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Climate Change and Plastic Pollution: A Review of Their Connections

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ABSTRACT: The world faces two major environmental issues concurrently, namely climate change and plastic pollution. Though seemingly unrelated, they intricately influence each other. This review aims to present the intricate connections between climate change and plastic pollution through the review of recent literature in these genres. The review explains that global warming could increase plastic degradation through physical, chemical, and biological processes, leading to an increased abundance of microplastics. Global warming enhances the leaching of chemicals from microplastics. Higher temperatures promote desorption of chemicals sorbed on plastics by providing the adsorbates with more kinetic energy to overcome attractions with the adsorbents. Higher temperatures can also promote biofilm formation and alter the microbial community structures of biofilms. Melting sea ice and glaciers associated with warming temperatures release the microplastics trapped in the environment. Sea-level rise and extreme weather events enhance the transfer of microplastics between land, ocean, and air, thus changing their distribution and transport, while ocean acidification may influence the biofouling of microplastics and increase the vulnerability of some corals to the impacts of microplastics. Plastic pollution, however, exacerbates climate change due to the release of greenhouse gases throughout the lifecycle of plastics. Microplastics also adversely affect the growth of microalgae, hence the ocean carbon cycle. Airborne microplastics can alter the energy balance of the Earth through scattering and absorbing radiation. This review suggests a circular economic approach to minimize waste, maximize the reuse and recycling of plastics, and promote the use of plastic substitutes to address both issues.

KEYWORDS: Climate change; extreme weather events; global warming; microplastics; plastic pollution; sea level rise

1. Introduction

The IPCC (Intergovernmental Panel on Climate Change) is the United Nations body that assesses the science related to climate change. It publishes periodic reports summarizing the current state of knowledge of climate change and projections for the future [1]. According to its latest Sixth Assessment Report (AR6), the global average temperature has increased by about 1.1°C since the pre-industrial period (1850-1900), with human activities being the main cause of this warming. The report states that under different emission scenarios, the global average temperature could increase by 1.5°C to 4.4°C by the end of the 21st century compared to 1850-1900 [1]. The higher the emissions, the more likely it is that the temperature will exceed 2°C or even 4°C [2]. The report reveals the projection that the global mean sea level will rise by 0.28 to 0.55 m by 2100 for a low emission scenario (SSP1-1.9) and by 0.63 to 1.01 m for a high emission scenario (SSP5-8.5). These projections are based on a combination of physical processes, such as thermal expansion, ice sheet and glacier melt, and surface water changes [1]. Additionally, the IPCC estimated the likelihood of sea level rise exceeding certain thresholds for different regions and time periods. For example, there is a 17% chance that sea level rise will exceed 0.8 m by 2100 in the Mediterranean Sea under the high emission scenario [1].

In terms of the global average surface ocean pH, the IPCC projected that it would decrease by 0.14 to 0.32 units by 2081-2100, relative to 2006-2015, depending on the emission scenario [1]. This means that the ocean will become more acidic, as lower pH values indicate higher acidity [3]. The IPCC pointed out the varying severity of projected ocean acidification in different regions, with, for instance, the Arctic Ocean and the Southern Ocean having lower pH than other regions attributed to their colder temperatures and higher CO_2 uptake [1]. Concurrently, the world will experience multiple changes in the drivers of climatic impacts, resulting in more extreme droughts, more intense and frequent extreme rainfall events, and flooding. These changes will be more widespread and severe at higher levels of global warming (2°C or more), compared to lower levels (1.5°C or less) [4]. In parallel to this, a 1-in-20-year hottest day is likely to become a 1-in-2-year event in most parts of the world by the end of the 21st century, except in the Arctic [1].

Meanwhile, the world is faced with increasingly severe plastic pollution. Every year, about 8 million tons of plastic waste escapes into the oceans from coastal nations. Plastics account for 85% of all marine litter and the amount will nearly triple by 2040 [5]. In the aquatic and terrestrial environments, plastics can undergo degradation, forming microplastics. Microplastics are tiny plastic particles with a diameter less than 5 mm. Microplastics can also come from primary sources such as cosmetic and personal care products, plastic pellets used for the manufacturing of plastic products, synthetic textiles which shed microfibers through wear-and-tear or washing, as well as the wearing of tires and road markings [6]. Microplastics pose numerous risks in the environment. They can be ingested by marine animals and accumulate in their tissues, causing physical damage, inflammation, and reduced growth [7]. They can transfer harmful chemicals, such as pesticides and heavy metals, to the food chain, affecting the health of animals and humans [8, 9]. They can also alter the physical and chemical properties of water and sediment, affecting the ecosystem functioning and biodiversity [10].

