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Review

Integrating the quintuple helix approach into atmospheric microplastics management policies for planetary health preservation

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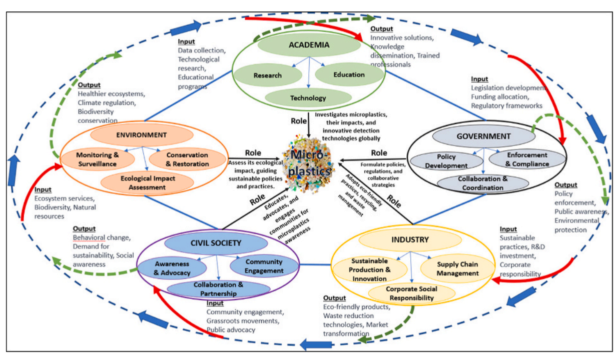
HIGHLIGHTS

- Quintuple Helix framework proposed for microplastic management.
- Emphasizes collaboration among academia, government, industry, civil society, and the environment.
- Aims to develop effective atmospheric microplastics management policies.
- Highlights the importance of interdisciplinary research and innovative technologies
- Advocates for public awareness campaigns and regulatory frameworks to mitigate microplastics.

GRAPHICAL ABSTRACT



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ABSTRACT

Microplastic pollution has become a major global environmental issue, negatively impacting terrestrial and aquatic ecosystems as well as human health. Tackling this complex problem necessitates a multidisciplinary approach and collaboration among diverse stakeholders. Within this context, the Quintuple Helix framework, which highlights the involvement of academia, government, industry, civil society, and the environment, provides a comprehensive and inclusive perspective for formulating effective policies to manage atmospheric microplastics. This paper discusses each helix's roles, challenges, and opportunities and proposes strategies for collaboration and knowledge exchange among them. Furthermore, the paper highlights the importance of interdisciplinary research, innovative technologies, public awareness campaigns, regulatory frameworks, and corporate responsibility in achieving sustainable and resilient microplastic management policies. The Quintuple

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Helix approach can mitigate microplastics, safeguard ecosystems, and preserve planetary health by fostering collaboration and coordination among diverse stakeholders.

1. Introduction

Plastic products have become indispensable in modern society due to their versatility and extensive applications across various sectors, including manufacturing, packaging, construction, and agriculture. Since the commencement of large-scale production in the 1950s, the global production of plastic has surged dramatically, with annual output reaching approximately 450 million tons (Mt) in 2022 (Ritchie et al., 2023). This unprecedented growth in production has led to a substantial accumulation of plastic waste. In 2015 alone, an estimated 6,300 Mt of plastic waste were generated (Geyer et al., 2017). The majority of this waste, approximately 79%, was either discarded into landfills or released into the environment, with only a small fraction, around 9% of plastic waste was recycled, and 12% was incinerated. If current trends continue, global plastic production is projected to exceed 1.1 billion tons annually by 2050. Consequently, the accumulation of plastic waste in

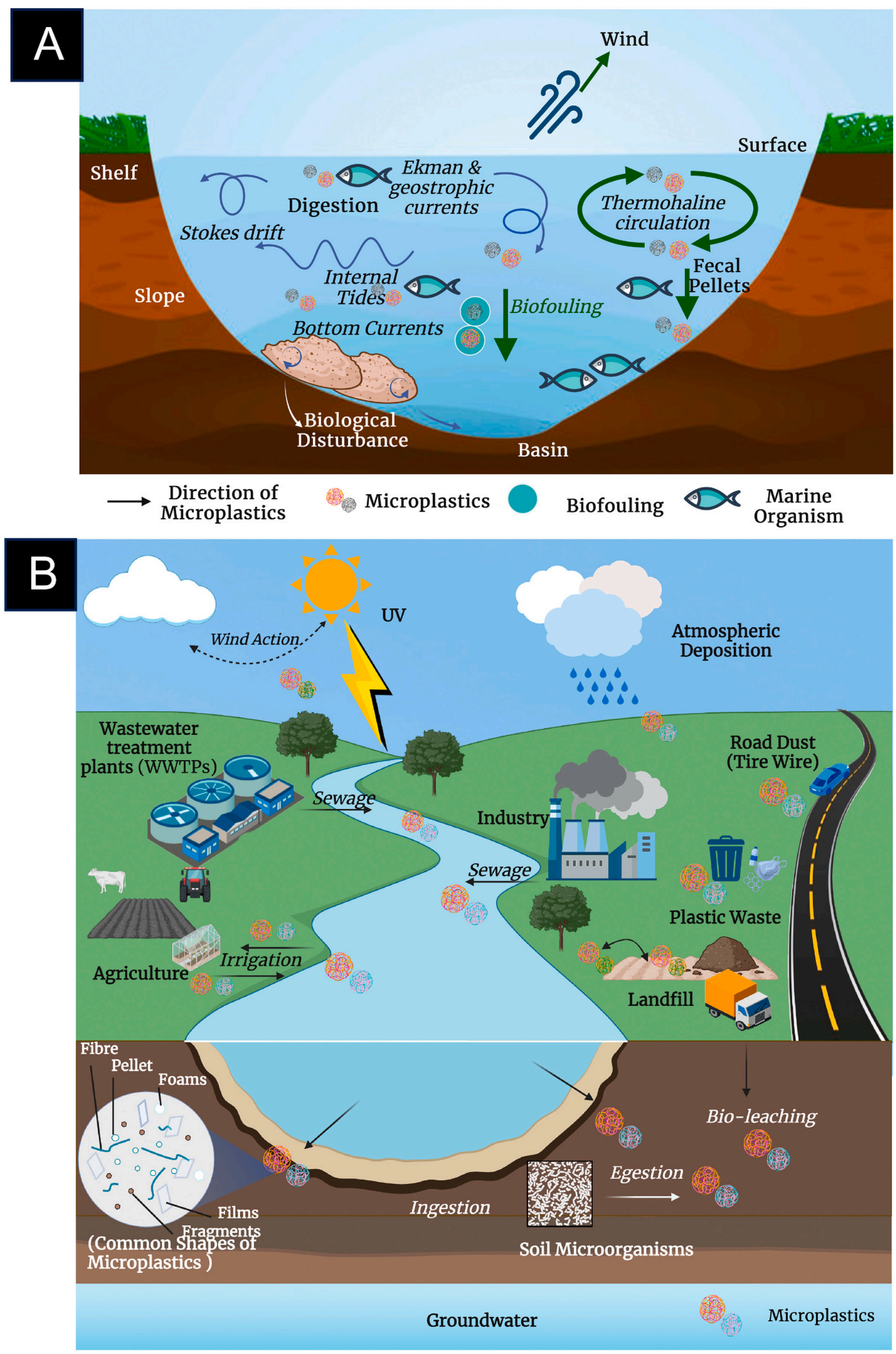

Fig. 1. (A) Transport pathway of microplastics in marine environment; (B) source and consequences of microplastics in soil.

landfills and natural environments is expected to reach 12,000 Mt (Geyer et al., 2017). This accumulation poses environmental risks, as plastic debris can fragment into smaller particles, ranging from several millimeters to submicron sizes, due to physical, chemical, and biological weathering processes. This fragmentation results in the formation of microplastics, a term first introduced by Thompson et al. (2004) to describe both granular and fibrous plastic particles that are less than 5 mm in size. More recent research has refined this definition, with microplastics classified as particles ranging from 5 mm to 1 μm (Chia et al., 2021; Tan et al., 2022).

Microplastics are broadly categorized into two main types: primary and secondary microplastics (Li et al., 2016; Peng et al., 2020). Primary microplastics are deliberately produced in small dimensions for various commercial applications, such as synthetic fabrics, microbeads in personal care items, and pre-production pellets in plastic manufacturing. Secondary microplastics, in contrast, are generated by the deterioration or erosion of bigger plastic objects, including packaging, bottles, agricultural film, tires, marine paints, and synthetic turfs. This creates a wide variety of sources from which microplastics are released into the environment (Peng et al., 2020; Xu et al., 2020). The ubiquity of microplastics in the environment has progressively increased over the past few years in tandem with rising global plastic production, which is anticipated to continue. According to the United Nation's environment program (UNEP), 3.0 Mt of microplastics are lost to the environment each year, with a significant portion likely ending up as marine plastic pollution (Ryberg et al., 2019; Suzuki et al., 2022). Microplastics deposited into the soil undergo processes such as storage, degradation, erosion, transportation and leaching into groundwater, thus posing considerable risks to soil and aquatic organisms as well as human health (Chia et al., 2021).

Recent studies have confirmed the presence of microplastics in food intended for human consumption (Prata et al., 2020), and their detection in human excrement further highlights the widespread exposure of humans to these pollutants (Schwabl et al., 2019). Aquatic ecosystems are particularly vulnerable, with microplastics being readily absorbed by organisms such as shellfish, plankton, and suspended algae. These microplastics can then bioaccumulate through the food chain, affecting invertebrates, fish, turtles, and larger animals. The ingestion of microplastics has been linked to a range of adverse health effects, including growth inhibition, reproductive disruptions, metabolic abnormalities, and potentially mortality (Chang et al., 2022; Thomas et al., 2021). Fig. 1 illustrates the complex transport pathways of microplastics through the environment, including atmospheric deposition, runoff, and biological transport. These pathways ultimately lead to the accumulation of microplastics in ecosystems, emphasizing the need for a comprehensive understanding of these processes to mitigate the environmental impacts of microplastic pollution.

The challenges associated with the management of microplastics are complex, including several aspects, such as their diverse physical and chemical characteristics and their potentially harmful impacts on ecosystems (Lamichhane et al., 2023; Yu et al., 2018). Furthermore, the lack of research on public attitudes, opinions, and behavioral preferences about microplastics makes microplastic management more difficult. Although attempts have been made to tackle plastic use via legislation, incidents of violations emphasize the need for more efficient measures (Deng et al., 2020). Another noteworthy concern is the absence of reliable analytical techniques for identifying and quantifying microplastics in complex matrices like food products (Hermsen et al., 2018). The assessment of microplastics or nano-plastics is hindered by the lack of established standards and specialized databases containing distinct spectra of polymeric materials (Ivleva, 2021; Lv et al., 2021). Additionally, plastic recycling faces significant challenges due to the difficulty in isolating the desired materials. This complexity arises from the presence of various polymer types and additives, which complicate the process of achieving high plastic purity (Brouwer et al., 2020). In another study, Peng et al., (2020) reported that despite global efforts to promote sustainability, developing economies often prioritize immediate concerns such as hunger, poverty, and economic development over environmental issues. The study further revealed that the moderate impact of financial development did not substantially alter sustainability practices. Consequently, it was recommended that policymakers reconsider their economic strategies and emphasize the allocation of financial resources towards sustainability initiatives, especially on plastic issues.

Given the complexity of microplastic pollution control, it is evident that addressing this environmental issue requires an integrated approach that combines interdisciplinary techniques and involves multiple stakeholders. The Quintuple Helix framework offers a comprehensive and inclusive perspective by incorporating the roles of academia, government, industry, civil society, and the environment. This framework employs a nonlinear innovation model that can effectively address the challenges associated with microplastic pollution. The model emphasizes the exchange and dissemination of knowledge across various subsystems within a state or nation, focusing on social dimensions and environmental sustainability (Durán-Romero et al., 2020). By fostering collaboration among educational, industrial, political, social, and environmental subsystems, and facilitating the flow of information between them, the Quintuple Helix framework supports innovation, creates value, and promotes a sustainable future (Carayannis et al., 2018; Carayannis and Campbell, 2010).

2. Atmospheric microplastics pollution: Impacts and challenges

2.1. Environmental impacts

Studying atmospheric microplastic pollution in terms of implications and problems involves a multifaceted investigation. Right from ecosystem disruption and biodiversity loss to habitat degradation, trophic transfer, and ecological imbalance, this study delves into the complex web of environmental effects, as shown in Fig. 2, paving the way for successful policy integration within the Quintuple Helix framework.

2.1.1. Ecosystem disruption

Atmospheric microplastic pollution contributes to the disruption of ecosystems by accumulating in water, biota, and sediments, leading to changes in water quality, ecological disruptions, and potential risks to

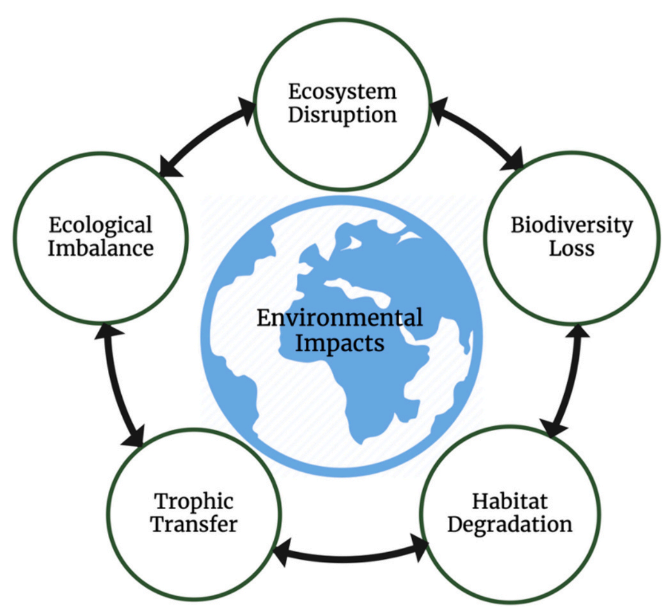

Fig. 2. Quintuple helix of environmental impacts.

human health (López et al., 2023). The dynamics of biotic and abiotic components are affected as microplastics can accumulate harmful pollutants from the surroundings, acting as transport vectors, and leach out chemicals (Enyoh et al., 2020). The presence of microplastics in the atmosphere is due to their low density, which allows for easy transport worldwide and direct contact with the human body through inhalation or ingestion (Issac and Kandasubramanian, 2021). The physical characteristics, chemical composition, environmental interactions, and degree of aging of microplastics contribute to their toxicity (Khan et al., 2023a, 2023b). The abundance and concentration of microplastics in the atmosphere are associated with nearby production sources and their displacement (Chen, 2023). Microplastics can adversely affect plant health in both short-term and transient ways, impeding growth and oxidative activity. Furthermore, microplastic contamination disrupts the trophic structure and functioning of ecosystems by altering the foundational levels of the food chain.

Sustained exposure to microplastics can lead to cascading effects on the resilience of ecosystems. Microplastics can contaminate fine particulate organic matter (FPOM) pools, potentially affecting the growth and survival of particle-feeding macroinvertebrates (Kong et al., 2023). Terrestrial ecosystems are also at risk of microplastic contamination, which can negatively impact soil health and fertility by affecting soil pH, porosity, water-holding capacity, and soil microbial enzymatic activities (Rai et al., 2023). Microplastic exposure has been shown to have detrimental effects on both marine and freshwater organisms. These effects include alterations in behavior, reductions in reproductive success, and damage to various organs (Enyoh et al., 2020). Additionally, contamination by microplastics in marine sediments can disrupt ecosystem functions, leading to increased rates of aerobic respiration and changes in the bioturbation behavior of benthic species (You et al., 2023). The pervasive presence of microplastics not only endangers aquatic and terrestrial ecosystems but also poses substantial risks to human health, highlighting the urgent need for comprehensive mitigation strategies (Saini and Sharma, 2022).

The altered ecological interactions caused by air microplastic contamination can have a major impact on ecosystem adaptability and stability. Microplastics, which are widely found in the environment, can interact with other pollutants and act as vectors for contaminants, causing alterations in the bioaccumulation and transfer of chemicals in biota (Rai et al., 2023; Saini and Sharma, 2022). These interactions can directly affect organisms, such as entanglement and ingestion, as well as indirectly through the sorption of environmental pollutants onto microplastic surfaces (Nath et al., 2023). The combined effects of microplastics and sorbed chemicals can result in toxicological effects on biota, posing a threat to ecosystem health (Menéndez-Pedriza and Jaumot, 2020). Understanding the factors influencing microplastics sorption capacities and the potential scenarios in which microplastics play a crucial role in the bioaccumulation and transfer of chemicals is essential for assessing the overall impacts on ecosystems. Further research is needed to investigate the specific toxicological effects of microplastic-pollutant interactions and their implications for ecosystem stability and adaptability.

2.1.2. Biodiversity loss

Microplastic contamination in the atmosphere contributes to biodiversity loss, although the full extent of its impact remains uncertain. In addition, the microplastics in terrestrial habitats, including soil and freshwater ecosystems, pose risks to soil organisms, land animals, and the breeding of disease vectors (Rojas et al., 2023). Plastic pollution is a considerable threat to biodiversity, impacting wildlife through entanglement, ingestion, and choking, leading to loss of body parts or mortality (Anunobi, 2022). The contamination of aquatic environments by microplastics is also a major threat to biodiversity, with evidence of microplastic contamination in fish fauna in the Amazon basin (Zhao et al., 2023a, 2023b). The toxic effects of microplastics on terrestrial microorganisms can significantly impact microbial community structure and function, with unknown consequences for ecosystem health (Khan et al., 2022). However, additional research is necessary to establish the sensitivity of different species to atmospheric microplastic contamination.

Microplastics significantly impact species composition in damaged ecosystems through both direct and indirect mechanisms. The direct effects of microplastics on organisms' functional features, such as metabolism, growth, and reproduction, can adversely affect their fitness and survival (You et al., 2023). Additionally, microplastics can have indirect effects on the microbiome, altering microbial community structure and function, leading to shifts in nutrient cycling, predator-prey interactions, and ecosystem stability (Berlino et al., 2023). Furthermore, microplastic contamination can affect the composition and behaviour of bioturbating species, which play an important role in controlling ecosystem functioning (Zhao et al., 2023a, 2023b).

The consequences of microplastic-induced changes in biodiversity can have far-reaching impacts on ecological functioning and health of ecosystems. For instance, microplastic contamination can lead to changes in ecosystem functions, such as nutrient cycling (You et al., 2023). The functional role of bioturbating species, which play a crucial role in regulating nutrient cycling in marine sediments, should be considered when assessing the global impact of microplastics (Yao et al., 2022). Additionally, microplastics can affect soil properties and microbial populations, which in turn can influence carbon and nitrogen turnover in terrestrial ecosystems (Beaumelle et al., 2020; Rillig et al., 2021). Declines in decomposer diversity and abundance caused by environmental stressors can result in reduced litter decomposition (Büks et al., 2020). These findings illustrate the intricate and multidimensional interaction between microplastics and changes in species composition in affected ecosystems, underscoring the need for further research to fully understand the complex relationships between microplastics and ecosystem health.

2.1.3. Habitat degradation

Atmospheric microplastic pollution contributes to habitat degradation through various pathways. The production and disposal of plastics result in the generation of microplastics, which contaminate terrestrial environments and disrupt soil sustainability. These contaminants are introduced into the environment through anthropogenic activities such as floodwater, sewage, and wind dispersal. Once in soil, microplastics alter soil habitats and negatively impact soil biota, affecting their activities and indirectly affecting food production (Anunobi, 2022). Additionally, microplastics can adsorb other pollutants, delaying their degradation and further impacting the soil and ecological activities (Du et al., 2022). Plastic debris undergoes mechanical, chemical, and biological degradation, resulting in the formation of nanoplastics and smaller fragments, such as oligomers and monomers, which further exacerbate environmental degradation (Corcoran, 2022). The accumulation of microplastics and their interactions with various pollutants, including organic and inorganic contaminants, can delay degradation processes and adversely affect soil health. This results in altered soil pH, reduced porosity, impaired water-holding capacity, and decreased soil microbial enzymatic activities (Rai et al., 2023). Furthermore, microplastics influence the behavior and survival of fauna, such as coral reef fish, by altering their activity levels and movement patterns, leading to ecosystem-level shifts in predator-prey relationships and nutrient cycling (McCormick et al., 2020; You et al., 2023). These cascading effects on ecosystem structure and function highlight the broad ecological implications of microplastic pollution.

