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Review

(Micro)plastic crisis: Un-ignorable contribution to global greenhouse gas emissions and climate change

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ABSTRACT

The rapid development of plastic industrials has created a variety of plastic products, causing revolutionary progress in chemistry, physics, biology, and medicine. Large-scale production and applications of plastics increase their possibility of entering the environment. Previous environmental impact studies typically focused on the toxicity, behavior and fate; limited attention was paid on greenhouse gas emissions and climate change. With the increase of plastic waste, the threat of plastic pollution to the earth's climate has been gradually taken seriously. Evidence showed that greenhouse gas emissions occur at every stage of the plastic life cycle, including extraction and transportation of plastic raw materials, plastic manufacturing, waste treatment and entering the environment. The oil and gas industries used to make plastics are the main sources of greenhouse gas emissions (from the extraction of raw materials to the manufacture of plastics). Emissions of greenhouse gases during manufacture are mainly controlled by the production facilities themselves, usually depending on the efficiency, configuration and service life of equipment. Additionally, there are some unintended impacts, including transport requirements, pipeline leakage, land use, as well as impeding forests as natural carbons sinks. Recycling of plastic waste energy seems to be a good way to deal with waste plastics, but this process will release a lot of greenhouse gases. With this energy conversion occurring, the incineration of plastic packing waste will become one of the main sources of greenhouse gas emissions. Furthermore, plastics released into the environment also slowly release greenhouse gases, and the presence of (micro)plastics in the ocean will seriously interfere with the carbon fixation capacity of the ocean. In its current form, greenhouse gas emissions from cradle to grave of plastics will reach 1.34 gigatons per year by 2030 and 2.8 gigatons per year by 2050. This will seriously consume the global remaining carbon budgets, thereby threatening the ability of the global community to keep global temperatures rising by below 1.5 °C even 2 °C by 2100. In order to achieve this goal, the total global greenhouse gas emissions must be kept within the remaining carbon budget of 420–570 gigatons. The accumulative greenhouse gas emissions from cradle to grave of plastics may exceed 56 gigatons by 2050 (approximately accounting for 10%–13% of the total remaining carbon budget). As the plastic industry plans to expand production on a large scale, the problem will worsen further. The World Economic Forum forecasted that by 2030, the production and use of plastics will grow at an annual rate of 3.8%, and this growth rate will fall to 3.5% per year from 2030 to 2050. However, there are significant challenges and uncertainties in this estimation, and challenge and uncertainty factors come from all aspects. Recently, several organizations and researchers have started to discern the relationship between greenhouse gas emissions and plastic industrials, but relevant research on these impacts is still in its infancy. Consequently, the contribution of plastic pollution to greenhouse gas emissions and climate change should be given immediate attention and it needs to further explore the impact of plastic pollution on greenhouse gas emission and climate change. The implementation of measures to solve or alleviate the (micro)plastic crisis was critical necessary and proposed: (1) production control of global plastics; (2) improving the treatment and disposal of plastic waste; and (3) assessment of the impact of global environmental (micro)plastics on climate.

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Contents

1. Introduction

Plastics are one of the most common materials in the global economy. It has become an inevitable part of the material world and is constantly flowing in various human activities, from plastic packing (plastic bags and bottles), clothes, and equipment parts to building materials. Global plastic production has increased from 2 million tons in 1950s to 348 million tons in 2017 (PlasticsEurope, 2018) and 359 million tons in 2018 (PlasticsEurope, 2019), and China is the largest global plastic producer, followed by Europe and North America (Fig. 1). In general, plastics are synthetic organic polymers, which possess a backbone consisting entirely of C—C bonds, and the raw materials mainly come from fossil fuel, coal, oil and natural gas. Massive production, widespread applications and mismanagement of plastics increase their chances of entering the environment. Because plastics are difficult to be decomposed naturally, they have accumulated in land, freshwater and oceans for many decades. People have become increasingly aware of and concerned about the emergency crisis of plastics in the environment over the past decade, especially microplastics and nanoplastics (Hu et al., 2019a, 2019b; Shen et al., 2019d; Thompson et al., 2004). This concern has expanded to the impact of microplastics and nanoplastics on ecosystems and human health. New evidence has emerged that microplastics not only accumulate in the environment, but also in our food (Gündoğdu, 2018; Gerd and Elisabeth, 2014; Karami et al., 2017; Rochman et al., 2015; Yang et al., 2015) and water supplies (Kosuth et al., 2018; Mintenig et al., 2019; Oßmann et al., 2018; Pivokonsky et al., 2018), even in our bodies. These microplastic and nanoplastic particles can be transferred along the food chain to higher trophic level organisms, or into the human food chain through other pathways (Yang et al., 2015). Because of the large size of microplastics, most microplastics will accumulate in the intestinal tract of animals, but a small amount of microplastics can enter the circulatory system through the abundant lymph nodes in the intestinal tract. For the larger size of microplastics, it is difficult to penetrate into the organs. In the current literature, the toxicity evaluation of microplastics in *vivo* and in *vitro* is less. But for nanoplastics, they can cross the intestinal barrier into the circulatory system and eventually lead to systemic exposure (Bouwmeester et al., 2015). Because of its stable nature, nanoplastics are easy to accumulate in tissues and cells, causing metabolic disorders and local inflammation. Especially in patients with intestinal diseases, the changes of tissue permeability caused by inflammatory infection will significantly increase the transport and absorption of nanoplastics, thus furtherly increasing the risk of exposure (Shen et al., 2019c). Therefore, the pollution of microplastics and nanoplastics should be seriously considered, and the potential toxicity of microplastics and nanoplastics to human health should be fully studied.

Recently, the hidden crisis of (micro)plastics, on the other hand, is also emerging in this growing concern: the un-ignorable contribution of plastics to global greenhouse gas emissions and climate change. With the rapid expansion of global plastic production, plastic industrials have become the most important and rapidly growing source of industrial greenhouse gas emissions. Evidence showed that according to the distribution of about 4% of crude oil as the raw material of plastics, greenhouse gas emission from well-to-refinery in 2015 were estimated 68 million tons CO_2 equivalents (CO_2e) by determining the weighted average carbon intensity of oil well energy production in global 8966 on-stream oil fields in 90 countries (Masnadi et al., 2018). Greenhouse gas emissions not only come from the production and manufacturing process, but also from the extraction and transportation of raw materials of plastics, to plastic waste management, to plastics entering the environment (Hamilton et al., 2019). Geyer et al. (2017) reported that 72 plastic manufacturing facilities in the United States emitted about 17 million tons of CO_2e in 2014 during plastic manufacturing. Emissions during from well to manufacturing are controlled by the production facilities themselves, usually depending on the efficiency, configuration and service life of equipment, etc. Additionally, when plastics are discarded, the impact of plastics on global climate will not stop. Actually, most of its impacts on climate occur after the end of its life span (Royer et al., 2018). Currently, recycling, incineration and landfill are used to manage most plastic waste. Evidence has shown that the net emissions from plastic packing waste incineration were

