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Environmental Microplastics Pollution and Control Strategies

Authors: Environmental Pollution and Control Strategy of Microplastics

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Abstract

Over the past decade, marine microplastic pollution has garnered widespread attention from the international community. Research on the impacts and hazards of microplastics on marine life has directly prompted the enactment of regulations such as “prohibiting the addition of plastic microbeads to cosmetics.” However, to facilitate further substantive actions in the control and management of global marine microplastic pollution, more robust scientific evidence is required to demonstrate the ecological and health risks posed by microplastics. This article underscores the urgency of conducting research on the ecological and health effects of marine microplastics, outlines future research directions and associated challenges, proposes mitigation measures for marine microplastic pollution, and advocates for the adoption of a “precautionary principle” policy to enhance risk management and control capabilities for marine microplastic pollution.

Full Text

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Editor’s note In recent years, microplastics—especially marine microplastic pollution—have attracted global attention as an emerging environmental issue, and countries in Europe and North America have successively introduced relevant regulations. However, the environmental impacts of microplastics are not confined solely to the ocean; microplastic pollution in fresh water and soil has also drawn broad concern, while their hazards have yet to be fully observed, verified, and understood. To strengthen society-wide awareness and research on environmental microplastic pollution, *Bulletin of the Chinese Academy of Sciences* has specially organized the topic “Environmental Microplastics Pollution and Control Strategies.” From the perspectives of the ecological hazards of

microplastics, related analytical and detection methods, and domestic and international regulation and management (legislation), this topic offers a multi-angle discussion. It is hoped that more scientists and managers will join research and governance related to microplastics, providing scientific evidence and methodological and technical support for the formulation of relevant national policies and regulations and for the implementation of supervision and management. This topic was promoted under the guidance of Researcher Luo Yongming.

Strengthening Research on the Ecological and Health Hazards of Marine Microplastics to Enhance Risk Management Capabilities

Xu Xiangrong^{1*}, Sun Chengjun², Li Rong³, Wang Juying⁴, Wu Chenxi⁵, Shi Huahong^{6,7}, Luo Yongming⁷

1. South China Sea Institute of Oceanology, Chinese Academy of Sciences; Key Laboratory of Tropical Marine Biological Resources and Ecology, Chinese Academy of Sciences, Guangzhou 510301
2. First Institute of Oceanography, State Oceanic Administration; Key Laboratory of Marine Active Substances, State Oceanic Administration, Qingdao 266061
3. School of the Environment, Nanjing University; State Key Laboratory of Pollution Control and Resource Reuse, Nanjing 210023
4. National Marine Environmental Monitoring Center; Marine Debris and Microplastics Research Center, Dalian 116023
5. Institute of Hydrobiology, Chinese Academy of Sciences; State Key Laboratory of Freshwater Ecology and Biotechnology, Wuhan 430072
6. East China Normal University; State Key Laboratory of Estuarine and Coastal Research, Shanghai 200062
7. Institute of Soil Science, Chinese Academy of Sciences; Key Laboratory of Soil Environment and Pollution Remediation, Chinese Academy of Sciences, Nanjing 210008

Abstract Over the past 10 years, marine microplastic pollution has attracted broad attention from the international community. Research on the impacts and hazards of microplastics to marine organisms has directly promoted the promulgation of regulations such as the “ban on adding plastic microbeads to cosmetics.” However, to prompt further substantive action on the control of global marine microplastic pollution, fuller scientific evidence is still needed

to demonstrate that microplastics pose ecological and health hazards. This article emphasizes the urgency of research on the ecological and health effects of marine microplastics, expounds future research directions and the challenges faced, proposes countermeasures for marine microplastic pollution, and calls for the adoption of policies based on the “precautionary principle” to enhance risk management and control capabilities for marine microplastic pollution.

Keywords microplastic pollution, marine environment, ecological and health hazards, risk management and control

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In 2004, Professor Thompson of the University of Plymouth in the United Kingdom first proposed the concept of “microplastics” (microplastic) in *Science*^[1], initiating extensive academic research on marine microplastics. At present, plastic fibers, particles, or films with any size smaller than 5 mm can be recognized as microplastics^[2]. Compared with large-sized marine plastic debris, microplastics are more abundant and more widely distributed in the marine environment, and may exist in seawater and sediments

* Corresponding author

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as well as in organisms at different trophic levels; they are a class of emerging environmental pollutants^[3]. In 2011, marine microplastic pollution was listed by the United Nations Environment Programme (UNEP) as a new environmental issue and challenge facing the world^[4].

