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(Review Article)

Assessing the environmental and health impacts of plastic production and recycling

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Abstract

Plastic production and recycling have become integral processes in modern society, but their environmental and health impacts have garnered significant attention in recent years. This review outlines key findings from a comprehensive assessment of these impacts, drawing from a range of scientific literature and empirical studies. The environmental footprint of plastic production encompasses various stages, from extraction of raw materials to manufacturing and distribution. These processes contribute to greenhouse gas emissions, energy consumption, and pollution of air, water, and soil. Additionally, plastic waste, particularly single-use items, poses a significant threat to ecosystems and wildlife, with marine environments being particularly vulnerable. While recycling is often promoted as a solution to mitigate the environmental impact of plastics, its effectiveness is limited by various factors. Challenges such as contamination, inadequate infrastructure, and low rates of collection and recycling hinder the potential benefits. Moreover, the recycling process itself can generate pollutants and emissions, albeit to a lesser extent than primary production. Beyond environmental concerns, the health implications of plastic use are increasingly recognized. Plastics contain additives such as phthalates and bisphenols, which have been linked to endocrine disruption, reproductive issues, and other health problems in humans and wildlife. Furthermore, the accumulation of microplastics in the environment raises concerns about potential bioaccumulation and transfer through the food chain, with implications for human health. Addressing the environmental and health impacts of plastic production and recycling requires a multifaceted approach, including reduction of plastic consumption, improvement of recycling infrastructure and technologies, development of alternative materials, and policy interventions to promote sustainable practices. This assessment highlights the complex interplay between plastic usage, environmental degradation, and public health, underscoring the need for concerted efforts to mitigate these challenges.

Keywords: Environment; Health; Plastic; Pollution; Recycling; Review

1. Introduction

Plastic, since its inception in the early 20th century, has revolutionized various industries due to its versatility, durability, and cost-effectiveness. From packaging to automotive parts, from medical devices to electronic gadgets, plastic has become an integral part of our daily lives. However, the widespread use and disposal of plastic have led to severe environmental consequences (Evode et al., 2021).

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The production of plastic begins with the extraction of raw materials, primarily crude oil and natural gas. These non-renewable resources undergo a series of chemical processes to produce various types of plastics, each tailored to specific applications. The global production of plastics has surged exponentially, with over 380 million tons produced annually, leading to concerns about resource depletion and environmental pollution (Sharma, 2023).

Plastic waste management has emerged as a critical challenge, as a significant portion of plastic products ends up in landfills, oceans, and other natural habitats. Plastic debris litters beaches, clogs waterways, and poses a threat to wildlife, often leading to entanglement, ingestion, and suffocation. Moreover, plastic pollution has far-reaching implications for human health, as toxic chemicals present in plastics can leach into the environment and accumulate in the food chain. In response to these challenges, there has been a growing emphasis on the need for sustainable practices in plastic production and consumption. Recycling and circular economy principles have gained prominence as viable solutions to mitigate the environmental impacts of plastic. By promoting resource conservation, waste reduction, and material reuse, stakeholders aim to minimize the ecological footprint of plastic while fostering a more sustainable society (Kumar et al., 2021).

The purpose of this assessment is to delve into the environmental impacts of plastic production comprehensively. By examining each stage of the plastic lifecycle, from raw material extraction to end-of-life disposal, we aim to provide a holistic understanding of the challenges and opportunities associated with plastic production and recycling (Iacovidou, 2021).

Identify the environmental hotspots and potential hazards associated with plastic production, including resource extraction, manufacturing processes, and waste disposal. Evaluate the magnitude and extent of environmental pollution resulting from plastic production, including air, water, and soil contamination. Assess the impacts of plastic pollution on ecosystems, wildlife, and human health, considering both direct and indirect effects. Explore strategies and technologies for mitigating the environmental impacts of plastic production, such as alternative materials, waste management practices, and policy interventions (Diggle and Walker, 2022). By elucidating the complex interplay between plastic production and environmental sustainability, this assessment aims to inform policymakers, industry stakeholders, and the general public about the urgent need for action. By embracing innovative solutions and adopting responsible consumption habits, we can collectively address the environmental challenges posed by plastic and transition towards a more sustainable future (Bin Abu Sofian et al., 2023).