While often presented and discussed separately, the two seemingly unrelated environmental issues may have connections. Climate change may influence plastic pollution and aggravate its severity. Likewise, plastic production could worsen climate change. However, these interactions have not been sufficiently probed. Studies have separately shown that higher temperature causes increasing leaching of chemicals from plastics and that higher temperature together with ultraviolet radiation hasten the degradation of plastic films [11, 12]. Extreme weather events such as floods and typhoons associated with climate change facilitate mechanical degradation of plastics, hence the formation of microplastics, while changing rainfall distribution might have brought microplastics to shallow lakes through surface runoff [13]. Melting of glaciers and permafrost associated with global warming may also release the microplastics trapped, thus contributing to plastic pollution [13]. On the other hand, plastics have been regarded as a major contributor to climate change since they are made from fossil fuels and emit greenhouse gases at every stage of their life cycle [14]. Nonetheless, there are few articles that present the links between plastic pollution and climate change in a systematic way to enable better comprehension of the issues. This review aims to present the connections and interactions between climate change and plastic pollution. It hopes to contribute to better understanding of the interactions between the two major environmental issues, thus, enabling more effective policymaking to address them concurrently.

2. Methods

This review examined more than 40 relevant scholar papers to systematically present the connections between climate change and plastic pollution. Online scholarly databases comprising Scopus, Web of Science and ScienceDirect were used for literature search [15, 16]. Keywords comprising climate change, plastic pollution, microplastics, global warming, ocean acidification, and extreme weather events were entered into the databases separately or in combination yielding key terms such as climate change and plastic pollution, global warming and microplastic formation. The articles retrieved were screened based on the inclusion criteria below:

a) They explicitly explore the connections between climate change and plastic pollution.
b) They explain how different aspects and impacts of climate change affect different aspects of plastic pollution such as microplastics formation and the leaching of chemicals from microplastics.
c) They illustrate how plastics contribute to climate change.
d) They contain recommendations or measures to address both problems.
e) They were published in the last 10 years.

The major limitation encountered during the literature search was the lack of studies explicitly examining the relationship between climate change and plastic pollution. The extant studies focus mainly on projections, simulations and theoretical perspectives based on studies related to the effects of temperature, pH, as well as tidal strengths and velocities on microplastics. There are only two regional studies conducted to examine the changes in microplastic abundance after regional occurrences of typhoons and rainstorms [17, 18]. In addition, there are limited studies quantifying the contribution of greenhouse gas emissions from plastic lifecycle to climate change.

3. Discussion

3.1. Influences of climate change on plastic pollution

3.1.1. Effects of global warming.

Climate change mainly affects plastic pollution through global warming, sea level rise, extreme weather events and ocean acidification. Global warming increases the temperature of the ocean, which can accelerate the degradation of plastics into microplastics, thus, resulting in increased abundance of microplastics in the ocean (Figure 1) [13]. Corcoran summarized the mechanical, chemical, and biological degradation of microplastics in the environment. The author stated that higher temperature can accelerate the chemical degradation of microplastics by increasing the oxidation, hydrolysis, and photodegradation reactions [19]. Furthermore, Pischedda et al. discussed the challenges and opportunities of plastic degradation by microbes. They argued that higher temperature can increase the metabolic rate of microbes and enhance their ability to degrade plastics [20]. The effect of higher temperature on plastic degradation was resonated by Käppler et al. who reported that higher temperature can induce physical and chemical changes in plastic, such as embrittlement, cracking and fragmentation, which can lead to the formation of microplastics [21]. In the same vein, global warming is foreseen to facilitate the degradation of microplastics into smaller plastic particles, such as nanoplastics. The degradative effect is more pronounced in the presence of ultraviolet radiation [22]. According to a study by Karlsson et al. which investigated the effects of thermal oxidation on the degradation of microplastics in simulated atmospheric conditions, thermal oxidation led to significant degradation of microplastics especially at higher temperatures and under air atmosphere [23]. While significant breakdown of microplastics reported in the study is unlikely under environmentally relevant temperature range, the breakdown of microplastics into smaller particles could possibly occur.