Since 2008, research on marine microplastics has entered a period of rapid development and has attracted broad attention from the international community^[5]. On the basis of establishing methods for the separation and identification of microplastics, numerous studies have confirmed that microplastics exist abundantly and widely in marine environments and organisms^[6], directly promoting the promulgation of regulations such as “banning the addition of plastic microbeads to cosmetics.” However, to prompt the international community to take further substantive action on the control of microplastic pollution, more adequate scientific evidence is still needed to demonstrate that microplastics pose ecological and health hazards.

Therefore, this paper analyzes the current ecological effects of marine microplastic pollution, emphasizes the urgency of research on the ecological and health effects of marine microplastics, discusses future research directions and the challenges to be faced, proposes countermeasures for marine microplastic pollution,

and calls for the adoption of policies based on the “precautionary principle” to enhance risk-control capacity for marine microplastic pollution.

1 Distribution and Transport of Microplastics in the Marine Environment

Microplastics have small particle sizes and low density, and can undergo long-distance, wide-ranging transport under the action of external forces such as wind, tidal currents, and ocean currents^[3]. They occur in all corners of the marine environment: from coasts to the open ocean, from the equator to the North and South Poles, from surface waters to deep-sea sediments, and even in sea ice and glaciers; microplastics are widely distributed^[6]. Studies have shown that river runoff is the most important pathway by which terrestrial microplastics enter the marine environment^[7]. According to statistics, approximately 1.15–2.41 million tons of plastic waste enter the ocean each year via rivers worldwide^[8]. At present, the average abundance of microplastic pollution in seawater is approximately (4.8×10^{-6}) – (8.6×10^{-3}) items/m³, with the highest reported abundance occurring in Swiss coastal waters^[9]. In the global marine environment, floating microplastics at the sea surface are mainly concentrated in the five oceanic gyre circulation zones of the North Pacific, South Pacific, North Atlantic, South Atlantic, and Indian Oceans^[10, 11]. According to 12 years (2001–2012) of long-term continuous monitoring, the abundance of microplastics in the North Pacific gyre circulation zone (156 800 items/km²) is significantly higher than that in other non-gyre circulation regions (1 864 items/km²)^[12], and these microplastics are mainly formed through the fragmentation or degradation of plastic pollutants discharged by countries around the world along their coasts^[10–12]. Although some surveys and research have already been carried out, studies on the distribution and transport characteristics of microplastics in different sea areas around the globe still need to be strengthened. Further understanding of the pollution characteristics of marine microplastics will help advance ecotoxicological studies and ecological risk assessments of microplastics based on environmental characteristics and concentrations.

In addition, characteristics of microplastics such as large specific surface area and strong hydrophobicity enhance their capacity to adsorb microorganisms, organic pollutants, heavy metals, and other substances on their surfaces^[13]. The strong adsorptivity and easy mobility of microplastics in the environment make them carriers for the transport and dissemination of toxic and harmful pollutants in the environment. Existing studies show that microplastics not only have a relatively high enrichment capacity for heavy metals and persistent organic pollutants, but also play a clear transport role in the environmental migration of pollutants and their accumulation and transfer within organisms^[14, 15]. Therefore, marine microplastics and the pollutants they carry have become a focus of attention in environmental science research.

2 Pollution Characteristics of Microplastics in Coastal Zones

The coastal zone is a region where land and sea interact, and microplastics readily accumulate there. In coastal zones, microplastics can be transported into river mouths and the ocean through terrestrial discharges, river transport, surface runoff, and other processes; they can also be pushed onto tidal flats by forces such as ocean currents, tides, and wind-driven currents. At the same time, microplastics are also generated, retained, or brought into tidal flats and nearshore areas through human activities such as coastal tourism, sea-salt drying, and aquaculture. Therefore, tidal flats, nearshore waters, and sediments in coastal zones are generally contaminated by microplastics. In particular, microplastic pollution is most severe in coastal aquaculture areas, tourist attractions, fishing ports, and other locations, and is dominated by fibrous, foamed, or fragment-type microplastics^[16]. The average abundance of microplastics in coastal-zone sediments is about 25–47 897 items/m², while the average abundance of microplastics in subtidal sediments ranges from 15 to 3 320 items/kg (dry weight)^[6]. In addition, the abundance of microplastics in tidal flats of different coastal ecosystem types differs markedly, mainly under the influence of factors such as river inputs and retention by plants (e.g., salt marshes and mangroves).