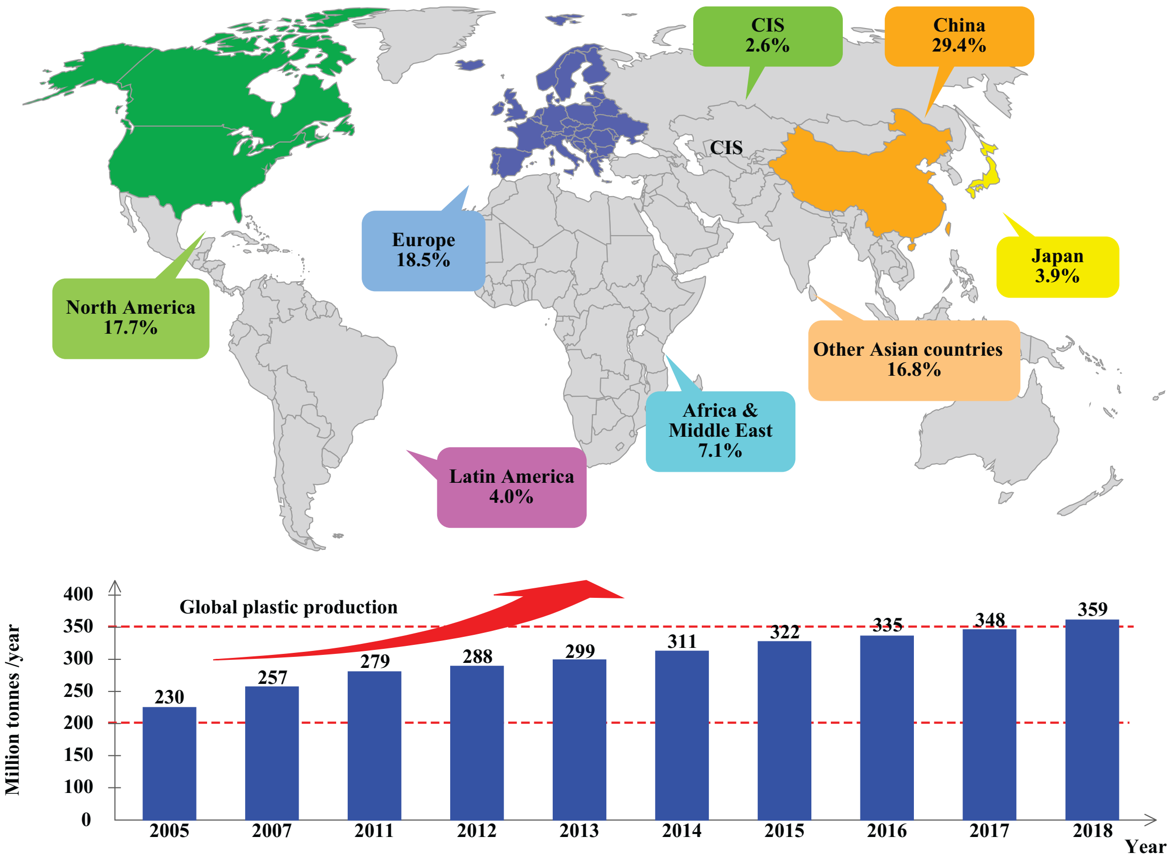

Fig. 1. Global distribution of plastic production.

estimated to be 16 million tons in 2015 (Fig. 2). And with the continuous plastic production, the net emissions from plastic packing waste incineration will increase to 84 and 309 million tons by 2030 and 2050, respectively (PlasticsEurope, 2016).

Since the Great Industrial revolution, the concentration of greenhouse gas in the global atmosphere has continued to rise. The concentrations of CO_2, CH_4 and N_2O have increased by 41%, 160% and 20% (Working Group I of the IPCC, 2013), respectively, compared with those before industrialization, which has caused serious global warming effects. During 1951–2010, greenhouse gases increased the global average temperature by 0.5–1.3 °C, and their continued emissions will lead to further global warming. It is expected that the global average surface temperature will increase by 0.3–0.7 °C by 2035 compared with 1986–2005, while it will increase by 0.3–4.8 °C in 2018–2100 (Moss et al., 2010). Global warming caused by the increase of greenhouse gas concentration has become a major environmental issue of concern to all mankind. Therefore, in October 2018, the Intergovernmental Panel on Climate Change's issued a special report, which proposed that global warming should be limited to 1.5 °C in order to avoid series of impacts of global climate change (IPCC, 2018). It means that to have any opportunity to keep within 1.5 °C, the global CO_2 emission level in 2030 needs to be reduced by about 45% compared with 2010, and carbon neutralization requires to be achieve by removing CO_2 to balance the remaining carbon budgets around 2050 (Hausfather, 2018). They furtherly reported that under this circumstance, the total warning of the reaming carbon budget cap is only 420 gigatons CO_2e not more than 570 gigatons in the carbon budget of 800 gigatons CO2e of energy and industrial sectors by 2100. The accumulative greenhouse gas emissions from cradle to grave of plastics may exceed 56 gigatons by 2050 (approximately accounting for 10%–13% of the total remaining carbon budget). Rapid plastic production expansion and emissions growth will exacerbate the climate crisis.

Moreover, a new study has confirmed that greenhouse gases are released during the degradation of environmental plastics (Royer et al., 2018). Although the emission by environmental degradation is relatively small compared to plastic incineration (about 2122 tons CO_2e per year), it is a continuous process. With the increase of plastic production and plastic waste, its impact will become more and more significant. The widespread presence of plastics in the ocean may have a negative impact on the carbon fixation. Ocean plants and animals play a key role in microbial carbon pump, which capture carbon from the atmosphere and transport it to the deep sea to prevent it from reentering the atmosphere. Evidence showed that the plastic pollution can reduce the ability of phytoplankton to fix carbon via photosynthesis (Nolte et al., 2017; Sjollema et al., 2016). Plastic pollution can also reduce metabolic rates, reproductive success rates and zooplankton survival rates, and zooplankton transfer carbon to the deep sea (Galloway et al., 2017; Long et al., 2017). Microplastics can also interfere with the operation of marine primary food chain/web (Shen et al., 2019a).

Despite limited information on greenhouse gas emissions consequence of plastics, the available data point to a fact that the climate impacts of greenhouse gas emissions from plastics are urgent. It is necessary to formulate emission reduction strategies and implement corresponding policies globally. The effect of "(micro) plastics & greenhouse gas emissions" on global climate has become a hot issue in the research of (micro)plastics. In this paper, greenhouse gas emissions of plastic from cradle to grave and the effects of (micro)plastics on carbon fixation capacity of the ocean are systematically discussed from different perspectives. Some future

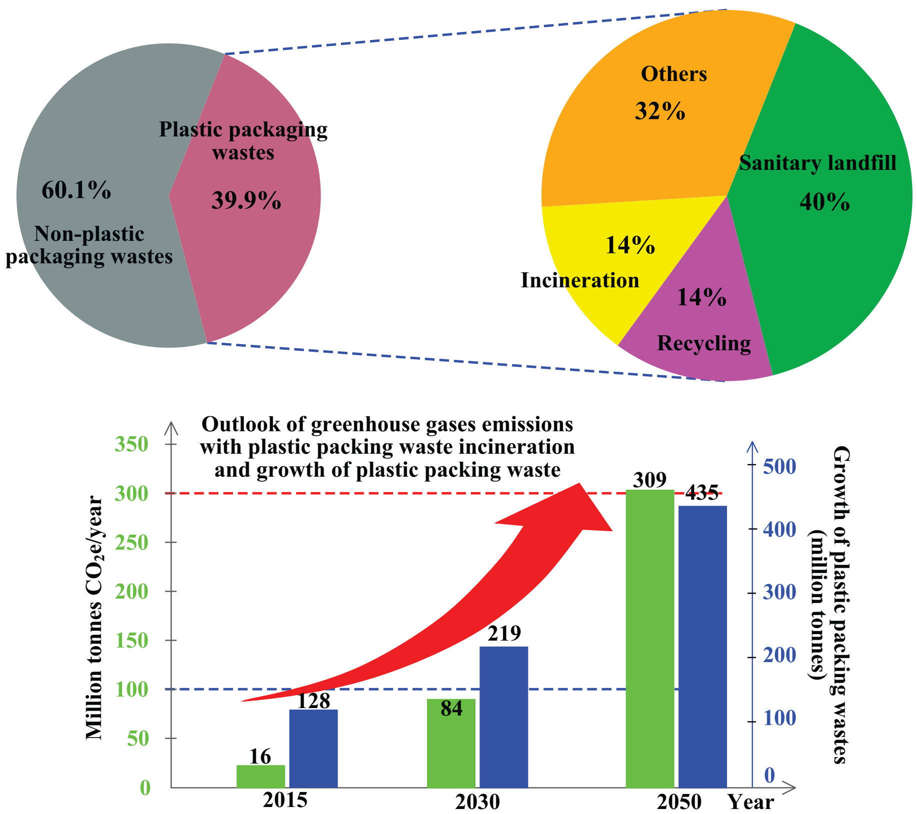

Fig. 2. Management of global plastic packing waste and outlook of greenhouse gases emissions from incineration.

research needs and challenges are also proposed in order to provide valuable reference for the formulation of relevant policies and scientific research.

