Current trends of unsustainable plastic production and micro(nano) plastic pollution

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***Abstract-* Unsustainable plastic production, use and mismanagement has resulted in increased global plastic pollution and subsequent degradation into micro(nano)plastics in the environment threatening sustainability. Micro(nano)plastic pollution is pervasive and has caused widespread ecological impacts globally, including greenhouse gas emissions, contributing to climate change. Although downstream strategies to curb plastic pollution exist, they are ineffective in the face of current plastic production and waste generation which is still outpacing existing regulations. Thus, the international community has recognized a more holistic approach is required to reduce plastic and micro(nano)plastic pollution. This critical review highlights studies showing that unsustainable global plastic production has resulted in increasing micro(nano)plastic pollution in all environmental compartments, yet few studies have documented successful micro(nano)plastic pollution prevention or removal techniques. This critical review offers constructive criticism into some strategies to help advance ambitious global plastic and micro(nano)plastic pollution reduction targets for a transition towards a sustainable global plastics future.**

***Keywords:* Plastic pollution, Microplastics, Nanoplastics, Micro(nano)plastics Sustainability.**

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Introduction

Plastic consumer products, particularly single-use plastics are ubiquitous, yet current production and use are unsustainable [1–5]. Plastic production has grown 20-fold in the past 50 years and globally, an estimated 9200 million metric tons (Mt) of plastic has been produced and more than 6900 Mt has been landfilled, or worse, contribute to environmental pollution [6,7]. In 2019, global plastic production reached 368 million metric tons (Mt) [8] but is predicted to double within 20 years[9]. Most consumer plastics are designed for single-use, with limited recyclability, which has resulted in increased global production and consumption leading to unprecedented plastic waste generation and widespread plastic pollution [1,3]. Approximately 9% of plastic waste globally has ever been recycled, 12% incinerated, with the remaining 79% has accumulated in natural ecosystems [6]. Borrelle et al. [1] estimated that 19–23 Mt of plastic waste generated globally in 2016 entered aquatic ecosystems but is predicted to reach up to 53 Mt annually by 2030.

Due to low degradation combined with unsustainable production, use, and disposal, plastic pollution has become a severe transboundary threat to natural ecosystems, human health and sustainability [10,11]. A growing body of evidence suggests that the presence of plastics in agricultural soils and in aquatic biota poses potential risks to human health via ingestion in food consumed by humans [12–15]. It is now undeniable that plastic over production and waste generation has resulted in a global plastic pollution crisis. Whilst some researchers have argued that tackling plastic pollution is a distraction from other global environmental threats (biodiversity loss and/or climate change) [16], these unsubstantiated arguments have been rebutted [17,18], as studies have now demonstrated unequivocally that the entire plastic life cycle contributes to climate change, biodiversity loss and is outside the safe operating space of the planetary boundaries[19,20]. Thus, plastic mismanagement threatens the ability of the global community to sustainably manage plastic production, plastic waste and plastic pollution [2,21].

Once in the environment, plastics, macroplastics (>25 mm) continuously degrade into plastic fragments (mesoplastics, >5 mm–25 mm) or smaller particles called microplastics (<5 mm) or nanoplastics (<1 μm or 1000 nm), although definitions between microplastic and nanoplastic size classifications have been debated in the literature [22]. There have been a plethora of studies documenting the extent and magnitude of macroplastic pollution, and more recently, a growing number of studies examining the harmful effects of microplastic and nanoplastic pollution on the environment, biota and humans [15,23]. However few studies have discussed the relationship between micro (nano)plastic pollution and sustainability[2,21]. This critical review highlights how unsustainable global plastic production, use and mismanagement has resulted in increasing micro (nano)plastic pollution in all environmental compartments. Further, this review offers constructive criticism into some strategies to help advance ambitious global plastic and micro (nano)plastic pollution reduction targets for a transition towards a sustainable global plastics future.

