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Review

Behavior, Characteristics and Sources of Microplastics in Tea

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Abstract: Microplastics have become a widespread environmental concern because they are found in most tested places, including the air we breathe and the food and beverages we consume. To explore the current status of microplastic pollution and future research trends in tea, we reviewed the distribution, abundance, shape, size and sources of microplastics in tea. Microplastics are plastic particles that are 5 mm in diameter or less. Those found in tea and tea gardens originate from agricultural plastic films, plastic packaging of products and tools used in tea production, organic fertilizers, even atmospheric deposition. The microplastics in tea gardens are typically fragments and fibers, mainly composed of polyethylene, polypropylene and polyethylene terephthalate. The prevention and control of microplastics in tea planting, tea processing and packaging should be strengthened, and reduce the input of products containing microplastics. Future research on microplastic detection methods in tea and determination of safety thresholds should be prioritized to provide a reference for microplastic contamination risk, control, and management in tea.

Keywords: microplastic contamination; tea leaves; source; morphology characteristics; polymer; plastic-based filter bag

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1. Introduction

Plastic products and packaging are ubiquitous, being widely used in healthcare, agricultural production and daily life, to name a few. It is estimated that there will be approximately 155–265 million tons of plastic waste worldwide in 2060 [1,2]. Plastic waste is not biodegradable, and it degrades into smaller and smaller particles by mechanical wear, heating and oxidation by UV radiation [3]. The concept of microplastics was first proposed by Thompson et al. [4], wherein microplastics were defined as plastic particles less than 5 mm in diameter. Microplastics are extremely chemically stable with half-lives of hundreds of years, allowing them to persistent in the environment [5].

Microplastics can be divided into primary and secondary pollutants. The former being plastic fragments produced for man-made industrial plastic products, such as cosmetics, which enter the environment through sewage discharge and other way, while the latter are plastic fragments and fibers formed from by the action of external forces such as weathering, light and physical friction on plastic products and plastic waste [6]. Unlike ordinary solid plastic waste, microplastics are highly migratory, due to their small size. They spread globally through both the water and atmospheric cycles, and can be ingested by marine life and enter the human food chain through the consumption of seafood, posing potential health threats, such as cytotoxicity and oxidative stress [5]. It is estimated that the average daily intake of micro- and nanoplastics by the population in China is about 512–898 microplastics/person/d [3]. The physiological effects of ingesting microplastics include inflammation, oxidative stress, cell damage, etc. Importantly, microplastics can easily expose organisms to carcinogenic and neurotoxic pollutants that adsorb to their surface, such as heavy metals, polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAHs) [7].

In recent years, microplastics have been found in bottled water, milk, salt, seaweed, honey and other foods [8–13]. Tea is not immune. Tea is generally considered to be safe to drink. It contains polyphenols, theanine, caffeine, etc.; bioactive substances with benefits of anti-aging (via antioxidants), reducing the risk of heart disease, improving mental alertness, and treating other diseases and their effects [14]. Drinking tea is widely considered a healthy lifestyle habit, in line with consumers' pursuit of health and a high quality of life. In 2021, China's tea production was 3063.200 tons and tea consumption was 2301.900 tons [15]. However, tea plants can contain various pollutants, including microplastics, from the soil in which they are grown, as well as from exposure to plastic during processing and storage. In 2019, Hernandez et al. [16] found that plastic tea bags released microplastics during brewing, and the released microplastics were as high as 11.6 billion microplastics per bag. In the same year, Qinglan Li et al. [17] found microplastic contamination in tea garden soil, up to 740 microplastics/kg soil. Detected microplastics were mainly white, blue and red fibers and fragments that were 20–250 μm in size. In 2022, Yinan Li et al. [18] found a lot of fibrous microplastics in green tea, black tea, dark tea and white tea. There are up to 5000 pcs/20 g of them.

Currently, due to the difficulty in identifying the progressive consequences of their presence, microplastics have been classified as emerging pollutants. [8] For the tea area, there is an important environmental concern that exists with microplastics and their adsorption by tea leaves. Research in this area is still in its initial stage. By January 2023, there were only 25 microplastics-related research papers in Web of Science (WOS) core collection database (search word: microplastic* AND tea), and their annual publication volume shows an increasing trend. These papers are involved Environmental Science, Engineering Environmental, Water Resources, Food Science Technology, etc. such as plastic pollution in commercially available tea bags, the study of microplastics in tea beverages, identification of Microplastics from Tea. They had found that the abundance, shape and size of microplastics in tea, but there is no detailed discussion of the source. Although the stress effect of microplastics on plant growth and development has been reported in vegetables and tobacco [19–22], there is no report on tea. While research in the field of tea microplastics has been advancing, they are doing research at scattered points and the progress has scarcely been systematically sorted out.