2. Methods and analysis

In this paper, many published data were collected to make a preliminary assessment of contribution to global greenhouse gas emissions and climate change in plastic life cycle from cradle to grave. Greenhouse gas emissions at each stage of the plastic life cycle were introduced. Un-ignorable contribution of (micro)plastics to global greenhouse gas emissions and climate change were discussed from the following three aspects: (1) direct contribution to greenhouse gas emissions from plastics; (b) indirect contribution to greenhouse gas emissions from plastics; and (c) un-ignorable contribution to global climate change. All search engines (Web of Science, Google Scholars, ScienceDirect, etc.) and journal data were used. Greenhouse gas emissions and the effects of (micro)plastics on ocean's carbon fixation capacity were systematically discussed. In addition, the implementation of measures to solve or alleviate the plastic crisis was critical necessary and proposed: (1) production control of global plastics; (2) improving the treatment and disposal of plastic waste; and (3) assessment of the impact of global environmental (micro)plastics on climate.

3. Direct contribution to greenhouse gas emissions from plastics

3.1. Plastic waste management

There are several ways to manage plastic wastes: recycling, incineration, sanitary landfill and others. Plastic packing is one of the most problematic types of plastic waste, accounting for approximately 40% (PlasticsEurope, 2016), because it is usually designed for single use and ubiquitous in garbage and extremely difficult to be recycled. The flexible increasing use and multi-layer packing poses challenges to collection, separation and recycling. Although some plastics can be recycled, there are many steps involved, requiring separate collection, long-distance transportation, processing and remanufacturing. The high cost of these steps, the low commercial value of recycled plastics and the low cost of raw materials mean that plastic recycling has little profit and requires a lot of government subsidies. Fig. 2 illustrates the management methods of global plastic packing waste. Recycling is the preferred option for plastic packing wastes, followed by the incineration with energy recovery. 14% of plastic packing waste was disposed at incineration industries to energy recycling, 40% of that was to sanitary landfills, and only 14% of that was collected and recycled. Whatever treatment method is used, plastic waste will cause harm to human health and the environment. When plastic waste is burned, the greenhouse gases, mainly CO_2, will be released. Plastic wastes also contain harmful chemicals that are released into the environment in the form of additives. The impacts of plastics on climate will not end after they are used and discarded. Depending on the way they are treated, plastic wastes can also pose an equally serious threat to climate change when they are reach the waste stage. These different plastic waste management approaches are discussed in more detail in the following sections (Table 1).

3.1.1. Recycling

Plastic waste recycling refers to the physical process of recovering materials without changing the molecular structure of the polymers. Compared with other existing plastic waste management methods, plastic recycling has significant greenhouse gas benefits.

Table 1
Effects of plastic waste treatment on global greenhouse gas emissions.

Treatment	Advantages	Disadvantages	Greenhouse gas emissions	Reference
Recycling	Recycling and reusing waste plastic can both treat white pollution and save oil resources. Increased recycling can lead to negative greenhouse gas emissions by reducing raw material use and avoiding emission from producing the same amount of raw materials.	Only a small percentage of "recyclable" plastic wastes are recycled into the original products, even the most easily recycled plastics. Challenges lie in the use of colorants, additives and fillers in the plastic production process, pollution from consumer use, and loss of production during recycling. Low-grade plastic waste, such as multi-layer plastic packing, is particularly difficult to separate and dispose.	The carbon footprint of 1 ton recycled PET tray containing 85% of recycled content from cradle to grave was 1.538 ton CO_2e. 3.17 million tons of plastic waste recycled in 2014 could save approximately 3.2 million tons of CO_2e, equivalent to 670,000 cars on the road in a year, and plastic packing recycling into new products could save 1.4 million tons of CO_2e.	Dormer et al. (2013), US EPA (2016)
Incineration	Incineration is recently considered a simple solution to large-scale contamination of land-based plastics. It not only can effectively manage plastic pollution, but also can provide energy and heat for use.	Greenhouse gases, usually CO_2, can be produced during the plastic waste incineration. With this energy conversion occurring, the incineration of plastic packing waste will become one of the main sources of greenhouse gas emissions.	Each ton of plastic packing waste generally contains approximately 79% combustible carbon, which will release 790 kg of carbon into the atmosphere, or about 2.9 tons of CO_2.	Hamilton et al. (2019)
Sanitary landfill	Sanitary landfill has the advantages of mature technology and low treatment cost, which is the main way of centralized disposal of urban plastic wastes.	The landfill refuse has not been treated innocuously. There are hidden dangers such as biogas and heavy metal pollution. Its waste leakage liquid will pollute groundwater resources for a long time	Up to now, there is no record of greenhouse gas emissions from plastic landfills. But this does not exclude the possibility of greenhouse gas emissions from plastic landfills.	Teuten et al. (2009)
Others (open burning)	Simple treatment and low treatment cost	It has a serious impact on climate and human health because it occurs at lower temperature and is performed without any air pollution control than in a waste incinerator.	Plastic packing waste can emit 2.9 million tons of greenhouse gas per ton of plastic packing waste when it is burned in the open air.	Hamilton et al. (2019)

In theory, increased recycling can lead to negative greenhouse gas emissions by reducing raw material use and avoiding emission from producing the same amount of raw materials. A research carried out by Dormer et al. (2013) investigated the carbon footprint related to plastic pallets, used as plastic packing. The results showed that the carbon footprint of 1 ton recycled polyethylene terephthalate tray containing 85% of recycled content from cradle to grave was 1.538 ton CO_2e. According to the US Environmental Protection Agency, 3.17 million tons of plastic waste recycled in 2014 could save approximately 3.2 million tons of CO_2e, equivalent to 670,000 cars on the road in a year, and plastic packing recycling into new products could save 1.4 million tons of CO_2e (US EPA, 2016). The efficiency of producing new plastics from recycled plastic packaging materials in terms of greenhouse gas emissions is more than three times higher than the efficiency of producing the same products from original raw materials. This is mainly due to the replacement of original products and the saving of renewable energy.

However, actually, only a small percentage of "recyclable" plastic wastes are recycled into the original products (Fig. 2), even the most easily recycled plastics, polyethylene terephthalate (PET) and high density polyethylene (HDPE) (MacArthur et al., 2016). Challenges lie in the use of colorants, additives and fillers in the plastic production process, pollution from consumer use, and loss of production during recycling. Low-grade plastic waste, such as multi-layer plastic packing, is particularly difficult to separate and dispose. Furthermore, the low price of raw plastics, which are overproduced, further inhibits the recyclability of plastics, reduces the economic value of recyclable plastics and hinders investment in appropriate infrastructure and markets (OECD, 2018). Despite all the obstacles mentioned above, each cycle of the recycling process shortens the length of the polymer chain, thus leading to mass loss and requiring further material treatment. Due to these challenges and limitations, plastic recycling alone will not reduce greenhouse gas emissions commensurate with the life cycle of plastic. Therefore, plastic recycling as the main method to solve the plastic crisis still has a long way to go.