Microplastics originating from coastal zones have diverse and complex surface morphologies. For example, under the influence of chemical processes such as seawater, salinity, and oxygen; physical processes such as particle abrasion, light, and wind; and biological processes such as microbial erosion and degradation, the surfaces of microplastics on tidal flats crack or fragment, forming new functional groups, and particles may adhere in their pores or carry iron oxides^{[16]–[18]},

thereby enlarging their specific surface area and charge, facilitating the adsorption of organic pollutants in the environment^[19] and forming complexes of microplastics–endogenous pollutants (e.g., additives)–exogenous pollutants (e.g., persistent organic pollutants). These may remain in marine and coastal environments or migrate toward sea–land areas, posing threats to nearshore marine and coastal terrestrial ecosystems.

3 Ecological Effects of Marine Microplastic Pollution

3.1 Main Pathways by Which Microplastics Affect Marine Ecosystems

Organisms are important components of ecosystems, and the negative impacts of microplastics on the survival of marine organisms can threaten the health and stability of marine ecosystems. The ecological effects of microplastic pollution mainly include the impacts of ingestion by organisms, the toxic effects of microplastics and their composite pollutants, and the impacts of microplastics as vectors of invasive species^[20].

3.1.1 Effects of Microplastic Ingestion on Marine Organisms An important pathway by which microplastics enter marine organisms is through swallowing or feeding behavior. Because microplastic particles are small, it is difficult for marine organisms—especially juvenile organisms—to distinguish them from other food particles during feeding, which can easily lead to accidental ingestion of microplastics. Studies have shown that biological “feeding” on microplastics occurs at all trophic levels of marine ecosystems, including marine zooplankton^[21], benthic animals^[22,23], fish^[24], birds^[25], and even large mammals^[26]. In addition, microplastics may also enter organisms through behaviors such as adhesion or respiration^[27].

According to laboratory exposure experiments, microplastics ingested into the body produce toxic effects in some marine organisms, mainly including poor growth and development, reduced reproductive capacity, abnormal behavioral activity, abnormal gene expression, and decreased survival rates^[28]. When particle size decreases further, microplastics may be transferred via the digestive tract of marine organisms into the circulatory system, immune system, and even tissue cells, inducing inflammatory responses in the immune system and other effects^[29,30]. In addition to their effects on individual organisms, ingested or adhered microplastics can also be transferred through the food chain from organisms at lower trophic levels to organisms at higher trophic levels and even to humans, posing potential threats to marine organisms and human health^[20,31].

3.1.2 Toxic Effects of Microplastics and Their Composite Pollutants

Microplastics are characterized by small particle size, large specific surface area, and strong hydrophobicity. They readily interact with environmental pollutants, especially organic pollutants. These interactions mainly include three aspects: absorption, adsorption, and release. The absorption of pollutants by microplastics stems from differences in pollutant concentration between the microplastic surface and the liquid interface; pollutants can diffuse through the surface layer of microplastics and enter their interior^[32]. Some studies hold that pollutant adsorption by microplastics is a physical process, and that adsorption capacity depends more on the physicochemical properties of the microplastic surface, such as hydrophobicity and smoothness^[33]. Microplastics formed by polymerization of nonpolar monomers (such as polyethylene, polypropylene, and polystyrene) can adsorb organic pollutants from the surrounding polluted marine environment and enrich them on their surfaces to concentrations as high as one million times the environmental concentration^[34].