Microplastics, being persistent pollutants, degrade slowly and accumulate across various environmental compartments, including the hydrosphere, pedosphere, and atmosphere. The interactions between these compartments create a source-sink dynamic that influences the transport and distribution of microplastics (Adeniji et al., 2023; Haque and Fan, 2023). Despite their widespread presence, the mechanisms governing microplastic transport, particularly in the pedosphere and atmosphere, remain poorly understood (La Nasa, 2022). While microplastics are frequently detected in aquatic environments, their actual concentrations, distribution patterns, and effects on natural waters, sediments, and biota are still largely unknown (Li et al., 2023). Rivers have been identified as major pathways for transporting microplastics from terrestrial areas into the ocean, and atmospheric circulation may also play a role in transporting microplastics between compartments (Corcoran, 2022). The persistence of microplastics in various environmental compartments can contribute to habitat degradation and pose ecological and health risks to biota and humans.

2.1.4. Trophic transfer

The trophic transfer of atmospheric microplastics, which refers to the movement of microplastics through different trophic levels, is not widely measured in marine food webs (Fu et al., 2023). While laboratory studies have demonstrated the ingestion of microplastics by marine organisms across trophic levels, a recent study in the Monterey Bay Submarine Canyon ecosystem found no evidence of trophic transfer (Hamilton et al., 2021). Instead, microplastics were detected in the gut contents of various marine taxa, including crustaceans, fish, mollusks, and gelatinous organisms, with no significant correlation between microplastic abundance and fish trophic level (López et al., 2023). However, a positive correlation was observed between body size and microplastic abundance across all taxa, with higher microparticle abundance observed in mobile individuals with broad horizontal distributions (Sarkar et al., 2022).

Trophic interactions play a significant role in amplifying the distribution and concentration of atmospheric microplastics in different environmental compartments. Microplastics can be transported long distances through the atmosphere and accumulate in various terrestrial and aquatic matrices, posing a threat to the biosphere (Bhat et al., 2023). Rivers have been identified as major pathways for transporting microplastics from terrestrial areas to the ocean, while atmospheric circulation can transport microplastics between different environmental compartments (Mbachu et al., 2020). The vector effect of microplastics can also change the behaviour of other pollutants, leading to compound toxicity (Li et al., 2023). Additionally, atmospheric deposition of microplastics can contaminate the environment, including soil, water, and the atmosphere itself (Munz et al., 2023). The transfer of microplastics through trophic interactions between organisms with varying nutrition levels can aid in their spread and concentration in the environment, highlighting the complex and interconnected nature of microplastic transport and fate.

Microplastics were identified in the gastrointestinal contents of several marine species, including crustaceans, fish, mollusks, and gelatinous creatures. Despite this broad occurrence, no significant correlation has been established between the abundance of microplastics and the trophic level of fish, suggesting that microplastic ingestion is not restricted to specific feeding behaviors or ecological niches. Additionally, recent studies have expanded the focus to freshwater species. For instance, the, Talitrid Amphipod *Cryptorchestia garbinii*, living on the shores of lakes, has been found to ingest microplastics, making it a valuable natural model for plastic exposure (Battistin et al., 2023). Similarly, the Nase fish has also been identified as a biological uptake vector for microplastics in freshwater ecosystems, with evidence of microplastic fibres in its gastrointestinal content (Curtean-Bănăduc et al., 2023). Furthermore, research has demonstrated that the midges *Chaoborus crystallinus* and *C. obscuripes* can ingest microplastics through predation, with a significant portion of these microplastics being regurgitated back into the aquatic environment (Michler-Kozma et al., 2022). These findings highlight a potential pathway for the redistribution and persistence of microplastics in freshwater ecosystems, contributing to the broader environmental impact of plastic pollution (Curtean-Bănăduc et al., 2023; Saeedi, 2023).

2.1.5. Ecological imbalance

Atmospheric microplastic pollution poses a growing threat to ecological balance and ecosystem stability. Microplastics have demonstrated the capacity to adsorb and transport a range of environmental contaminants, thereby delaying their degradation and altering bioavailability within soil systems. This interaction with co-pollutants can directly impact soil health, fertility, and microbial enzymatic activities (Anunobi, 2022). Beyond sorption effects, microplastics can also induce structural changes to soil environments by altering the quantity and composition of plant-derived organic matter inputs, including litter and root biomass. Such disturbances in the carbon source can shift the composition of dominant bacterial phyla and modify functional genes and enzymatic activities related to nutrient cycling (Rai et al., 2023). Moreover, atmospheric transport and deposition of microplastics can act as vectors for the translocation of adsorbed pollutants, posing exposure risks to terrestrial and aquatic biota as well as human population (Yao et al., 2022). Collectively, these microplastic-induced imbalances lead to disturbances in belowground community structure and biogeochemistry, ultimately undermining the functional integrity and long-term stability of ecosystems.

2.2. Human health implications

Microplastics pose a potential threat to humans as they can be introduced into the body through exposure occurring via the consumption of contaminated soil, dust, or food (Abbasi et al., 2019). The atmospheric presence of microplastics further increases the risk, with humans being susceptible through two primary routes: inhalation and ingestion (Dewika et al., 2023). This dual exposure pathway emphasizes the need for comprehensive research and awareness to address the potential health implications associated with microplastic contamination in various environmental mediums. Fig. 3 provides a comprehensive overview of microplastic prevalence and their associated health effects on humans.

2.2.1. Ingestion and accumulation

Humans can ingest microplastics through various pathways and exposure scenarios whereby they have been found in biological samples such as feces, sputum, saliva, blood, and placenta (Osman et al., 2023). Ingestion of microplastics can occur through the consumption of beverages, including soft drinks and cold tea, which have been found to contain microplastics (Crosta et al., 2023). Drinking water intended for human consumption can also be a significant pathway for microplastic ingestion (Méndez-Rodríguez et al., 2023). Inhalation is another route of exposure to microplastics, with airborne microplastics being detected in human lungs (Cao and Cai, 2023). The rates of ingestion of atmospheric microplastics by humans vary depending on the source and exposure scenario. For instance, studies have found that soft drinks contain an average of 9.94 ± 0.33 microplastics per liter, while cold tea contains an average of 7.11 ± 2.62 microplastics per liter (Râpă et al., 2023). Furthermore, humans may consume 74,000–121,000 microplastic particles per year, with inhalation contributing approximately half of the annual exposure estimates.

Environmental and physiological factors play a significant role in the accumulation and distribution of microplastics within the human digestive tract. Microplastics, which are complex mixtures containing various additives and contaminants, can be present in food packaging materials, beach litter, and other sources (Peters et al., 2022; Tamargo et al., 2022). In vitro models simulating the human digestion process have shown that microplastics can undergo biotransformation in the gastrointestinal tract, leading to structural changes (Godoy et al., 2020). The release of chemicals and metals from microplastics can occur during worst-case chemical extraction scenarios as well as under physiological conditions simulating human digestion (Fournier et al., 2023; Garcia et al., 2024). The behaviour of microplastics and associated substances is influenced by factors such as pH, interaction mechanisms with

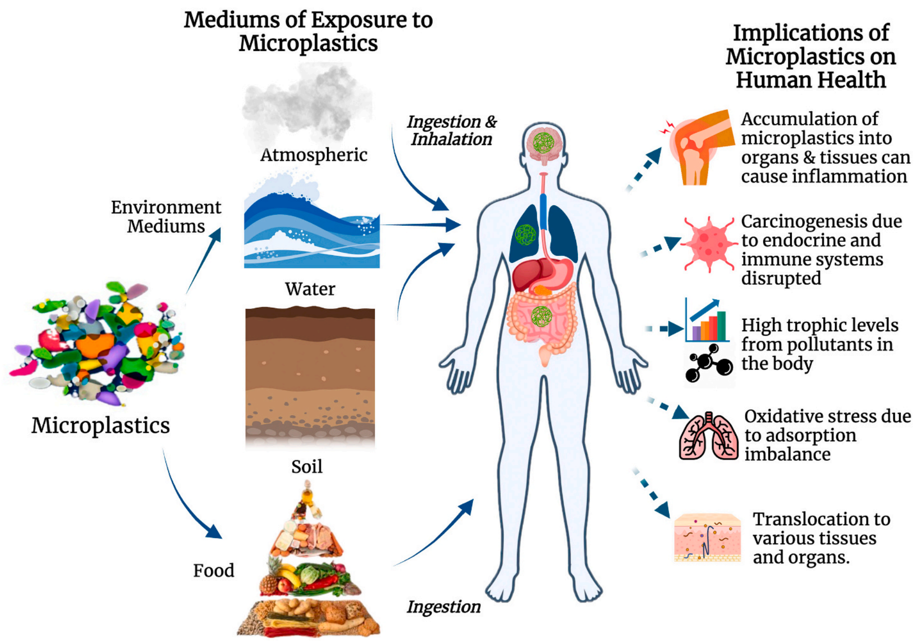

Fig. 3. Occurrence of microplastics and their impact on human health.

physiological fluids, and properties of the polymers. Repeated exposure to microplastics has been found to alter the composition of the gut microbiota, with potential shifts towards harmful pathobionts and decreased abundance of beneficial bacteria. Furthermore, ingested microplastics can cross the gut barrier, enter the systemic circulation, and accumulate in various tissues, including the brain, liver, and kidney.

Several studies have explored the relationship between the types and sizes of ingested microplastics and their potential for accumulation in human tissues and organs. For instance, Garcia et al. (2024) reported that ingested microplastics can pass through the gut barrier and enter the systemic circulation, ultimately accumulating in distant tissues, including the brain, liver, and kidney. Similarly, Ziani et al. (2023) observed that once absorbed, microplastics could be distributed to various organs, including the liver, spleen, heart, lungs, and brain. The detection of microplastics in human kidneys and urine by Exacoustos et al. (2023) suggests that renal clearance pathways may play a role in the elimination of microplastics from the body. Moreover, Paul et al. (2022) showed that submicron- and nano-plastics can be taken up and transported through intestinal cells, with uptake behavior varying depending on the type of plastic. Additionally, Chen et al. (2022) identified microplastics in human lung tissues and found a correlation between microplastic exposure and the formation of ground glass nodules in the lungs. These studies suggest that the types and sizes of ingested microplastics can influence their accumulation in different human tissues and organs.

2.2.2. Health risks associated with ingested microplastics

The ingestion of microplastics poses potential short-term and long-term health risks. The composition, size, and surface characteristics of the particles play a role in these risks. Microplastics can contain additives and monomers that can interfere with important biological processes in the human body, disrupt the endocrine and immune systems, and potentially cause carcinogenesis (Zhao et al., 2023b). Once absorbed, microplastics can be distributed to various organs in the body, including the liver, spleen, heart, lungs, and even the brain (Ziani et al., 2023). Moreover, ingested microplastics can also act as transporters of persistent organic pollutants and heavy metals, facilitating their transfer to higher trophic levels. The effects of microplastic ingestion on marine organisms include damage to digestive organs, choking, spread of microbes, and reduction in growth and reproductive output (López et al., 2023). The potential health risks associated with ingesting microplastics in drinking water sources highlight the need for unified detection methods and awareness among regulators, policymakers, and the public (Râpă et al., 2023).

Microplastics can interact with the human immune system by being taken up by cells and disrupting intracellular signalling pathways, altering immune homeostasis, and causing damage to tissues and organs. Microplastics can generate reactive oxygen species, induce the production of danger-associated molecular patterns, and disrupt toll-like receptors, cytokine production, and inflammatory responses in immune cells (Alijagic et al., 2023). Microplastics can also modify the physical, structural, and functional characteristics of microbes and biomolecules, thereby changing their interactions with the host immune system and potentially affecting immune reactivities (Yang et al., 2022). Ingested microplastics can be distributed to various organs, including the liver, lungs, kidneys, and even the brain, and can transport persistent organic pollutants or heavy metals, further enhancing their toxicity (Ziani et al., 2023). The accumulation of microplastics and their associated toxic substances in the body can lead to inflammation, which is linked to renal disease and can contribute to developing autoimmune disorders (Yang et al., 2023a, 2023b).

Ingested microplastics can contribute to the bioaccumulation of harmful substances in the human body, leading to potential chronic diseases. Recent studies have shown that microplastics can carry pathogenic microorganisms, acting as vectors for disease transmission (Saeedi, 2023). Additionally, microplastics are known to adsorb toxic chemicals, thereby exacerbating their harmful effects (Jassim, 2023). In marine organisms, the ingestion of microplastics has been linked to various physiological disturbances, including alterations in gastrointestinal tract function, immune suppression, oxidative stress, cytotoxic effects, changes in gene expression, and inhibited growth (Mills et al., 2023).

2.2.3. Inhalation of microplastics

Atmospheric microplastics originate from various sources, including textiles, traffic-related plastic particles, agricultural and marine activities, cosmetics, personal skin care products, and medical field-related products. These microplastics can be transported through the air and inhaled by humans in both indoor and outdoor environments, posing a significant threat to human health (Boakes et al., 2023). The levels of atmospheric microplastics vary depending on the location, with higher concentrations found indoors compared to outdoor air. The dominant size range of microplastics is 100–300 μm, and the most common shapes observed are fibres and fragments (Osman et al., 2023). The types of microplastics found indoors are related to indoor-generating sources and the occupant's lifestyles (Mehmood et al., 2022). Outdoor microplastic abundance is highest near industrial zones, followed by urban and inland locations in high-density areas. The concentration of microplastics in the atmosphere shows clear daily and weekly patterns, which may be related to people and vehicle movement.

Environmental and physiological factors play a significant role in the accumulation and distribution of microplastics within the human respiratory tract. The shape, size, and flow rate of microplastics influences their deposition pattern, with higher flow rates leading to lower deposition efficiency (Islam et al., 2023). The nasal cavity has been found to have a high deposition rate compared to other regions (Huang et al., 2022). Inhalation is a major route of exposure to microplastics, and the presence of microplastics in human sputum indicates that inhalation is a potential way for plastics to enter the human body (Mehmood et al., 2022). The quantities of microplastic types in the respiratory tract are related to factors such as smoking and invasive examination (Lombardi et al., 2022). Different microplastic types, such as polyethylene, can have distinct features and health risks, emphasizing the importance of explicitly defining exposure intensity and health risks for each type (Chen et al., 2022). Inhaled microplastics or plastic additives may have detrimental effects on human health, promoting respiratory diseases or carcinogenic processes. The presence of microplastics in human lung tissues has been validated, and their correlation with ground glass nodules formation has been explored, suggesting a possible link between microplastic exposure and respiratory diseases.

Exposure to polyethylene microplastics has been found to enhance the contractile responses of airway smooth muscle tissue, mimicking the pathophysiological responses in respiratory diseases (Anuar et al., 2022). Inhaled microplastics can induce pro-inflammatory or pro-carcinogenic effects on the respiratory system, depending on the particles' concentration, size, type, and surface charge (Lombardi et al., 2022). Different polymer types of microplastics, such as polyamide and polystyrene, have been detected in the air and have been shown to induce redox and mitochondrial stress responses in human respiratory cells (Emilia et al., 2023; Hernández-Fernández et al., 2023). These findings indicate that the properties of microplastics play an important role in their possible respiratory health consequences, emphasizing the necessity of understanding and taking these parameters into account when assessing the hazards associated with microplastic inhalation.

2.2.4. Chemical exposure and toxicological effects

Microplastics are complex mixtures that contain multiple additives, including plasticizers, flame retardants, stabilizers, pigments, unreacted monomers, starting substances, and non-intentionally added substances (Peters et al., 2022). These microplastics can also adsorb environmental contaminants, such as polycyclic aromatic hydrocarbons (PAHs) and persistent organic pollutants (POPs) (Peters et al., 2022). The leaching of chemicals from microplastics into the human body can occur through ingestion and inhalation. Ingested microplastics can reach the gastrointestinal tract, where they can release chemical substances and cause oxidative stress, cytotoxicity, and translocation to other tissues (Alberghini et al., 2023). The leaching process is influenced by factors such as the hydrophobicity of the microplastics, diffusion through the aqueous boundary layer, and the presence of environmental factors (López et al., 2023).

Notably, microplastics can also release chemical substances present in their matrix or absorbed from the environment, including polybrominated diphenyl ethers (PBDE), bisphenol A (BPA), nonylphenol (NP), octylphenol (OP), and potentially toxic elements, which can be harmful to humans (Osman et al., 2023). The ingestion of microplastics has been linked to toxicological effects on human organs, tissues, and cellular functions, including the induction of oxidative stress, cytotoxicity, and translocation to other tissues (Cervello et al., 2023). Moreover, accumulation of microplastics has been observed in human organs and experimental models, leading to detrimental effects on the male and female reproductive systems, particularly affecting the development of gametes, embryos, and offspring (Goodman et al., 2022). These findings highlight the urgent need for further research on the toxic effects of microplastics on human health (Dubey et al., 2022).

2.3. Challenges in atmospheric microplastics management

Addressing the issue of atmospheric microplastics presents a range of complex challenges. For instance, the current methods for detection and monitoring need significant improvement, while innovative approaches are required for both mitigation and remediation efforts. Moreover, the adoption of circular economy principles is essential in enhancing waste management practices, and existing legislative frameworks must be strengthened to close regulatory gaps. Additionally, raising public awareness and promoting behavioral changes are critical components for achieving comprehensive and effective management of atmospheric microplastics. Fig. 4 provides an overview of these challenges.

2.3.1. Detection and monitoring

Emerging technologies, particularly artificial intelligence (AI), are increasingly being utilized in the detection and monitoring of atmospheric microplastics. AI-based methods are proving to be effective in developing automated and cost-efficient systems for quantifying microplastics based on their appearance characteristics, such as shape, size, volume, and topology (Rußwurm et al., 2023). For instance, AI-driven image analysis techniques can enhance the precision of microplastic identification and classification, enabling large-scale monitoring efforts. In addition, remote sensing technologies, such as medium-resolution satellite data, have been successfully employed to estimate plastic pollution by monitoring marine debris in coastal regions (Balsi et al., 2023). Moreover, hyperspectral sensing in the SWIR band, coupled with drone technology, has been demonstrated to effectively detect environmental plastic litter (Belioka and Achilias, 2023; Zhang et al., 2023). The integration of these technologies with advanced AI algorithms allows for the rapid identification and volume assessment of microplastics, as well as the analysis of their interactions with soil and water ecosystems (Zhang et al., 2023). By optimizing existing deep learning models and creating robust datasets, the accurate detection and monitoring of atmospheric microplastics on a global scale can be achieved.