3.1.2. *Incineration*

Incineration is recently considered a simple solution to large-scale contamination of land-based plastics. It not only can effectively manage plastic pollution, but also can provide energy and heat for use. Incineration converts plastic wastes into bottom ash, fly ash, combustion gas, waste water, and generated heat by combustion. In urban areas, plastic waste incineration happens in waste incineration power generation facilities and other industrial facilities, mainly including paper mills, cement kilns and utility boilers, in which gathered plastic waste is burned via the co-incineration of biomass or fossil fuel. However, greenhouse gases, usually CO_2, can be produced during the plastic waste incineration. Evidence showed that each ton of plastic packing waste generally contains approximately 79% combustible carbon, which will release 790 kg of carbon into the atmosphere, or about 2.9 tons of CO_2 (Hamilton et al., 2019). Even taking into account the power generated by the combustion process, a ton of plastic packing waste will produce about 0.9 tons of net CO_2e emissions. It is recognized that net greenhouse gas emissions can be significantly reduced by energy recovery and through compensating for fossil energy demand. Therefore, the power generation potential of plastic packing waste combusted in facilities can be quantified by average calorific value of these wastes and power generation efficiency of an incinerator. Possibilities for offsetting greenhouse gas emissions may vary by a variety of factors, such as the composition of burning waste materials and the type of energy used in incinerators. When the moisture content of wastes is too high or the calorific value of wastes is too low, additional other materials with high calorific value, such as fossil fuel, are required to maintain incineration. For instance, the proportion of coal in waste incinerator is as high as 50%–70% in China to maintain incineration, which is owing to the large amount of organic waste. According to a report led by Hamilton et al. (2019), the net greenhouse gas emissions from plastic packing waste incineration are estimated to be 16 million tons in 2015. These figures are based on the estimated amount of plastic packing waste gathered for management (40% of all plastic waste). In addition, the US Environmental Protection Agency reported also showed 11 million tons of CO_2e emissions from waste incineration in the United States in 2015, more than half of which came from plastic waste (5.9 million tons), including plastic packing and unpacked plastic waste (US EPA, 2018b). The impact of plastic waste incineration on climate in the United States is equivalent to 1.26 million cars driving for a year or consuming more than 5 billion gallons of gasoline.

On the good side, while plastic packing waste mixed with other municipal solid waste is burned in a waste incinerator, the heat and electricity will be generated, which usually are generated by other fossil fuels such as coal and natural gas. Additionally, new electricity production also can come from renewable solar, wind power facilities and geothermal energy. It is estimated that global natural gas incineration generates almost five times as much as electricity as renewable solar, wind and geothermal energy (US Energy Information Administration, 2018). As the proportion of renewable energy in the energy mix continues to grow in the coming decades, the greenhouse gas emissions from plastic incineration will relatedly increase with the increase of electricity production. Plastic packing production is forecasted to nearly double by 2030 and nearly quadruple by 2050 on the basis of the increase of plastic packaging production and the expansion of incineration capacity (MacArthur et al., 2016). Fig. 2 shows the outlook of greenhouse gases emissions from plastic packing waste incineration. Greenhouse gas emissions from plastic packing waste incineration will increase by 84 and 309 million tons in 2030 and 2050, respectively. With this energy conversion occurring, the incineration of plastic packing waste will become one of the main sources of greenhouse gas emissions. Whether plans to increase the industrial incineration and expand petrochemical construction are realized in 2030 and 2050, the impact of plastic waste management on global climate change will be more significant.

3.1.3. Sanitary landfill

Sanitary landfill usually refers to use clay and/or plastic liners to isolate waste from groundwater and add a layer of soil to reduce waste exposure to the air. As shown in Fig. 2, sanitary landfills are still the main treatment method for plastic packing waste. Greenhouse gas emissions from sanitary landfills mainly come from organic waste, such as waste food, wood and paper decomposition. Up to now, there is no record of greenhouse gas emissions from plastic landfills. The emission related to landfill plastic packing waste come from the classification and treatment of pre-landfill waste and the use of fossil fuels related to the transport of waste from collection sites to landfills. But this does not exclude the possibility of greenhouse gas emissions from plastic landfills.

Because plastic packing waste landfill has less impact on global climate change than incineration, in some cases such as absence of a collection system or appropriate material recovery infrastructure, landfill may be the only option for plastic waste management. However, landfills pose significant environmental health risks due to the infiltration of toxic substance from plastics on soil and groundwater. As such, landfills cannot be regarded as a long-term solution for plastic waste management (Teuten et al., 2009). More efforts are needed to explore more reasonable methods for plastic waste management.

3.1.4. Others

In addition to the above management methods, approximately 32% of plastic packing waste are not managed (Fig. 2). There are several possibilities for unmanaged plastic packing waste, including open dumping, burning, and littering, which are prevalent in places with less developed waste management infrastructure. However, the impact of unmanaged plastic packing waste on global climate change is not yet clear. Open burning, a method of burning unnecessary combustible material in natural, has a serious impact on climate and human health because it occurs at lower temperature and is performed without any air pollution control than in a waste incinerator. Evidence showed that plastic packing waste would emit 2.9 million tons of greenhouse gas per ton of plastic packing waste when it is burned in the open air (Hamilton et al., 2019). Generally, the impact of dumping plastic waste on the ground on climate change is not clear. Recently, a research led by Royer et al. (2018) reported that degradation of plastic exposed to sunlight in terrestrial environment may release greenhouse gases at a higher rate than in the aquatic environment. However, the annual rate and magnitude of these emissions have not yet been measured. Despite significant data gaps in many treatment approaches, exploring a range of greenhouse gas emissions from unmanaged sources can reveal the full threat to global climate change by plastic packing waste. The impact of unmanaged plastic packing waste on global climate change largely depends on the proportion of open burning, and also contributes to other global environmental problems.

3.2. Degradation of environmental plastics

The greenhouse gas emissions and effects of (micro)plastics will not stop while (micro)plastics are discarded. Once plastics are released into the environment, the effect of pre- and post-consumption waste from polluting urban streets, natural areas, landfills, farmlands, and waterways, and following to the ocean via freshwater streams and rivers, has been least researched and poorly understood. Plastics would span centuries or more in the environment. To date, three main conclusions have been drawn from the research on marine plastic pollution. Firstly, plastic debris can be found in the most far-flung corners of the globe, including the deep oceans and polar region, and can break into smaller species, microplastics (Thompson et al., 2004). Secondly, (micro)plastics can act as vectors for a mix of toxic chemicals and living organisms, causing harm to the environment (Shen et al., 2019d; Teuten et al., 2007; Velzeboer et al., 2014). Finally, microplastics can harm aquatic organisms by ingestion and entanglement at all levels of the food chain/web, leading to harm to humans through a variety of pathways (Li et al., 2015; Sharma and Chatterjee, 2017).

Degradation of plastics can cause chemical changes, thereby reducing the molecular weight of polymers. Plastic degradation begins when exposed to environmental conditions. With time, polymers become weak and brittle, and decompose into small pieces. Weathering processes hydrolysis, oxidation degradation, biodegradation and solar radiation contribute to this breakdown in the environment. Interestingly, the photodegradation of plastics can cause greenhouse gas production. Recently, a research studied by Royer et al. (2018) has firstly revealed the greenhouse gas emissions from plastics under natural conditions in both terrestrial and marine environments. It investigated some of most used types of plastics, including high-density polyethylene, low-density polyethylene (LDPE), polypropylene, and polystyrene, from virgin plastic and marine plastic sources. Plastics were exposed to ambient solar radiation and ultraviolet radiation for several months. It was found that measurable amounts of two greenhouse gases (methane, CH_4 and ethylene, C_2H_6) were produced by these plastics after radiation exposure. The rate of emissions was in a range 10–4100 pmol per day per gram for CH_4, and approximately 20–5100 pmol per day per gram for C_2H_6 (Royer et al., 2018). The highest emission rate for CH_4 and C_2H_6 was observed from LDPE. Additionally, the morphology of plastics and aged level also influenced the extent to which it emitted greenhouse gases. Plastic cracking, breaking and fracturing increase the surface area and increase the total surface which can be used for photodegradation.