Methodology

This critical review was descriptive in character and was designed to provide a constructive criticism about the current state of the art involving nanoplastics, microplastics, plastic, plastic pollution, and sustainability for a subset of consulted works.

Potential papers were searched following the TOPIC search (Title, Abstract and Keyword) in the Scopus database, employing a range of terms relating to plastic and sustainability. The aim of this high-level scoping literature search was to identify relevant studies on nanoplastics, microplastics, plastic, plastic pollution, and sustainability

The search focused specifically on “sustainable” OR “sustainability” subject areas and four plastic subject categories (“nanoplastic”, “microplastic”, “plastic”, and “plastic pollution”). For this critical review, peer-reviewed journal articles, books, reports, conference abstracts and papers over the entire database record were included, thus, there was no defined the time frame.

Although there are many papers or documents published that have included sustainability issues related to plastic pollution or plastics, that would be relevant to this discussion, for the purposes of this critical review only a limited number of papers primarily focused on nanoplastics, microplastics, and sustainability were included. Acknowledging this as a potential limitation, future research could be expanded to include a systematic review or meta-analysis by exampling all studies listed in the Scopus database literature search.

Results and discussion

Database search results and publication trends

The total number of publications or research articles, including review publications, returned during this review are shown in Table S1. There has been a considerable body of work discussing the direct relationship between “plastic” or “plastic pollution” and “sustainability”, but far fewer discussing the relationship between “microplastics” or “nanoplastics” and “sustainability”.

Most studies discussing topic keywords of sustainability or sustainable were related to plastics, with most of these studies appearing as regular articles in journals. The number and type of articles returned for plastic pollution and sustainability or sustainable were articles, conference papers (n = 3099), reviews (n = 1413), book chapters (n = 687), conference reviews (n = 193), books (n = 122), notes (n = 85), short surveys (n = 69), editorials (n = 52), letters (n = 23), erratums (n = 11), data papers (n = 4) and retracted papers (n = 4). Many of these studies were focused on increasing the recyclability of plastics or developing biobased or biodegradable plastics [24]. Most of the original polymers to create a closed loop system [25]. However, this has been something that has been the holy grail of sustainable plastics.

There were fewer studies related to plastic pollution that also discussed the topic keywords of sustainability or sustainable, returned 517 research articles, including review publications. The number and type of articles returned for plastic pollution and sustainability or sustainable were articles, reviews , conference papers, book chapters, notes, editorials, letters, books, erratums, conference review and short survey. Most of these studies appeared in regular articles such as Science of the Total Environment and Marine Pollution Bulletin.

Fewer studies still were returned that focused on microplastics. The number and type of articles returned for microplastics and sustainability or sustainable were articles, reviews, conference papers, book chapters, editorials, conference reviews, notes and short survey, book and letter. Most of these studies appeared in regular articles such as Science of the Total Environment, Journal of Hazardous Materials and Marine Pollution Bulletin. The total number of articles returned for nanoplastics were much lower than for other subject categories. The number and type of articles returned for nanoplastics and sustainability or sustainable were articles, reviews, book chapter 1, editorial and note. Most of these studies appeared in regular articles such as Environmental Research, Chemosphere and Science of the Total Environment. This is not surprising as this trend mirrors other studies that have reported recent increasing trends in nanoplastic and microplastic studies compared to the vast number of studies that have already been published on plastics or plastic pollution [23].