Despite these advances, developing standardized protocols for the sampling and analysis of airborne microplastics presents several challenges. One major issue is the potential for external contamination of microplastic samples, particularly for smaller particles, which can significantly skew results (Gangula et al., 2023). To mitigate this problem, it is crucial to design sampling devices that minimize contamination and maximize the recovery of microplastics (Boakes et al., 2023). Another challenge is the inconsistent use of blank controls during sample preparation. The absence of standardized blank controls can lead to sample contamination and produce unreliable data (Ju et al., 2023). To address this, incorporating blank controls in all phases of sample preparation should become a mandatory practice to ensure the accuracy and reliability of the data (Jarosz et al., 2022). Furthermore, advancements in spectroscopic analysis methods are needed to chemically confirm the presence of microplastics with greater precision (Noonan et al., 2023). Improved techniques in spectroscopic analysis will enhance the accuracy and reliability of microplastic detection, making it easier to identify and quantify these particles.

Moreover, the reliability and accuracy of atmospheric microplastics detection methods are also influenced by atmospheric conditions and geographical locations. Research has demonstrated that the abundance of microplastics decreases with increasing remoteness of sampling sites

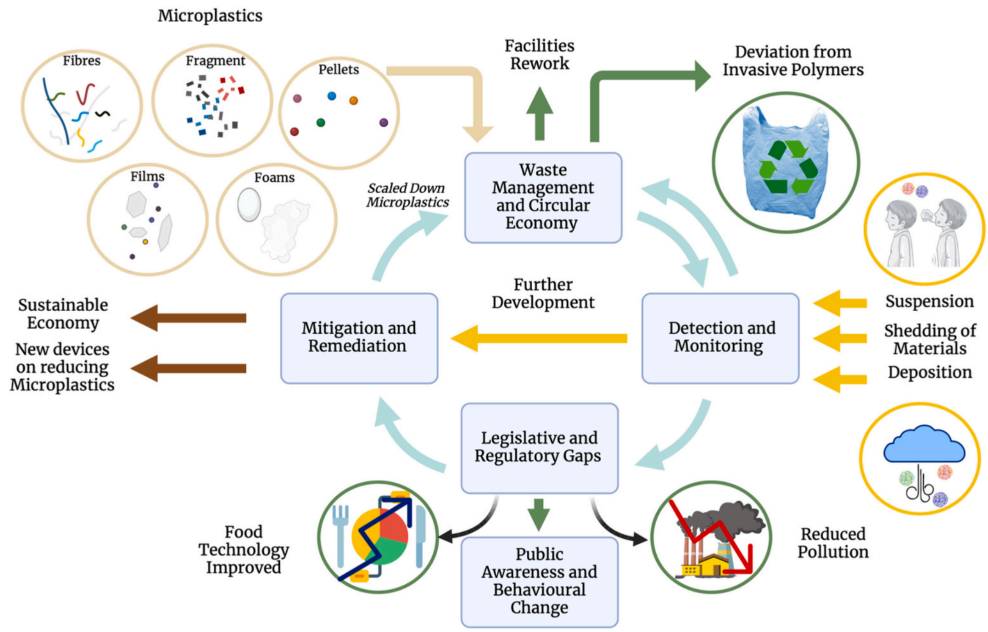

Fig. 4. Cause and effect of challenges in atmospheric microplastics management.

(Ohno and Iizuka, 2023). The composition and size of microplastics also vary depending on the location, with different types of polymers being more abundant in certain areas (Boakes et al., 2023; Jarosz et al., 2022). Additionally, microplastic concentrations in the air can be influenced by human and vehicle activity, resulting in daily and weekly fluctuations. It is important to note that detection methods for atmospheric microplastics are continuously evolving, and further research is needed to improve spectroscopic analysis and the chemical confirmation of microplastic identification.

2.3.2. Mitigation and remediation

Mitigating microplastic pollution in the atmosphere involves several advanced technological and strategic solutions. Key methods include coagulation, membrane bioreactors, sand filtration, adsorption, photocatalytic degradation, electrocoagulation, and magnetic separation (Grünzner et al., 2023). These methods can help remove microplastics from the air and reduce their concentration. However, scaling these technologies for widespread application necessitates a multifaceted approach. First, reducing plastic use is essential. This can be achieved by encouraging behavioral changes, incorporating biodegradable alternatives (López et al., 2023), and implementing policies such as bans or taxes on plastic carrier bags, which have successfully decreased plastic consumption in various countries (Osman et al., 2023). Additionally, educational and awareness programs can also be effective in reducing microplastic pollution by promoting responsible plastic use and disposal (Carvalho and Matamoros, 2022). Adopting circular economy principles and simplified product design can help minimize the generation of microplastic waste (Lamichhane et al., 2023). By integrating these strategies and implementing them at a larger scale, significant progress can be made in mitigating atmospheric microplastics.

Technological innovations also contribute to remediation efforts in several ways. One approach is the use of ultrafiltration technology, which uses membranes with small pores to filter microplastics from water, could potentially be adapted for air filtration (Sarma et al., 2022). Another method is the application of advanced oxidation processes as a pretreatment to enhance the biodegradation of microplastic particles (Bule Možar et al., 2023). Additionally, the use of bare and composite photocatalysts has shown promise in the degradation of microplastics (Wani et al., 2023). Despite these advancements, environmental and economic challenges remain. For example, the efficiency of ultrafiltration is influenced by the structure and composition of microplastics, and membrane fouling due to accumulation of particles can reduce effectiveness (Xie et al., 2023). Similarly, biodegradation processes may have limited removal rates and efficiency (Osman et al., 2023). Furthermore, the use of photocatalysts requires careful consideration of the benefits and drawbacks of each catalyst, as well as factors influencing degradation.

The effectiveness of remediation techniques is highly dependent on the physicochemical properties of microplastics. For example, the structure, size, and type of microplastics affect the efficiency of ultrafiltration technology for microplastic remediation (Sharma et al., 2023a, 2023b). The presence of microplastics in heavy metal-contaminated soil can modify the soil microenvironment and affect metal speciation, increasing the amount of easily exchangeable and potentially bioavailable forms of heavy metals (Sarma et al., 2022). Additionally, preoxidization of microplastics can change their physicochemical characteristics, such as hydrophobicity and functional groups, which can affect the adsorption of trace pollutants (Medyńska-Juraszek and Jadhav, 2022). Tailored approaches can be developed by understanding how various types and shapes of microplastics react during remediation processes. This knowledge can help improve the efficiency of filtration techniques and develop strategies to mitigate the impact of microplastics on the environment in the near future (Wani et al., 2023).

2.3.3. Waste management and circular economy

Integrating microplastic waste into existing circular economy models poses several challenges. One of the primary obstacles is the limitations of mechanical recycling processes, which are commonly employed in circular economy models. These processes are not equipped to handle mixed material or coloured feeds, thereby restricting their effectiveness in recycling microplastics (Brepohl et al., 2023). Additionally, the lack of adequate recycling plants and facilities, as well as low circular use, contribute to the accumulation of plastic waste in the environment (Steenmans and Lesniewska, 2023). Overcoming these challenges requires the development of complementary technologies that can recover pure monomers, hydrocarbon mixtures, or syngas from mixed secondary raw materials (Wamba et al., 2023). Furthermore, adopting effective eco-environmental strategies, such as microbial and enzymatic technologies, can help treat plastic waste and increase synthetic plastic recycling rates (Hammami et al., 2023). In order to promote sustainable practices, it is crucial to address the limitations of existing circular economy laws, such as unclear boundaries, oversimplification of goals, and side-lining of justice dimensions (Thapa et al., 2024). A systematic approach to designing and implementing circular economy laws, incorporating justice dimensions and considering the entire global waste value chain, can help overcome these challenges and promote sustainable practices.

Extended producer responsibility (EPR) programs can be enhanced to address the unique challenges posed by atmospheric microplastic pollution through various strategies. One approach is to regulate littering and dumping of plastic waste near roads, as road-related sources contribute significantly to atmospheric microplastic emissions (Ramasubramanian et al., 2023). Another strategy is to integrate responsibilities between the government, society, and producers, ensuring that producers are fully accountable for the entire life cycle of their products, including responsible waste management (Tumu et al., 2023). Such integration ensures that the environmental impacts of products are addressed holistically, from production to disposal. Collaboration between municipalities and EPR programs is also essential for enhancing program legitimacy, securing funding, and achieving logistical efficiencies (Leclerc and Badami, 2023). Moreover, the rapid implementation of standardized practices, infrastructure investments, and partnership models is crucial for creating a more circular economy. This includes fostering supply chain collaborations to produce higher-value recycled materials, ultimately reducing the environmental footprint of plastic waste (Steenmans and Malcolm, 2023).

In addition to regulatory measures, economic incentives and policy mechanisms can play a crucial role in encouraging the development of innovative technologies for the sustainable management of microplastic waste within a circular economy framework. One of the mechanisms is the provision of government incentives to firms, which can act as a dual mediator between circular economy innovation and digital sustainability (DS) (Samitthiwetcharong et al., 2023). These incentives can include financial support, tax breaks, and grants, which can encourage firms to invest in research and development of innovative technologies for microplastic waste management. Additionally, partnership models and supply chain collaboration are recommended to foster the production of higher-value recycled materials and promote circularity (Ramasubramanian et al., 2023). To support these efforts, investment in infrastructure and the standardization of waste management processes are necessary to advance innovative solutions for microplastic pollution (Torres-Giner, 2023). By implementing these strategies, EPR programs can more effectively address the pervasive and diverse sources of atmospheric microplastic pollution, supporting broader efforts to mitigate environmental harm.

2.3.4. Legislative and regulatory gaps

Current national and international regulations concerning atmospheric microplastics have several gaps that must be identified and addressed to strengthen policy frameworks. The fragmented nature of legal instruments regulating marine plastics and microplastics requires cooperation and coordination between sector-specific instruments and between multiple layers of regulation at global, regional, and national levels (Jung, 2023). There is a lack of research on the toxicological effects and risks of low-level exposure to inhaled microplastics in the general population under realistic exposure scenarios (López et al., 2023). Additionally, there is a need for more environmentally relevant exposures in toxicity studies, as microplastics have been reported in human lung tissue (Cao and Cai, 2023). Policy formulation overlooks several aspects of microplastic pollution, and there is a laxity in policy implementation, as well as a lack of indices to ascertain the impact of regulations (Jenner et al., 2022). Furthermore, there is currently no regulation on microplastic contamination of food and drinking water, and there is a lack of funding for research into the health effects of plastics and their alternatives (Usman et al., 2022). These gaps can be addressed by promoting cooperation and coordination between different regulatory instruments, conducting more research on the toxicological effects of microplastics, and implementing comprehensive policies that cover all forms of plastic pollution.

A harmonized regulatory approach for addressing atmospheric microplastic pollution globally can be established through cooperation and coordination between sector-specific instruments and multiple layers of regulation at global, regional, and national levels (Aliani et al., 2023). This approach should reflect a lifecycle perspective of plastics, focusing on waste management rather than just preventing plastic generation (Jung, 2023). In order to ensure consistency across diverse socio-economic and political contexts, flexible decision-making tools such as Reproducible Analytical Pipelines (RAPs) and Technological Readiness Levels (TRLs) can be used to validate and harmonize monitoring methods for plastic pollution (López et al., 2023). Additionally, there is a need for research on the health implications of exposure to airborne microplastics and the development of relevant mitigation policies and procedures (Usman et al., 2022). A global agreement on plastic pollution should include quantitative reduction targets and regular measurements to track progress (Zhu et al., 2023). By implementing these measures, a well-coordinated and measurable approach can be achieved to address atmospheric microplastic pollution globally.

2.3.5. Public awareness and behavioral change

Several key factors influence public perception and understanding of the risks associated with atmospheric microplastic pollution. These factors include knowledge transfer from macro- to microplastics, the concepts of accumulation and dose-response relationship, and the perception of the interconnectedness between human health and the environment (Janzik et al., 2023). The general public often perceives microplastics primarily as a pollutant in oceans that threatens marine life, but there is limited awareness of the various sources of microplastics and potential solutions to mitigate their impact (López et al., 2023). Demographic factors such as gender, age, and education also shape these perceptions. Studies indicate that women and younger individuals tend to be more aware of the sources and spread of microplastics, while those with higher educational backgrounds are more likely to consider solutions to the problem (Felipe-Rodriguez et al., 2022). To design effective public awareness campaigns, it is critical to address these factors by conveying information that clarifies scientific uncertainties, emphasizes the human-environment connection, and promotes potential solutions to the microplastics issue (Cao and Cai, 2023; Walker, 2022).

Cultural and societal norms have a significant influence on individual behaviors related to microplastic consumption and disposal. Studies have shown that attitudes towards plastic pollution are generally negative, and individuals are willing to support campaigns, pay for environmentally friendly alternatives, and endorse government interventions (Tang, 2023). However, lack of alternatives and forgetting reusable goods are common barriers to behavioral changes (Garcia-Vazquez et al., 2022). Furthermore, local waste management practices significantly influence recycling behaviors, as community norms dictate individual participation in waste disposal (Kountouris, 2022). In order to promote sustainable practices, strategies such as increasing ocean literacy and marine citizenship, tailored campaigns based on local policies and habits, and investment in the development of a sustainable waste management culture are recommended (Northen et al., 2023; Ramasubramanian et al., 2023). Additionally, EPR initiatives and deposit refund schemes (DRS) have shown success in enhancing plastic waste collection and recycling, and supply chain collaboration is crucial for standardization, infrastructure investment, partnership models, and the production of higher-value recycled materials. Effective local plastic governance is also vital in promoting sustainable practices.

Education and outreach programs can play a crucial role in fostering long-term behavioral change towards reducing the generation and release of microplastics into the atmosphere. These programs can increase public understanding of microplastics, their sources of exposure, and their associated health impacts (Coffin et al., 2021; Reed and Chen, 2022). These programmes can raise awareness and urge individuals to adopt a healthy lifestyle that reduces microplastic exposure by offering education about microplastics and their negative consequences (Tang, 2023). Additionally, education can help individuals learn about the importance of reducing plastic waste and the benefits of recycling (Willis and Fytianos, 2022). By providing information on plastic recycling and the formation of microplastics, these programs can empower individuals to make informed choices and take action to reduce plastic pollution (Liu et al., 2023a, 2023b, 2023c).

3. The quintuple helix approach

3.1. Overview of quintuple helix

The Quintuple Helix approach extends from the triple helix and quadruple helix model. The triple helix model emphasizes university-industry-government relations by explicitly highlighting the importance of higher education for innovation. On the other hand, the quadruple helix model embeds the structure of the triple helix model by adding the fourth helix that represents "media-based and culture-based public" as well as the "civil society" where knowledge and innovation policies should include the public to attain goals (Carayannis and Campbell, 2010). Within this model, media plays a crucial role in shaping public perception by continuously constructing and communicating societal realities, while also reinforcing cultural values and norms.

The advanced Quintuple Helix model introduces a crucial fifth component to the innovation process, focusing on ecological sensitivity with an emphasis on nature and social ecology. The European Commission identified socioecological transition as a significant obstacle in the development roadmap in 2019. The Quintuple Helix model, addressing the collective and interactive dynamics among education, economy, environment, society, and political systems, is considered an analytical framework essential for sustainable development and social ecology. This model offers an active and human-centric approach, integrating knowledge, know-how, and the natural environment within an "interdisciplinary" or "transdisciplinary" framework (Durán-Romero et al., 2020). The knowledge produced via the circular process generates a step-by-step model that allows quality, effective and sustainable development while maintaining a balance with nature for future generations to witness the natural resources and diversity on earth.

Given the significant ecological implications of microplastics, the evolved Quintuple Helix model offers a potential framework for addressing microplastic-related concerns. This model seeks to synergize innovation, ecology, and development in a knowledge-based society, fostering a win-win scenario. For instance, knowledge transfer and method development can substantially increase microplastic data, facilitating policy development and aiding decision-making processes aimed at reducing microplastic concentrations in the environment. Furthermore, collaborative projects involving industries and governments can enable the design and implementation of short-term interventions or long-term policies and strategies to address the emerging challenges posed by microplastics effectively.

3.2. Significance of the quintuple helix approach

Co-creation is the unique advantage of the Quintuple Helix approach, where citizens can co-create processes via transdisciplinary partnerships and knowledge exchange partnerships. For example, the co-created platform "iNaturalist app" is an established online platform that enables the sharing and exchange of biodiversity and citizen science data. Such platforms enable human populations to generate the most appropriate research tools as well as methodologies that citizens can apply. Textiles are well known as the major source of microplastic pollution. Co-creating industry output and providing suggestions for practice and behavioral change among citizens, scientists and industries can ensure industry partners understand their contribution towards microplastic pollution. This could lead textile industries to develop more sustainable products that can reduce environmental and health risks associated with microplastics. Appropriate research skills, knowledge, lived experience of participants and empowerment will allow citizens to drive bottom-up change that emphasizes a shift from issues to actions, which can play a major role in tackling issues concerning microplastic pollution.

Furthermore, the "Okayama Model" of education for sustainable development (ESD), a collaborative effort between public and private entities, has gained considerable recognition. This initiative was honored with the "UNESCO–Japan Prize" in 2016 for its notable contributions to reorienting education towards sustainable development, as depicted in Fig. 5 (Zen and Shibakawa, 2022). The "Okayama Model" necessitates the establishment of regional centers of expertise (RCE) that engage local stakeholders and community projects to seamlessly integrate school education and social education with existing community practices. This approach transformed education for sustainable development into a public project, as local governments consistently allocated financial and human resources to involve businesses, schools, and citizens, resulting in profound societal transformations. The effectiveness of implementing ESD within the "Okayama Model" can be attributed to the shared sense of urgency regarding the sustainability of the Earth among all participating groups.

3.3. Sustainable development goals

The Sustainable Development Goals (SDGs) provide a blueprint for achieving a better and more sustainable future for all. Within this framework, the Quintuple Helix model can be a valuable tool in addressing several important goals, as illustrated in Fig. 6. Specifically, this model can facilitate the achievement of the following goals:

i. **SDG 3 (Good health and well-being)**: By empowering individuals with education for sustainable development to adopt green and healthy lifestyles, reduce plastic usage, and develop solutions to mitigate health risks associated with microplastics.
ii. **SDG 4 (Quality Education)**: By fostering innovative thinking, equipping individuals with modern information and communication technologies, and enabling higher education institutions to drive sustainability at regional and global levels.
iii. **SDG 11 (Sustainable Cities and Communities)**: By implementing sustainable practices and applying knowledge into actionable steps—such as reducing the use of plastic products—contributes to the development of more sustainable cities and economies.
iv. **SDG 12 (Responsible Consumption and Production)**: By equipping industries and business owners with sustainability knowledge, encouraging investments in green technologies, and promoting environmentally friendly manufacturing processes and products.

Attainment of the aforementioned SDG goals would significantly contribute to achieving other SDG objectives. For instance, in addressing SDG 6: Clean water and sanitation, efforts to reduce pollution, eliminate dumping, and minimize the release of hazardous chemicals and materials such as microplastics can lead to improved water quality. Similarly, mitigating microplastic-related issues can contribute to the realization of SDG 14: Life below water, as it aids in preventing and reducing marine pollution. Additionally, addressing microplastic concerns can align with SDG 15: Life on land by preventing and significantly reducing the introduction of invasive alien species such as microplastics into terrestrial and aquatic ecosystems.