With the decomposition of plastics into microplastics even nanoplastics, the production rate of greenhouse gases gradually increases. The authors reported that as the ocean weathers and degrades, the surface area of plastics increases, and the same amount of plastics will release more and more greenhouse gases as time goes on (Royer et al., 2018). Greenhouse gases emissions from virgin plastics increased with time, while those from aged plastics remained unchanged. In addition to CH_4, greenhouse gas emissions from virgin plastics were significantly greater than that from aged plastics. This is probably because of the occurrence of some anti-ultraviolet plasticizers to inhibit the effects of ultraviolet radiation and slow down the degradation process (Royer et al., 2018).

Based on the emission rate of greenhouse gases reported by Royer et al. (2018), the annual rate from marine plastics can be preliminarily and roughly estimated using a standing stock of sea surface microplastics and greenhouse gas emission rates. The standardized prediction models of global mass done by Van Sebille et al. (2015) estimated that the amount of small microplastic debris floating on the sea surface ranging from 15 to 51 trillion particles and weight between 93,000 and 236,000 tons. The highest emission rate of methane by LDPE was 55 nmol per day per gram (Royer et al., 2018). As such, at the worst case, the annual emission is 4.738×10^{15} nmol/year, that is, 75.8 tons/year. Utilizing the global warming potential of methane, greenhouse gas emissions of 2122 tons CO_2e are annually produced. Moreover, the annual production of ethylene is 51 tons via the same calculation.

However, there are significant challenges and uncertainties in this estimation. Firstly, the rate and amount of plastic input into the ocean is variable. The mentioned above methods for estimating greenhouse gas emissions assume that both the rate and amount of plastic entering the ocean remains constant. According to the current production and use, plastic production is expected to increase by 33–36% by 2050 (PlasticsEurope, 2018). If mitigation measures are not taken to prevent land input, the annual methane and ethylene emissions from marine surface plastics will continue to grow. Secondly, these estimations are based on the emission rates of greenhouse gases from microplastics exposed to ultraviolet radiation on the sea surface in tropical environments. They do not include plastics that are slightly immersed in the water column and all possible emission rates for varying degrees of plastic degradation. Furthermore, these calculations only take into account the highest hydrocarbon gas producing plastic type, LDPE, to represent the entire floating plastics. Although PE accounts for most of the plastics found in the environment, the calculation still exist many uncertainties. Thirdly, the aging degree and treatment of plastics also affect the estimation of greenhouse gas emission. The age of plastics is usually unknown at the time of collection, and the subsequent treatment methods are also uncertain. The annual estimates take into account only a small fraction of marine plastics found on the sea surface, do not take into account plastic emissions from larger debris such as water columns, shoreline grounding, or fishing gear. Additionally, plastic "removal" rates from ocean surface also affect the estimated emissions rates. The grounding and final sinking of suspended plastics may be the main reasons for "surface removal". Moreover, animal ingestion, transport to land and reflux, and dropping of fecal particles to the seabird may also contribute to "surface removal". Finally and more significantly, plastics produce more greenhouse gases when exposed to air than immersed in water. According to the report performed by Royer et al. (2018), 2.3 times more methane and 76 times more ethylene were produces from LDPE in air than in water. Compared with plastic exposed to air, the emission rate in water is different because of the accumulation of temperature and heat. This demonstrated that more research is needed on the emission of plastics exposed to higher ambient temperatures. Besides, not only the plastic floating on the ocean surface, but also the accumulation of large quantities of plastics in other places such as beaches, rivers and terrestrial environments worldwide, as well as the estimation of plastic decomposition is still very low. Greenhouse gas emissions must take into account not only the immense volume of emission worldwide, but also the various environments in which they occur.

The production rate of greenhouse gases from plastics may seem mild compared with other ways of releasing greenhouse gases such as industrial activities, vehicle transportation even agricultural activities. Nevertheless, as plastic production increases and the amount of mismanaged waste plastics entering oceans increases (Jambeck et al., 2015), greenhouse gas emissions from degrading plastics will likely increase and may warrant increased concern. There are still many limitations and challenges, but Royer et al. (2018) have already taken the lead. Future studies are needed to address the role and mechanism of plastics in releasing methane, ethylene, and other greenhouse gases.

4. Indirect contribution to greenhouse gas emissions from plastics

4.1. Potential emissions during plastic manufacturing

Olefins are important raw material for plastic production. In 2014, the global ethylene production was 134 million tons and propylene is the second most common raw material after ethylene, with an estimated demand of 89 million tons in 2014 (Plotkin, 2015). Olefins are monomers and can bind together to form long chains. In order to become plastics, olefins are stitched together to from extremely long chains of molecules or polymers. Plasticizers are also usually added in the production process. Olefins are generally produces by pyrolysis of fossil fuels such as coal and crude oil. Natural gas is also very important in olefin production. The post-production process of olefins depends on what is produced, not on the raw materials from olefins. Whether coal, oil and natural gas are used as raw material depends on their cost and availability (Hamilton et al., 2019).

Greenhouse gases are inevitably released during the production of plastics, including mining, transportation, refining and manufacturing (Fig. 3). The global greenhouse gas emissions from well-to-refinery in 2015 are estimated to be 1.7 gigatons CO_2e through determining the weight average carbon intensity of oil well energy production in global 8966 on-stream oil fields in 90 countries (Masnadi et al., 2018). According to the distribution of about 4% of crude oil as the raw material of plastics, it is estimated that global oil production contributes approximately 68s million ton of CO_2e to the emission of plastic production in 2015. In contrast, the coal-to-olefin process emits 7.1–10.6 tons of CO_2e per ton of olefin production (ICIS, 2013). In addition, the oil and gas industry is also the largest source of methane emissions (US EPA, 2018a). However, the impact of coal, oil and gas development related to the plastic industry on global greenhouse gas emissions remains poorly understood. In some cases, direct data are rarely, such total emissions from mining, transportation and refining process (Fig. 3), and other projects seem to underestimate other known source of data. Furthermore, there are some unintended impacts, including transport requirements, pipeline leakage, land use, as well as impeding forests as natural carbons sinks. Up to now, new infrastructure related to natural gas production are being constructed or actively proposed, and there will be more expansion plans in the coming decades. These infrastructures are not only driven by the demand of natural gas in energy production, but by the rapid expansion of plastic production. Therefore, the total impact of coal, oil and gas extraction on global greenhouse gas has been worrisome. Without significantly reducing these large