Recent trends recognizing unsustainable plastic pollution

Plastic pollution threatens global social, environmental, and economic sustainability [2]. Many single-use plastic items are difficult to recycle or can only be recycled a few times before they become unsustainable plastic waste which is predicted to reach up to 53 million metric tons annually by 2030 [1]. Plastic waste generation (percentage of total solid waste) has increased from 1% in 1960 to >10% in 2005 in high-income countries [28]. Although previous studies have estimated that half the global mismanaged plastic waste is generated by China, Indonesia, the Philippines, Vietnam, and Sri Lanka [7,29], it should be recognized that these countries have, until recently, imported poor quality plastic waste from high-income countries for recycling [30–32]. Imports of poor quality plastic (e.g., contaminated plastics, co-mingling of with low values after-market plastics) results in disproportionately higher plastic waste generation per capita, much of which is landfilled, incinerated or leaks into the environment, although recent amendments to the Basel Convention are designed to restrict international trade in plastic waste to curb plastic pollution [31].

Changes in industrial production and end-of-life disposal can be the best forms of mitigating impacts plastics and micro (nano) plastics on the environment. Industry transitions to circular economies through resource efficiency and help ameliorate the issue of plastics ending up in landfills or being incinerated. The circular economy approach can prevent plastic from negatively impacting the environment by reusing and recycling materials [33]. Plastic producers should consider end-of-life options when designing products and materials that may pose problems for recycling or reusing products in the future [34].

Increasing waste management as a singular measure cannot challenge the predicted growth of plastic production and waste generation [1]. Increasing recycling and reuse of plastic products will not solve the issue of plastic pollution. Still, it can be a remediation measure to transition from linear to circular models. The waste hierarchy can provide a pathway for dealing with mismanaged plastic waste. The waste hierarchy comprises five steps: prevention, reuse, recycling, recovery, and disposal [35]. Based on this waste hierarchy reducing the quantity of plastic produced is better than the effort to reuse and recycle plastic materials at the end of their primary use.

Most plastic sent to recycling facilities from the household collection is downcycled, meaning that once the material has been sorted and produced into another product, it is of lower quality than the original material [36]. Plastic waste is mainly conducted through mechanical recycling, which is the collection, sorting, shredding and melting down of plastics into pellets to be resold as recycled plastic products [37]. Since plastics are comprised of complex polymers and chemicals, sorting and collecting plastic products can be difficult to melt down into one large group of plastics as many different chemical additives can react throughout this process. The quality of recycled plastic can be low, reducing chances of the recycled plastic product being sold to manufacturers to resell as a recycled plastic product. Increased waste management may marginally lower the quantity of plastics lost at the end-of-life disposal phase, but it will not be a solution to solve global plastic pollution.

In some low-income countries where safe drinking water is unavailable the unsustainable use of single-use plastic sachets or bottled water for drinking has resulted in unprecedented amounts of plastic pollution [38]. Unsustainable importation of plastics to countries with inadequate waste management systems chokes critical urban infrastructure, resulting in widespread and unsustainable economic and environmental impacts from plastic pollution [38]. For example, plastic waste and pollution costs up to US$2.5 trillion per year based on reduced ecosystem services [39]. Increasing global plastic waste generation has also resulted increased public awareness about the negative impacts environmental of plastic pollution [4]. As most consumer plastics (98–99%) are derived from fossil fuels, plastics account for 6% of global oil consumption contributing to greenhouse gas (GHG) emissions and are inextricably linked with every step of the plastic life cycle from production to disposal [18,19]. Thus, to ensure sustainable plastic consumption and to reduce plastic waste and subsequent plastic pollution, extraordinary efforts are required by the international community.

The ongoing Plastics Treaty negotiations is an example of an extraordinary effort by the international community [27]. Although still under negotiation, there have been calls by scientists and governments for the Plastics Treaty to include caps on plastic production, removal of harmful chemicals and to be strict and legally binding [40–42]. Other examples include, dramatically decreasing plastic consumption, developing circular economies where end-of-life plastics retain value rather than becoming waste to dramatically increase domestic recycling rates and to adopt zero plastic waste strategies by reducing, reusing and recycling singleuse plastics [21,35,43].