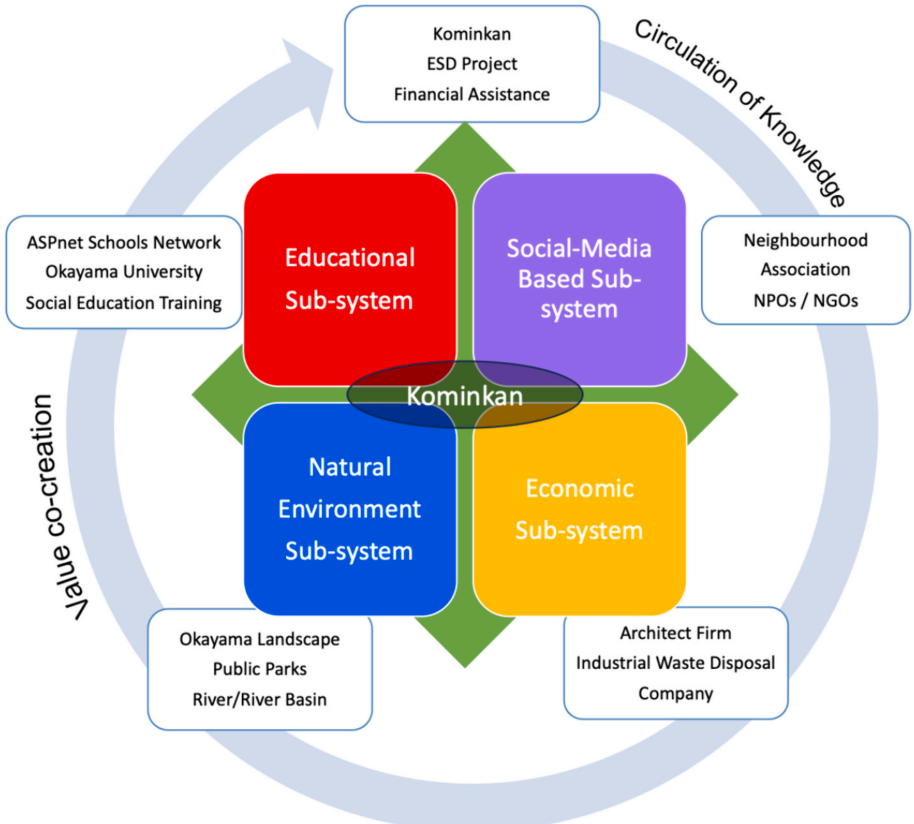

Fig. 5. Okayama model of education for sustainable development adopting the Quintuple helix model approach adapted from (Zen and Shibakawa, 2022).

Fig. 6. Sustainable development goals that can be achieved by adopting the Quintuple Helix model; red boxes represent key goals that can be achieved, while green circles indicate the possible positive impact on mitigating issues concerning microplastics.

4. Roles of each quintuple helix

The Quintuple Helix model is crucial in managing atmospheric microplastics, integrating five sectors: academia, industry, government, civil society, and the environment. Each helix offers unique insights—scientific research, technological innovation, regulatory frameworks, community action, and ecological sustainability—collaboratively shaping a comprehensive approach to mitigate the impact of microplastics on the atmosphere.

4.1. Academia

To effectively address the complex issue of atmospheric microplastics and their impact on planetary health, a cooperative and innovative approach is essential. This approach is integral to the Quintuple Helix model, which emphasizes the collaboration of academia in managing this environmental challenge. Universities and academic institutions play a crucial role by engaging in a range of activities, including conducting research, advancing technology, and implementing educational and awareness programs. These efforts collectively contribute to the understanding and mitigation of atmospheric microplastics. As shown in Fig. 7, the diverse roles of academia are pivotal in developing solutions to address and potentially reduce the presence of microplastics in the atmosphere.

4.1.1. Research data collection

Academia actively engages in the scientific research of microplastics, focusing on the sources, movements, and environmental impacts to contribute comprehensive data for informed decision-making processes. Researchers have systematically reviewed the literature to understand the distribution and behaviour of microplastics in the environment (Guerrini, 2023; Li et al., 2023). They have identified rivers as major pathways for transporting microplastics from terrestrial areas into the ocean and atmospheric circulation as an important avenue for transporting microplastics between environmental compartments (Casillas et al., 2023). Additionally, researchers have developed modeling frameworks to study the advection-diffusion processes of microplastics and the pollutants they carry, providing insights into their spatiotemporal patterns and ecological impacts (He et al., 2022). Studies have also focused on the pollution status of microplastics in surface water bodies, particularly in agricultural non-point sources, to provide a scientific basis for controlling microplastic pollution in river basins (Grünzner et al., 2023).

Recent advances in scientific research have significantly expanded our understanding of microplastics, shedding light on their environmental impacts and potential risks. Researchers have assessed the distribution and pollution of microplastics in various environmental media, including aquatic ecosystems (Adeniji et al., 2023; Zhao et al., 2023a, 2023b). They have also investigated the toxic effects of microplastics on terrestrial microorganisms and the resulting impacts on microbial community structure and function (Almeida et al., 2023). Additionally, studies have focused on the adsorption and absorption of chemicals to microplastics, as well as human exposure to microplastics in the environment (Casillas et al., 2023). These rigorous scientific studies have provided valuable insights into the complex dynamics involved in microplastic pollution, helping to identify the sources, distribution patterns, and accumulation trends of microplastics in the environment. Furthermore, they have shed light on the potential health effects of microplastic exposure and highlighted the need for further research in this area. These studies have helped policymakers and scholars better understand the impact of microplastics on the worldwide ecosystem.

The involvement of academics includes systematic data gathering on microplastics, which improves the accuracy and reliability of information available to policymakers and aids in developing successful microplastic pollution management measures. Academic research contributes to understanding the physics of microplastic transport behaviors (Ikenson, 2023). Numerical models incorporating physical parameters have improved the prediction of microplastic pathways in marine environments (Phan and Luscombe, 2023). Additionally, machine learning and computer-vision tools can aid in acquiring environmental information and developing more accurate models (Ju et al., 2023). Standardized sampling and pretreatment methods are crucial for obtaining accurate and reproducible results for microplastic contamination. The

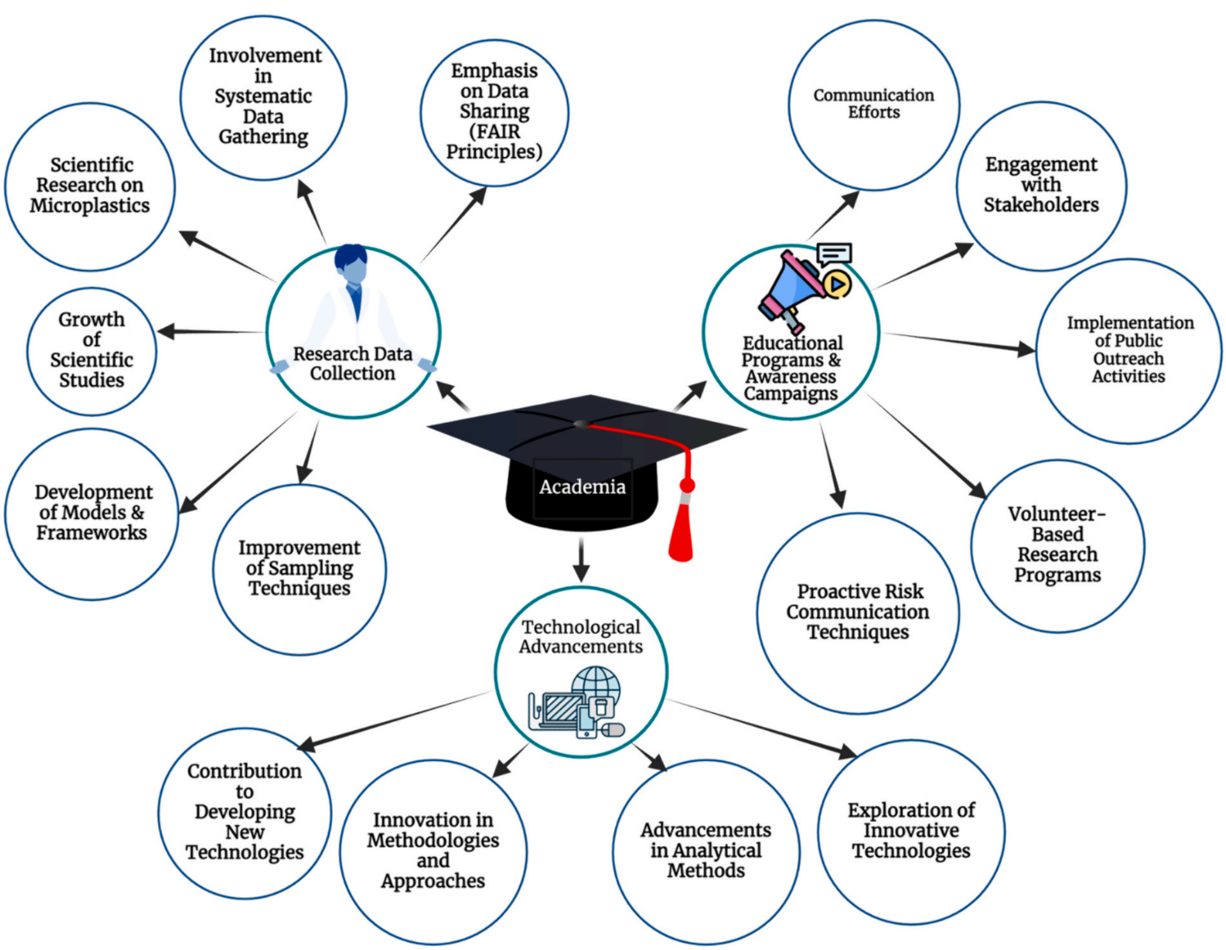

Fig. 7. Roles of each helix in the quintuple helix model on atmospheric microplastics issue.

use of a microplastic sampling device has shown high recovery rates and prevention of contamination during the sampling process (Jenkins et al., 2022). Furthermore, ensuring that environmental microplastic research data are findable, accessible, interoperable, and reusable (FAIR) is essential for informing policy and mitigation strategies. To strengthen data-sharing practices in the environmental microplastics research community, recommendations have been proposed to facilitate collaboration and accelerate progress in addressing microplastic pollution.

4.1.2. Educational programs and awareness campaigns

Using various strategies, academia effectively communicates knowledge about microplastics to students, researchers, and the general public. One approach is through qualitative interviews, which help to understand the perceptions and reasoning behind concerns about microplastics (Janzik et al., 2023). Another method is using educational materials, such as the Plastics Crash Course, which combines visual learning with knowledge about plastic recycling and microplastic formation (Reed and Chen, 2022). This course could be introduced in both primary and secondary schools to educate young kids. Project-based learning (PBL) is also employed, allowing students to engage in hands-on research and collaborate with international peers to investigate microplastics in urban waterways (Meiller et al., 2022). Additionally, questionnaire-based surveys are conducted to assess the willingness and motivation of stakeholders within academic settings to change daily habits and minimize plastic and microplastic pollution. These communication efforts aim to foster a deeper understanding of the issue and promote a sense of shared responsibility for mitigating microplastic pollution.

Academia contributes to raising awareness about microplastics through various means. Studies have shown that stakeholders within academic settings, such as universities and institutions, are willing to change daily habits to minimize plastic and microplastic pollution (Willis and Fytianos, 2022). Additionally, research conducted by people with higher education levels, including young individuals, has focused on analyzing the knowledge and awareness of consumers regarding the sources, exposure, and potential health hazards of microplastics in food and water (Ziani et al., 2023). Furthermore, academia engages with the wider community by involving volunteers in monitoring efforts to study microplastic pollution (Oleksiuk et al., 2022). This volunteer-based research program, in collaboration with environmental programs and groups, allows for the collection of "believable" data on microplastics on a local to regional scale (Sanders and Brandes, 2020). The involvement of academia in raising awareness extends beyond traditional educational settings by conducting qualitative interviews with citizens to understand their perceptions of microplastics and the reasoning behind their concerns (Janzik et al., 2023). This supports proactive risk communication techniques that address scientific uncertainty and the interconnectivity of human health and the environment.

In order to instigate positive change and sustainable practices, it is important to combine new measures or policies with proper education to raise awareness and receptivity among those unfamiliar with microplastics and their pollution (Willis and Fytianos, 2022). Public outreach activities, such as filling out pre-tests and post-tests, have effectively increased public understanding of microplastics, their sources of exposure, health impacts, and ways to reduce exposure. Strategies that have proven effective include supporting campaigns, paying for environmentally friendly alternatives, and supporting solution-based interventions from governments, such as policies, regulations, and guidelines (Coffin et al., 2021).

4.1.3. Technological advancements

Academia actively contributes to developing new technologies for detecting, monitoring, and mitigating microplastics. One specific advancement is the use of mass spectrometry (MS) techniques, such as gas chromatography mass spectrometry (GC–MS), liquid chromatographic mass spectrometric (LC-MS), and matrix-assisted laser desorption ionization-time of flight mass spectrometry (MALDI-TOF MS), for the detection of microplastics pollutants (Chun et al., 2022).

GC–MS is particularly effective in identifying and quantifying microplastics by separating complex mixtures into individual components, which are then determined based on their mass spectra. This method is highly sensitive and can detect microplastics in various environmental matrices, including water and soil (Chun et al., 2022; Huang et al., 2024). LC-MS, on the other hand, is advantageous for analyzing microplastics in food matrices, offering high sensitivity and specificity. It can handle a wide range of polymer types and is particularly useful for detecting microplastics that may have undergone chemical changes due to environmental exposure (Willans et al., 2023; Huang et al., 2024). MALDI-TOF MS is another powerful technique that excels in the rapid identification of microplastics by ionizing the sample and measuring the time it takes for ions to reach the detector. This method is beneficial for its high throughput and ability to analyze large biomolecules, making it suitable for complex environmental samples. GC–MS is particularly effective in identifying and quantifying microplastics by separating complex mixtures into individual components, which are then identified based on their mass spectra. This method is highly sensitive and can detect MPs in various environmental matrices, including water and soil (Chun et al., 2022; Huang et al., 2024). LC-MS, on the other hand, is advantageous for analyzing microplastics in food matrices, offering high sensitivity and specificity. It can handle a wide range of polymer types and is particularly useful for detecting microplastics that may have undergone chemical changes due to environmental exposure (Willans et al., 2023; Wu et al., 2023). MALDI-TOF MS is another powerful technique that excels in the rapid identification of microplastics by ionizing the sample and measuring the time it takes for ions to reach the detector. This method is beneficial for its high throughput and ability to analyze large biomolecules, making it suitable for complex environmental samples (Chun et al., 2022; Wu et al., 2023). In addition to these advances, the application of metagenomics in combination with metatranscriptomics and metabolomics approaches has been used to identify and select remediation-efficient microbes for microplastic remediation (Wani et al., 2023). Furthermore, advancements in bioinformatics and sequencing tools allow for rapid screening, mining, and prediction of genes capable of polymer degradation (Ikenson, 2023). Continuous monitoring and analytical method development further assesses microplastic hazards and sources, while appropriate sampling techniques and laboratory procedures are crucial for accurate pollution assessment (Belioka and Achilias, 2023; Willans et al., 2023).

Academia has also innovated methodologies and approaches to tackle the issue of microplastics in several ways. For example, novel microfluidic techniques have been developed for sampling and characterizing microplastics in seawater, eliminating the need for labelling and simplifying the identification process (Gong et al., 2023). Another approach involves the calculation of a Microplastics Index (MPI) based on the mechanical and physical properties of polymers, which can be used to choose or redesign plastics to reduce microplastic formation (Boersma et al., 2023). Furthermore, innovative technologies such as bare and composite photocatalysts are also being explored to effectively eliminate microplastics from the environment through photocatalytic degradation (Xie et al., 2023). Additionally, machine learning techniques, such as deep learning algorithms, are being utilized for the analysis of microplastic Raman spectra, enabling high recall and precision in microplastic identification (Weber et al., 2023). These innovations contribute to more efficient and effective environmental monitoring and mitigation strategies by providing improved sampling and identification methods, reducing microplastic formation, facilitating microplastic degradation, and enhancing microplastic sample analysis (Zhao et al., 2023a).

4.2. Government

The Quintuple Helix model makes the role of government even more important as concern over air microplastics grows on a global scale. The government's position as a vital force in maintaining planetary health is examined, with a focus on policy formation, enforcement and compliance, collaboration, and coordination. Fig. 8 emphasizes proper steps and policies that can nurture the global community's awareness of atmospheric microplastics.

4.2.1. Policy development

Microplastic pollution is a pressing environmental issue that requires immediate attention from governments worldwide. To combat this problem, governments are formulating and implementing regulations, policies, and guidelines that target the reduction of plastic pollution and promote sustainable practices. A crucial step in this direction is the prohibition of specific types of microplastics, such as microbeads (Usman et al., 2022), and the establishment of more comprehensive policies to tackle other forms of microplastics. Additionally, there is a push for imposing taxes on single-use plastic products and implementing bans to curb plastic waste (Li, 2022a, 2022b). While international and regional legal frameworks address plastic pollution, they often do not explicitly cover microplastic pollution (Rifa and Hossain, 2022). In response, governments are adopting various approaches, incorporating preventive strategies such as the circular economy, behavioral change initiatives, and the development of bio-based polymers (Munhoz et al., 2023). Downstream responses, including waste-to-energy initiatives, degradation processes, water treatment plants upgrades, and litter clean-up strategies (Chen et al., 2022). Furthermore, multifaceted responses are being implemented in fisheries and aquaculture facilities to prevent and mitigate microplastic pollution, which poses a significant threat to the environment, ecosystems, and human health.

A well-coordinated approach at international and national levels is needed to scale up policies and address all forms of plastic pollution. Effective policymaking on microplastics requires collaboration between academic researchers, industry stakeholders, and government officials. While traditional models of science-policy interaction position science as a key input to policy formulation, there is a growing consensus that a more co-productive relationship between researchers and policymakers is necessary to ensure the creation of effective and legitimate policies that address the complexities of microplastic pollution (Maas et al., 2022; Nielsen et al., 2023). Scientific research plays a crucial role in informing and shaping government policies on microplastics. It provides evidence-based information on the risks of plastic pollution to human health and the environment, including ecological impacts, consumption patterns, and sources of plastic (Rasooly et al., 2023). Scientific tools such as risk assessment, impact assessment, and life cycle assessment are applied in shaping policy initiatives (Adeniji et al., 2023). Furthermore, marine litter monitoring data contributes significantly to the evidence base for policy development on plastic pollution (Usman et al., 2022). Despite ongoing uncertainty surrounding the harm of plastic pollution, preventive actions are justified, and the aim is to continue science-informed policy development, allowing for flexibility and adjustment based on ongoing knowledge generation.

4.2.2. Enforcement and compliance

Government agencies actively enforce atmospheric microplastic regulations by implementing monitoring mechanisms and inspections to ensure compliance (Čerkasova et al., 2023). However they face challenges in enforcement, such as limited resources and diverse industries. In order to address these challenges, strategies are implemented, including the development of a specific, tailor-made database for microplastic data (Biber, 2013). This database allows for the integration and accessibility of data, as well as manipulation and quality assurance of microplastic data (Markell and Glicksman, 2014). Additionally, structural solutions, such as creating separate agencies for monitoring and decision-making, are considered promising solutions (Markell and Glicksman, 2014). The enforcement and compliance promotion function of administrative agencies is structured using a three-layered conceptual framework, which includes components of effective enforcement and compliance, their interrelated character, and contextual design issues. By considering all three layers, an effective enforcement and compliance promotion regime can be developed.