Global warming can also affect the interactions of microplastics with other environmental factors, such as biota, nutrients, pollutants, and pathogens. Microplastics are known to adsorb or leach chemicals that can affect the health and behaviors of organisms [24]. Higher temperatures have been reported to increase the leaching of chemicals from microplastics (Figure 1) [12]. A study revealed higher leaching of dissolved organic matter from aged plastics retrieved from a sand beach than virgin plastics by up to 100 times and irradiation increased the leaching significantly. This implies that higher radiative forcing associated with global warming could increase chemical leaching particularly from aged plastics [25]. This release of chemicals can be facilitated by the accelerated degradation of plastics under higher temperatures in the presence of ultraviolet radiation, causing the breakdown of the polymers and the escape of plastic additives from the polymer matrix [8]. Moreover, higher temperatures can increase the solubility and diffusion of chemicals from microplastics through enhancing the molecular motion and the partitioning of chemicals between the plastic particles and the surrounding medium. This results in higher leaching rates of chemicals from microplastics (Figure 1) [8]. Generally, adsorption relates to temperature inversely. As temperature increases, the adsorption of chemicals on microplastics decreases because higher temperatures provide the adsorbate molecules with more kinetic energy to overcome attractions with the adsorbents, thus, promoting desorption [26]. Consequently, global warming is likely to reduce the adsorption of chemicals to microplastics and promote the desorption of chemicals which are already adsorbed by microplastics. A study by Sørensen et al. revealed higher adsorption of polycyclic aromatic hydrocarbons on microplastics at lower temperatures in natural seawater [27].

Microplastics serve as vectors or habitats for microorganisms that can cause diseases or alter biogeochemical cycle, causing biofilm formation on their surfaces [28]. Temperature is known to play a significant role in biofilm formation on microplastics which can potentially alter the morphology and physicochemical properties of microplastics in the environment, thus influencing their environmental fate particularly weathering, vertical transportation, co-migration with chemical pollutants and pathogens, as well as biodegradation [29]. In general, higher temperatures are associated with higher rates of biofilm formation as observed by Zhang et al. that biofilm thickness in the summer was higher than winter due to higher temperatures and nutrient contents (Figure 1) [30]. Oberbeckmann et al. reported that temperature affects the community structure of microorganisms on polyethylene and polystyrene. This implies that higher temperatures promote biofilm formation but have varying effects on the microbial community structures on different microplastic surfaces [31]. The increased biofilm formation could be attributed to higher enzymatic activities and metabolic rates which spur microbial growth [28].

Global warming causes the melting of sea ice and glaciers. This affects the distribution and concentration of microplastics in the environment (Figure 1). Microplastics have been detected in sea ice and glaciers. For instance, Stefánsson et al. found microplastics in the snow cores retrieved from the remote ice cap in Iceland [32]. In these cold environments, they experience very slow degradation and tend to accumulate. When the sea ice and glaciers melt, the microplastics trapped are returned to the environment, resulting in increased microplastic pollution of waterbodies [13].