Even before the Plastics Treaty negotiations began, multilevel mitigation strategies have been proposed, in response to the growing global plastic pollution problem [10]. With global plastic production and plastic pollution continuing to increase, so does the number of national and international commitments to reduce plastic pollution [3]. National governments are implementing bans or levies on single-use plastics [38,44–47], combined with strong consumer and industry support [4]. At the international level, the United Nations Environment Assembly (UNEA) has made commitments to reduce plastic pollution under the Plastics Treaty [41]. Also at the international level, marine plastics are being addressed by the UN and by individual countries at national, sub-national and supra-national, including at regional levels [21,48]. At the global level, the issue of marine plastics has been recognized in the UN Sustainable Development Goals (SDGs) under Goal 14 to reduce the density of floating plastic debris which has been recognized by the international community as being essential for sustainable ocean use [2]. However, there are currently no specific targets to reduce plastics or indicators to measure plastic reduction for all other SDGs which presents immense challenges for the international community to implement the SDGs due to the transboundary and pervasive nature of plastic pollution impacting all three pillars of sustainability (environment, society and the economy) [21,49,50].

To achieve a global plastic pollution strategy and a sustainable global plastics future, unprecedented solutions, approaches, and mitigation strategies must be widely adopted and implemented urgently [1,3]. However, despite these national and international commitments widespread plastic pollution continues to threaten the ability of the international community to sustainably manage the full plastics life cycle [21,50].

Recent trends recognizing unsustainable micro(nano)plastic pollution

Micro (nano)plastic pollution is invisible to the naked eye and like climate change, has largely been ingnored by scientific, public, and policy makers until relatively recently due to the lack of direct personal impact or visibility [23]. Highly visible macroplastics such as single-use plastics (e.g., plastic bottles, bags and packaging) or plastic fragments (mesoplastics) have garnered most public, policy and research interest [51]. Effects of microplastics on marine species in the early 2000s started the trend of increasing scientific research interest in tiny microplastics[23]. In response to increased interest on microplastics in the environment, researcher began to consider the potential impacts to human health. Thus, research focus shifted to smaller particles including nanoplastics [52]. As collection and analysis of smaller particles became possible, the quantification of micro (nano)plastics in a plethora of environmental media rapidly increased [13,23,53].

Sustainability of global food, drinking water and sanitations systems depends on soil, ocean, and aquatic ecosystem health, yet there is growing body of evidence of micro (nano)plastic accumulation in agricultural soils [54], fruits and vegetables[55], drinking water [56] and seafood [12–14]. There is now a growing body of recent literature reporting the presence of micro (nano)plastics in drinking water and treated wastewater effluent [56,57]. The World Health Organization (WHO) has recognized the presence and potential hazards of microplastics in municipal and bottled drinking water [2]. However, the presence of (micro)plastics in drinking water from treatment plants varies widely from undetectable to >900 particles/L and largely depends on water sources, plant design, and methods used for analysis [57]. Although wastewater treatment plants have relatively efficient removal rates of 90–99%, they are also point sources for releasing micro (nano)plastics into the environment [2,21,57]. Micro (nano)plastics are released both directly in aquatic ecosystems via effluent release and indirectly to agricultural soils via biosolids amendment application. Thus, these sources of micro (nano)plastics pollution still poses serious challenges to implementing sustainable management of water and sanitation [2]. The presence of micro (nano)plastic in drinking water, agricultural soils and aquatic biota poses potential risks to human and ecological health and threatens global sustainability.

Micro (nano)plastics have now become so ubiquitous in the global environment [2,15,23], that they have been detected in thousands of species, including humans in placentas and blood [58,59] or inhaled or consumed via food and drinking water [14,60]. Due to their ubiquitous and persistent nature and small sizes, the health effects and toxicity micro (nano)plastics have recognized as major threats to substantiality and accordingly have attracted increasing research efforts [15,23].

