinary collaboration, adaptive management, stakeholder engagement, policy integration, sustainable financing, resilience building, capacity enhancement, technological innovation, policy reform, ecosystem-based management, disaster risk reduction, and advocacy. The management of plastic pollution in the Anthropocene requires strategic planning, innovative thinking, and unified global efforts, ultimately providing an opportunity to redefine our relationship with the planet and steer toward a more sustainable future.

Graphical abstract

Highlights

► The Anthropocene encapsulates the influence of human activities on Earth ► The Anthropocene is marked by the widespread use of plastics in our everyday lives. ► The management of plastic pollution represents a defining challenge of the Anthropocene. ► Managing plastic pollution involves complex environmental, social, and political dimensions. ► Anticipatory and flexible strategies, over reactive measures, enhance coastal and marine litter management.

Keywords : Anthropocene, Plastics, Coastal, Ocean, Pollution, Management

Plastics: The Indelible Imprint on the Anthropocene

The Anthropocene, a term still officially unrecognized yet frequently discussed, signifies a proposed epoch encapsulating the significant influence of human activities on Earth's biophysical systems (Crutzen and Stoermer 2000; Waters and Turner 2022). Geological epochs are typically characterized by substantial and identifiable transitions in Earth's systems. The Anthropocene meets this criterion by representing a time in Earth's history when humans have become the foremost influence on the global environment (Waters et al., 2016).

This new epoch emerged as a result of a discernible shift from the relatively stable Holocene epoch to a period dominated by human-induced environmental transformations. Many environmental indicators point toward the mid-20th century as a likely candidate for the Holocene/Anthropocene boundary. This suggests that our planet diverged from the Holocene's comparatively stable conditions into a phase defined by pervasive, human-driven changes (Zalasieicz et al., 2019).

The significance of the Anthropocene lies in its testament to the magnitude and scale of human activities' impacts on Earth's systems. The term itself stands as a stark reminder of our responsibilities to our home planet and the pressing need to acknowledge and address the environmental transformations we have induced. The Anthropocene epoch brings with it an urgent call for humanity to consider its actions and strive for more sustainable practices, highlighting the deep intertwining of human actions with the state of the Earth's environment.

One of the most pervasive and enduring hallmarks of this epoch is the production and accumulation of plastic litter (Rangel-Buitrago et al., 2022). Plastic was invented in the late 19th century, but its production did not truly skyrocket until the mid-20th century, precisely the period many scientists consider the starting point of the Anthropocene. As a material, plastic is incredibly versatile, durable, and inexpensive, making it highly popular for a wide array of applications (Geyer 2020). Everything from packaging materials and disposable cutlery to automobile parts and medical equipment is made of plastic. This surge in production and application coincides with the human-driven environmental changes that define the Anthropocene.

The characteristics that make plastic an optimal material for our anthropocentric, throw-away society also make it a pervasive and detrimental agent in the Anthropocene era. Lightweight, flexible, inexpensive, and readily molded into various forms and sizes, plastics have become ubiquitous due to their excessive manufacture and consumption (Williams and Rangel-Buitrago 2019 and 2022). As a testament to their pervasiveness, plastic residues and their adverse effects have been documented throughout all environments emblematic of the Anthropocene epoch, from mountaintops to the deep sea, traversing cities, and even suspended in the atmosphere.

Their extensive reach has led to their integration into our water, food, blood, and, in an indicative sign of the Anthropocene, their contribution to the formation of new geological substrates such as plastiglomerates (Figure 1 - Corcoran et al., 2014). Simultaneously, our understanding of the severe impacts of plastic litter, particularly within marine environments, continues to grow (Figure 1). The detrimental effects on wildlife are manifested through various processes, including ingestion, entanglement and ghost fishing, the facilitation of nonnative species dispersal, and direct habitat damage (Figure 1 - Gracia et al., 2018 and 2020). In essence, in the Anthropocene epoch, the

advantageous properties of plastics that spurred their widespread adoption are the very factors contributing to their omnipresence and significant harm to wildlife and ecosystems.

The Anthropocene is marked by the widespread use of plastics in our everyday lives, from food storage and transportation to healthcare. While these versatile materials offer many conveniences, their disposal presents significant environmental challenges (Andrady 2022). Plastic production has grown exponentially since the mid-20th century, from 2 million tonnes in 1950 to a staggering 500 million tonnes by 2022 (UNEP 2021). Estimates suggest that if this trend continues, the annual global plastic production could reach 1000 million tonnes by 2050. Incredibly, over half of all plastics ever used were produced in the last 15 years, and half of these were intended for single use.