To promote compliance with established standards regarding microplastics, government agencies use a combination of punitive measures and incentives to encourage industries and individuals to adopt sustainable practices and reduce microplastic pollution. They develop and implement public certification standards, such as eco-industrial park certification, to enhance resource use efficiency and coordinate complex policy domains like industrial ecology (Walker, 2022). National governments also play a role by banning single-use plastic products or imposing taxes on them and by making commitments to reduce microplastic pollution through international agreements like the UN SDGs (Tran et al., 2023). Furthermore, government

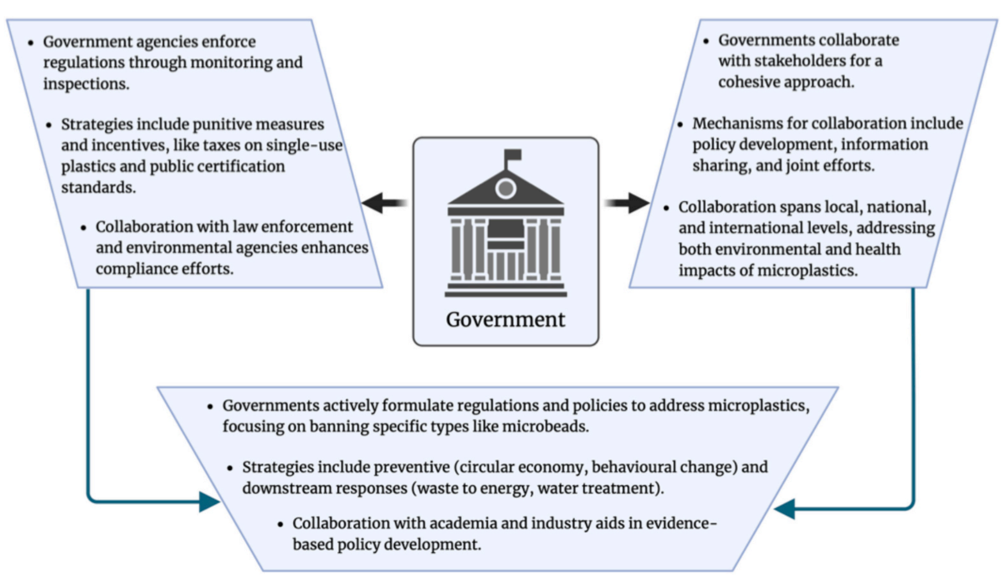

Fig. 8. Summary of government actions and roles for microplastics management.

agencies implement policies and responses to tackle plastic pollution, including upstream strategies like circular economy approaches and source-specific strategies for industries like the clothing industry and tire manufacturing (Rifa and Hossain, 2022). Downstream responses, including waste-to-energy technologies and advanced water treatment facilities, are utilized to manage microplastics (Munhoz et al., 2023). These multifaceted responses are crucial to mitigating and preventing microplastic pollution, while punitive measures and incentives provide the necessary framework for compliance and adoption of sustainable practices (Coffin et al., 2021).

4.2.3. Collaboration and coordination

The government collaborates with law enforcement, environmental agencies, and other stakeholders to create a cohesive and coordinated approach to enforcing regulations on atmospheric microplastic. This collaboration is crucial in addressing the widespread presence of microplastics and their impact on the environment and human health (Walker, 2022).

Mechanisms for information sharing and joint efforts include the development of local and international policies, resolutions, and directives aimed at mitigating plastic pollution (Usman et al., 2022). However, there are limitations in policy formulation and implementation, as well as a lack of regulation on microplastic contamination of food and drinking water (Batory and Svensson, 2020). Hence, to address these challenges, a well-coordinated approach at international and national levels is needed to scale up policies and translate them into measurable actions (Barrett and White, 2017). Trust and relationships are also important in maintaining cooperative arrangements for environmental law enforcement (Fältström and Anderberg, 2020).

This collaboration is essential due to the complexity and diversity of microplastics, which require open collaboration between scientists, regulators, and policymakers (Coffin et al., 2021). Various local and international policies, resolutions, and directives have been developed to address plastic pollution, but there are limitations in policy formulation, implementation, and impact assessment (Usman et al., 2022). In Africa, traditional perspective approaches such as plastic bans and levies have been employed, but market-oriented approaches like private-public waste management may be more effective (Deme et al., 2022). Indonesia is proactively addressing marine plastic pollution through a collaborative governance approach involving multiple stakeholders (Chotimah et al., 2022).

Efforts to address the transboundary nature of atmospheric microplastics involve coordination between the government, international bodies, Non-Governmental Organizations (NGOs), and local communities. The government must work together with scientists, industry, society, and policymakers to integrate their views and ways of working (Walker, 2022). Increased awareness of the environmental and health impacts of plastic pollution has attracted attention from the public, governments, and industry, leading to a focus on addressing the issue (Usman et al., 2022). The presence of plastics in the environment poses a significant threat to both the aquatic ecosystem and the livelihoods of people relying on it, leading to the development of policies and directives to mitigate plastic pollution (Tiernan et al., 2022). The lack of knowledge and consensus regarding airborne microplastics presents an obstacle to action, highlighting the need for more interdisciplinary research and collaborative approaches (Tiernan et al., 2022). Policy coordination between the public health and environmental protection sectors is lacking, and more permanent sector policy integration is needed, potentially through governmental projects and strong local innovation programs (Holm and Kj, 2015).

The government facilitates information sharing and collaboration among different sectors to create a unified front against microplastic pollution through initiatives such as environmental information transparency and the integration of third-party institutions. These initiatives aim to build trust, promote transparency, and foster mutual support among stakeholders within the Quintuple Helix framework. As an example, in China, the Institute of Public & Environmental Affairs (IPE) collects public environmental information. It uses it as a pressure mechanism to encourage companies and citizens to participate in environmental governance (Walker, 2022). Additionally, there is a growing recognition of the need for interdisciplinary research and collaborative, integrated approaches to address the challenges of microplastic pollution (Lampitt et al., 2023). Scientists, industry, society, and policymakers must work together to find solutions and integrate their views and ways of working (Tiernan et al., 2022). However, it is important to ensure that collaborative governance is equal for each sector and that power relations and dominant discourses are critically analysed (Li, 2016).

4.3. Industry

The Quintuple Helix framework highlights the industry's role in mitigating the environmental impact of microplastics. This framework integrates sustainable production practices, innovative solutions, responsible supply chain management, and corporate social responsibility into a cohesive strategy for mitigating microplastic pollution. By prioritizing eco-friendly manufacturing processes and effective waste management, industries can significantly reduce their environmental footprint. The role of the industry as a platform for combating microplastics is further illustrated in Fig. 9, demonstrating how leveraging these practices can lead to more sustainable outcomes.

4.3.1. Sustainable production and innovation

The industry is actively adopting sustainable practices in production processes to reduce the use of plastics and microplastics. Strategies such as EPR, DRS, and the use of bio-based and biodegradable materials are being implemented to address environmental concerns (Ramasubramanian et al., 2023). Innovative solutions include incorporating plastics into the circular economy, source reduction, waste valorization, and suitable waste management techniques (Sarkar et al., 2022). Moreover, promoting renewable electricity generation (REG) from green sources such as wind, solar, and biomass has become a key public policy agenda, offering advantages in energy security, price stability, and job creation while addressing negative externalities associated with traditional energy sources (Shah et al., 2023). Technologies such as mechanical and chemical plastic recycling with clean energy like REG, in-stream clean-up methods, and wastewater treatment are being used to control plastic waste and microplastic contamination (Nikiema and Asiedu, 2022). Policymakers are also implementing measures such as bans, levies, and EPR to reduce plastic use and enhance recycling (Lučin et al., 2023). Additionally, engineers need to consider the ecological aspects of design in shipbuilding, particularly in relation to plastic pipes, to reduce microplastic pollution. These efforts aim to address environmental concerns while maintaining efficiency and competitiveness in the industry.

The industry contributes to eco-friendly production processes by integrating green, Six Sigma, and lean methodologies into existing manufacturing systems. These approaches aim to make manufacturing processes sustainable, efficient, and environmentally friendly. They help minimize emissions, carbon footprints, and the use of harmful substances while improving process efficiency and reducing waste. The integration of these practices is driven by the importance of eco-friendly and sustainable business operations, as well as public pressure, government regulations, and social responsibilities (Nagadi, 2022). Sustainable machining techniques, such as using biodegradable and eco-friendly cutting fluids, are also being adopted to eliminate the negative environmental impacts associated with traditional cutting fluids (Sharma et al., 2021). Additionally, there is a growing emphasis on incorporating eco-efficiency principles and considering the environmental implications of advances in production research to promote environmental sustainability in industrial systems (Despeisse and Acerbi, 2022). The industry also incorporates time-of-use electricity

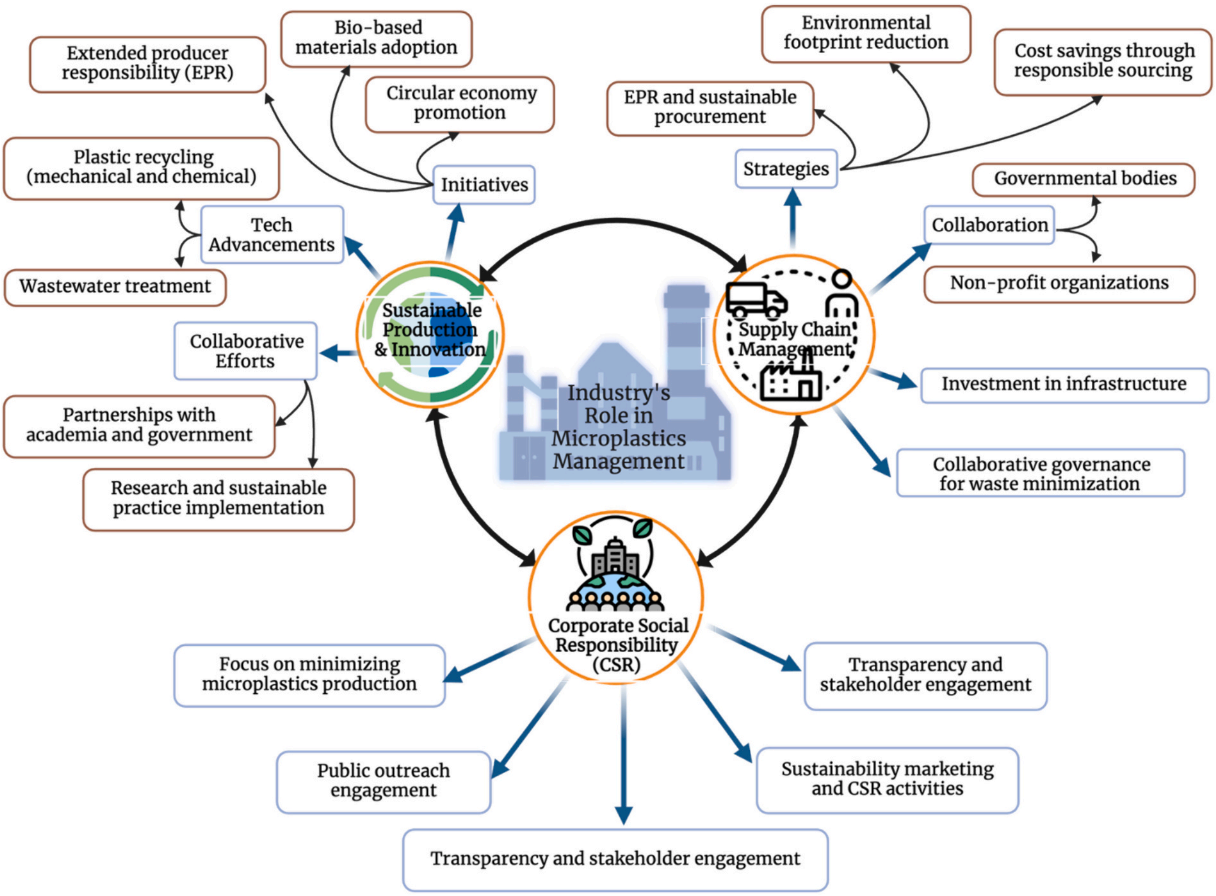

Fig. 9. Triple helix model representing role of industry in microplastics management.

pricing models and considers human factors in production processes to promote energy efficiency and sustainability (Mokhtari-Moghadam et al., 2023). Integrating lean and green practices and tools in the manufacturing industry has shown a strong synergy, positively contributing to environmental sustainability and overall business performance (Gaikwad and Sunnapwar, 2020).

The industry collaborates with academia and governmental bodies to research and implement sustainable practices through partnerships and cooperation with external actors such as research organizations, public institutions, and NGOs (Ruippo et al., 2023). These collaborations are important for organizational performance and the development of sustainable innovations (Khurana et al., 2022). Government initiatives influence firm size, technological resources, and financial resources, which in turn affect collaboration capability and sustainable-oriented innovation (Calik et al., 2020). The government's commitment and open approach towards innovative sustainable practices, along with the presence of initial and ongoing training and the development of advertising campaigns, enable the successful implementation of eco-innovations for sustainable development at the local level (Mazzanti et al., 2020). Innovation plays a crucial role in creating a more sustainable production landscape with reduced reliance on plastic and microplastic-containing products. Sustainable innovations require partnerships and collaboration among different stakeholders, including government agencies, industry innovators, and supportive community education (van de Meene et al., 2020).

4.3.2. Supply chain management

The industry can ensure responsible sourcing within their supply chains to minimize the use of materials contributing to microplastics by implementing strategies such as EPR initiatives, non-profit EPR, door-to-door collection systems, and DRS (Ramasubramanian et al., 2023). These strategies have been implemented in countries like the UK and Germany and have successfully enhanced the independent collection of plastic waste. Additionally, sustainable procurement practices can be adopted, which involve purchasing goods and services in a way that considers their environmental, social, and economic impacts (Zhu et al., 2022). By sourcing from sustainable suppliers, companies can reduce their environmental footprint, enhance their social responsibility, and achieve cost savings, thus contributing to improved supply chain performance. It is also important to establish a structured framework for responsible sourcing and green supply chains, which can provide competitive advantage, stakeholder value, and improved supply chain management (Hasan and Habib, 2022). Collaboration and partnership models, along with infrastructure investment and the production of higher-value recycled materials, are crucial for promoting waste minimization and fostering the adoption of recycling methods (Ball et al., 2022).

Efficient resource management practices are implemented in the industry to minimize the release of atmospheric microplastics into the environment. These practices include adopting cleaner production techniques, such as smart environmental management practices, which focus on minimizing pollution load and resource consumption (Kumar et al., 2022). Additionally, advanced treatment technologies are being explored to eliminate microplastics from industrial wastewater effectively (Gkika et al., 2023). The management of micro- and nanoplastics (MNPs) is also crucial, and approaches such as source reduction, incorporation of plastics into the circular economy, and suitable waste management are being considered to tackle pollution associated with MNPs (Sarkar et al., 2022). In order to improve waste disposal practices, it is vital to develop appropriate infrastructure, implement economically sound plastic waste management techniques, and establish environmental regulations for achieving environmental sustainability. By implementing these measures, the industry aims to minimize the environmental impact of microplastics and improve waste disposal practices (Zhao et al., 2022).

The industry collaborates with governmental bodies and non-profit organizations to develop and implement effective waste management strategies within their supply chains. This collaboration involves enhancing institutional and social collaboration with supply chain partners and other stakeholders (Yang et al., 2023a, 2023b). Collaborative governance approaches, such as food policy councils, are used to address food waste issues and engage diverse stakeholders and organizations in food waste reduction efforts (Nadeau and Koebele, 2023). The concept of "intelligence" is used in waste-to-energy strategies, where intelligent nodes in the supply chain are analytically presented and discussed (Vlachokostas, 2020). Manufacturing companies are motivated to implement solid waste management through government encouragement, non-government organization support, and socio-psychological incentives (Masrom et al., 2018). Challenges and opportunities associated with integrating responsible practices include the need for forecasting, product range management, performance measurement, infrastructure investment, and partnership models.

4.3.3. Corporate social responsibility

Efforts to minimize the generation and release of atmospheric microplastics align with corporate social responsibility objectives. The textile industry focuses on finding environmentally friendly long-term solutions to reduce microfiber emissions caused by the domestic washing process (Periyasamy, 2023). Industrial wastewater treatment plants (WWTPs) play a crucial role in eliminating microplastics from industrial wastewater (Gkika et al., 2023). Public outreach programs aim to enhance understanding of microplastics and their impact on health, promoting a healthy lifestyle to reduce exposure (Coffin et al., 2021). Risk minimization, gender diversity, and environmental certification are factors that affect corporate social responsibility (CSR) disclosure (Almaqtari et al., 2023). Governments, organizations, and industry initiatives are launching new projects to reduce plastic waste and improve waste infrastructure, monitoring, and research (van Emmerik, 2021). These initiatives contribute to a thorough understanding of plastic sources, emissions, fate, effects, and risks, aligning with CSR objectives.

The industry promotes transparency in reporting efforts to minimize atmospheric microplastics by publishing sustainability reports that disclose corporate sustainability activities and initiatives. These reports comply with mandatory reporting requirements and provide information on the environmental impact of business activities, including the management of microplastics. The reports employ modern rhetoric and subtle persuasion techniques supported by facts and figures to ensure credibility and transparency in reporting efforts (Camoletto et al., 2022). CSR initiatives can be structured to ensure accountability for sustainable practices by incorporating accountability perspectives of CSR (APCSR). APCSR emphasizes the need for accountability in CSR implementation and its role in enhancing CSR's contribution to environmental sustainability. By adopting APCSR, companies can enhance their CSR practices and contribute more effectively to sustainable development, particularly in developing countries with weak state institutions and governance (Osman and Kadri, 2022).

The industry engages with stakeholders, including consumers and communities, to communicate their commitment to minimizing atmospheric microplastics through various means, such as sustainability marketing and CSR activities (Janzik et al., 2023). These efforts aim to shape public perception and influence sustainable behaviour by highlighting the environmental and social impacts of microplastics (Walker, 2022). Stakeholder engagement and CSR initiatives play a crucial role in building trust and strengthening relationships between industry and stakeholders, including consumers (Heath and Cotton, 2022). By demonstrating their commitment to minimizing microplastics and engaging in responsible practices, the industry can enhance its brand image and foster responsible, sustainable consumer behaviour (Liu et al., 2023c). The impact of CSR on shaping public perception and influencing sustainable behaviour is further influenced by factors such as the level of engagement in CSR activities and the effectiveness of sustainability marketing strategies (Jia et al., 2023).

4.4. Civil society

The Quintuple Helix model highlights civil society's role in combating atmospheric microplastics through awareness, advocacy, community engagement, and collaboration. It emphasizes the importance of NGOs, grassroots movements, academia, government, and industry in promoting sustainable alternatives, policy reforms, and citizen science projects.