This paper evaluates the latest research on the characteristics of microplastics pollution in tea, including the distribution, abundance, sources and morphological characteristics of tea microplastics. As there are few studies on microplastics in tea gardens or tea leaves, this study combined with existing research results on microplastics in farmland, orchards and vegetable gardens to make a comprehensive comparative analysis, so as to fully understand the current situation of microplastics pollution in tea gardens. Ultimately, research on tea microplastics is projected to provide a scientific basis for risk estimation, control and management of microplastics in tea.

2. Pollution Status of Microplastics in Tea

There is a lack of research on microplastic contamination in tea worldwide, and there is no uniform standard for detecting and counting microplastics, resulting in a large variation in the reporting of microplastic contamination in tea. The main focus has been on tea bags, tea drinks and bulk tea. In existing studies, tea microplastics have been investigated across the globe, and microplastics were detected in all instances (Table 1).

Table 1. Tea microplastic contamination distribution table.

Sample	Year	Country	Abundance	Size	Shape	Materials	Literature
Empty plastic tea bags	2019	Canada	1.16×10^{11} pcs/pack	200–1000 nm	Particles, fragments	Nylon, PET	[16]
Empty plastic tea bags	2020	Germany	800~20,400 pcs/pack	200–1000 nm	Particles, fragments	Nylon, PET, PP	[23]
Empty tea bags	2020	Dublin	1.3×10^{10} pcs/pack	0.5~5000 μm	Debris, fiber	Cellulose, PP	[24]
Empty tea bags	2022	China	34 pcs/30 mL	0~5000 μm	Fibers, fragments, particles	PET, PE	[25]
Empty tea bags	2022	China	18 pcs/30 mL	0~5000 μm	Fibers, fragments, particles	PET, PE	[25]
Empty tea bags	2022	China	15 pcs/30 mL	0~5000 μm	Fibers, fragments, particles	PP	[25]
Empty tea bags	2020	Bangladesh	477 pcs	202.67~238.53 μm	Debris, fiber	EVA, CA, PTFE, HDPE, PC, ABS, PVC, PETE	[26]
Tea bags	2020	Bangladesh	504 pcs	200.38~241.02 μm	Debris, fiber	EVA, CA, PTFE, HDPE, PC, ABS, PVC, PETE	[26]
Cold Tea	2020	Mexico	5.74—16.26 pcs/L	0~5000 μm	Fiber	PA, PEA, BP	[27]
Green Tea	2022	China	1.1003×10^4 pcs /20 g	0~5000 μm	Debris, fiber	PET	[18]
Black Tea	2022	China	4.9033×10^3 pcs /20 g	0~5000 μm	Debris, fiber		[18]
Dark Tea	2022	China	4.5033×10^3 pcs /20 g	0~5000 μm	Debris, fiber	PE	[18]
White Tea	2022	China	5.4699×10^3 pcs /20 g	0~5000 μm	Debris, fiber		[18]

ABS: nylon, acrylonitrile butadiene styrene; PET: polyethylene terephthalate; PP: polypropylene; PE: polyethylene; EVA: ethylene vinyl acetate; CA: cellulose acetate; PTFE: polytetrafluoroethylene; HDPE: high-density polyethylene; PC: polycarbonate; PVC: polyvinyl chloride; PETE: polyethylene terephthalate.

2.1. Microplastics in Empty Tea Bags

Research on microplastics in tea bags was first conducted in 2019 in Italy [16], wherein it was found that steeping a plastic tea bag at brewing temperature released approximately 11.6 billion microplastics and 3.1 billion nanoplastics into each cup, sparking a debate on the safety of tea bag materials. However, this research focused only on plastic tea bags (i.e., nylon and polyethylene terephthalate (PET)) and lacked research on other tea bags in the market. In 2020, both the European Commission [28] and Kristin Busse [23] confirmed that migration of microplastics from tea bag materials to the imbibed beverage occurs. In the same year, Jun-Li Xu et al. of the University of Dublin [24] studied tea bags made of plastics, mixtures of cellulose and plastics, and biodegradable materials by purchasing six brands of commercial tea bags locally. After testing these empty tea bags, it was found that cellulose and polypropylene were the main components. It was estimated that each tea bag produced 1.3 billion plastic particles from 0.5 to 5000 μm. In 2022, Tingna Mei et al. from Wuhan Engineering University [25] investigated microplastics in teabag filter bags. They collected three types of commercially available filter bags, including plastic food filter bags, nonwoven fabric, and woven bags. Most microplastics were tiny fragments and particles, a few were fibrous microplastics 620–840 μm in size, and they were composed of polyethylene terephthalate (PET), polyethylene (PE) and polypropylene (PP).