Microplastics exposed in the marine environment for long periods are ingested by marine organisms; under certain conditions, before being released from the digestive tract, they absorb and adsorb pollutants. Moreover, under conditions in the organism’s intestine, pollutants adsorbed to microplastics desorb more than 30 times faster than in seawater alone^[35]. The desorbed pollutants are then absorbed by biological tissues, thereby causing toxic effects^[36]. Not

only that, chemical agents added during plastic production to improve specific properties may, after seawater immersion and weathering, be released back into the environment, causing pollutant concentrations in polluted areas to be significantly higher than the original environmental background concentrations and thereby producing adverse effects on the health of aquatic organisms^[37]. It can thus be seen that composite pollution by microplastics and pollutants in the marine environment will have more complex impacts on marine organisms, and the related ecotoxicological effects and mechanisms of action urgently require further study.

3.1.3 Microplastics as Vectors of Invasive Species After microplastics enter the marine environment, microorganisms in the environment rapidly attach to their surfaces, and within about one week a relatively stable biofilm can form. Because microplastics are extremely abundant, scientists have estimated that the biomass of microorganisms on the surfaces of marine microplastics reaches 1,000-15,000 tons^[38]. Under the action of ocean currents and tides, on the one hand, microorganisms can use these “rafts” to migrate long distances across sea areas, thereby increasing opportunities for the migration and spread of marine microorganisms and causing invasion by alien species^[39]. On the other hand, pathogens may also be ingested by organisms via microplastics as carriers, or may cause biological toxic effects through direct contact^[40,41], even endangering human health. Recent studies show that harmful substances carried by marine microplastics can increase coral diseases, such as a 24% increase in skeletal eroding band disease, a 17% rise in white syndrome, and a 5% rise in black band disease^[42].

3.2 The Urgency of Research on the Ecological Effects of Marine Microplastic Pollution and the Challenges Faced

Research over the past 10 years has demonstrated, through a large body of evidence, the “ubiquitous presence” of microplastics in the ocean. However, the current state of research on the ecological risks of marine microplastics is as follows: in field environments, there is still no direct evidence showing that microplastics have affected ecosystems. Although laboratory experiments indicate that microplastics can produce a variety of toxicological effects on organisms, because laboratory studies are far removed from real environments, their data still cannot be well applied to ecological and health risk assessment of microplastics.

The main reason that research on the ecological effects of microplastics has fallen into its current bottleneck is that microplastics are a complex emerging pollutant, and our understanding of them remains far from sufficient. Yet the rapid and continuous increase in the quantity of microplastics in the environment, and their ubiquitous presence, have become indisputable facts. A lack of understanding of this issue will leave us unable to predict potential risks and unable to further advance strong policies for the management and control of marine microplastics. Therefore, it is currently urgent to strengthen research

on the ecological and health risks of marine microplastics, so as to provide scientific evidence and technical support for the formulation of effective management and control policies.

Finding field evidence of microplastic hazards and obtaining effective laboratory toxicological data will be the most severe challenges facing future microplastic research. To solve this problem, we need to further deepen our understanding of the essential characteristics of microplastic pollutants and, on this basis, establish a methodological system suitable for microplastic toxicological research.

First, the unique physicochemical properties of microplastics—such as size, shape, and density—determine their heterogeneous distribution in the environment. Moreover, the continual changes in multiple environmental conditions mean that microplastics in the environment are also in a state of dynamic change. Therefore, microplastics in the environment can essentially be regarded as a composite pollutant with multiple dynamic characteristics and heterogeneous spatial distribution.

Second, owing to limitations in current methods for sample collection, separation, and identification, only information on a fraction of the microplastics present in the environment can be obtained. There are very few reports, domestically or internationally, on microplastics at small particle sizes (e.g., particle size $< 20 \mu\text{m}$), and separation and identification of nanoscale microplastics in the environment have yet to be achieved[43]. At the same time, the characterization indicators for microplastics in the environment are mainly abundance, while size, shape, and color are often characterized only by broad ranges or proportions. In the aqueous phase, simply referring to characterization methods for chemical pollutant concentrations is not feasible for microplastics; establishing a “microplastic characteristic spectrum” may be a more comprehensive and effective method for characterizing microplastics in the environment.