Micro (nano)plastics studies in laboratories have mostly focused on aquatic species and have shown accumulation of micro (nano) plastics in organs and tissues, causing impaired development, oxidative stress, inflammation, neurotoxicity, and intestinal injuries [15]. However, empirical data on the ecological and human health impacts of micro (nano)plastics are still relatively lacking and few published studies have directly quantified the effects of micro (nano)plastics on humans [15]. Although, current concentrations of micro (nano)plastics in the environment may be low compared to laboratory toxicological studies, their increasing inputs are unsustainable based on current and projected plastic production data [1]. Unlike larger macroplastics, there are currently no specific targets or indicators to measure micro (nano)plastic pollution.

With absolutely no consideration of micro (nano)plastics in any of the set, it has become even more critical to evaluate the ecological and human health impacts of micro (nano)plastics along with the threats to environmental, social and economic sustainability [2]. This is an astonishing oversight by the global community, especially when microplastics and nanoplastics researchers are building a growing body of evidence of the harmful effects of these contaminants to the environment, biota and human. Although scientific consensus is in broad agreement on the toxic effects of microplastics and nanoplastics in the environment, there is a paucity of research related to their impacts on long-term sustainability.

Although there are a plethora of reduction strategies (policies and technologies) to curb larger plastic pollution [44,45,51,61], current strategies to address micro (nano)plastic pollution are scarce and mostly focus on regulatory prohibitions of intentionally manufactured primary microplastics such as microbeads [44,45,62]. Microbeads are intentionally manufactured plastic particles and are most frequently made of polyethylene, polypropylene and polystyrene. As consumer products, they are commonly used in exfoliating personal care products, and toothpastes, but are also used in the health care sector [44,45]. Several countries have already banned microbeads from rinse-off cosmetics, including Canada, the US, France, the United Kingdom, India, New Zealand, Sweden, and Taiwan [45] (Fig. 2). In Canada, regulatory measures to prevent microplastics at the source include the Microbeads in Toiletries Regulations of 2017 SOR/2017–111. The microbeads ban was a direct measure to stop the production of microplastics for certain products, such as facial scrubs and toothpaste. Similarly, in the US, the Microbead-Free Waters Act of 2015 phased out microbeads in rinse-off cosmetics in July 2017 [44,45].

Measures to address secondary microplastic or nanoplastic pollution derived from degraded macroplastics exist, but they often focus on capture techniques and are only effective for larger microplastics [60]. For smaller microplastics and nanoplastics, current sampling, analytical or removal technologies are lacking or are still under development. For example, the WHO revised safety guidelines for the presence of microplastics in drinking water [63]. The California State Water Board adopted a method for testing drinking water for microplastics and established a policy handbook on a standard method for four years of testing and reporting microplastics in drinking water [64,65]. This new standard method is the only of its kind in the world and it includes flexibility for adaptation to further science or technology that may be developed in the future [64]. As research on the sampling and monitoring of microplastics will continue to develop in the future, this guideline for monitoring microplastics in water should apply best practices. However, there are currently no specific safety guidelines or threshold limits for microplastics in drinking water [65]. Thus, further research is required to address this uncertainty and unsustainable impacts of micro (nano)plastics.

Implementing more robust regulatory measures could be the most viable option for reducing the amount of plastic generated and subsequent plastic and micro (nano)plastic pollution. As seen through Canadian legislation, the prevention of primary microplastics (i.e., microbeads) at their source is essentially turning off the tap to reduce plastic from entering the environment. “Turning off the tap” or capping plastic production has been called for by many [41]. While plastic materials are still essential for many industries and applications, it is important to reduce overall plastic consumption. The transition to renewable products will require transformative behaviour changes for industry, governments, and consumers.

Sustainable solutions to address both plastic and micro (nano) plastic pollution

There is an urgent need to move from reliance on unsustainable fossil fuel-based plastics to sustainable biobased plastic alternatives to help contribute to a circular economy [26]. However, although biobased plastics may appear offer a sustainable alternative, they only account for 2% of plastics, but a cradle-to-grave life cycle assessment of biobased alternatives is urgently required [26]. Although the impacts of fossil fuel-based plastic production and resultant plastic and micro (nano)plastic pollution are indisputable and are currently unsustainable, there needs to be a transition to reduced consumption of biobased alternatives to avoid unintended environmental consequences [2].