The extraction of raw materials for plastic production primarily involves the extraction of fossil fuels, such as crude oil and natural gas. Crude oil is processed in refineries to obtain various fractions, including ethylene and propylene, which serve as the building blocks for most plastics. Natural gas, through processes like steam cracking, yields ethane and propane, which are also essential feedstocks for plastic manufacturing. The extraction of fossil fuels involves extensive drilling, fracking, and extraction operations, which can have significant environmental consequences. Oil spills, a common occurrence during offshore drilling and transportation, pose severe risks to marine ecosystems, leading to habitat destruction and contamination. Fracking, used to extract natural gas from shale formations, has been associated with groundwater pollution, seismic activity, and habitat disruption, raising concerns about its long-term environmental impact (Soeder, 2020).

Moreover, the extraction and processing of fossil fuels contribute to air pollution through the release of volatile organic compounds (VOCs), nitrogen oxides (NOx), and particulate matter. These pollutants can have adverse effects on human health, including respiratory problems, cardiovascular diseases, and cancer. Additionally, the combustion of fossil fuels for energy-intensive processes, such as plastic production, releases greenhouse gases, contributing to climate change and global warming (Cabernard et al., 2022).

The manufacturing of plastics involves a series of chemical processes, each tailored to produce specific types of polymers with desired properties. The most common methods include polymerization, extrusion, injection molding, and blow molding, which require significant energy inputs and raw material consumption. Petrochemical plants, where plastic is synthesized from raw materials, are major sources of air and water pollution. During polymerization processes, volatile organic compounds (VOCs), such as benzene, toluene, and xylene, are released into the atmosphere, contributing to smog formation and air quality degradation. Additionally, the release of toxic byproducts, such as dioxins and furans, poses risks to human health and ecosystems (Jeno, 2021).

Moreover, petrochemical plants consume large quantities of water for cooling and processing purposes, leading to water scarcity and contamination. Wastewater discharged from these facilities often contains hazardous chemicals, heavy metals, and organic pollutants, which can contaminate surface water and groundwater sources, posing risks to aquatic ecosystems and public health (Elizalde-Velázquez. and Gómez-Oliván, 2021). The distribution and transportation of plastic products involve the use of fossil fuel-powered vehicles, such as trucks, ships, and airplanes, which emit greenhouse gases and other pollutants. The transportation of raw materials, intermediates, and finished products over long distances adds to the carbon footprint of plastic production and contributes to climate change. Furthermore, the packaging used for transporting plastic products, such as plastic wraps, pallets, and containers, further exacerbates plastic waste generation and environmental pollution. Single-use plastics, such as packaging materials and disposable products, contribute significantly to the global plastic waste stream, posing challenges for waste management and recycling efforts (Vanapalli et al., 2021).

Throughout the lifecycle of plastic, from production to disposal, various pollutants are released into the environment, contaminating air, water, and soil. Air pollutants emitted during plastic production include volatile organic compounds (VOCs), nitrogen oxides (NOx), sulfur oxides (SOx), and particulate matter (PM), which can have adverse effects on human health and ecosystems. Water pollution from plastic production arises from wastewater discharge containing toxic chemicals, heavy metals, and organic pollutants. These contaminants can persist in the environment, bioaccumulate in aquatic organisms, and biomagnify through the food chain, posing risks to human health and ecosystem integrity. Moreover, plastic debris can act as vectors for transporting pollutants in aquatic environments, exacerbating the spread of contaminants and their impacts on marine life (Arienzo, 2021).

Soil contamination from plastic production occurs through the deposition of airborne pollutants, leaching of chemicals from plastic waste, and the accumulation of microplastics in soil ecosystems (Li et al., 2024). Plastic debris can leach harmful additives, such as plasticizers, flame retardants, and stabilizers, into the soil, affecting soil fertility, microbial communities, and plant growth. Additionally, microplastics can adsorb and transport organic pollutants and heavy metals in the soil, leading to bioaccumulation and toxicity in terrestrial organisms.