This massive plastic production leads to severe litter management issues. Each year, approximately 8 million tonnes of plastics are discarded into our oceans. Despite recycling efforts, a distressing 91% of all plastics discarded since the 1950s have never been recycled. Instead, 32% of plastic ends up directly in environmental ecosystems, 40% in landfills, and 14% is incinerated (UNEP 2021).

Recycling is an appealing solution but is hindered by complex requirements, including substantial infrastructure, significant funding, and supportive regulatory frameworks. Of the plastic that is recycled, only 2% is optimally recycled, often only once, with the remaining 12% being downcycled into lower-quality materials (Williams and Rangel-Buitrago 2022).

As an extension of the Anthropocene, a concept has been proposed to encapsulate the environmental consequences associated with the pervasive use of plastic, aptly termed "The Plasticene" (Rangel-Buitrago et al., 2022 and Rangel-Buitrago and Neal 2023). The Plasticene epitomizes a period within the Anthropocene where the adverse impacts of plastic pollution have become a globally significant and recognizable aspect of Earth's biophysical systems. The ubiquity and longevity of plastic litter that we've observed in the Anthropocene is magnified in this proposed term, underscoring the deeply entrenched role of plastic within our environment and daily lives.

The Plasticene elucidates the convergence of human technological advances, overconsumption, and environmental neglect. This term emphasizes how our 'throw-away' culture perpetuates the production and disposal of single-use plastics, fundamentally reshaping global ecosystems. This shift has created a new, anthropogenically modified environment, where plastic debris is an all-too-common feature. It is a critical reminder of our interconnectedness with the Earth's system, reinforcing the urgency to address this pervasive issue for the health and longevity of our planet and future generations.

Thus, our dependence on plastics and our inadequate litter management practices are emblematic of the Anthropocene epoch, highlighting the pressing need for more sustainable strategies. Without drastic interventions, projections show a dire future where up to 37 million tonnes of plastic could enter our oceans annually by 2040, and up to 265 million tonnes per year could be discharged into the environment by 2060 (Lebreton and Andrady 2019).

Existing Responses

Global efforts to address this issue, which span from policy interventions to scientific innovations and public education, reveal the complex dynamics of managing human-induced environmental transformations in this time of Earth´s geological history.

Policy Responses

The understanding that plastic pollution is an Anthropocene phenomenon that transcends national boundaries and requires unified global action has instigated several crucial policy responses.

- **International Agreements:** Recognizing the plastic crisis as an integral part of the Anthropocene narrative, the United Nations Environment Assembly adopted a resolution in 2017 to eliminate marine plastic pollution, advocating for robust international cooperation and action. This has led to actual negotiation (Intergovernmental Negotiating Committee on Plastic Pollution, in process) under the UNEA to reach an agreement in the form of a treaty or a convention to be achieved by the end of 2024.
- **Regional and National Policies:** Numerous countries, acknowledging their contribution to the plastic issue in the Anthropocene, have formulated policies to curb single-use plastics. Notably, the European Union's Single-Use Plastics Directive (2019) aspires to mitigate plastic pollution by banning specific plastic items and mandating member states to recycle 90% of plastic bottles by 2029. In an even more radical move, Rwanda implemented a total ban on plastic bags.
- **Extended Producer Responsibility (EPR) Programs:** Some jurisdictions have introduced EPR programs, which obligate producers to manage the waste generated by their products, encouraging more sustainable product design and challenging the traditional production-consumption-disposal paradigm in the Anthropocene.

Scientific

As an integral part of the Anthropocene narrative, science is providing a range of innovative solutions to combat the plastic issue.

- **Development of Biodegradable Plastics:** Designed to naturally degrade over time, biodegradable plastics hold the potential to lessen the long-lasting impact of conventional plastics. However, these materials present an Anthropocene conundrum; they still contribute to microplastic pollution as they degrade, and their widespread use can confound recycling efforts.
- **Improvements in Recycling Technologies:** Enhanced recycling technologies, such as advanced mechanical recycling and chemical recycling, could promote a more circular plastic economy, a transformation much needed in the Anthropocene. Artificial intelligence (AI) is generating improvements in the technology for sorting recyclables.
- **New materials:** Research in chemistry may bring new-material formulas that are “environmentally friendly”.