Recently, researchers in Germany report of a new type of polyethylene derived from renewable oils that has greater recyclability by recovering most of the original polymers to create a closed loop system [25]. This is something that has been the holy grail of ‘sustainable plastics’. To achieve a future with truly sustainable plastics and zero plastic waste [3,43], this technology needs to be scaled up to wean society off a dependence on fossil fuel-based plastics [66]. Recent interest in ‘sustainable plastics’ has resulted in a rapid increase in petroleum-based biodegradable plastics, which has led to consumers mistaking these products for ‘bioplastics’, which has resulted in widespread public confusion over waste disposal [67]. Current plastic production use and disposal may continue undermine implementation of many of the UN SDGs by 2030 without the rapid scaling up of bioplastic alternatives [2]. This also needs to be implemented in parallel with reductions in global consumption of fossil fuel-based plastics.

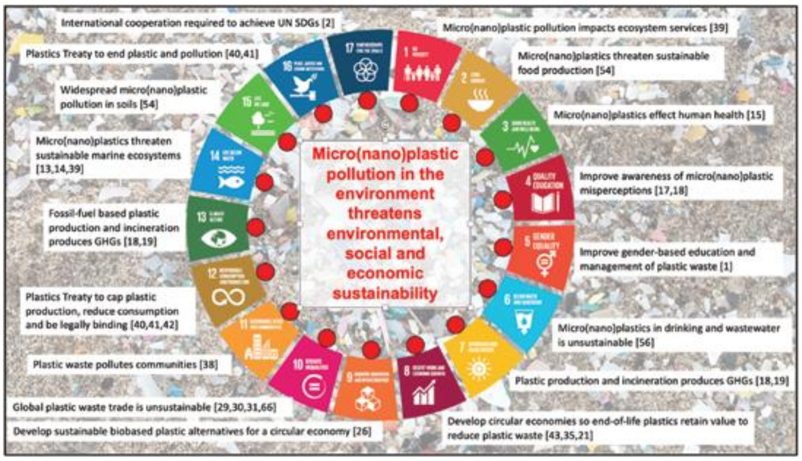

Fig. 1. Micro (nano)plastics and the UN SDGs. Red circles indicate that all 17 UN SDGs lack any indicators to address micro (nano)plastic pollution. The UN SDGs icons and colour wheel are free to re-use as per the UN guidelines (https://www.un.org/sustainabledevelopment/wpcontent/uploads/2019/01/SDG_Guidelines_AUG_2019_Final.pdf). Adapted from Walker [2].