Finally, in field investigations, to identify associations between microplastics and indicators of ecological effects in the field, it is necessary to consider and apply the concept of a microplastic environmental characteristic spectrum, and the key task is to seek evidence at the population level and above. In laboratory exposure experiments, only by preparing and using “environmentally characterized microplastics” can the possible ecological toxicity and risks of microplastics in the environment be revealed more accurately. In summary, if the past 10 years of marine microplastic research have demonstrated their “ubiquitous presence,” then one of the main goals for the next 10 years is to clarify their “ecological and health hazards.”

4 Response Measures for Marine Microplastic Pollution

4.1 Domestic and International Laws and Measures

To address increasingly serious microplastic pollution, the United Nations (UN), the International Maritime Organization (IMO), the Convention for the Pro-

tection of the Marine Environment of the North-East Atlantic (OSPAR), the European Commission (EC), the Helsinki Commission (HELCOM), and other international organizations have successively formulated relevant laws and regulations. The EU Marine Strategy Framework Directive (MSFD) uses 11 indicators to describe the quantity, properties, and potential impacts of microplastics in the marine environment, and has formulated investigation and monitoring reports[44]. With the release of the European Commission's Green Paper in 2013, global calls to address microplastic pollution have grown increasingly strong. In March 2015, the International Council for the Exploration of the Sea (ICES) drafted a specification for monitoring microplastic pollution in the stomachs of marine fish, as a response to OSPAR's January 2015 proposal to "establish standards for monitoring microplastics in shellfish and fish stomachs" [45]. In December 2014, the Netherlands, Austria, Luxembourg, Belgium, and Sweden issued a joint statement calling on the EU to ban the addition of microplastics to personal care products[46]. In December 2015, Obama signed the *Microbead-Free Waters Act*, which requires the reduction and cessation, before 2019, of the sale within the United States of all personal care products containing "intentionally added plastic microbeads." The United States thus became the first country in the world to comprehensively ban the addition of plastic microbeads to cosmetics. In addition, Canada, India, Australia, the United Kingdom, and other countries have successively enacted legislation banning the sale of personal care cosmetics containing microplastic particles.

The Chinese government and relevant competent departments have also shown great concern regarding the issue of marine microplastic pollution. For example, at the first special meeting of the China-U.S. "Ocean Protection" initiative in 2015, "preventing and reducing marine plastic-litter pollution" was listed as this ...

an important part of sub-strategic dialogue. In the 2016 Ministry of Science and Technology "13th Five-Year Plan" national key R&D program, the project "Research on Monitoring of Marine Microplastics and Assessment Technologies for Ecological and Environmental Effects" was successfully approved. In December 2017, the State Oceanic Administration issued the *2016 Bulletin on the State of China's Marine Environment*, explicitly stating that microplastics would be incorporated into environmental monitoring programs; pilot monitoring of floating microplastics in the surface waters of transects in the Bohai Sea, East China Sea, and South China Sea was carried out, and the distribution characteristics of marine microplastics in China were preliminarily grasped. In April 2018, the Chinese Research Academy of Environmental Sciences convened the kick-off meeting for preparation of the proposal for the Northwest Pacific Action Plan (NOWPAP) special project "Monitoring Methods and Evaluation of Marine Microplastics," aiming to strengthen comparability among NOWPAP member states in research on methods for marine microplastic investigation and assessment.

4.2 Social activities

Although more and more countries have begun to recognize that microplastic pollution has profound impacts on the environment, the legislative process for microplastic bans in fact remains unsatisfactory, and the governance situation for microplastic pollution is still not optimistic. The reason is that, from early scientific investigation and evidence collection to the drafting, adoption, and implementation of laws and regulations, a great deal of time is required and enormous resistance is encountered; this is of no help in addressing the imminent problem of microplastic pollution. However, if publicity and education activities positively guide public awareness and thereby promote reforms by relevant enterprises and institutions, this situation may be greatly improved. To accelerate the legislative process for microplastic bans and improve the effectiveness of microplastic pollution governance, the United Nations Environment Programme launched a campaign entitled “Cosmetics: Are Our Personal Care Products Polluting the Environment?” [47] Through a mobile application and a website called “Beat the Microbead,” the campaign helps consumers confirm whether cosmetics contain microplastics, with the aim of improving public awareness of microplastic pollution in aquatic environments.