The production and incineration of plastic generate significant greenhouse gas emissions, primarily carbon dioxide (CO_2) and methane (CH_4) (Nicholson et al., 2021). The extraction, refining, and transportation of fossil fuels for plastic production contribute to CO_2 emissions, as well as other greenhouse gases, such as methane and nitrous oxide. Additionally, the combustion of fossil fuels for energy-intensive processes, such as plastic manufacturing, releases CO_2 and other pollutants into the atmosphere. Plastic waste management also contributes to greenhouse gas emissions, particularly through landfilling and incineration. In landfills, plastic waste undergoes anaerobic decomposition, producing methane as a byproduct, which is a potent greenhouse gas with a higher global warming potential than CO_2. Moreover, incineration of plastic waste releases CO_2 and other pollutants into the atmosphere, contributing to air pollution and climate change (Shen et al., 2020).

Plastic pollution poses a significant threat to ecosystems and wildlife, both on land and in water. Plastic debris can entangle marine animals, such as seabirds, turtles, seals, and whales, leading to injury, suffocation, and death (Dar et al., 2022). Moreover, marine organisms can ingest plastic particles, mistaking them for food, which can cause internal injuries, blockages, and starvation. Plastic pollution also affects terrestrial ecosystems, as plastic debris can accumulate in soil and freshwater habitats, posing risks to plants, animals, and microorganisms. Microplastics, defined as plastic particles smaller than 5 millimeters, can absorb and transport contaminants, such as pesticides, heavy metals, and persistent organic pollutants, in terrestrial environments, leading to bioaccumulation and toxicity in soil organisms (Cai et al., 2021).

Furthermore, plastic pollution alters habitat structure, disrupts ecosystem functions, and threatens biodiversity by introducing invasive species and altering nutrient cycles (Kumar et al., 2021). Plastic debris can smother benthic habitats, block sunlight, and inhibit gas exchange, affecting the growth and survival of aquatic organisms. Moreover, plastic pollution can serve as a vector for transporting invasive species and pathogens, contributing to the spread of diseases and ecological disruptions.

In conclusion, the environmental impacts of plastic production are widespread and multifaceted, affecting air, water, soil, and ecosystems worldwide (Zeb et al., 2023). Addressing these impacts requires concerted efforts to reduce plastic consumption, promote recycling and reuse, and develop sustainable alternatives to plastic. By understanding the environmental implications of plastic production, we can work towards a more sustainable future and mitigate the negative effects of plastic on the planet (Evode et al., 2021).

2. Environmental Impacts of Plastic Recycling

While recycling holds promise as a solution to mitigate plastic pollution, numerous challenges hinder its effectiveness. Insufficient recycling infrastructure, particularly in developing countries, limits the collection, sorting, and processing of plastic waste (Vanapalli et al., 2021). Inadequate investment in recycling facilities and lack of standardized collection systems result in low recycling rates and increased reliance on landfilling and incineration. Moreover, the complexity of plastic materials and the presence of contaminants further complicate the recycling process. Mixed plastic waste streams, contaminated with food residues, labels, and other materials, require extensive sorting and cleaning, increasing processing costs and reducing the quality of recycled materials. As a result, many recyclable plastics end up being discarded or downcycled, diminishing the environmental benefits of recycling (Minunno et al.,2020).

Contamination poses a significant challenge to plastic recycling, as impurities and non-recyclable materials reduce the quality and marketability of recycled plastics (Santos, 2023). Contaminants such as food residues, grease, and incompatible plastics can compromise the integrity of recycled materials, leading to performance issues and safety concerns in downstream applications. Contamination also affects the efficiency of recycling processes, as it requires additional sorting, cleaning, and processing steps to remove impurities and ensure product quality. However, these additional steps increase energy consumption, water usage, and greenhouse gas emissions, offsetting some of the environmental benefits of recycling.

Although recycling conserves energy compared to primary plastic production, the recycling process itself consumes energy and generates emissions (Jeswani et al., 2021). Mechanical recycling, the most common method of recycling plastics, involves shredding, melting, and reprocessing plastic waste into new products. These processes require energy inputs for heating, mixing, and molding, contributing to greenhouse gas emissions and air pollution. Chemical recycling, an emerging technology that breaks down plastic polymers into monomers or other chemicals for reuse, also requires energy-intensive processes such as depolymerization, pyrolysis, or gasification. While chemical recycling offers the potential to recycle mixed or contaminated plastics and produce high-quality materials, it currently faces technical challenges and high costs compared to mechanical recycling.