- **Clean-Up Efforts:** Initiatives such as The Ocean Cleanup project deploy specially designed equipment to extract plastic waste directly from the oceans, offering a symptomatic treatment for the plastic pollution ailment of the Anthropocene.

Public Awareness and Education:

Responsibility in the Anthropocene extends to public education and awareness about our planetary impact. These efforts play a vital role in addressing plastic pollution.

- **Media and Education:** Through documentaries, media campaigns, and public outreach programs, global awareness of the Anthropocene's plastic pollution issue is increasing. Such efforts can instigate more sustainable behaviors, promoting the reduction, reuse, and recycling of plastic products.
- **Community Involvement:** The engagement of local communities in beach and river clean-up activities not only mitigates plastic pollution but also fosters broader awareness and active participation in Anthropocene stewardship.

Nevertheless, these responses highlight the intricate challenges of tackling Anthropocene issues. Policies may falter due to enforcement limitations or the sheer scale of the problem, while scientific innovations grapple with issues of scalability, cost, and unforeseen environmental impacts. While public awareness is expanding, effecting large-scale behavioral change remains a daunting task. It demands relentless commitment and systemic shifts to make sustainable alternatives more attainable and appealing, encapsulating the evolving and adaptive nature of human-environment relationships in the Anthropocene.

The Anthropocene Challenge

The management of plastic litter is an essential strategy in the Anthropocene. The application of any strategy to address plastic pollution in coastal and marine environments presents several complexities and challenges:

- **Environmental Changes:** The rise in plastic production and pollution in the Anthropocene complicates the prediction, planning, and implementation of effective strategies. The enormous volume of plastics entering coastal and marine environments significantly alters ecosystems and necessitates urgent and adaptive responses.
- **Socioeconomic Pressures:** The growing demand for plastic products and mismanagement of plastic waste exacerbate socioeconomic pressures on coastal environments. These disparities can lead to disproportionate impacts on coastal communities, particularly those in developing nations that often serve as the world's dumping grounds for plastic waste.
- **Technological Limitations:** Despite advancements, technological limitations in monitoring, managing, and mitigating plastic pollution persist. These can range from inadequate recycling technologies to insufficient remote sensing capabilities for tracking plastic waste in the ocean.
- **Knowledge Gaps and Uncertainty:** Much remains unknown about the full impact of plastic pollution on marine and coastal ecosystems, especially the long-term effects of microplastics. This uncertainty complicates the prediction of outcomes from management decisions and the formulation of effective strategies.

- **Overlapping Jurisdictional Boundaries:** Plastic pollution is a transboundary issue, and managing it requires international cooperation. However, differing legislative and regulatory frameworks often complicate this.
- **Environmental justice**: In the context of plastic litter pollution, environmental justice seeks the fair and equitable distribution of both the environmental burdens and benefits associated with plastic waste. Justice must recognize that marginalized and disadvantaged countries and communities often bear a disproportionate share of the negative impacts caused by plastic litter while having limited access to resources and solutions.
- **Stakeholder Conflicts:** Different stakeholders may have conflicting interests. For instance, industries might resist regulations restricting plastic production or mandating extended producer responsibility, even as environmentalists and local communities push for such measures.
- **Lack of Adequate Funding and Resources:** Addressing plastic pollution requires the commitment of significant resources, including funding for research into plastic alternatives, enhanced waste management systems, cleanup efforts, and public education campaigns. These resources may not be readily available, especially in developing nations. Even first-world countries lack a universal commitment to environmental protection.
- **Legal Constraints:** Current laws may not adequately address the complex issues surrounding plastic pollution. For instance, legislation may be lacking or insufficient to hold producers accountable for the end-life of their products. Most legislation has loopholes (e.g., variances) that allow exemptions that defeat the purpose of the law. Laws must be strengthened and enforced.
- **Political Instability:** Political instability can impede continuous support for efforts aimed at managing plastic pollution. Changing political priorities might derail long-term strategies.
- **Resistance to Change:** There may be resistance to changes in plastic production and consumption due to economic implications or a lack of understanding of the severity of plastic pollution.

Despite these complexities, the Anthropocene necessitates innovative, adaptive, and integrated approaches to tackle the escalating issue of plastic pollution in our coastal and marine environments.

Navigating Plastic Pollution in the Anthropocene: A Multidisciplinary Approach

In the Anthropocene, coastal and marine ecosystems face distinctive challenges due to plastic pollution, necessitating the adoption and integration of precautionary management principles. The integration principle advocates for a holistic perspective considering not only the scientific implications of decisions but also the sociocultural, legal, and institutional dimensions. Within the context of marine litter management, this principle requires understanding plastic pollution's origins, its effects on marine life and humans, and the societal and legal considerations involving mitigation.