4.4.1. Awareness and advocacy

Civil society organizations (CSO) effectively raise public awareness about atmospheric microplastics by adopting various strategies and channels. They develop educational programs and conduct outreach activities to enhance public understanding of microplastics and their impact on health (Janzik et al., 2023). These activities include providing technical information, educating about microplastic exposure, and promoting healthy lifestyles to reduce sources of microplastic exposure (Coffin et al., 2021). Moreover, CSO are instrumental in risk communication by addressing scientific uncertainties and emphasizing the intricate linkages between human health and environmental well-being (Elgammal, 2023). They strategically position themselves in social and institutional networks, mobilize public support, and generate media coverage to initiate and accelerate transitions towards more sustainable choices (Buijs et al., 2023). However, it is important to note that the step from local impact to broader transition remains a challenge, and the contribution of CSO should be seen as part of a larger movement towards sustainability (Felipe-Rodriguez et al., 2022).

NGOs and grassroots movements advocate for policy changes related to atmospheric microplastics through various strategies. They engage in lobbying efforts, both inside and outside of government, to influence environmental policy (Bey, 2022). They also utilize citizen science initiatives to generate data and collaborate with the public, which can aid in policy influence (Oturai et al., 2023). These organizations work to raise awareness about the health and ecological risks of plastics and promote sustainable alternatives (Usman et al., 2022). In order to optimize their efforts, NGOs and grassroots movements need to have access to resources and employ effective strategies, such as large staff size, lobbying multiple venues, and utilizing both inside and outside lobbying tactics (Coffin et al., 2021). Additionally, their advocacy should be inclusive, ensuring equal access for all participants and prioritizing harmonization and sharing policy input (Dauvergne and Islam, 2023). By strengthening their networks, engaging in transnational advocacy, and addressing the root causes of plastic pollution, these organizations can have a meaningful impact on developing and implementing policies addressing microplastic pollution.

Civil society plays a significant role in influencing consumer behaviors towards more sustainable choices in the context of atmospheric microplastics. Studies have shown that environmental concerns and activism are predictors of sustainable behaviors, such as avoiding plastic and looking for recyclable packaging (Pinho and Gomes, 2023). Additionally, the theory of planned behaviour (TPB) has been used to explain sustainable consumption, which often results from planned decisions rather than hedonic reasons. Collaboration with other helix components, such as government and CSR, can enhance the effectiveness of advocacy efforts. For example, the No Plastic Bag Campaign in Malaysia suggests a comprehensive approach that includes informational campaigns, the establishment of new social norms, and the promotion of zero-waste initiatives to nudge sustainable shopping lifestyles (Zen, 2018). Ultimately, civil society's commitment to sustainability, combined with collaboration with other stakeholders, can drive consumer behaviors towards more sustainable choices in the face of atmospheric microplastics. By promoting sustainable consumption and reducing plastic use, civil society can play a crucial role in mitigating the environmental impacts of microplastics.

4.4.2. Community engagement

Civil society mobilizes communities to actively participate in addressing microplastics at the local level through various strategies. These strategies include organizing workshops and online events to create a shared vision for reducing plastic bag usage (Buijs et al., 2023). engaging citizens in citizen science initiatives to generate data on plastic pollution and influence policymaking (Oturai et al., 2023), conducting outreach activities to educate the public about microplastics and their impact on health (Neef et al., 2023), and implementing innovative sustainable practices such as Tiny Forests and Beach Clean-Ups. Successful community engagement strategies in promoting sustainable practices and reducing microplastic pollution involve a combination of economic, structural, and behavioral interventions, including financial incentives, the introduction of environmentally friendly alternatives, promoting of reusable bags, and using social channels such as education and social norms (Walker, 2022). These strategies aim to increase public understanding of microplastics, encourage behaviour change, and inspire collective action to minimize microplastic exposure and promote sustainable practices.

CSO play a crucial role in initiating and supporting clean-up initiatives to mitigate the impact of microplastics. These organizations engage in activities such as beach clean-ups and plastic waste management (Catarino et al., 2023). Citizen science projects can be leveraged to engage communities in monitoring and addressing microplastic pollution. These projects involve the participation of citizens, including students and frontline sanitary personnel, in collecting data on plastic litter and its impact on the environment (Oturai et al., 2023; Severin et al., 2023). By involving citizens in data collection, citizen science projects can increase the spatial coverage of monitoring efforts and provide valuable information on the abundance and distribution of microplastics in different environments, such as coastal ecosystems and surface waters (Setälä et al., 2022; Shruti et al., 2022). This collaboration between CSO and citizen scientists can contribute to a better understanding of microplastic pollution and support the development of effective strategies to mitigate its impact.

Furthermore, civil society promotes citizen-led initiatives to address microplastics by engaging citizens in data generation, collaboration, and policy influence (Oturai et al., 2023). Initiatives like the Citizen Observation of Local Litter in Coastal ECosysTems (COLLECT) project and citizen science projects involve local students and communities in collecting data on coastal plastic litter (Catarino et al., 2023; Janzik et al., 2023). These initiatives contribute to fostering a sense of community responsibility and ownership in the fight against atmospheric microplastic pollution by raising awareness, providing education, and involving citizens in the decision-making process (Setälä et al., 2022). Participating in these efforts helps residents understand the impact of microplastic pollution on health and the environment, as well as how to eliminate it. This sense of ownership and responsibility motivates people to live more sustainably and actively participate in the fight against microplastic contamination, resulting in a stronger community-driven approach to resolving the problem.

4.4.3. Collaboration and partnership

CSO collaborate with academia, government, and industry to amplify their impact in tackling atmospheric microplastics. CSOs aim to influence public policy and often work with governments to formulate and implement policies (Bohrer et al., 2023). In authoritarian contexts, CSOs face restrictions but still need to highlight public problems caused by governmental inaction. CSOs involved in waste management in Russia use communication strategies to achieve their objectives. They employ different narrative strategies, such as angel shifts and devil shifts, depending on their activities and working relationship with the government (Walker, 2022). CSOs also engage in intense communication, improving synergy and collaboration between government regulation, academia, business sector, and civil society (Schlaufer et al., 2022). Effective communication and cooperation are facilitated through social media platforms, which allow CSOs to bypass mainstream media and mobilize supporters (Nelms et al., 2022). By strategically using narratives and engaging in collaborative efforts, CSOs can enhance their impact in addressing the issue of atmospheric microplastics.

Collaborative initiatives between civil society and other helix components contribute to sharing resources and knowledge in the fight against atmospheric microplastics. These initiatives aim to bring together academia, industry, government, and civil society to strengthen regional innovation and create sustainable and inclusive growth. By engaging with and facilitating the participation of civil society, regional governments can foster the Quintuple Helix model and promote the sharing of resources and knowledge. The Quintuple Helix model, which emphasizes the participation of all stakeholders, including civil society, has been identified as a mechanism to support the design and implementation of research and innovation strategies for smart specialization. Additionally, open innovation approaches and collaboration platforms, such as the Challenge Lab, can further enhance the triple helix innovation capacity by involving students and providing neutral platforms for deeper collaboration between the helix actors (Jenkins et al., 2022; Roman et al., 2020).

Furthermore, CSO face unique challenges and opportunities in collaborative environments. Their interactions with state agencies and other partners are influenced by factors such as agency dynamics, the interplay of interests, and the evolving nature of these relationships. These organizations continually shape their roles through collaborative processes with government entities, guided by mutual perceptions and diverse considerations (Sjögren Forss et al., 2021). Successful cooperation models between CSO and other helix components exist in various contexts. For example, a Penta-helix collaboration in a health promotion program in Malmo, Sweden, involved representatives from academia, voluntary organizations, the business sector, the public sector, and citizens, with citizen-driven processes playing a crucial role (Syal et al., 2021). In the context of water, sanitation, and hygiene (WASH) and gender equality and social inclusion (GESI) organizations, partnerships were driven by identifying community service gaps and aligning advocacy agendas, leading to increased inclusion, empowerment, and strengthened knowledge and capacity (Grant et al., 2023). These examples highlight the importance of interprofessional cooperation, citizen involvement, and addressing power dynamics in successful collaborations.

4.5. Environment

The last role in the Quintuple Helix emphasizes the environmental role in addressing atmospheric microplastics. Ecological Impact Assessment evaluates their effects on ecosystems, conservation, and restoration. It involves organizations preserving ecosystems and monitoring and surveillance to track their presence and distribution, enabling informed decision-making and targeted interventions.

4.5.1. Ecological impact assessment

Environmental scientists assess the ecological impacts of atmospheric microplastics on diverse ecosystems using various methodologies and indicators. In marine environments, researchers focus on the ingestion and impact of microplastics on aquatic organisms, including benthic organisms and fishes. Functional traits of aquatic organisms, such as metabolism, growth, and reproduction, are negatively affected by microplastics, which can also impact fish behaviour and trophic interactions (Khan et al., 2023a, 2023b). In freshwater systems, studies have used model organisms like *Daphnia magna* to assess the toxicity of microplastics. Bioassays have been conducted to measure acute and chronic toxicity endpoints, including mortality, reproductive, and behavioral measurements. Microscopy is used to visualize microbeads within and surrounding the organisms (Belioka and Achilias, 2023; Berlino et al., 2023). In terrestrial habitats, the prevalence and hazardous effects of microplastics on biota are still being studied, with a focus on their presence in soil and their potential impacts on soil organisms and plant growth (McNamee, 2023).

Environmental scientists are critical in determining the long-term ecological effects of air microplastics and guiding the creation of sustainable practices and policies to reduce microplastic contamination. They research to understand the types and concentrations of microplastics in different environments, such as freshwater rivers (Jung et al., 2023), coastal areas (Belioka and Achilias, 2023), and terrestrial ecosystems (Adeniji et al., 2023). By studying the prevalence, distribution, and ecological implications of microplastics, scientists can identify the sources and pathways of microplastic pollution and evaluate its effects on organisms and ecosystems. This knowledge can inform the development of management strategies and mitigation efforts to reduce microplastic contamination. Additionally, scientists investigate remediation techniques, such as filtration, coagulation, and membrane technology, to address microplastic pollution (Zhao et al., 2023b). Their findings contribute to understanding the environmental consequences of microplastic pollution and provide valuable insights for policymakers, researchers, and stakeholders in developing sustainable practices and policies to protect the environment from the harmful effects of microplastics.

4.5.2. Conservation and restoration

Environmental organizations and conservation groups play an important role in conserving ecosystems that have been impacted by air microplastic pollution. They contribute by increasing awareness about the impact of microplastics on habitat integrity and pushing for legislative changes and legislation that minimize pollution (Chen, 2023; Li, 2022a). These organizations also engage in research and monitoring efforts to understand the ecological effects of microplastics better and develop effective conservation strategies. Some conservation strategies being developed include source reduction, wastewater treatment, education and awareness campaigns, policy and regulatory measures, and ecosystem-based approaches (Saini and Sharma, 2022). Restoration plans focus on restoring habitat quality and promoting the recovery of affected ecosystems through measures such as habitat restoration, pollution control, and the implementation of sustainable practices (Rai et al., 2023). By implementing these strategies and plans, environmental organizations and conservation groups aim to mitigate the impact of microplastics on habitat integrity and safeguard the health and sustainability of ecosystems (Berlino et al., 2023).

Conservation efforts address sustainable land and water management practices to minimize the release of atmospheric microplastics into the environment. These efforts focus on various aspects such as plastic waste management, source reduction, incorporation of plastics into the circular economy, suitable waste management, and infrastructure development (Rai et al., 2023). Additionally, research has been conducted on the adsorption and removal technologies of microplastics in aquatic environments, including natural freshwater, marine, drinking water treatment plants, and WWTPs (Sarkar et al., 2022). Efforts have also been made to understand the occurrence, transport, fate, and health risks of microplastics in soil and freshwater environments (Pan et al., 2023). These practices can be integrated into broader conservation initiatives by implementing legislation or regulatory plans to reduce microplastic contamination, harmonizing sampling and analysis methods, and addressing research gaps to improve our understanding of microplastic contamination in complex environmental systems (Kallenbach et al., 2022; Raza et al., 2022).

Environmental organizations also serve as mediators between the government and the public, advocating for environmental integrity and creating awareness about the importance of preserving the environment (Shaharudin et al., 2020). Community-based initiatives, initiated and implemented by community members, are effective in addressing environmental concerns and promoting sustainable practices (Chen et al., 2023). Public participation in environmental protection is motivated by factors such as mainstream policy leadership, social dynamics, and cognitive preferences (Axon, 2020). Furthermore, successful initiatives require collaboration between government agencies, NGOs, and community members, leading to comprehensive and sustainable solutions. In the context of restoration projects, individuals who are willing to engage in environmental restoration stewardship are motivated by personal agency, the value of their contributions to the community, and their knowledge about environmental issues. To foster public participation and support for sustainable initiatives to combat atmospheric microplastic pollution, environmental organizations need to provide education, promote sustainable development projects, and raise awareness about the importance of environmental protection (Sorensen et al., 2018).

4.5.3. Monitoring and surveillance

The monitoring of atmospheric microplastics in the environment is crucial for tracking their presence and distribution. Microplastics have become a chronic contaminant in various environmental sectors, including terrestrial, marine, and atmospheric (Belioka and Achilias, 2023). The widespread presence of microplastics necessitates the development of efficient monitoring and surveillance programs to enable informed decision-making. Analytical methods for monitoring microplastics are challenging and time-consuming, but technological advancements have provided potential solutions. For instance, hologram imaging and post-processing techniques have shown promise for rapidly detecting microplastics in seawater (Willans et al., 2023). Additionally, the development of a specific, tailor-made database for microplastic data can aid in harmonizing and comparing monitoring results (Ikenson, 2023). This structured relational database is adaptable to the diverse sampling, processing, and analytical methods used for microplastics, ensuring accurate data manipulation and quality assurance (Calore and Fraticelli, 2022).

Efficient surveillance programs for microplastics require the use of appropriate sampling techniques, laboratory procedures, and identification methods, along with the integration of real-time information transfer systems (Čerkasova et al., 2023). These programs provide data on the prevalence and distribution of microplastics in various environments, including marine and Arctic ecosystems (Belioka and Achilias, 2023). These initiatives collect data on the quantity and properties of microplastics to assist in identifying sources and understanding the ecological consequences of microplastic contamination (Ikenson, 2023). The collected data can be utilized to develop targeted interventions that mitigate the environmental impacts of microplastic pollution. For example, Monitoring programs can guide the selection of species and monitoring locations depending on local community goals (Lusher et al., 2022). Additionally, the data can be used to assess the effectiveness of mitigation efforts and guide the development of strategies to limit the quantity of plastic waste entering the environment (Čerkasova et al., 2023).

By utilizing wireless sensor networks and Internet of Things (IoT) technologies, real-time environmental monitoring systems can be implemented. These systems use sensors to collect data on environmental parameters such as temperature, humidity, and CO levels, which are then transmitted to the cloud for storage and analysis. The collected data can be accessed remotely through mobile applications and can be used to take remote actions to control environmental conditions and send notifications (Ling et al., 2011; Narayana et al., 2024). Effective collaboration among government bodies, industry stakeholders, and environmental protection agencies is vital for optimizing the collection, distribution, and integration of sensor data. Such cooperation ensures the seamless interaction between sensor networks and high-level services and applications. Furthermore, the application of machine learning techniques enables the identification of environmental patterns and potential hazards, significantly enhancing the efficacy of environmental monitoring (Hino et al., 2018). These advanced monitoring and surveillance programs are vital in addressing global issues such as microplastic pollution and in devising effective intervention strategies. A summary of the subsystems of the Quintuple Helix Model and associated actions for addressing microplastic-related issues is presented in Table 1.

5. Opportunities and challenges in collaboration

Integrating the Quintuple Helix approach into atmospheric microplastic management policies presents both significant and unique opportunities. On the one hand, this approach offers a remarkable opportunity for fostering collaboration and knowledge-sharing among the five key helices - government, industry, academia, civil society, and the natural environment. By bringing together diverse stakeholders, the Quintuple Helix model creates a platform for a more inclusive and comprehensive understanding of atmospheric microplastics. This inclusivity not only enriches the policy development process but also ensures the implementation of holistic solutions that address the intricate web of challenges associated with microplastic pollution (Carayannis et al., 2022). However, significant challenges exist, particularly in managing the divergent interests and priorities among the helices. Achieving effective communication and coordination across these diverse stakeholders can be complex and demands careful navigation.

Furthermore, incorporating the natural environment as an active stakeholder introduces a unique set of challenges, demanding a delicate balance between human concerns and ecological considerations. Despite these challenges, the opportunities presented by the Quintuple Helix approach hold the potential to revolutionize atmospheric microplastic management policies, providing a path towards sustainable and impactful solutions for the preservation of planetary health. Fig. 10 illustrates the opportunities and challenges in integrating the Quintuple Helix approach into atmospheric microplastic management policy.

Table 1
Subsystems of quintuple helix model and possible actions to address issues concerning microplastics.

	Subsystems of quintuple helix model	Description
i.	Universities	• Academia actively engages in scientific research of microplastics (focusing on sources, movements, environmental impacts) to gather comprehensive data for informed decision-making processes. • Development of new technologies for the detection, monitoring, and mitigation of microplastics. • Collaboration among academic/research institutions to open data.
ii.	Industries	• Knowledge transfer, method development or projects that contributes to eco-friendly production processes by integrating green, six sigma and lean methodologies into existing manufacturing systems • Adopting sustainable practices in production processes to reduce use of plastics/microplastics • Industry collaborates with academia & governmental bodies to research and implement sustainable practices
iii.	Government	• Formulating regulations, long-term policies/strategies/guidelines or implement short term interventions aimed at addressing microplastics • Developing comprehensive waste management strategies to combat atmospheric microplastics. • Enforce regulations through implementation of monitoring mechanisms and inspections to ensure compliance.
iv.	Media/Public	• Media to constantly construct and communicate public reality, reinforce culture and values. • Educational programs/outreach activities by NGOs and grassroots movements to enhance public understanding of microplastics. • Consumer behaviour towards more sustainable choices (e.g. avoiding plastic for recyclable packaging)
v.	Natural environment/society	• Environmental scientists assess ecological impacts of atmospheric microplastics and guide in creating sustainable practises and policies to reduce microplastic contamination on diverse ecosystems using various methodologies and indicators • Environmental organizations/conservation groups to conserve ecosystems that to have been impacted by air microplastics pollution • Continuous monitoring and surveillance for tracking microplastics presence and distribution

5.1. Synergy in policy development

Incorporating the Quintuple Helix approach into policies for managing atmospheric microplastics presents significant opportunities for synergistic policy development. This approach promotes collaboration between five key sectors: government, industry, academia, civil society, and the natural environment. Current research has identified a total of 291 relevant policies at different levels—international (67), national (147), and subnational (77). The trend shows a growing number of national-level policies addressing plastic pollution, with a significant focus on banning various types of plastics (Diana et al., 2022). These policies are designed to reduce plastic waste, and global efforts have emerged to monitor governmental responses to the issue. However, the current policy landscape predominantly involves government-led initiatives, highlighting a key limitation in incorporating diverse perspectives from non-governmental sectors, a critical aspect of the Quintuple Helix approach (Fig. 11).