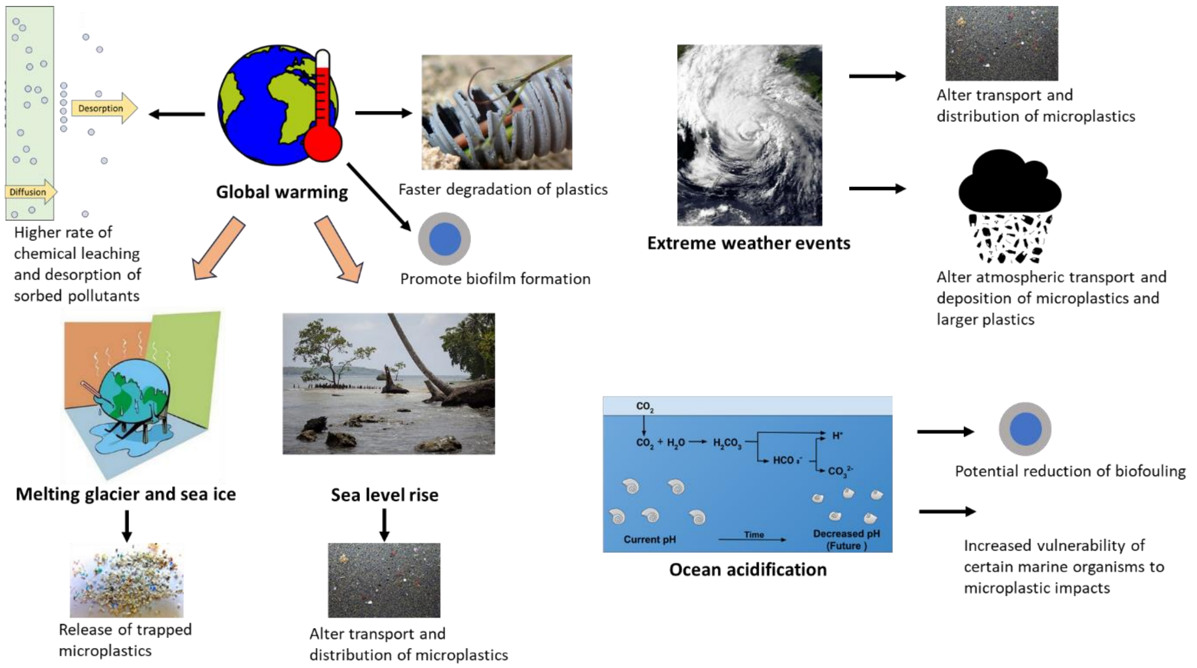

Figure 1. Influences of climate change on plastic pollution.

3.1.2. Effects of sea level rise and extreme weather events.

Sea level rise is a result of global warming, which causes the melting of sea ice and glaciers as well as the expansion of ocean volume [3]. Sea level rise can aggravate coastal erosion and flooding which subsequently lead to the increased transfer of microplastics from land, for instance, from waste management facilities, landfills and sewage systems into the ocean (Figure 1). Sea level rise is also likely to change ocean currents and circulation, which can alter the distribution and accumulation of plastic pollution in different water columns and on the seafloor [33]. Alteration in ocean currents could cause sediment resuspension and this potentially causes microplastics trapped in the sediments to be released into the marine environment and thus, entering the food chain [34]. It was found that resuspension of microplastic aggregates was initiated at critical shear velocities of 0.67 – 1.33 $cm.s^{-1}$ [35]. Additionally, positive feedback between the melting ice and sea level rise may aggravate the melting of ice sheets and glaciers, leading to increased release of microplastics trapped in the ice into the ocean [33].

Higher frequency or intensity of extreme weather events associated with climate change also alter the distribution of microplastics in the environment. Extreme rainfall events and flooding can increase soil erosion and runoff volume, causing more terrestrial microplastics from urban areas, agricultural fields and waste disposal sites to be transported to rivers and the ocean (Figure 1) [36]. Up to 40% increase in the abundance of microplastics in seawater and sediment was, in fact, reported after a typhoon hit Sanggou Bay, China [17]. Another study also revealed an increase in microplastics in beach sediment by as much as 36.4 times and 11.0 times after typhoons and rainstorms, respectively. The microplastics consisted mainly of the larger and hard ones, indicating higher transport of heavier plastic debris during such events [18]. Increased heat energy trapped by the ocean fuels storms and hurricanes, which could in turn, change the atmospheric transport and deposition of microplastics. A study by Yuan et al. measured the vertical distribution and transport of microplastics in the urban atmosphere of Guangzhou, and found that stronger winds at higher altitudes increased the dispersion of local microplastics while introducing microplastics from surrounding areas [37]. Additionally, variations in the frequency and intensity of winds may have an implication on the types of microplastics transported. Bullard et al. showed that microplastic fibers were preferentially transported by wind compared to microbeads, and that particle shape was an important factor in determining the atmospheric transport distance of microplastics [38]. In connection with rising sea levels, extreme weather events such as storm surge can also alter the ocean circulation and mixing, which can affect the distribution and fate of microplastics in the water column and on the seafloor [33].