The effectiveness of recycling efforts varies depending on factors such as collection rates, sorting efficiency, market demand for recycled materials, and technological advancements (Knickmeyer, 2020). High collection rates and efficient sorting systems increase the quantity and quality of recycled plastics, improving the economic viability of recycling and reducing reliance on virgin materials. However, achieving high recycling rates requires collaboration among stakeholders, including governments, businesses, consumers, and waste management agencies. Public awareness campaigns, incentives for recycling, and extended producer responsibility (EPR) schemes can encourage participation in recycling programs and promote sustainable consumption habits.

Comparing the environmental impacts of plastic recycling with primary production involves assessing factors such as energy consumption, resource depletion, greenhouse gas emissions, and pollution (Gabisa, 2023). While recycling conserves energy and reduces greenhouse gas emissions compared to primary production, it still consumes resources and generates waste. Life cycle assessments (LCAs) can provide insights into the environmental benefits and trade-offs of recycling versus primary production, considering factors such as material inputs, energy requirements, emissions, and end-of-life management. LCAs help identify opportunities to optimize recycling processes, improve resource efficiency, and minimize environmental impacts throughout the product lifecycle.

Overall, while recycling offers environmental benefits compared to primary production, its effectiveness depends on factors such as infrastructure, technology, market demand, and consumer behavior (Dinu et al., 2020). Addressing challenges such as contamination, energy consumption, and collection rates can enhance the environmental performance of recycling and contribute to a more sustainable approach to plastic waste management.

3. Health Impacts of Plastic Usage

Plastics contain various additives, including plasticizers, flame retardants, stabilizers, and colorants, which can leach into the environment and pose risks to human health (Luo et al., 2022). Phthalates and bisphenols are common additives used in plastics, such as PVC and polycarbonate, to improve flexibility, durability, and heat resistance. However, these additives have been linked to adverse health effects, including endocrine disruption, reproductive disorders, and developmental abnormalities.

Phthalates and bisphenols are known endocrine-disrupting chemicals (EDCs) that mimic or interfere with hormonal signaling pathways in the body (Kawa et al., 2021). Exposure to EDCs, particularly during critical periods of development, can disrupt reproductive function, hormone regulation, and neurological development. Pregnant women, infants, and children are especially vulnerable to the effects of EDCs, as their bodies undergo rapid growth and hormonal changes.

The widespread use of plastics in consumer products, food packaging, and medical devices increases human exposure to plastic additives and contaminants (Ugoeze, 2021). Studies have linked exposure to phthalates and bisphenols with an increased risk of obesity, diabetes, cardiovascular diseases, and certain cancers. Additionally, inhalation or ingestion of microplastics, nanoparticles, and airborne pollutants from plastic production and disposal can pose respiratory and gastrointestinal health risks.

Plastic pollution poses significant risks to wildlife health, as marine and terrestrial animals can ingest or become entangled in plastic debris (Naidoo, and Rajkaran, 2020). Ingestion of plastic particles can lead to physical injuries, intestinal blockages, and malnutrition in wildlife. Moreover, plastics can adsorb and accumulate toxic chemicals, such as polychlorinated biphenyls (PCBs) and persistent organic pollutants (POPs), which can bioaccumulate in the food chain and harm ecosystem health.

Microplastics, defined as plastic particles smaller than 5 millimeters, pose emerging risks to human and wildlife health. Microplastics can adsorb and transport contaminants, such as heavy metals, pesticides, and pathogens, in aquatic and terrestrial environments. Moreover, microplastics can serve as vectors for transferring pollutants and pathogens to organisms upon ingestion, leading to bioaccumulation and toxicity (Amelia et al., 2022).

In conclusion, the health impacts of plastic usage extend beyond the physical properties of plastics themselves to include additives, contaminants, and degradation products. Addressing these health risks requires comprehensive strategies to reduce plastic consumption, promote safer alternatives, and improve waste management practices. By minimizing exposure to harmful chemicals and pollutants, we can protect human health and ecosystem integrity while fostering a more sustainable approach to plastic usage.

4. Current Research and Studies

The current body of research on plastic pollution encompasses a wide range of disciplines, including environmental science, chemistry, engineering, public health, and policy studies. Empirical studies have investigated various aspects of plastic production, usage, disposal, and environmental impacts, providing valuable insights into the magnitude and complexity of the issue (Tramblay et al., 2020).