At the same time, nongovernmental organizations (NGOs) have also played a fairly important role in actively protecting the marine environment. For example, in terms of raising public awareness, the Algalita Marine Research Foundation in the United States is currently investigating the distribution of microplastics and persistent organic pollutants (POPs) in five major ocean gyres. Project Kaisei, organized by the world nonprofit marine expedition research organization, is cooperating with the Scripps Institution of Oceanography in the United States to jointly study plastic debris in the North Pacific gyre. Each year, the International Coastal Cleanup campaign organized by the Ocean Conservancy collects all kinds of waste from beaches; domestic civil environmental organizations in China, such as the Shenzhen Marine Conservation Association and the Shanghai Rendu Ocean Community Development Center, have carried out marine plastic-waste cleanup activities by establishing shore-beach marine-litter monitoring networks and other means. With the joint efforts of governmental organizations and social organizations, preliminary results have been achieved in the management of microplastic pollution, and several multinational companies (such as Unilever and Johnson & Johnson) have announced that they will abandon the use of microplastics in cosmetics. It is worth noting that controlling microplastic pollution cannot rely only on policymakers and legal provisions; rather, it requires the joint efforts of multiple industries, including manufacturing, retail, tourism, and fisheries, in order to reduce microplastic pollution of the marine environment to the greatest extent.

5 Risk Management and Control of Marine Microplastic Pollution

5.1 Existing problems in the current management and control of marine microplastic pollution

As a new type of marine environmental pollutant, microplastics are still at an early stage in terms of related research and regulatory measures, which is mainly reflected in the following three aspects: Policy formulation still lacks strong evidence on ecological and health effects. As noted above, because marine microplastics are a new and complex environmental problem, research on their ecotoxicology remains seriously insufficient, and research on their health effects is almost blank. The current focus of management and control of marine microplastics is unclear. The internationally proposed “control of microbeads in cosmetics” has a very limited role in controlling environmental microplastic pollution, because microplastics added to cosmetics account for only a very small fraction of the sources of microplastics in the environment. Of course, this legislation is of very positive significance for raising public awareness. In situ governance of microplastics in the marine environment is extremely difficult, and the effect is minimal. Because microplastics are extremely small in size and very widely distributed, directly removing marine microplastics from the vast ocean is difficult to achieve.

5.2 Risk management and control

Although the international community and some countries have made unremitting efforts to prevent and reduce marine litter such as discarded plastics, because marine plastic litter crosses national and regional boundaries, this pollution has already become a global and complex environmental problem. China is the world's largest producer and user of plastics, and is also a major emitter of marine plastic litter^[48]; therefore, the problems of marine plastic litter and microplastic pollution that it faces are even more severe. To effectively control marine plastics and microplastic pollution, the following three points are proposed:

Recommendations.

- (1) **Vigorous efforts must be made to strengthen research on the ecological and health effects and risk assessment of marine microplastics.** With respect to ecological effects, emphasis should be placed on research in real offshore marine environments, especially in areas where microplastic pollution is severe, such as sites for recycling and processing waste plastics; with respect to health risks, priority should be given to studying the long-term effects on the quality and safety of aquatic products under multi-pathway exposure.
- (2) **The “precautionary principle” should be adopted in formulat-**

ing policies on marine microplastic pollution. The risk of marine microplastic pollution is a global and complex scientific issue. Judging from the research cycle for a class of pollutants and the currently prevailing ecological risk assessment standards, qualitative conclusions on the ecology and health of microplastics may still require 10–15 years. If control is delayed until all scientific evidence is fully available, the ecological and health risks brought about by marine microplastic pollution may no longer be controllable. Therefore, from the perspective of risk control, the current scientific data indicate that China must adopt the “precautionary principle” in regulating microplastics—that is, begin to take necessary actions gradually to prevent and contain further deterioration of marine pollution by microplastics.