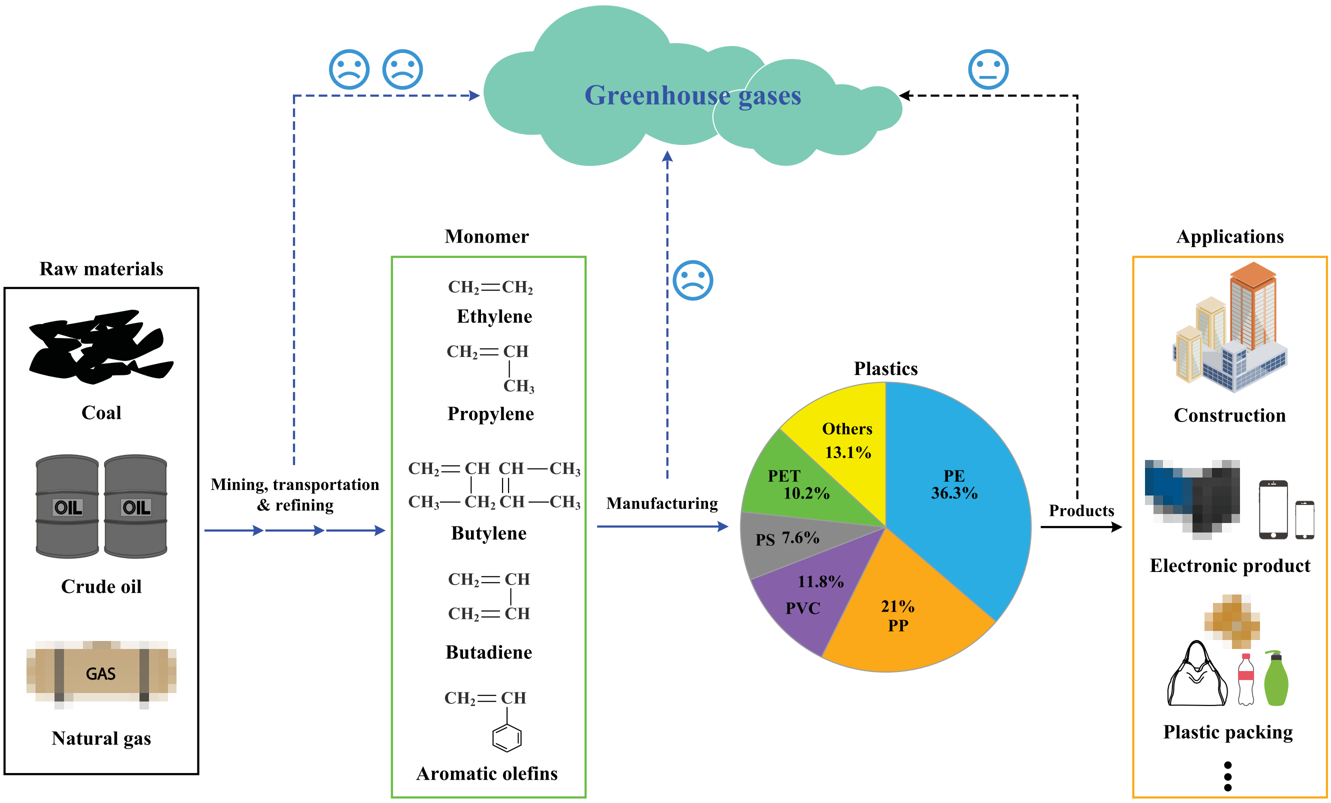

Fig. 3. Whole processes of plastic production and potential emission pathways greenhouse gases.

industrial, it is unlikely to reduce the greenhouse gas emissions, while these industries are only the first step in plastic production.

Moreover, greenhouse gas emissions also occur during the production and manufacture of plastics (Fig. 3). Process emissions include from petrochemical raw materials converted into useable products such as ethylene, propylene, etc. (Posen et al., 2017). Emissions of greenhouse gases during manufacture are controlled by the production facilities themselves, usually depending on the efficiency, configuration and service life. According to reports, in 2014, 72 plastic manufacturing facilities in the United States emitted 46,324 tons of CO_2e per day, about 17 million tons a year (Geyer et al., 2017). However, numerous industrial processes and pathways for the conversion of fossil fuels into plastics, as well as the number of production stages, make it extremely difficult to attribute greenhouse gas emissions from industry to plastics production. Nonetheless, limited information on greenhouse gas emissions from whole plastic production process, the available data showed that plastic production would lead to greenhouse gas emissions. Plastic production is global, and greenhouse gas emissions and their impacts are also global. Consequently, these two globalities need more cooperation and coordination around the world.

4.2. Potential effect of (micro)plastics on carbon fixation in the ocean

In addition to direct emissions of greenhouse gases, plastic pollution, especially marine plastic pollution, may play a less direct but ultimately greater role in climate change by impacting species that form the basis of the marine food chain (Brierley, 2017). The oceans are the most important part of the global carbon cycle. The effects of marine plastics on ecosystems responsible for the gas exchange and circulation of CO_2 may be resulting in more greenhouse gas emissions. Phytoplankton, as a primary producer in the ocean, takes CO_2 from the air via photosynthesis and provides food sources and oxygen security for marine living organisms. However, evidence has shown that the widespread presence of microplastics in the ocean has a negative impact on its growth, leading to changes in phytoplankton communities, thus destroying the stability of marine ecosystems (Toseland et al., 2013). Shielding and reflecting of sunlight by floating microplastics on the sea surface will hinder the absorption of sunlight by phytoplankton and affect their photosynthetic capacity (Fig. 4). Laboratory experiments showed that microplastic exposure is toxic to phytoplankton, and the smaller the particle size, the higher the toxicity (Anbumani and Kakkar, 2018). This toxicity can be able to disturb phytoplankton feeding, physical ingestion, metabolism, even reproduction. A research carried out by Sjollema et al. (2016) showed that microplastics could reduce the photosynthetic rate of the polluted phytoplankton by 45%. In addition, other similar studies also reported that microplastics can adsorb on the surface of algae, which hinders the adsorption efficiency of light and CO_2 by cells, thus reducing the rate of photosynthesis and respiration and affecting the growth and reproduction of algae (Bhattacharya et al., 2010; Nolte et al., 2017). These effects are of practical significance outside the laboratory. Phytoplankton, such as *Keratinococcus* spp. and *Erythrocystis salina* spp., can secrete polysaccharides and other viscous substances to form algae cultures when the growth conditions are limited, and polymerize with the surrounding microplastics (Long et al., 2017; Underwood et al., 2004). This behavior can not only change the density of algae clusters and affect their distribution in seawater (Long et al., 2015), but promote the transfer of microplastics to seabed (Ward and Kach, 2009). Microplastics can also increase the active oxygen content of algae, decrease the