The management of plastic pollution is complex, without unique solution, as there are as many sources of litter as the number of inhabitants on earth. Then, fluxes cannot be mastered. The precautionary principle urges proactive environmental guardianship, which is especially crucial when addressing plastic pollution (Williams and Micallef 2009). The unpredictable changes inherent to the

Anthropocene often surpass our comprehension and predictive abilities, necessitating preventive actions against plastic pollution, despite lacking a complete scientific agreement on its total impact.

Applying these principles to mitigate plastic pollution in the Anthropocene requires innovative strategies, multidisciplinary cooperation, and progressive policy formulation. These strategies may comprise the following:

Addressing the whole life cycle of plastic involves considering the environmental and social impacts associated with every stage of the plastic life cycle, starting from oil extraction to the end of its life.

Interdisciplinary Collaboration: Addressing the intricate problem of marine plastic pollution demands knowledge from various sectors, such as marine biology, ecology, social sciences, economics, and law. This diverse collaboration can fill knowledge voids, provide a holistic view of coastal ecosystems, and establish effective plastic waste management strategies.

Adaptive Management: The use of dynamic management tactics, developing and revising strategies based on up-to-date knowledge, can tackle the uncertainties and rapid alterations typical of the Anthropocene era.

Stakeholder Inclusion: The active participation of all stakeholders—local communities, indigenous people, government agencies, businesses, among others—in the decision-making process guarantees the successful execution and societal endorsement of plastic waste management strategies.

Policy Coordination: Cross-sectoral policies (such as fishing, tourism, conservation, etc.) and multilevel governmental cooperation can address intersecting jurisdictional challenges, ensuring a consolidated response to plastic pollution. Cross-border unity between countries is also essential.

Sustainable Financing: Multiple funding sources are vital for implementing plastic waste management strategies. These can range from government budgets, international aid, and private sector investments to ecosystem service payments.

Enhancing Resilience: Amid Anthropocene pressures, boosting the resilience of coastal systems and communities is essential. This can include safeguarding and restoring key habitats, advocating sustainable resource use, and supporting community-led plastic waste management strategies.

Capacity Building and Education: Enabling all stakeholders to understand and engage with plastic waste management through education programs, training workshops, and knowledge sharing initiatives can fortify the control of plastic pollution.

Technological Advancement: Technologies such as remote sensing, GIS, AI, and blockchain can enhance coastal ecosystem monitoring, anticipate changes, and formulate effective waste management strategies.

Policy Reforms: Regulatory modifications may be needed to facilitate plastic waste management. Such reforms could involve resolving jurisdictional conflicts, modernizing obsolete laws, and establishing legal structures for adaptive and integrated management.

Ecosystem-Based Management: Recognizing the totality of interactions within an ecosystem, including human influences, can lead to effective strategies such as marine protected areas, integrated watershed management, and habitat restoration.

Research and Development: Continuous research can contribute to a better understanding of Anthropocene changes and more effective plastic waste management strategies.

Strategic planning for plastic pollution management in the Anthropocene necessitates a profound understanding of coastal and marine processes influenced by human activities. It calls for a broad, inclusive approach involving integration, adaptive management, and participation from all stakeholders. Strategies should be proactive, flexible, and forward thinking rather than reactive to enhance coastal and marine litter management in this era.

In the Anthropocene context, informed by French's (2005) work and adjusted for the unique challenges posed by plastic litter, the prerequisites for robust plastic litter management might include the following:

- A sustainable and comprehensive approach to managing plastic litter, taking into account environmental and socioeconomic factors, Anthropocene-driven changes, and the pervasive issue of plastic pollution.
- Promotion of harmonious and compatible coastal uses, balancing human demands with the need for conservation, particularly in the face of escalating plastic pollution.
- The adoption of precautionary measures to preemptively address potential coastal sustainability challenges, given the rapid and unpredictable shifts inherent to the Anthropocene.
- Comprehensive environmental and economic assessments of plastic management strategies to ensure their effectiveness in managing plastic litter while maintaining viability.
- Careful alignment of management actions with institutional capabilities, given the complex interplay of coastal, litter, and Anthropocene issues.