2.2. Microplastics in Tea Bags

In 2020, Sadia Afrin et al. [26] studied the plastic contamination of commercially available tea bags in Bangladesh, where 504 and 477 suspected plastic particles were observed in uncut and cut tea bag samples, respectively. The particle sizes ranged from 3.0 μm to 2180 μm (uncut teabags: 220.7 ± 20.32 μm and cut teabags: 200.6 ± 17.93 μm). The microplastics were fragments and fibers, and various colors were identified, mainly brown, blue and red. The polymer types were identified as ethylene vinyl acetate (EVA), cellulose acetate (CA), polytetrafluoroethylene (PTFE), high density polyethylene (HDPE), polycarbonate (PC), nylon, acrylonitrile butadiene styrene (ABS), polyvinyl chloride (PVC), and polyethylene terephthalate (PET); the last three being the most common in the analyzed samples. It was estimated that tea bags could emit an average of 10.9 million grams of microplastics per year.

2.3. Microplastics in Tea Beverages

In 2020, V. C. Shruti et al. [27] from Mexico investigated the microplastics contents in cold tea beverages. They purchased samples from Mexican supermarkets, tested the beverages and found that the average quantity of microplastic particles in the tested cold tea samples was 11 ± 5.26 particles/L. Among the cold tea samples tested, only fibers were detected, with blue fibers predominating, followed by brown and red fibers with particle sizes ranging from 0.1 to 3 mm. Among them, particles smaller than 1 mm accounted for >80% of the total microplastic particles found in the cold tea samples. The microplastic polymers in cold tea were polyamide (PA), polyester amide (PEA) and blue pigment, respectively. It was suspected that the observed microplastics originated from the water used to make the drinks, and the plastic materials used in the bottle and cap.

In 2022, Yinan Li et al. from Ocean University of China [18] investigated the microplastic contamination of tea in China. They purchased four types of tea, namely green tea, black tea, dark tea and white tea, from local supermarkets in China. The black tea was stored in tins, while green tea, white tea and dark tea were packed in paper bags. Upon testing, they found that per 20 g of black, white and dark tea leaves there were about 5000 fibers, while 4433 fibers and 6570 fragments were found in the same quantity of green tea leaves. In green tea, the main form of microplastics was debris, while in black, white and dark tea, the main form was fibers, with particle sizes ranging from 100–5000 μm. The common plastics in the tested tea were polyethylene (PE) and polyethylene terephthalate(PET).

3. Sources of Microplastics Pollution in Tea

The main sources of microplastics in tea leaves were agricultural plastic films, plastic packaging of tea garden inputs, organic fertilizers, atmospheric deposition, and the plastic in tools or containers that release microplastic particles during processing (Table 2) [29].

Table 2. Sources of microplastic contamination in tea.

Sample	Year	Country	Abundance	Size	Shape	Materials	Literature
Tea Garden	2019	China	740 items/kg	0~5000 μm	Fibers, debris	PE, PP, PET, CL	[17]
Orchard	2021	China	188~279 pcs/pack	0~5000 μm	Debris and fibers	PE, PP, PS, PVC	[30]
Vegetable field	2021	China	79~112 pcs/pack	0~5000 μm	Debris and fibers	PE, PP, PS, PVC	[30]
Cotton field	2020	China	80.3~1076.5 pcs/pack	0~5000 μm	Fragments and films	PE	[31]
Atmospheric deposition	2021	China	114 ± 40 pcs/m/d	50~5000 μm	Fibers, chips, films, microbeads	PET, PAN, PP, PA	[32]
Atmospheric deposition	2021	Spain	35.97 ng·m^{-3}	-	-	PS	[33]
Atmospheric deposition	2017	China	1.46 × 10^5 pcs/(m^2 a)	0~5000 μm	Fibers, chips, films and Foaming	PET, PE, PVC, PS	[34]
Organic fertilizer	2022	China	325 ± 511 pcs/kg	1000~3000 μm	Film	-	[35]

PET: polyethylene terephthalate; PP: polypropylene; PE: polyethylene; PS: polystyrene; CL: cellophane; PVC: polyvinyl chloride; PAN: polyacrylonitrile; PA: polyamide (nylon).