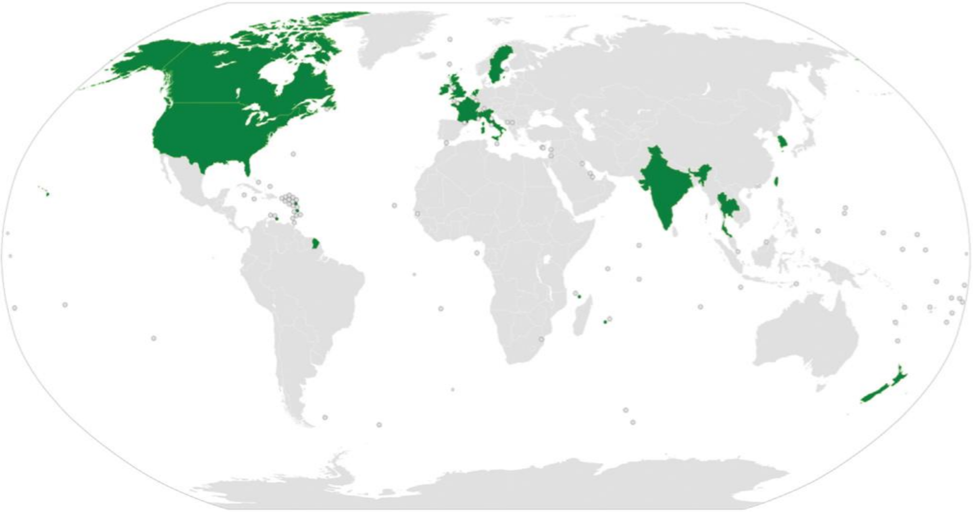

Fig. 2. Current global microbead policy interventions showing national bans (solid green) (by Delusion 23 - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php? curid¼65416735). Grey circles indicate island nations or overseas territories.

Although solutions required to reduce plastic and micro (nano) plastic pollution are diverse and cannot be properly addressed in this short critical review, some current and future solutions include: extended producer responsibility programs [35]; prevention initiatives to reduce single-use plastic use [38,44e47]; and the Plastics Treaty which will consider the entire plastics life cycle including curbing production, circular economy and environmental reporting standards, increased consumer awareness and improved performance measures.

Plastics are complex materials consisting of over 10,000 chemical substances such as additives, processing aids, and nonintentionally added substances, and many of them are known to be hazardous to human health and the environment[33,42,68]. Thus toxic chemicals used in plastic production hamper the effectiveness of many of these so called "sustainable" solutions to address use of plastics and micro (nano)plastics such as: mechanical recycling, waste-to-energy, chemical recycling, biobased plastics, biodegradable plastics, and durable plastics [68].

The global Plastics Treaty agreement will be designed to end plastic pollution. The Nordic Council of Ministers [69] argue that it will also need to specifically address microplastics as a distinct category of plastic pollution, warranting specific control measures. For example, the Plastics Treaty should include requirements for the reporting on production, composition, and trade of secondary microplastics such as plastic pellets, flakes and powders [69]. All non-essential intentionally added primary microplastics (i.e., microbeads) should be phased-out with timebound targets, compliance, and enforcement measures, and subjected to trade restrictions on exports and imports [69]. The Plastics Treaty should also include commitments to develop global plastic product standards or design for end-of-life criteria for problematic sources, hotspots and pathways of use-phase secondary microplastics with minimum requirements to prevent abrasion and fragmentation [68]. The Nordic Council of Ministers [69] argue that an agreement must include measures to reduce secondary microplastic emissions from macroplastics, including measures to prevent and reduce production of unnecessary and problematic plastic products; improve durability for safe reuse, recycling, repair, and remanufacture and improved plastics waste management for all sectors, including the informal sector. An agreement should include dedicated measures to prevent microplastics pollution from the repurposing, reuse and recycling of plastics to achieve a sustainable plastics future.

Conclusion

Plastic and micro (nano)plastic pollution threatens global social, environmental, and economic sustainability. Plastic production use and disposal, particularly single-use plastic packaging, has grown 20-fold in the past 50 years. Many single-use plastic items are difficult to recycle or can only be recycled a few times before they become waste. Ambitious responses to plastic waste reduction from governments, industry and consumers have not keep pace with current unsustainable plastic production and use. Addressing the complex global issue of plastic and micro (nano)plastic pollution requires extraordinary efforts to transform the global plastics value chain to achieve zero-plastic waste. To achieve this, specific actions are required beyond legislation and policy-driven changes.

Although still under negotiation there have been calls by scientists and governments for the Plastics Treaty to include caps on plastic production, removal of harmful chemicals and to be strict and legally binding Additionally, society needs to dramatically decrease plastic consumption, develop circular economies where end-of-life plastics retain value rather than becoming waste to dramatically increase domestic recycling rates and to achieve a sustainable plastics future by reducing, reusing and recycling single-use plastics.

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