The Quintuple Helix model addresses this limitation by engaging all five helices in a collaborative and inclusive manner. By fostering collaborative research initiatives, this approach contributes to developing advanced monitoring technologies, detection methods, and effective mitigation strategies. The synergy among academia, industry, and government accelerates the translation of research findings into practical solutions, promoting the development of cutting-edge technologies. Engaging civil society ensures public participation, awareness, and acceptance of microplastic management policies, making them more likely to be socially accepted and effective in implementation. Individuals, encompassing a wide spectrum of the populace, can significantly contribute by engaging in data collection, collaborating in the development of participatory and analytical methodologies, and expressing challenges and opportunities associated with such interactions. This input has the potential to shape adjustments in both industry practices and regulatory frameworks (Williams et al., 2023).

Additionally, the Quintuple Helix approach facilitates policy coherence by aligning goals and strategies across diverse stakeholders, contributing to a more efficient and effective response to atmospheric microplastic challenges. Integrating the natural environment as a stakeholder ensures policies consider ecological impacts, contributing to environmental sustainability (Williams et al., 2023). Collaboration with civil society enhances the effectiveness of public awareness campaigns and educational initiatives, fostering an informed and engaged public that is more likely to adopt sustainable practices.

However, applying the Quintuple Helix approach to atmospheric microplastic management policy is not without its challenges. Divergent interests and goals among the five helices—government, business, academia, civil society, and the natural environment—pose significant hurdles. Effective communication and coordination across these diverse stakeholders can be complex and may impede the smooth

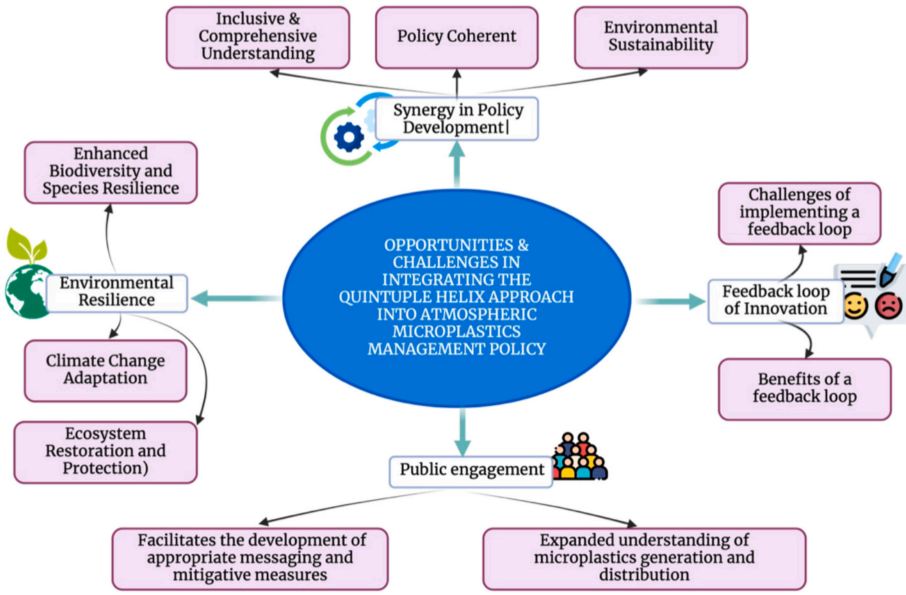

Fig. 10. Opportunities and challenges of quintuple helix approach integration in managing atmospheric microplastics.

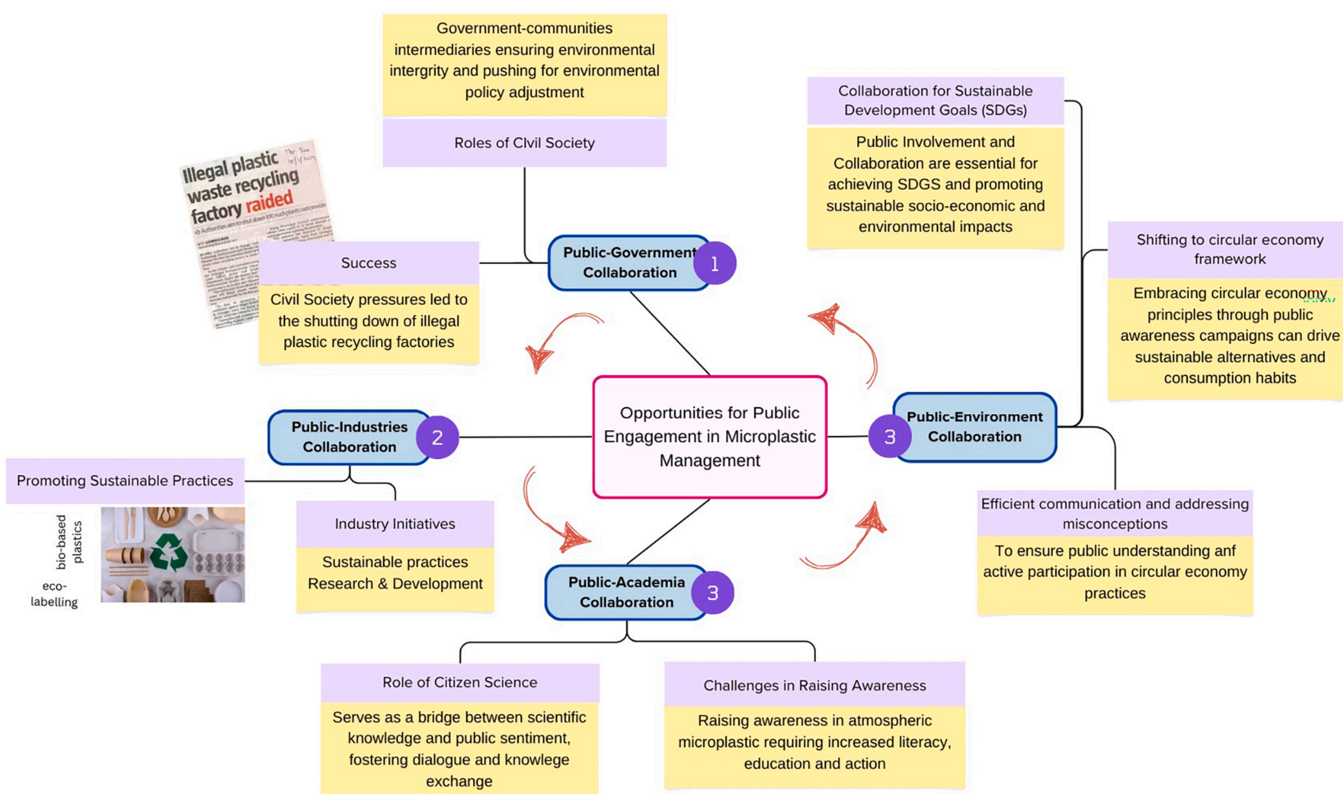

Fig. 11. A quintuple helix interaction of public involvement in atmospheric microplastics management in Malaysia.

implementation of policies. Additionally, civil society representatives highlight the issue of time constraints, as engagement with NGOs often requires voluntary commitment outside regular working hours. To address these challenges, future solutions such as leveraging online platforms could facilitate greater participation and involvement (Grundel and Dahlström, 2016).

Furthermore, the inclusion of the natural environment as an active stakeholder introduces another layer of complexity, demanding a delicate balance between human concerns and ecological considerations. Striking this balance poses inherent difficulties, requiring thoughtful policy formulation to address both human needs and environmental preservation. Moreover, the complexity of integrating diverse perspectives may lead to slower decision-making processes and increased resistance to change. The public, civil society, and the environment can be viewed as corrective influences on decision-making, challenging the ethical, normative, and ecological aspects of knowledge and innovation (König et al., 2021). Despite these challenges, the potential benefits and opportunities presented by the Quintuple Helix approach highlight the importance of overcoming these hurdles to ensure a successful, inclusive, and sustainable approach to atmospheric microplastic management.

5.2. Feedback loop of innovation

Incorporating a feedback loop of innovation into the Quintuple Helix approach for atmospheric microplastic management offers a multitude of opportunities for dynamic and adaptive strategies. Through iterative solutions, the feedback loop allows for continuous refinement of policies, strategies, and technologies, ensuring their ongoing effectiveness. This adaptive policy development process responds dynamically to emerging challenges and changing circumstances, promoting resilience in the face of evolving atmospheric microplastic issues.

The evolution of the number of adopted policies and their design is evident over time, as demonstrated, for instance, by Canada's classification of plastic as a toxin under the Canada Environmental Protection Act (Diana et al., 2022). Enhanced collaboration among government, industry, academia, civil society, and the natural environment is facilitated by regular feedback exchanges, fostering a deeper understanding of each stakeholder's needs and perspectives. Considering citizens' behaviors and motivations in plastic and textile usage in collaboration with the industry could contribute to reducing the generation of these particles. In this context, future studies should recognize the importance of citizen inclusion when designing research strategies for measuring and reducing microplastic concentrations in homes. Citizen feedback is crucial for the Quintuple Helix approach, as it enables a nuanced understanding of microplastic generation and distribution. Additionally, it facilitates the development of appropriate behavioral, industrial, and regulatory messaging, as well as effective mitigative measures (Williams et al., 2023).

The feedback loop cultivates a culture of continuous learning and improvement, where stakeholders can glean insights from both successes and failures. The rapid feedback mechanism facilitates the Swift identification and integration of innovative ideas and technologies, accelerating the overall innovation process in atmospheric microplastic management. Additionally, regular feedback from the public ensures that policies align with societal expectations, enhancing public acceptance and fostering a sense of shared responsibility. Acting as an early warning system, the feedback loop enables the timely detection of potential issues, allowing for proactive monitoring and corrective actions to prevent the escalation of problems. Ultimately, integrating a feedback loop of innovation within the Quintuple Helix approach empowers decision-makers with data-driven insights, contributing to informed and effective decision-making processes in the pursuit of sustainable atmospheric microplastic management.

However, including an innovative feedback loop into the Quintuple Helix approach for atmospheric microplastic management presents obstacles. One key challenge is to build and maintain good communication channels for ongoing input among varied stakeholders, including government, business, academia, civil society, and the natural environment. According to Kholiavko et al. (2021), five key communication channels are critical: education, methodical development, financial support, project collaboration, and research involvement. These channels facilitate stakeholder engagement through activities such as training, program development, funding, collaborative projects, and research initiatives within the Quintuple Helix model. In addition, overcoming potential resistance to change and fostering a culture that values ongoing learning and adaptation poses a considerable challenge, particularly when dealing with entrenched practices or policies. It is also crucial to balance the need for rapid iteration with the requirement for comprehensive evaluation, as premature adjustments may lead to unintended negative outcomes.

Furthermore, ensuring the transparency and accountability of the feedback loop process is crucial to maintaining trust among stakeholders. The potential for information overload and the need for robust data management systems also pose significant challenges. Managing large volumes of feedback data requires careful consideration and strategic planning to prevent data overload and ensure that the feedback loop remains a valuable tool for driving innovation and improvement. Addressing these challenges is essential to harnessing the benefits of a feedback loop of innovation and developing a responsive, adaptive, and effective approach to atmospheric microplastics management.

5.3. Public engagement

5.3.1. Opportunities and challenges in public-government collaboration

Civil society acts as a monitoring body, keeping a close eye on the implementation of microplastic management policies. Through independent assessments and evaluations, NGOs ensure transparency and accountability, providing valuable feedback to policymakers and the public. This continuous monitoring helps identify areas of improvement and informs future policy adjustments. Environmental NGOs serve as essential intermediaries between governments and communities, bridging expectations and enhancing communication. The effectiveness of microplastic management policies, particularly at local and national levels, is largely supported by public pressure and civil society advocacy. A notable example is the Malaysian government's decision to permanently ban the import of waste, allowing only clean, recyclable plastics after receiving widespread complaints regarding illegal plastic waste imports through Port Klang, Selangor. In response, the government launched coordinated enforcement operations, led by the Ministry of Energy, Science, Technology, Environment, and Climate Change (MESTECC), alongside local authorities and agencies such as Tenaga Nasional Bhd (TNB) and the Department of Environment (DoE), to shut down illegal plastic recycling factories (Shaharudin et al., 2020).

Effective management of plastic pollution requires full public engagement. In 2018, the Malaysian government introduced the "Roadmap to Zero Single-Use Plastics 2018–2030" in response to the escalating plastic pollution crisis. In order to guarantee the effectiveness of this roadmap plan, several initiatives, such as the 'No Plastic Bags Campaign' or 'No Plastic Bags Day', have been implemented in various states, including Pulau Pinang, Selangor, Kedah, and Pahang (Ma et al., 2020). However, challenges remain, including low plastic waste recycling rates, insufficient knowledge regarding sustainable behaviors and habits, inadequate integration of waste management, insufficient availability of biodegradable products, high expenses associated with plastic alternatives, and a lack of cooperation and enforcement from relevant governmental stakeholders (Tang, 2023). To address these barriers, it is critical that all relevant stakeholders—including federal and state governments, NGOs, manufacturers, and the public—work collaboratively. This collaborative effort is essential to achieving the roadmap's target by 2030, facilitating the shift from a plastic-dependent economy to a circular and sustainable one.

Despite these efforts, public awareness regarding microplastic pollution remains limited due to a lack of information and negative perceptions of governance. Studies suggest that policy instruments and awareness campaigns can positively influence public perception (Tang, 2023). Interestingly, the public generally believes that environmental legislation can effectively address pollution, and satisfaction with environmental governance is positively correlated with regulatory efforts (Geng and He, 2021). This is reflected in the increasing demand for better environmental circumstances, driven by growing environmental awareness. Therefore, involving the public in the assessment of government environmental laws is advantageous as it expands the scope of evaluation and enhances the legitimacy and effectiveness of the regulations. Simultaneously, the assessment of the public's environmental governance catalyzes pressing the government to regulate any environmental policy. The obstacles to enhancing public awareness must be overcome. Especially with the rapid development of contemporary media, an increasing number of people are consciously and systematically paying attention to pollution issues and aggressively demanding environmental governance. This mass dissemination and communication enable the people to better focus on environmental issues, promote collective action, and drive the improvement of environmental governance, especially in cities under low economic pressure (Liu et al., 2023a, 2023b, 2023c).

5.3.2. Opportunities and challenges in public-industry collaboration

The growing presence of microplastics in the environment poses potential opportunities and challenges that demand collaborative effort between the general public and the industry. Addressing this issue is crucial, as it fosters a sense of collective responsibility and promotes the adoption of more sustainable practices. The opportunities lie in promoting alternatives to plastic and advocating for a circular economy. In an effort to mitigate atmospheric microplastic pollution, the investigation and advocacy of alternatives to conventional plastics present a promising path forward. Public participation serves as a catalyst, instigating heightened consciousness regarding sustainable materials and directing a societal transition towards environmentally conscious alternatives. The current paradigm shift is propelled by evolving perspectives regarding the ecological ramifications of plastic waste, an occurrence that both political and industrial entities are tactfully capitalizing on. As evidenced by initiatives conducted by Consumers International and UNEP in 2020, environmental consumerism reflects this growing anti-plastic sentiment (UNEP, 2021). In order to maintain the market value of plastics, an increasing number of industries and politicians are contemplating feedstock substitution, the expansion of consumer reuse options, and the adoption of novel delivery models.

A notable example of this shift is the work led by the Ellen MacArthur Foundation, UNEP, and the International Trade Centre. Between 2016 and 2021, these organizations spearheaded efforts to promote sustainable packaging, national recycling programs, and the development of reusable, renewable, or recyclable packaging (UNEP, 2021). Multinational corporations have also embraced these sustainability goals, aligning their packaging strategies with broader industry commitments to meet public demands for responsible production, disposal, and recycling. One notable trend in the push for sustainable alternatives is the rise of bio-based plastics, which have gained popularity and positive public reception. Biodegradable plastics, in particular, are seen as more environmentally friendly than conventional plastics, including those marketed as “easily recyclable” (Dilkes-Hoffman et al., 2019). The term "bio-based" is often associated with positive environmental attributes, such as naturalness and sustainability (Sijtsema et al., 2016). However, it is essential to acknowledge that public perception is complex, with concerns surrounding the potential health risks and technological implications of these new materials. Nonetheless, promoting industry investment in research and development of innovative materials presents a significant long-term opportunity, particularly as companies respond to increasing consumer demand for environmentally responsible products (Prata et al., 2019).

Industry-led initiatives play a pivotal role in supporting and advancing policy actions to achieve government-mandated objectives or those currently under consideration. These efforts serve as a connection between the practices of the private sector and the goals of public policy, promoting collaboration and synergy between industries and government entities. Industries can provide significant ideas, experience, and resources by actively participating in the development and execution of policies. This ensures that regulatory measures are not only effective but also in line with the practicalities of business operations. An important way for industries to get involved is by sharing product information, which is crucial for promoting transparency and accountability. This can be accomplished through several methods, such as implementing voluntary labeling programs or using environmental indicators. Voluntary labeling programs or eco-labeling allow enterprises to offer precise and concise information about their products, including details about their environmental impact, sustainability characteristics, or compliance with specified requirements. This not only enables consumers to make well-informed decisions in line with their values but also encourages healthy competition among industries to embrace more sustainable practices. Industries demonstrate their dedication to responsible business practices and contribute to a wider corporate social responsibility and environmental stewardship culture throughout the entire value chain by willingly adopting and promoting such programs. Public bodies can ensure eco-labeling method alignment with the most up-to-date scientific findings and best practices by engaging in collaborative efforts with industries. This collaboration can incentivize firms to allocate resources towards research and development in order to mitigate their impact on atmospheric microplastics, thus promoting a culture of ongoing enhancement. From a business standpoint, engaging in eco-labeling efforts presents a chance to demonstrate dedication to environmental conservation and sustainable methodologies. Products that have been certified with eco-labels and comply with policies for managing atmospheric microplastics have a distinct advantage in the market, as they appeal to ecologically aware consumers. By engaging in collaboration, industries can actively contribute to advancing and enhancing eco-labelling standards, ensuring their practicality, feasibility, and effectiveness. The synergy between public activism, well-informed consumer decisions, and business compliance with eco-labeling can together foster a positive feedback loop, leading to enhanced regulations for managing atmospheric microplastics and a more sustainable future.

5.3.3. Opportunities and challenges in public-academia collaboration

Understanding and mitigating public concerns surrounding the accumulation of plastic waste and its environmental consequences is imperative for the formulation of effective policies and interventions. In this complex landscape, citizen science emerges as a vital link between scientific expertise and public sentiment, providing a collaborative platform for meaningful dialogue and knowledge exchange. As scientific discoveries and innovations continue to shape societal development, public engagement becomes a fundamental necessity in contemporary research initiatives. Establishing successful public engagement strategies involves cultivating a productive two-way dialogue between scientists and the public, where both parties contribute to each other's understanding of scientific developments and their applications to society (Mofokeng et al., 2024). Given the ever-evolving state of scientific comprehension, community engagement becomes indispensable, fostering knowledge and consciousness. The active participation of citizens in the scientific process elevates their viewpoints and knowledge. It becomes an essential element in decision-making processes, thereby enhancing the democratic aspect of scientific governance.