3.1. Microplastics from Agricultural Plastic Film and Plastic Packaging of Tea Garden Inputs

Plastic films are widely used in agricultural fields, orchards, cotton fields, tea plantations, etc. [17,30,31] because of their significant economic benefits. The use of ground covers, such as plastic films, is good for retaining moisture, improving soil fertility and regulating soil temperature. Their main components are PVC and PE. China is a large consumer of agricultural films [29]. According to the National Bureau of Statistics, 2.389 million tons of agricultural plastic film were used in 2020 over the country, and 42,558 tons were used in 2020 in Guangdong. In recent years, many studies have found that mulch film can cause microplastics pollution in agricultural soils [36,37], and the abundance of microplastic particles increases with the duration of mulch use [31]. Yang Rui-ju et al. [38] found that the long-term degradation of agricultural mulch will gradually release microplastics, which will affect the physicochemical properties of the soil and ultimately be detrimental to crop growth.

Additionally, tea plantations employ a large number of laborers during the tea picking season, and litter from laborers is frequently left in the fields. Most of the food and drink items left behind use plastic packaging, leading to significant plastic litter in tea plantations, which will eventually degrade into microplastics and enter the soil through tillage and other routes. As tea is an important economic crop that is widely consumed in China, the quality of tea garden soil is of concern for both soil vitality and food safety. Therefore, it is urgent to strengthen the removal and recycling of mulch residues and plastic packaging from tea gardens.

3.2. Microplastics from Organic Fertilizers

Organic fertilizers are an important input in tea production to promote healthy plant growth, improve the soil structure, and improve the quality of tea [39]. Since organic fertilizers are derived from natural sources, they are considered to be more environmentally friendly than synthetic fertilizers. At present, China is promoting the policy of substituting chemical fertilizer with organic fertilizer for fruit, vegetable and tea cultivation. A potential downside is that organic fertilizers are a prominent source of microplastics in agricultural soils [40]. Organic fertilizers are made from a variety of raw materials, including livestock manure (chicken, cattle, goat, and pig manure) and compost (from aerobic composting of food and organic waste) [35]. A recent study [35] detected an average of 325 ± 511 microplastics/kg organic fertilizer. The microplastics in organic fertilizers were white, 1–3 mm, and film-like.

They also found that microplastics were concentrated in agriculture-intensive provinces and the average import flux of organic fertilizer microplastics to fertile soil was 5.07×10^{12} y^{-1}. According to the National Bureau of Statistics, China used about 15.6 million tons of organic fertilizers in 2020. Therefore, we must strictly control the raw materials of fertilizers and increase recycling of plastic films used in agricultural production to mitigate microplastic soil pollution.

3.3. Atmospheric Deposition

Atmospheric deposition is another way for microplastics to enter tea, both during growth and during processing. During the growth process, microplastics can enter the soil environment through atmospheric deposition [41–46]. The main sources of microplastics in the air are degradation products of synthetic textiles and automobile tires, and urban dust suspensions [47]. These microplastics can be transported through the atmosphere as far as 95 km [29]. As early as 2017, a study [34] pointed out that the atmospheric deposition of microplastics in Yantai (a coastal city in China) can reach 1.46×10^5 pcs/m^2/year. Most of the fibers were smaller than 0.5 mm, and they were mainly composed of polyester, PVC, PE and polystyrene.

Atmospheric deposition is also one of the ways that microplastics pollute tea during processing. Sun fixation is an important step in tea processing, tea leaves are spread out on the ground and are sun-dried (i.e., irradiated by ultraviolet rays of sunlight). The purpose is to inactivate the enzymes contained in the leaves, block further fermentation and promote the formation of quality tea. During the process, microplastics may fall onto the tea through atmospheric deposition. Little research has been done on microplastic pollution that occurs during tea processing, and there is an urgent need to strengthen research and exploration in this area in the future.