Researchers have conducted field studies, laboratory experiments, and modeling analyses to quantify the sources, pathways, and fate of plastic pollution in terrestrial and aquatic environments. These studies have examined the distribution, abundance, and characteristics of plastic debris in oceans, rivers, lakes, soils, and sediments, shedding light on the scale and spatial variability of plastic pollution worldwide (Talbot and Chang, 2022). Moreover, researchers have investigated the ecological, economic, and social implications of plastic pollution, including its effects on wildlife, ecosystem services, human health, and socioeconomic well-being. Studies have explored the interactions between plastics and organisms at various trophic levels, from microbes to apex predators, and assessed the risks posed by plastic additives, contaminants, and microplastics to human and wildlife health (Huang et al., 2021).

Key findings from research on plastic pollution highlight its pervasive and multifaceted environmental and health impacts. Studies have documented the widespread distribution of plastic debris in marine environments, with concentrations highest in coastal regions, ocean gyres, and deep-sea sediments. Plastic pollution poses risks to marine life through ingestion, entanglement, and habitat degradation, affecting species diversity, ecosystem function, and fisheries productivity (Akindele and Alimba, 2021).

Furthermore, research has demonstrated the accumulation of plastic debris in terrestrial ecosystems, including soils, freshwater habitats, and urban environments. Microplastics, in particular, have been detected in soil, water, air, and food sources, raising concerns about their potential impacts on agricultural productivity, food safety, and human health. Studies have also identified plastic additives, such as phthalates, bisphenols, and flame retardants, as emerging contaminants of concern, with implications for endocrine disruption, reproductive disorders, and chronic diseases. Moreover, research has highlighted the role of microplastics as vectors for transporting toxic chemicals and pathogens in aquatic and terrestrial environments, amplifying the risks to human and wildlife health (Masud et al., 2023).

Despite significant advances in understanding the environmental and health impacts of plastic pollution, several gaps remain in current research. Key areas for future investigation include; Limited research exists on the long-term ecological and health effects of plastic pollution, including its persistence, bioaccumulation, and ecosystem recovery dynamics. Research on the cumulative effects of multiple stressors, such as climate change, pollution, and habitat loss, on plastic pollution and its interactions with ecosystems and human communities is needed. Further studies are needed to identify and assess the risks posed by emerging contaminants in plastics, including nanoplastics, additives, degradation products, and associated pollutants. Research on the social, cultural, and behavioral dimensions of plastic pollution, including consumer attitudes, waste management practices, and policy responses, requires interdisciplinary approaches and community engagement (Berke et al., 2021).

5. Mitigation Strategies and Solutions

Reducing plastic consumption is a critical strategy for mitigating plastic pollution and its environmental and health impacts (Ali et al., 2022). Strategies include promoting reusable products, implementing product design changes to minimize packaging waste, and adopting circular economy principles to reduce plastic use, reuse materials, and recycle resources.

Investment in recycling infrastructure and technologies is essential to enhance the efficiency and effectiveness of plastic recycling. Improving collection systems, sorting processes, and material recovery facilities (MRFs) can increase recycling rates and reduce contamination, while innovations in recycling technologies, such as chemical recycling and advanced sorting techniques, offer opportunities to recycle mixed or contaminated plastics and produce high-quality materials (Lange, 2021).

Developing and adopting alternative materials to plastics, such as biodegradable polymers, compostable packaging, and bio-based materials, can reduce reliance on fossil fuels and mitigate plastic pollution. Research and development efforts focus on designing sustainable materials with comparable performance, affordability, and environmental benefits to conventional plastics, while minimizing adverse impacts on ecosystems and human health (Titirici et al., 2022).

Policy interventions and regulations play a crucial role in addressing plastic pollution by setting targets, standards, and incentives to promote sustainable practices and reduce plastic waste. Measures include bans or restrictions on single-use plastics, extended producer responsibility (EPR) schemes, plastic taxes or levies, deposit-return schemes, and product stewardship programs, which encourage producers, consumers, and governments to take responsibility for the lifecycle impacts of plastics (Kehinde Oladipupo, 2020).