Furthermore, public risk perception becomes a focal point for leveraging citizen science initiatives to address the pervasive issue of plastic pollution in the biosphere. The efficacy of citizen science extends beyond data production; it lies in its ability to offer valuable recommendations. Scientists and policymakers can harness the insights and suggestions derived from citizen science activities to develop effective methods for addressing environmental challenges. Public engagement should focus on education, collaborative discussion, and precautionary policy changes to counteract scientific negationism and denialism. Consensus conferences and deliberative forums within citizen science become pivotal in fostering transparency and civic engagement.

Despite ongoing efforts to address atmospheric microplastics, raising public awareness through scientific communication remains a significant challenge. One major barrier is the lack of comprehensive scientific data, particularly regarding the types, sources, and ultimate fate of microplastics in both indoor and outdoor air. These knowledge gaps hinder the ability to convey the full scope of the issue to the public. Additionally, public risk perceptions often differ from expert evaluations, as the public tends to consider a broader range of factors beyond formal scientific risk assessments. Variables such as demographics and educational background further complicate this divide in understanding (Garcia-Vazquez and Garcia-Ael, 2021; Onyena et al., 2021). In particular, addressing the challenges of atmospheric microplastic pollution in regions like Asia, where knowledge remains relatively limited, requires promoting environmental literacy and education (Deng et al., 2020).

To overcome resource limitations and maintain advocacy and monitoring efforts, innovative and resource-optimized engagement strategies are essential. The dynamic nature of civil society requires a thorough analysis of innovative strategies that can be employed to optimize effectiveness. An essential aspect of productive policy discussions is promoting inclusiveness, necessitating proactive steps to reduce the potential influence of specific viewpoints and ensuring representation from different communities. Community engagement programs, grassroots movements, and inclusive forums are instrumental in ensuring that policy conversations encompass a diverse range of opinions present in society.

Furthermore, ethics and human rights play a critical role in policies governing microplastics, particularly regarding their entry into the food chain due to the absence of reliable risk information. Ethics appeal to individual actors' social responsibility, such as fishers' responsibility for their gear or market actors' and consumers' responsibility for choices of food and drinks packaging and recycling (Koelmans et al., 2019). Effective policy implementation requires more than just legal measures; it demands a concerted effort to engage with various stakeholders and foster behavioral change. This can be achieved through targeted engagement campaigns and dialogues that raise awareness about the risks associated with microplastics and promote responsible practices. By combining scientific expertise with public engagement, policymakers can navigate the complex landscape of environmental policy and develop comprehensive solutions to the multifaceted challenges posed by microplastics.

5.3.4. Opportunities and challenges in public-environment interaction

The intersection of public-environment interaction within the framework of policies addressing atmospheric microplastic management not only poses difficulties but also offers an opportunity for cooperation and participation in SDGs initiatives. As people become more aware of the extensive impact of atmospheric microplastics on ecosystems and human well-being, there is a special chance for them to participate in SDG projects actively. When effectively utilized, public awareness and involvement can become a powerful advocate for policies that support the SDGs, especially those pertaining to environmental sustainability, health, and responsible consumerism. The successful attainment of the United Nations SDGs by 2030 depends on efficiently tackling the intricate issues presented by the management and recovery of plastic waste. Sarkar et al. (2022) highlight the importance of implementing economically feasible, socially agreeable, and environmentally sustainable approaches in the field. Efficiently incorporating strategies for managing microplastics necessitates a collaborative effort encompassing regulatory entities, businesses, and the general population. Engaging in a collaborative approach with these stakeholders will not only help accomplish specific SDGs but also promote a comprehensive and sustainable influence on the wider socio-economic and environmental context. The United Nations, in 2010, established specific aims to achieve goal number 12 of the SDGs, which is "responsible consumption and production." These targets emphasize the importance of effectively managing chemicals and other types of waste from their creation to their disposal.

The focus is on minimizing waste to alleviate adverse effects on ecosystems. An essential element in attaining SDG 12 entails shifting from the linear economic paradigm of "take, make, and dispose" to a circular economy framework that promotes recycling and resource recovery (Brennholt et al., 2018). This paradigm change can profoundly alter plastic disposal practices, introducing enhanced plastic recovery through new approaches such as recycling and upcycling (Blank et al., 2020). Tackling plastic waste management extends beyond the scope of SDG 12, yielding positive impacts on multiple other sustainable development goals. Progress towards achieving SDG 3, "Good health and wellbeing"; SDG 12, "Responsible Consumption and Production"; SDG 13, "Climate Actions"; SDG 14, "Life below water"; and SDG 15, "Life on land" is made by reducing plastic waste and minimizing the discharge of microplastics into the environment. The detrimental impacts of microplastics on both aquatic and terrestrial creatures, including people, emphasize the pressing need to promptly adopt efficient methods for recovering plastic waste. Promoting research and studies that provide sustainable solutions for microplastics in the ecosystem is essential, in line with the wider global objective of meeting the United Nations SDGs and fostering a healthier and more resilient planet.

In conjunction with the SDGs, the public-environment interface provides an opportunity to improve understanding and effectiveness in applying circular economy ideas to various lifestyles. As people understand the consequences of ambient microplastics, there is an increasing need for sustainable alternatives. This entails shifting from the conventional take-make-dispose paradigm to a circular mindset that prioritizes the processes of recycling, reusing, and renewing resources. Public awareness campaigns can have a crucial impact on clarifying the concrete advantages of circular economy principles and motivating individuals to embrace more environmentally friendly consumption habits. The growing awareness of microplastic issues is a key factor behind the swift adoption of a circular economy. The concept of a circular economy is founded on the intricate equilibrium between ecological sustainability, economic growth, and social equity. It represents a departure from the traditional linear method to build a closed-loop system in which resources are continuously reused, recycled, and regenerated (Syberg et al., 2022). This holistic plan acknowledges the interdependence of environmental health, financial prosperity, and social fairness, fostering a mutually advantageous symbiotic relationship between human society and the planet. To develop a circular economy, it is important to undergo a substantial shift at various phases of a product's life cycle, encompassing design, manufacturing, use, and disposal, with a specific emphasis on plastic commodities. This modification requires innovative design thinking that prioritizes recyclability, durability, and ease of disassembly. It involves the revision of industrial processes in order to minimize both waste and energy consumption. Furthermore, consumer behavior plays a crucial role; individuals must adopt more sustainable purchasing patterns by selecting products that align with circular ideals. Embracing a comprehensive transformation safeguards the environment and enhances economic progress by creating fresh markets for recycled materials and fostering employment in sustainable industries.

As awareness of the detrimental effects of microplastics on ecosystems and human health grows, consumers are increasingly making more informed and eco-conscious purchasing decisions. This increased awareness serves as a powerful tool for fostering a deeper understanding of sustainable lifestyles. As a result, it encourages consumers to make educated decisions that prioritize products made using circular economy principles. Society may promote the use of ecologically friendly alternatives and stimulate the market for circular economy products by launching educational programs and increasing awareness. Ultimately, this cultural shift can significantly influence the creation of a more ecologically sustainable and harmonious future for both our planet and its residents.

However, obstacles continue to exist, and the importance of efficient communication remains crucial. It is essential to disseminate clear and accurate information about the link between microplastics and circular economy practices to gain widespread public support. Addressing misconceptions and explaining complex scientific concepts are crucial for ensuring that the public is well-informed and actively engaged. Overcoming conflicting agendas and fostering a sense of individual empowerment within the circular economy framework are also vital. By effectively addressing these issues and leveraging opportunities for collaboration, the interaction between the public and environmental initiatives can be optimized. This dynamic engagement supports the achievement of SDGs and helps build a more resilient and environmentally conscious society.

5.4. Environmental resilience

Microplastics present a diverse and significant environmental challenge requiring a comprehensive understanding and response. Their pervasive presence across a wide variety of ecosystems, including marine settings, freshwater systems, the atmosphere as a medium of transportation, and terrestrial habitats, is a major cause for concern. Microplastics have the potential to act as vectors for hazardous chemicals and pathogens, posing risks to the physiological health of diverse species and, consequently, the resilience of entire ecosystems. As the concentration of microplastics in the environment increases, the likelihood of their interactions with various components of ecosystems also rises. The impacts of microplastics on ecosystems can manifest in various ways, including physical damage, toxicity, and disruptions to ecosystem functions. For instance, microplastics can cause physical entanglement and obstruction in smaller organisms such as zooplankton, similar to the effects observed with macroplastics on larger fauna (Ziajahromi et al., 2017). Moreover, microplastics can disrupt biological functions by introducing toxicants into the food chain, which may ultimately affect human health through dietary pathways. The complex pathways through which microplastics make their way into food webs and have the potential to influence human health highlight the interconnected nature of environmental and public health concerns.

Microplastics also pose a significant threat to vulnerable ecosystems, particularly those with low genetic diversity and extreme ecological conditions. These ecosystems, already stressed by climate change, face additional challenges due to plastic pollution. The accumulation of microplastics in the environment over time is a direct result of human activities, which have increased carbon footprint and led to issues that threaten the survival of living species. Therefore, to mitigate the negative effects that plastic pollution has on the environment, proposals have been made to reduce greenhouse gas emissions by approximately 45% by 2030 and achieve net-zero emissions by 2050 (Sarma et al., 2022).

Additionally, microplastics contribute to the broader climate crisis. Similar to other aerosols, these particles scatter and absorb sunlight, influencing Earth's temperature. A study by Revell et al. (2021) measured the effective radiative forcing (ERF) of microplastics at approximately 0.75 milliwatts per square meter, compared to the ERF of other aerosols, which ranges from 0.71 to 0.14 watts per square meter. Although these values seem small, the cumulative effect of microplastics contributes to global warming by exacerbating the overall energy imbalance. On a global scale, this warming effect, in conjunction with greenhouse gases, outweighs the cooling impacts of other aerosols. Recent research by Parvez et al. (2024) has also indicated that airborne microplastics may facilitate cloud formation and disrupt atmospheric cooling.

To establish a definitive link between microplastic exposure and harm to biota and humans, it is essential to enhance the quality of analytical procedures (Ziani et al., 2023). However, a major limitation in addressing microplastic pollution is the lack of international standardization in methods used to assess microplastic exposure, hazards, and impacts. This hinders the development of effective mitigation strategies and emphasizes the need for a consistent and standardized approach to measuring policy performance. A crucial step towards addressing this limitation is to establish transparent and accessible metrics available for broad use. Implementing a uniform monitoring system across all plastic policies within a nation, with data collection synchronized across the same time periods, would enable direct comparisons between different policy types. To facilitate global coordination and comparability, data collection for plastic policies should be linked to international standardization metrics. The development of an internationally legally binding convention to end plastic pollution could provide a framework for establishing these metrics. By harmonizing data collection and analysis, policymakers can develop more effective strategies to mitigate the impacts of microplastics and ultimately protect environmental and human health.

6. Sunway city, a case study

Using the Quintuple Helix model in microplastic pollution control involves collaborating and integrating ideas from government, academia, industry, civil society, and the environment. Sunway City in Malaysia has embraced a forward-thinking sustainability approach by implementing a plastic ban, showcasing its dedication to environmental conservation as modelled in Fig. 12.

Sunway City demonstrated strong leadership by enacting comprehensive legislation to ban single-use plastics. This decisive action was underpinned by the government's commitment to environmental protection and public health by eliminating single-use plastic consumption by 2030 across various components. Policymakers worked closely with environmental experts to draft laws that are both practical and impactful, setting a clear timeline for the phase-out of plastics via Malaysia's Roadmap Towards Zero Single-Use Plastics 2018–2030 (MyGOV - The Government of Malaysia's Official Portal, *n.d.*).

Sunway University, a prominent university within Sunway City, is at the forefront of research and education on sustainability. It spearheads projects like "Turning Waste to Watts" which aims to convert plastic waste into valuable materials with reduced environmental impact. The team upcycles single-use plastic into carbon nanomaterials such as graphene through an innovative technique. The resulting materials show tremendous potential in developing advanced batteries and supercapacitors to store and discharge energy from renewable yet intermittent sources like solar and wind. These initiatives not only contribute to scientific understanding and innovation but also educate and engage the university community in sustainable practices (Abdah et al., 2024).

Within Sunway city, businesses and industry are actively engaging in sustainable practices, showcasing a concerted effort towards environmental stewardship. Notably, Sunway Hotels & Resorts has implemented impactful measures to combat plastic pollution, such as transitioning to biodegradable materials and adopting zero-waste

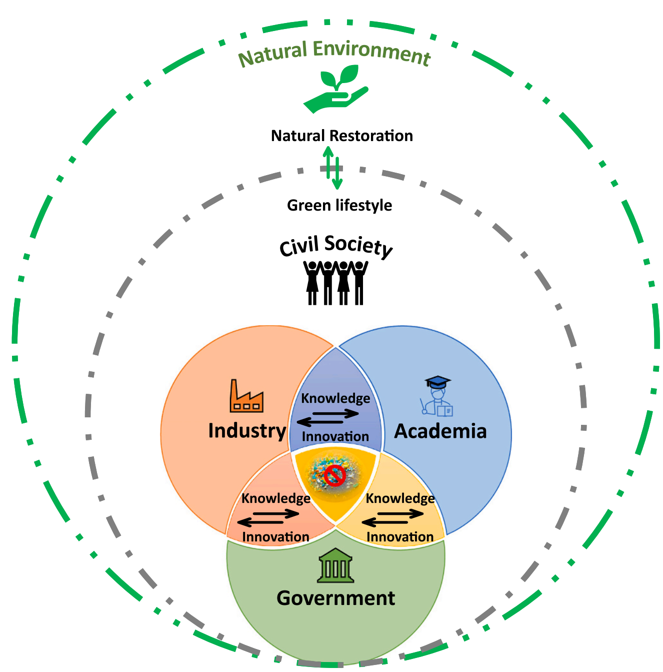

Fig. 12. Quintuple helix model for plastic ban in Sunway City.

policies across its chain of hotels and malls. An exemplar of their commitment is the cessation of single-use plastic straws in 2019, replaced solely with sugarcane alternatives, aligning with Malaysia's Roadmap Towards Zero Single Use Plastics 2018–2030. This proactive stance extends to partnerships with academia, particularly Sunway University, fostering research and development of eco-friendly materials. Such collaborations emphasize the pivotal role of the industry sector in driving innovation and sustainability, contributing to a collective effort towards a greener future (*Towards Zero Single-Use Plastic by 2030*, n.d.).

NGOs and community groups within Sunway City play a critical role in raising awareness about the dangers of plastic pollution and mobilizing community action and campaigns such as "Say No to Plastics". Through educational programs, community clean-ups, and recycling drives, civil society acts as both a conscience and a catalyst, encouraging sustainable habits among residents and businesses alike (*Say 'No' to Plastics! Sustainability, Sunway University*, n.d.)

The Quintuple Helix model recognizes the environment as an active participant in the development process. In Sunway City, sustainable practices such as the banning of plastics and the promotion of recycling are designed to protect and enhance the natural environment. The success of these initiatives is ultimately measured by their positive impact on the local ecosystem, demonstrating a harmonious balance between development and environmental preservation. However, there is no existing data on the effectiveness of the model yet, which limits our ability to fully assess its impact; further research and data collection are needed to evaluate its long-term outcomes.

Sunway City's application of the Quintuple Helix approach in tackling plastic pollution is a testament to the power of collaborative effort across all sectors of society. By engaging academia, industry, government, civil society and considering the environment's well-being, Sunway City sets a global benchmark for sustainable urban development. This model city not only addresses the immediate challenges of plastic waste but also fosters a culture of sustainability that will benefit future generations.

7. Limitations of the study

The integration of the Quintuple Helix approach into atmospheric microplastic management policies represents a significant step forward in addressing the complexities of microplastic pollution and its impact on planetary health. However, this approach is not without its limitations, which must be acknowledged and addressed to ensure effective policy implementation. One major challenge lies in coordinating efforts across the five key sectors involved in the Quintuple Helix model: academia, government, industry, civil society, and the environment. The complexity of aligning objectives, resources, and timelines across these diverse sectors can hinder seamless collaboration. Furthermore, the need to coordinate actions across local, national, and international levels further complicates the implementation of integrated policies.

Despite the increasing focus on microplastics research, significant data gaps remain, particularly concerning the long-term impacts of microplastics on human health and ecosystems. The lack of standardized methods for detecting and quantifying microplastics, especially in atmospheric contexts, further exacerbates these gaps. Additionally, the interdisciplinary nature of the Quintuple Helix approach necessitates the integration of diverse data sources, which can be inconsistent or incomplete, thereby limiting the effectiveness of policy decisions. While the Quintuple Helix model promotes a holistic approach, existing regulatory frameworks are often fragmented and inconsistent across different regions and sectors. This fragmentation hinders the development of comprehensive policies that effectively address microplastic pollution. Moreover, the lack of specific regulations targeting atmospheric microplastics creates a gap in the legislative landscape, limiting the ability to enforce meaningful changes.

The application of advanced technologies, such as AI and remote sensing for microplastics detection and monitoring, is a promising aspect of the Quintuple Helix approach. However, these technologies are often expensive and require significant investment in infrastructure and training. Financial constraints, especially in developing regions, can limit access to these technologies, thereby reducing the overall effectiveness of microplastic management policies. Public awareness and engagement are also crucial to the success of the Quintuple Helix model, but a lack of understanding among the general public about atmospheric microplastics can lead to resistance to policy measures or insufficient public support for necessary behavioral changes. Effective civil society engagement requires sustained efforts in education and outreach, which can be resource-intensive and time-consuming.

Additionally, the environmental and ecological impacts of microplastics, especially in the atmosphere, remain largely unknown. The Quintuple Helix approach, despite its thoroughness, is constrained by these uncertainties, hindering the creation of precise and effective management strategies. Moreover, the dynamic nature of ecosystems and the possibility of unexpected interactions between microplastics and other environmental pollutants introduce additional complexity to policy implementation. To overcome these challenges, continued research, enhanced coordination among stakeholders, and the development of more comprehensive and cohesive policies are necessary. By acknowledging and addressing these limitations, the full potential of the Quintuple Helix model can be realized in preserving planetary health in the face of microplastic pollution.

8. Conclusion

The Quintuple Helix model offers a comprehensive framework for addressing the complex issue of microplastic pollution, which poses significant environmental and health concerns. By integrating the perspectives of government, academia, industry, civil society, and the environment, this approach can inform the development of effective policies and strategies to mitigate microplastic pollution. Key policy interventions, such as banning single-use plastics, implementing EPR, and introducing a plastic tax, can significantly reduce plastic waste. Additionally, upgrading wastewater treatment facilities and promoting Eco-labeling initiatives can help minimize microplastic pollution. Furthermore, cross-disciplinary research is essential to address knowledge gaps and obstacles related to human-environment interactions with microplastics, transfer pathways, and associated risks. Ultimately, addressing the challenges and limitations that arise from prioritizing short-term economic gains and industry lobbying is crucial for advancing research and developing effective strategies to combat microplastic pollution, thereby protecting both human health and the environment.

CRediT authorship contribution statement

M. Dewika: Writing – original draft, Supervision, Project administration, Formal analysis. **Kalaimani Markandan:** Writing – original draft, Formal analysis. **J. Nor Ruwaida:** Writing – review & editing, Investigation. **Y.Y. Sara:** Writing – review & editing, Resources. **Anjan Deb:** Writing – original draft, Visualization. **N. Ahmad Irfan:** Visualization, Investigation, Formal analysis. **Mohammad Khalid:** Writing – review & editing, Resources, Project administration, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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