The existing Directive 2006/12/EC of the European Parliament and of the Council (EC 2006) on waste remains highly relevant in the Anthropocene, with a few modifications:

- Adoption of a broad perspective that considers the entire environment, including human influences, biological aspects, the full 'plastic cycle', and the alterations introduced by plastic litter and the Anthropocene.
- Embracing a long-term viewpoint, acknowledging the uncertain trajectory of Anthropocene changes and the enduring effects of litter pollution.
- Always advocating for adaptive management, flexible enough to respond to rapid environmental changes, and the evolving challenges of plastic litter management.
- Development of specific, flexible measures to address the unique plastic litter-related challenges posed by the Anthropocene.
- Working in line with natural processes while acknowledging and mitigating human-induced alterations, particularly litter pollution.
- Promoting participatory planning involving all stakeholders in aspects of coastal and ocean management, especially those directly affected by plastic litter issues.

- Fostering collaboration among all relevant administrative bodies, fostering a cohesive response to the plastic litter problem.
- Encouraging the use of a mix of instruments and strategies, recognizing the multifaceted nature of the coastal and marine environment in the Anthropocene, particularly regarding plastics pollution.

The shift to integrated management in the Anthropocene, particularly addressing plastic pollution, may be gradual, with tangible results expected in the medium to long term. A proactive stance is vital.

CONCLUSIONS

The Anthropocene, characterized by profound human-induced environmental transformations, poses complex challenges that call for innovative and concerted responses. A salient issue of our time is plastic pollution, a ubiquitous environmental threat that is particularly potent in coastal and marine environments. The issue of plastic pollution is emblematic of the larger Anthropocene dilemma, interlacing human societies, ecosystems, and the global environment in a web of causes, impacts, and responses.

Global efforts to tackle this problem span policy interventions, scientific innovations, and public education. Policies and regulatory frameworks, from international agreements to national directives and extended producer responsibility programs, reveal the commitment of political institutions to confront this issue. However, their effectiveness can falter due to enforcement limitations, the scale of the problem, and various socioeconomic pressures.

Simultaneously, scientific innovations, such as the development of biodegradable plastics and advancements in recycling technologies, offer novel solutions. Nonetheless, these innovations grapple with challenges of scalability, cost, environmental impact, and integration into existing waste management systems.

Public awareness and education efforts are vital for engendering sustainable behaviors and empowering citizens in their roles as stewards of the Anthropocene. However, achieving large-scale behavioral change remains a formidable task, underscoring the need for sustained commitment and systemic shifts to render sustainable alternatives more attainable and attractive.

Managing plastic litter, particularly in coastal and marine environments, is fraught with complexities and challenges that arise from environmental changes, socioeconomic pressures, technological limitations, knowledge gaps, jurisdictional issues, stakeholder conflicts, resource constraints, legal obstacles, and resistance to change. However, despite these hurdles, the Anthropocene epoch compels us to devise innovative, adaptive, and integrated approaches to handle the escalating issue of plastic pollution.

An integrated approach employing principles of interdisciplinary collaboration, adaptive management, stakeholder engagement, policy integration, sustainable financing, resilience building, capacity enhancement, technological innovation, policy reform, ecosystem-based management, disaster risk reduction, and advocacy can potentially revolutionize plastic pollution management in this epoch.

The management of plastic pollution in the Anthropocene demands an understanding of the intricate relationship between humans and the environment and the dynamic forces at play. The path forward demands strategic planning, innovative thinking, and above all, a unified global effort. The Anthropocene is not just a period of unprecedented challenges but also a window of opportunity to redefine our relationship with the planet and steer toward a more sustainable future.

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FIGURES

Figure 1: The extensive reach of plastic has led to its integration into different environments and has allowed it to become an indicative sign of the Anthropocene. This figure showcases the following examples: a) plastic bottles on a South African beach, b) various types of plastic litter in the dune systems of the Caribbean Coast of Colombia, c) microplastics found in beach sediments, d) plastic litter interacting with seabirds, and e) an example of an Anthrosol on the Central Caribbean Coast of Colombia. Anthrosol is an anthropic soil composed of a combination of litter items such as glass, plastics, and rubber mixed with reworked sedimentary fill. f) A close-up of a plastiglomerate. This rock consists of subrounded to well-rounded clasts of quartz (Qz), feldspar, sand-sized rock fragments, and clay minerals. Forty percent of the clasts are bound together by quartz cement, while the remaining 60% are held together by a plastic matrix. This plastic matrix is formed by polyester (55%), polyethylene high-density (PE-HD - 35%), and a copolymer of an alkyl acrylate or methacrylate (10%).