Public awareness and education initiatives are essential for changing attitudes, behaviors, and consumption patterns related to plastic use and disposal. Campaigns, outreach programs, and educational resources raise awareness about the environmental and health impacts of plastic pollution, promote sustainable consumption habits, and empower individuals, communities, and businesses to take action to reduce plastic waste and protect the planet. By implementing a combination of mitigation strategies and solutions, stakeholders can address the environmental and health impacts of plastic pollution and transition towards a more sustainable and circular economy that minimizes harm to ecosystems, wildlife, and human health. Collaboration among governments, businesses, civil society organizations, researchers, and citizens is essential to achieve meaningful progress in tackling the global challenge of plastic pollution (Sandu et al., 2020).

6. Case Studies

San Francisco, USA implemented a comprehensive Zero Waste program, which includes mandatory recycling and composting ordinances, bans on single-use plastic bags and polystyrene foam containers, and incentives for businesses to reduce waste. As a result, the city achieved a landfill diversion rate of over 80%, significantly reducing plastic waste and greenhouse gas emissions (Kang et al., 2022).

Taiwan implemented a successful waste management system, including a comprehensive recycling program with source separation at households and community recycling centers. The government also introduced a waste disposal fee system, encouraging residents to reduce waste generation and increase recycling rates. Taiwan now boasts one of the highest recycling rates globally, with over 55% of municipal solid waste recycled (Kurniawan et al., 2022).

Successful programs integrate various policy instruments, such as bans, incentives, and education, to create a holistic approach to waste management and recycling. Engaging communities through public awareness campaigns, outreach programs, and participatory decision-making processes fosters a sense of ownership and responsibility for waste reduction and recycling efforts (Karduri, 2023).

Lessons from successful case studies highlight the importance of political will, stakeholder collaboration, and public engagement in implementing effective plastic reduction and recycling programs. These strategies can be adapted and scaled up in other regions to address plastic pollution and promote sustainable waste management practices globally (Lau et al., 2020).

7. Future Directions

Long-term environmental and health impacts of plastic pollution. Development of innovative recycling technologies and materials. Socioeconomic factors influencing plastic consumption and waste management behaviors.

Implement extended producer responsibility (EPR) schemes to incentivize producers to design eco-friendly products, reduce packaging waste, and take responsibility for post-consumer recycling. Enact regulations to ban or restrict single-use plastics, promote reusable alternatives, and encourage sustainable packaging designs. Invest in infrastructure for recycling and waste management, including collection systems, sorting facilities, and recycling technologies (Pluskal et al., 2021).

Encourage businesses to adopt circular economy principles, such as product redesign, material reuse, and closed-loop recycling, to minimize waste generation and resource consumption. Promote collaboration among industry stakeholders, governments, and research institutions to develop sustainable materials, technologies, and supply chain practices. Empower communities through education, training, and capacity-building initiatives to promote sustainable consumption habits, waste reduction strategies, and community-led recycling programs. Foster partnerships between local governments, NGOs, businesses, and grassroots organizations to mobilize collective action and address plastic pollution at the grassroots level (Zapata Campos et al., 2023).

8. Recommendations

Plastic pollution poses significant environmental and health risks, requiring urgent action to address its impacts. Key findings from this assessment highlight the pervasive nature of plastic pollution, its detrimental effects on ecosystems and human health, and the importance of adopting sustainable practices and policies to mitigate its impacts.

Addressing plastic pollution is critical for safeguarding ecosystems, protecting wildlife, and promoting human health and well-being. Plastic pollution threatens biodiversity, disrupts ecosystem functioning, and exacerbates climate change, highlighting the urgent need for concerted efforts to reduce plastic consumption, promote recycling, and develop sustainable alternatives.

To address the challenges posed by plastic pollution, stakeholders must take collective action to implement effective solutions at the local, national, and global levels. Governments, businesses, civil society organizations, researchers, and citizens all have a role to play in promoting sustainable practices and policies that minimize plastic waste, protect the environment, and create a more resilient and equitable future for all.

9. Conclusion

In conclusion, by adopting a multi-faceted approach that integrates policy interventions, technological innovations, community engagement, and public awareness, we can mitigate the environmental and health impacts of plastic pollution and transition towards a more sustainable and circular economy. It is imperative that we act now to preserve the health of our planet and future generations.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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