3.1.3. Effects of ocean acidification and salinity change.

Ocean acidification is not climate change but is associated with climate change in the sense that it is caused by the increasing dissolution of carbon dioxide in the ocean as its emissions increase [26]. The increased emissions of carbon dioxide, together with other greenhouse gases, contribute to the modern climate change [2]. While it has been shown that pH is an important factor affecting the chemical leaching and sorption behaviors of microplastics [12], it is uncertain if the extent of ocean pH change caused by ocean acidification will have any significant effects on such behaviors. As reported by IPCC, the global average surface ocean pH would decrease by 0.14 to 0.32 units by 2081-2100. The variation is foreseen to have significant impacts on marine ecosystems through reducing calcification, and lowering of metabolic rates and immune responses, among others [1]. However, the small changes in pH are not expected to alter the surface properties of microplastics and their interactions with other chemicals significantly. Even with faster acidification of the Arctic Ocean foreseen and the decrease of pH by 0.3 units projected by 2100, the impacts of plastic pollution are deemed to be far less significant than those on the marine ecosystems [1].

Some studies highlighted the potential effects of ocean acidification on biofouling of microplastics and suggested that it can reduce or alter the biofouling of microplastics by some marine bacteria, algae, and animals, which can affect their transport, fate, and ecological impacts [36, 39]. Nonetheless, the effects remain inconclusive and require the confirmation of further studies. Ocean acidification may increase the vulnerability of some corals to mechanical damage by microplastics since it reduces calcification (Figure 1) [40]. The melting sea ice and glaciers have been found to alter ocean salinity, causing localized reduction of salinity in the melt zone. The Antarctic Immediate Water has seen significant reduction in salinity due to the northward movement of sea ice meltwater [41]. Nonetheless, currently, there is very limited research on how changes in ocean salinity affect microplastic fate and properties. Generally, salinity of seawater affects the buoyancy of microplastics, which can influence their transport and distribution in the water column [13]. Salinity can also affect the sorption and desorption of pollutants on microplastics, which can affect their toxicity and bioavailability [42]. For instance, pollutants, such as heavy metals, organic compounds, or antibiotics, can bind to the surface of microplastics or penetrate their matrix. However, salinity can influence the strength and reversibility of these interactions [43].

3.2. Influences of plastic pollution on climate change.

Climate change can potentially exacerbate plastic pollution and likewise, plastic pollution may aggravate climate change. Plastic pollution contributes to greenhouse gas emissions. Increasing plastic consumption results in the increased manufacturing of plastics. The extraction, transportation and processing of raw materials for plastics production release carbon dioxide (Figure 2) [44]. More than 56 billion tons of CO_2 equivalent of greenhouse gases were foreseen to be released between 2015 and 2050 due to increased plastic production (Ford et al., 2022). The disposal of plastic waste may involve incineration, which also emits potent greenhouse gases particularly carbon dioxide and methane (Figure 2) [44]. It has been estimated that the production and incineration of plastics currently emit 850 million tons of greenhouse gases and the emissions would increase to 2.8 gigatons of carbon dioxide per year by 2050, equivalent to 615 coal-fired power plants [45].

Landfilling of plastic waste and its entry into oceans expose the waste to heat and sunlight, causing it to gradually degrade and release methane and ethylene (Figure 2) [36]. Additionally, microplastics impact the ocean carbon cycle. Microplastics have been shown to adversely affect the growth of microalgae and their photosynthetic efficiency, thus reducing their ability to capture carbon (Figure 2) [14]. They can also impact the alkalinity of ocean, hence their ability to neutralize acids. An experimental study revealed the potential of aged plastics to decrease seawater pH when subjected to abiotic degradation. This is probably due to the release of organic acids, carbon dioxide and dissolved organic carbon during the degradation process [26]. Large-scale plastic leaching was deemed to cause a maximum decrease of 0.5 units of seawater pH, a magnitude comparable to that of ocean acidification projected under the worst-case emission scenarios by the end of the 21st century [26].