3.4. Microplastics Released by Tools or Containers during Production

The aging of plastic products due to photothermal oxidation and wear is a source of secondary microplastics [48,49], and is related to the use scenarios and environments of different plastic products [50]. Aging of plastic-containing tools used in the production and processing of tea are an important route for microplastics to enter tea leaves. For example, particles generated by the wear of rubber rings on tea kneading machines are released to tea and are a source of secondary microplastics. Secondary microplastics are also generated by the aging of plastic containers that store tea during processing. In addition, sources of microplastics in tea may be generated by plastic packaging of tea bags, where volatiles can be transferred from the tea bag material to the tea leaves during storage [22]. Currently, the contamination sources of microplastics in tea production and processing and the exposure and risk assessment to humans are still in their infancy. More research is needed to enhance tea production and processing environments to provide protection from microplastics.

4. Suggestions for Prevention and Control of Microplastics in Tea

The main sources of microplastics in tea leaves included tea plantation, tea processing and packaging, it is recommended to strengthen the prevention and control of microplastic inputs in these main links. Based on the analysis of the sources of tea microplastics pollution, there are some prevention measures for reducing the microplastics content in tea. During the growth process, strengthen the removal and recycling of mulch residues and plastic packaging from tea gardens. It is advisable to eliminate plastic products left in the tea garden as far as possible, reduce human activities in the tea garden, and arrange the working time of tea farmers reasonably. In view of the problems of organic fertilizer and atmospheric deposition carrying microplastics, it is necessary for all relevant departments to coordinate and jointly prevent and control the input of microplastics. While in tea process links, such as Sun fixation, Fixation, rolling, etc., it is importance to reduce the use of plastic products, through wood products, cloth as an alternative; Secondly, tea processing places should be far away from residential communities and industrial zones as far as possible to reduce

microplastic pollution brought by daily life and industrial activities. In terms of packaging, businesses can use aluminum bags, paper bags, paper-aluminum composite cans instead of plastic bags to avoid the carrying and input of microplastic products. At present, Research in this area is still in its initial stage and the safety threshold of microplastics in tea related to human health has not been established. In the future, it is necessary to strengthen the research on this aspect to scientifically prevent and control tea pollution.

5. Conclusions and Outlook

Microplastic pollution and its ecological effects have become a hotspot in global environmental science research [47]. This study systematically reviews the current status of microplastic pollution in the field of tea and finds that current research only involves the detection of microplastics in finished tea products. The shapes of microplastics in tea are mainly fragments and fibers, and the materials PE and PET are the most common. The sources of microplastic pollution in tea fields are mainly concentrated on the growth stage and processing stage. Exposure to microplastics during cultivation is from agricultural plastic film, plastic packaging of tea garden inputs, and organic fertilizers, while exposure during the processing stage is atmospheric deposition, wear on plastic-containing tools and plastic containers used to store tea. In view of the fact that the global research on tea microplastic pollution is in its initial stage, the data are not comprehensive. Moreover, not only in the field of tea, but also in the field of agriculture or food, there is no specific threshold to measure and compare the degree of microplastic pollution. At the same time, the research methods for the analysis and identification of microplastics in food lack uniformity and standardization, resulting in low comparability of data from different papers. It is suggested that focus be placed on the standardization of tea microplastic detection methods and the safety threshold of tea that contains microplastics.

(1) Standardization of microplastic detection methods for tea

Analytical methods, such as separation, extraction and detection, to determine microplastics in tea lack unified standards. This research is in its infancy, many analytical techniques have limits of detection which hinder their use for the study of these particles in these sample matrices. while a qualitative sample analysis could be achieved, no quantitative data can be accurately reported [51];thus, it is difficult to scientifically and objectively compare the level of microplastics in raw and processed tea. Moreover, these methods have the high cost of testing. Standardized methods should be developed for low-cost and widely applicable. Additionally, standardized technical specifications should be established.

(2) Study on the safety threshold of microplastics in tea and tea plantations

Currently, there are few studies related to microplastics pollution in tea gardens and microplastics released from tools and equipment used in production and processing of tea. There is also a lack of relevant testing indicators in terms of safety thresholds. Giving rise to difficult to measure whether the pollution exceeds the limit. It is advisable to strengthen the research on microplastics safety thresholds so that the presence of microplastics in tea does not negatively affect the production of the tea industry, while guaranteeing ecological safety and human health. It is important to develop relevant testing standards to effectively monitor and scientifically control microplastic pollution in tea gardens and tea leaves.

To find a scientific, reasonable and efficient testing method, we should establish a database and determine the safety threshold, so as to provide a theoretical basis for the formulation of control policies for microplastics in tea. At the same time, corresponding scientific prevention and control measures should be found in each link for the source of tea microplastics. Such policies would enable better protection of the ecological environment of tea gardens and guarantee the sustainable and healthy development of the tea industry.

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