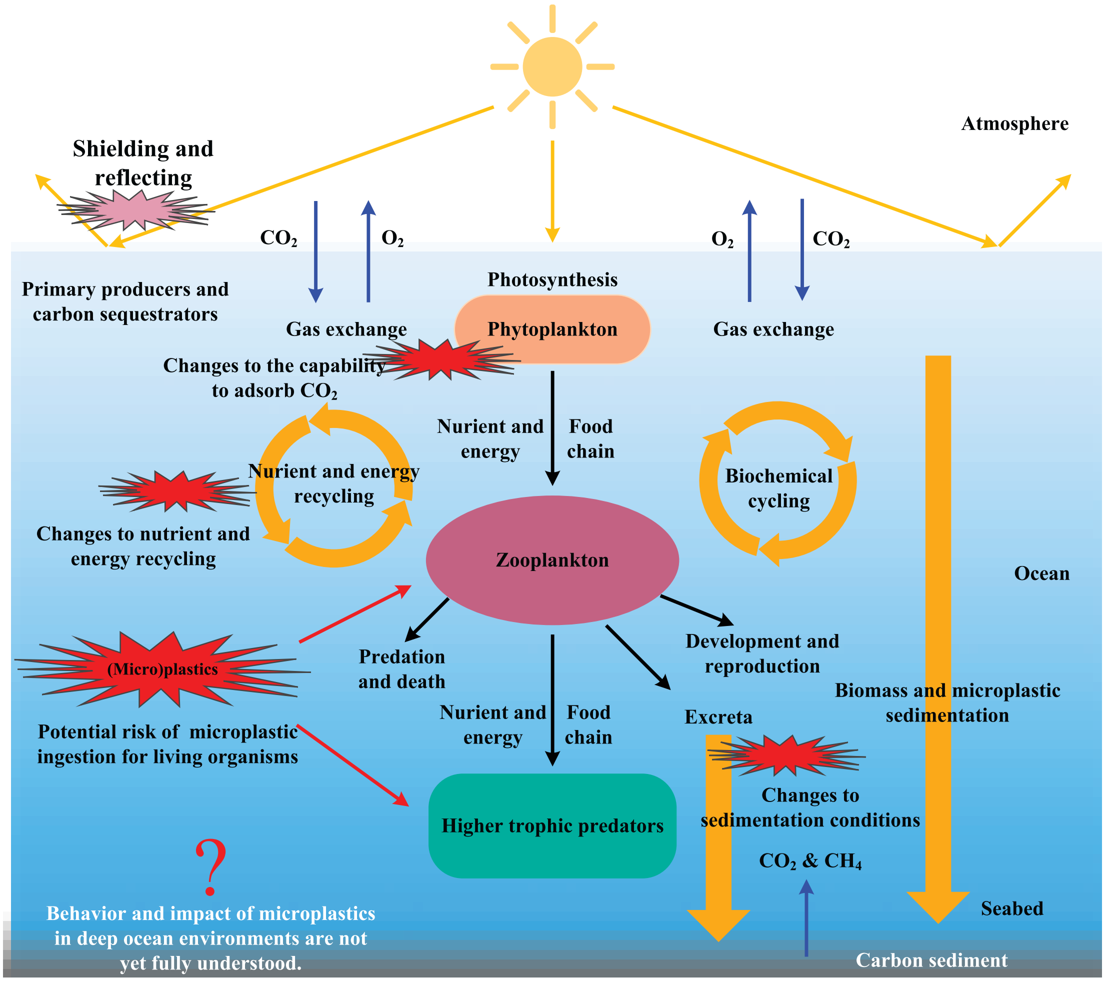

Fig. 4. Carbon transportation and cycling processes in the ocean.

biofilter efficiency in ecosystem, increase the chance of being ingested by marine organisms, and ultimately change the population distribution in ecosystem (Galloway et al., 2017). As such, marine (micro)plastics may affect the metabolism, development and reproduction of the basic organisms in the marine food chain/web, and indirectly affect the process of gas exchange and disturb the biological carbon cycle in the ocean. Nevertheless, more efforts are needed to explore how much plastic affects on marine carbon cycle via primary production.

Moreover, (micro)plastics not only disturb the photosynthesis of phytoplankton, but may damage zooplankton. Like phytoplankton, the main carbon fixator in marine ecosystem, zooplankton is the first and most important consumer of phytoplankton. Fig. 4 illustrates the role of plankton in carbon transportation and cycling processes in the ocean. More significantly, zooplankton can help adsorb fixed carbon from phytoplankton and transport it to the deep sea. Without this critical step, the CO_2 fixed by phytoplankton will soon reenter the atmosphere and surface water. However, evidences have shown that except for a small amount of microplastics are excreted, most of them accumulated in the digestive system of zooplankton, obstruct the digestive tract, reduce appetite and result in malnutrition, slow growth, weight loss and even death (Lee et al., 2013; Shen et al., 2019c). A research led by Cole et al. (2015) showed that microplastic exposure has a negative impact on metabolism and health of copepods. First, copepods reduced their food intake by 40% after plastic ingestion, and with time, copepod eggs became smaller and less likely to hatch, and increased the total mortality of contaminated copepods. The authors concluded that an increase in the amount of exposure to microplastics over time could lead to a significant reduction in carbon biomass intake by zooplankton (Cole et al., 2016). Plastic ingestion by zooplankton is a global phenomenon. A sampling in the Baltic Sea done by Setälä et al. found that microplastic can be ingested by various taxa of zooplankton, mainly including mysid shrimp, rotiferans, polychaete worm larvae and copepods (Setälä et al., 2014). Moreover, microplastic ingestion by zooplankton was also recorded in the Indian Ocean off the coast of Kenya (Kosore et al., 2018) and the Yellow Sea off the coast of China. Evidence also showed microplastics can be transferred from smaller to larger zooplankton when predation occurs (Shen et al., 2019d). Zooplankton may consume less and less carbon fixed by marine phytoplankton, even though these phytoplankton themselves are reducing carbon fixation. Therefore, shifts in this part of the food chain/web (phytoplankton and zooplankton) may affect the ability of the oceans to absorb and store CO_2 (Fig. 4). Considering the importance of marine carbon sinks to global climate, the potential of microplastic pollution on phytoplankton CO_2 fixation and zooplankton CO_2 transport to the deep sea should be highly concerned.

When zooplankton predates phytoplankton, the carbon they assimilated is transferred to the deep sea by fecal particles (Fig. 4). Fecal particles slowly descend into deep water and deposition in the mud of the seabed. Cole et al. (2016) reported that microplastics can be transported below the ocean surface via fecal pellets. A recent research also showed that when fecal pellets are polluted by microplastics, their equivalent spherical diameters significantly decrease, and sink rate decrease by 1.35-fold (Wieczorek et al., 2019). Additionally, pellets polluted by microplastics sink more slowly and break down more easily than unpolluted pellets, thereby reducing the proportion of carbon that reaches the deep ocean. The ocean surface is not the end of ocean plastics. Ocean surface estimates only represent approximately 1% of the estimated million tons of plastic waste generated from the land (Lebreton et al., 2017). The ability of plastic to sink is related to its density and biological contamination (Long et al., 2015). Biofilm can change the buoyancy and viscosity of floating microplastics and weaken their hydrophobicity (Kaiser et al., 2017; Lobelle and Cunliffe, 2011), and it can cause microplastics to settle deep in the ocean, making the ocean become a sink of microplastics (Woodall et al., 2014), which may change the floating mechanics of microplastics and the circulation of organic matter and nutrients. However, their behavior and impact in deep ocean environments are not yet fully understood. Obviously, additional research is immediately needed to understand the potential size and scope of the problem to global climate.

5. Perspectives and challenges

The impacts of plastics on global climate change have attracted more and more attention all over the world. Raising public awareness of the plastic pollution crisis and increasing public concern have simulated many strategies for mitigating plastic pollution. Due to the increase in global plastic production and plastic waste, greenhouse gas emissions have intensified. However, lack of efficient and standard technologies and methods for determination and monitoring of greenhouse gas emissions from cradle to grave is also a big challenge. Thus, the implementation of measures to solve or alleviate the plastic crisis is critical necessary. Herein, we suggest that these following aspects should be considered:

a. Production control of global plastics
b. Improving the treatment and disposal of plastic waste
c. Assessment of the impact of global environmental (micro) plastics on climate

5.1. *Production control of global plastics*

Reduce or unnecessary or excessive use of plastics by changing process and behaviors. Whether in terms of greenhouse gas emissions related to extraction, transportation, plastic manufacturing and treatment or in terms of reducing the impact of the environmental plastics, the most direct and effective way to solve the plastic crisis is to ban the global production of unnecessary plastics. In plastics, this will include measures to reduce or ban the use of non-essential plastics, including plastic packing, food and beverage services and disposable plastics commonly used in fast-moving consumer goods. Of course, this requires joint action from government decision-making and mass participation all over the world. In addition, it is also necessary to control the construction of new coal, oil and natural gas infrastructure. Evidence showed that greenhouse gas emissions from coal, oil and natural gas reserves have exceeded the remaining global carbon budget (Hausfather, 2018). However, the surplus of cheap raw materials of plastic manufacturing is driving the large-scale expansion of plastic production infrastructure. These new facilities will continue to generate demand of new materials and produce more and more plastic products, which will exacerbate the current situation and consume remaining global carbon budget. Therefore, it is indispensable to control the construction of new coal, oil and natural gas infrastructure.

Research also has shown that plastic industrial can obtain raw material from renewable source of energy where possible to reduce greenhouse gas emissions (Posen et al., 2017). However, the use of renewable energy to plastics does not address the impact of plastics on global climate change. Because a large part of greenhouse gas emissions from plastic production come from chemical processes, which are not affected by the use of renewable energy (Hamilton et al., 2019). Additionally, the production of plastics from renewable energy sources has no effect on reducing the treatment of plastic waste and their impacts on marine ecosystems. Although it is essential to improve energy efficiency in the necessary processes of plastic production, it has little effect on reducing greenhouse gas emissions and protecting the climate or the planet.