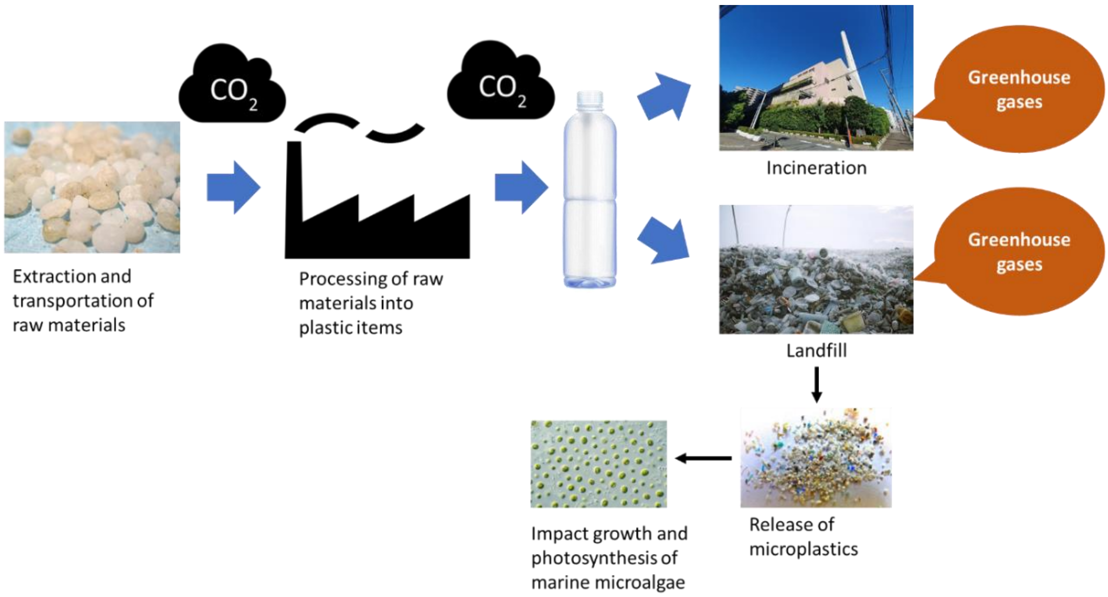

Figure 2. Plastic manufacturing and pollution contribute to climate change through greenhouse gas emissions and disrupting ocean carbon cycle.

Airborne microplastics can alter the energy balance of the Earth through the scattering and absorption of radiation [46]. Similar to aerosol particles, microplastics can have a cooling or warming effect depending on their size, shape, color, and composition. For example, some types of microplastics, such as noncolored fragments and fibers shed by synthetic fabric, scatter ultraviolet and visible lights and absorb infrared light. Airborne microplastics produce a small cooling effect if they are near the Earth's surface, but a small warming effect if they are higher in the atmosphere [47].

4. Conclusions

Conventionally addressed as two separate environmental issues, climate change and plastic pollution are pressing problems intricately related. Climate change has the potential to worsen plastic pollution by accelerating the degradation and fragmentation of plastic waste through rising temperatures. It can also alter the distribution of plastic debris and microplastics through storms, floods, and sea-level rise, resulting in the transport of terrestrial plastics to rivers and the marine environment. Additionally, climate change promotes the leaching of toxic additives from plastic waste and the desorption of chemicals from microplastics due to warming ocean temperatures. Moreover, climate change causes changes in ocean currents and winds, influencing the transport and accumulation of plastic waste in different regions. The melting of sea ice and glaciers induced by global warming releases microplastics trapped in the ice into the environment. While the effects of ocean acidification and changes in ocean salinity on microplastics have not been extensively studied, ocean acidification may alter biofilm formation on microplastics and increase the susceptibility of certain marine organisms to the impacts of microplastics. On the other hand, microplastics could disrupt the ocean carbon cycle and affect Earth's temperature through the scattering and absorbing of radiation. Deteriorating plastic pollution emits more greenhouse gases into the environment, worsening climate change. To address plastic pollution and climate change concurrently, a shift towards a circular economy is necessary to minimize waste and maximize the reuse and recycling of plastics. Circular economy principles, involving redesigning, repairing, reusing, and recycling plastic products, can significantly extend their life cycles, reducing the demand for fossil fuels, emissions from plastic production and disposal, and the accumulation of plastic waste in the environment. In addition, avoiding single-use plastics and opting for alternative materials, such as biodegradable or biobased plastics, is crucial. This contributes to the reduction of plastic waste and the release of greenhouse gases from plastic degradation. Education and awareness-raising play a crucial role in garnering public support for behavioral change to combat plastic pollution and climate change. Solving plastic pollution and climate change concurrently requires a holistic and integrated approach that considers the environmental, social, and economic dimensions of both problems. It also requires collaboration and cooperation among various stakeholders, such as governments, businesses, civil society, researchers, and individuals.

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Competing Interest

The author declares that there is no competing interest.

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