- (3) **Scientific responses should be adopted in the control of marine microplastics to enhance risk-management capacity.** Given the characteristics of microplastics, both in-situ treatment of microplastics and direct control measures have very limited effects; source control is the key to managing marine microplastics. The most important source of microplastics is fragmentation of large plastics, and the ecological risks caused by large plastics have been clearly demonstrated by evidence. Therefore, reducing the amount of plastic products used and the flux of plastic waste entering the sea through the formulation of stricter management standards and regulations for plastic products, guidance of consumption habits, and development of efficient, low-cost degradable substitute plastic products is at the core of microplastic control. Another source of microplastics is plastic microbeads and primary plastic particles added to various products; however, control of primary particles should be addressed by formulating corresponding measures suited to China’s specific national conditions. China’s plastic-processing industry is well developed, and the primary microplastic pollution generated especially during waste-plastic processing may be more serious.

In summary, marine microplastic pollution has become a marine environmental issue that is widely present and of common global concern. China urgently needs to strengthen research on its ecological effects and health risks, so as to provide a scientific basis for the control of marine microplastics; at the same time, the formulation of policies for marine microplastic governance must adopt the “precautionary principle,” and scientific and effective control measures should be developed according to China’s national conditions to reduce marine microplastic pollution and protect our blue ocean homeland.

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Strengthening Ecological and Health Hazards Study of Marine Microplastics and Promoting Risk Regulatory and Control Capacities

XU Xiangrong^{1*} SUN Chengjun² JI Rong³ WANG Juying⁴ WU Chenxi⁵ SHI Huahong⁶ LUO Yongming⁷

(1 CAS Key Laboratory of Tropical Marine Bio-resources and Ecology, South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou 510301, China;

2 Key Laboratory of Marine Bioactive Substances and Analytical Technology, the First Institute of Oceanography, State Oceanic Administration, Qingdao 266061, China;

3 State Key Laboratory of Pollution Control and Resource Reuse, School of the Environment, Nanjing University, Nanjing 210023, China;

4 Marine Debris and Microplastics Research Center, National Marine Environmental Monitoring Center, Dalian 116023, China;

5 State Key Laboratory of Freshwater Ecology and Biotechnology, Institute of Hydrobiology, Chinese Academy of Sciences, Wuhan 430072, China;

6 State Key Laboratory of Estuarine and Coastal Research, East China Normal University, Shanghai 200062, China;

7 CAS Key Laboratory of Soil Environment and Pollution Remediation, Institute of Soil Science, Chinese Academy of Sciences, Nanjing 210008, China)

Abstract In the last decade, microplastic pollution in marine environments has aroused great concern of international society. The adverse biological impacts of microplastics on marine biota directly promote the issue of laws to ban the sale or distribution of cosmetics containing synthetic plastic microbeads. However, it is still necessary to find more scientific evidences for the testification of potential harms of microplastics to the ecological and human health in order to take the further action to manage and control the global microplastic pollution. This paper emphasizes that it is urgent to study the ecological and health hazards of marine microplastics. The prospects and challenges in this field are also discussed. Furthermore, the measures to solve microplastic pollution in marine environments are proposed and a precautionary principle in administration is recommended with an aim to elevate management capacity for controlling microplastic pollution in marine environments in the future.

Keywords microplastic pollution, marine environment, ecological and health hazard, risk management

XU Xiangrong is a professor and doctoral supervisor at the South China Sea Institute of Oceanology, Chinese Academy of Sciences, and was selected for the Chinese Academy of Sciences “Hundred Talents Program.” Her research direction is environmental geochemistry. She has published more than 120 papers in important international and domestic academic journals, including more than 90 academic papers in international SCI journals, with an h index of 29. She has obtained 3 national invention patents, led the translation of 1 book, and participated in compiling 10 book chapters. She was awarded the title of Outstanding Postgraduate Supervisor of the Guangzhou Education Base, Chinese Academy of Sciences, in 2014.

E-mail: xuxr@scsio.ac.cn

XU Xiangrong Professor at South China Sea Institute of Oceanology (SCSIO), Chinese Academy of Sciences (CAS). She was awarded the 100 Talent Program of CAS (2010) and the Excellent Postgraduate Supervisor by Guangzhou Branch of CAS. Her research fields mainly focus on marine environmental geochemistry and risk assessments. So far she has published more than 120 research papers, among which more than 90 papers are published in international SCI journals, with h index 29. Furthermore, she has published a translation book and 10 chapters of English monographs, and held 3 authorized patents.

E-mail: xuxr@scsio.ac.cn

*Corresponding author

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