Moreover, biodegradable plastics have been also on the agenda. Nevertheless, biodegradable plastics still face some limitations and challenges. Despite biodegradable plastics can be degraded by microbes, these can only be degraded under special conditions and within a limited range. The use of biomass in plastic industries can reduce greenhouse gas emissions associated with fossil fuel production, but also generate a large number of new emissions because of biomass raw material harvesting, transportation and processing. Biodegradable plastics still have a positive impact on alleviation the adverse effects of carbon cycle of plastics in the environment.

5.2. *Improving the treatment and disposal of plastic waste*

There are three main ways to manage plastic waste: recycling, incineration and landfill. Whatever treatment method is used, plastic waste will cause harm to human health and the environment. Compared to other management methods, plastic recycling is more effective in the treatment. However, there are still limitations and challenges. Recycled plastics can hardly be guaranteed to be of the same or similar quality as their original counterparts. The use of recycled plastic after consumption in plastic manufacturing does not imply a real closed-loop recycling (MacArthur et al., 2016). Firstly, the plastic recycling is unlikely to be effective because it is not suitable for many common plastics such as polyvinyl chloride. The value of recycled plastics is too low compared with new raw materials. Without a government subside, plastic recycling is not financially feasible. Secondly, the treatment of colorants, additives and fillers in recycled plastics also increase costs. Because of the limitations of plastic recycling, plastic packing must be eliminated as a priority in order to prevent today's substitutes from becoming tomorrow's problems.

In addition, in the name of energy recovery, plastic incineration may significantly increase greenhouse gas emissions from plastic treatment, as well as increase toxic exposure to humans. The action of converting plastic waste into energy changes the threat of plastics from the land to the air, as well as exacerbates its climate impact. Importantly, people are increasingly aware of the danger of plastic incineration. Increasing reliance on plastic incineration has led to more and more greenhouse gas emissions. Incineration of municipal solid waste does not end with increased greenhouse gas emission from the incineration of plastic waste. Therefore, it is recommended that measures should be taken to phase out plastic incineration. In addition to phase out plastic incineration and stopping production and reducing use of disposable plastic packing, it is also necessary to determine the best use of all waste streams, not just plastic wastes. Reducing plastic use at the source means reducing the per capita production of plastic waste, which may be an effective way to reduce greenhouse gas emissions. The elimination of disposable plastic packing strengthens recycling by improving the quality of recycled waste. Contaminated mixed wastes generate larger waste streams than they actually exist, thus artificially increasing the perceived need for industrial-scale waste management solutions.

Sanitary landfill does not contribute much to greenhouse gas emissions from plastic treatment, but it is a long-term solution. Biodegradable technology seems to be a good choice (Paço et al., 2017, 2018). However, unfortunately, there are still many challenges to eliminate plastics by microbes in practical application (Shen et al., 2019b). Firstly, biodegradable technology will not reduce or solve the large amount of greenhouse gas emissions in the plastic life cycle. Secondly, the biodegradation tests of plastics were carried out under laboratory conditions at present. But, laboratory conditions are quite different from field conditions. The biodegradation efficiency under field conditions is not yet clear, and it will also generate great risks and uncertainties released these microbes into the environment. Finally, potentially cost limits the benefits of plastic biodegradation. Therefore, it is urgent to formulate necessary polices, technologies and standards to regulate plastic waste, improve the product design and waste treatment.

5.3. Assessment of the impact of environmental (micro)plastics on global climate change

Numerous studies have shown that marine plastic pollution cannot be ignored (Keswani et al., 2016; Khatmullina et al., 2017; Kirstein et al., 2016; Lagana et al., 2019). The presence of (micro) plastics may affect carbon storage in the ocean (Cole et al., 2016). The behavior and impacts in ocean environment are still unclear, especially in deep-sea and seabed. In 2018, Royer et al. (2018) has firstly revealed the greenhouse gas emissions from plastics under natural conditions in both terrestrial and marine environments. The experiment was carried out in the tropics (Hawaii, US), but (micro)plastics are distributed globally, which cannot extend to the case to the whole world. Future research is required to address the role and mechanism of global (micro)plastics in greenhouse gas emissions. Although there are still many limitations and challenges, Royer et al. has already taken the lead. In addition, evidence showed that the widespread presence of (micro)plastics in the ocean has a negative impact on the ability of carbon fixation via affecting the growth and production of plankton and changing the food chain/web of marine ecosystems (Cole et al., 2015; Corcoran, 2015). However, up to now, there are few clear discussions on the effect of microplastics on the carbon fixation capacity of marine phytoplankton. Accordingly, more studies are needed to understand the potential size and scope of the problem to the carbon fixation capacity of phytoplankton and potential effects on global climate change.

Due to the potential impact of the extensive occurrence of marine plastics on marine ecosystems and humans, some management strategies of marine plastics have been called for, such as recycling and cleanup ocean plastics. Although the concept of cleanup plastics from the ocean is attractive, this strategy is impossible to achieve. Ocean cleaning is labor-intensive and resource-intensive, which will cast a lot of money. This strategy has little effect on reducing greenhouse gas emissions from plastics in their life cycle. It does not address the impact of plastic on other areas, such as freshwater and land, nor the problem of plastic manufacturing. In addition, this strategy does not capture large quantities of microplastics that pollute the surface and depth of the ocean. Such cleanup operations may have potential impacts on marine life. But cleaning up and recycling marine plastics may make a meaningful contribution to the local ecosystem and also contribute to livelihoods.

6. Conclusions

The increasingly serious impact of the plastic crisis on marine ecosystems has attracted worldwide attention. There is growing evidence that cradle to grave of plastics poses risks not only to the environment, but to human health. Despite challenges and uncertainties, the impact of the existing plastic economy on climate is real, significant and cannot be ignored. The impact of plastics on global climate change cannot be neglected. Plastic industrials are one of the fastest growing sources of industrial greenhouse gas emissions. Greenhouse gas emissions from plastic production, use and treatment of plastic waste will consume a large amount of remaining carbon budgets. The current scientific consensuses show that global warming poses will cause great damage to global ecosystems, even irreversible damage, as well as loss of human livelihoods and life. Cumulative emissions from the energy and industrial sectors cannot exceed 800 gigatons by 2010 in order to keep global warming below 2 °C. To have any opportunity to remain within 1.5 °C, greenhouse gas emissions must be lower, and global net greenhouse gas emissions must be reduced to zero by 2050s. Under the case of below 2 °C, in the carbon budget of 800 gigatons CO_2e of energy and industrial sectors by 2100, the total warning amount of remaining carbon budget cap is only to be 420 gigtons CO_2e, not more than 570 gigatons. However, plans to expand plastic production in the plastics and petrochemical industrials may break this situation and exacerbate the impact of plastics on global climate, and may make it impossible to limit global temperature rise to 1.5 °C even 2 °C. If the production, disposal and incineration of plastics continue to follow the current growth trajectory, these global emissions will reach 1.34 and 2.80 gigatons per year by 2030 and 2050, respectively. Greenhouse gas emissions from plastic incineration may increase by 4.2 gigatons CO_2e to the atmosphere by 2050, and cumulative emissions will exceed 56 gigatons by 2050, which may consume 10–13% of the remaining carbon budget. Even if the production of renewable energy-based plastics can reduce production-related greenhouse gas emissions, they will not solve the large amount of emissions generated by the chemical conversion process itself. Problematically, it is still highly uncertain whether and when this transition to renewable energy. The challenges facing the former are enormous, however, the latter has already happened to some extent. While maintaining the plastics economy, minimizing greenhouse gas emissions is what the future plastics industry is pursuing. In addition, the impact of (micro)plastics in the ocean on marine carbon cycle is increasing. Significant knowledge gaps still remain in this regard. Plastic pollution in the ocean raises more questions than answers. These problems also deserve our attention. Policy formulation needs us to make more cooperation and coordination all over the world.

Declaration of competing interest

The authors have no conflict of interest to declare regarding this article.

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