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Littered cigarette butts in both coastal and inland cities of China: occurrence and environmental risk assessment

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Cigarette butts (CBs) pollution is a critical global environmental issue, yet limited research exists on CBs pollution in both coastal and inland Chinese cities with varying development levels. This study investigated CBs occurrence, contamination, Cigarette Butts Pollution Index (CBPI), and heavy metal leakage in four cities. The results of CBs collected over multiple days revealed higher contamination levels in coastal city of Dalian (0.10 ± 0.03 CBs/m^2), inland cities of Baoding (0.06 ± 0.02 CBs/m^2) and Meizhou (0.07 ± 0.02 CBs/m^2) compared to first-tier coastal city of Guangzhou (0.03 ± 0.02 CBs/m^2). Patterns of CBs occurrence and CBPI varied across land usage and cities development level. SEM and EDS analysis identified microplastics and heavy metal particles released from CBs in water environments. ICP-MS detected a total of 629.7 μg/L of 14 heavy metals. Approximately 1.9 ± 0.9 g/km^2 of heavy metals are leaked daily in Chinese cities due to CBs, posing a severe threat to soil and water safety given the indiscriminate disposal of CBs. This study offers scientific insights into CBs pollution and underscores the pressing need for effective measures to mitigate environmental hazards, particularly heavy metal and microplastics contamination released from CBs in China.

KEYWORDS

cigarette butts, cigarette butts pollution index, heavy metals, microplastics, measures

1 Introduction

Cigarette smokers make up approximately 20% of the world's population and cigarette consumption has sharply increased compared to other tobacco products in recent decades due to the low cost-to-income ratios, income growth, and misconceptions about the lesser damage to personal health (Mishra et al., 2016; Soleimani et al., 2022). It has been estimated that over 6 trillion cigarettes are produced worldwide every year and consumed by one billion smokers (Novotny and Slaughter, 2014; Beutel et al., 2021). Due to lack of regulation, more than three-in-four smokers casually discarded their cigarette butts (CBs) (Rahman et al., 2020). Irresponsible discarding of CBs has caused a visible increase in their presence, with a large portion of them inevitably ending up in the ocean (Novotny et al., 2009; Ribeiro et al., 2022). The increase in CBs waste has posed a threat to the safety of environmental ecosystems. However, the amount of data on the impact of CBs pollution on the broader environment remains limited (Green et al., 2022).

With the widespread pollution of CBs in the environment, researchers and environmental advocates are increasingly concerned about the environmental fate of CBs and their potential release of pollutants such as microplastics, nanoplastics, and other toxic chemicals (Bonanomi et al., 2020; Belzagui et al., 2021; Yang et al., 2023b). CBs are predominantly composed of plastic fibers, comprising over 15,000 strands of cellulose acetate fibers designed to reduce the harm of smoking by filtering out toxic substances (Pauly et al., 2002; Novotny et al., 2009). Currently, the degradation of CBs in the environment raises concerns about the potential release of microplastics and nanoplastics (Chevalier et al., 2018). Micro- and nanoplastics have been found to cause cytotoxic and genotoxic effects on both terrestrial organisms (including humans) and aquatic life (Bouwmeester et al., 2015). Evidence has shown that the presence of micro- and nanoplastics in intestines and other tissues of animals and humans cause tissue rejection and inflammation (Lim, 2021). Apart from this, the balance of the ocean ecosystem is threatened by the disruption of the food chain caused by micro- or nanoplastics, which have been shown to cause a reduction in the growth and reproduction of zooplankton as well as a decrease in the absorption of chlorophyll by phytoplankton (Sun et al., 2021; Dedman et al., 2022). There is also evidence demonstrate that the contamination of soil environments by microplastics can cause changes in soil biota and restrict root growth and nutrient uptake of plants, posing a threat to food production (Rillig et al., 2019).

Moreover, as the metals found in tobacco are released into smoke and CBs during combustion, elements such as Ni, Al, Cr, Cd, Zn, Pb, Cu, and Sb have been reported in CBs and released into the environment (Soleimani et al., 2022). Consequently, CBs in soil and aquatic environments not only pose a toxic potential for microbial community and aquatic lifeforms, but also cause mild allergic reactions and serious human health issues such as cancer, diabetes mellitus, fetal growth development and renal disease by food chain or water cycle (Mitra et al., 2022; Munzel et al., 2023). Moreover, hazardous organic chemical substances released from CBs, such as aromatic amines, polycyclic aromatic hydrocarbons (PAHs), nicotine, benzene, and xylene (BTEX), have had dramatic effects on human health and environmental safety (Novotny et al., 2009) and most of these toxic organic chemical substances have been linked to their carcinogenicity (Talaska, 2003; Devi et al., 2016).

Given CBs ubiquity, toxicity and persistence in global environment, its increasing has raised concerns among researchers worldwide. Many studies have investigated CBs littering in various environments, such as cities and beaches. For example, Ribeiro et al. (2022) conducted a study on CBs density pollution in two cities in Brazil and found that CBs occurrence and distribution were independent of land use types and city population density. However, the city of Santos exhibited the highest recorded Cigarette Butt Pollution Index (CBPI) value at 17.6. Additionally, Gholami et al. (2020) assessed CBs littering in six urban areas in Qazvin, Iran, and observed average pollution rates of 5.22 items/100 m in administrative land and 9.59 items/100 m in recreational land, with the highest pollution rate of 185.96 items/100 m found in commercial land. Nevertheless, to date, there is no existing research reporting data on CBs littering across different cities in China, despite the evident prevalence of CBs littering. In this study, our objectives were to quantify CBs littering in different cities and different land types, estimate the degree of CBs pollution, and characterize pollutants leached from CBs under simulated environmental conditions (where CBs were gently agitated in deionized water). The aims were to raise awareness of the CBs littering issue and promote effective waste management. The information gathered from this study could contribute to the development of guidelines for effective CBs management.

2 Materials and methods

2.1 Study area and sampling procedures

In this study, Guangzhou, Dalian, Baoding, and Meizhou were selected as research locations to represent various levels of development and distinct urban characteristics. Guangzhou, a first-tier coastal city, stands as an international metropolis with a population of 18.7 million. Dalian, a second-tier coastal city, is renowned for its tourism industry and hosts 7.5 million residents. Baoding, a second-tier inland city, with a population of 9.2 million, exhibits a relatively less developed economy. Meizhou, a fourth-tier inland city, with 3.9 million inhabitants, represents a less developed urban setting. Figure 1 illustrates a conceptual flowchart detailing the sample design, encompassing city and site selection, data collection campaigns, data generation, and subsequent statistical analysis.

The investigation specifically targeted discarded CBs and other plastic littering on walkways, and a total of 12 sampling sites were selected across different land-use types. These included beaches, parks, and markets in both Guangzhou and Dalian, as well as culture squares, parks, and markets in both Baoding and Meizhou (see Supplementary Figure 1). The sites were randomly chosen to ensure representation of various urban areas.

Sampling occurred from June to August 2023, with each designated sidewalk ranging in width from 2 m to 4.5 m and a length between 2 km and 5.2 km. CBs were collected in garbage bags and subsequently sorted and counted in the laboratory. Sampling at each sidewalk was conducted continuously for 5 to 7 days, with daily sampling occurring from 4:00 PM to 11:00 PM. This specific timeframe was chosen, as it follows morning cleaning activities and approaches the evening, providing an approximate representation of the daily generation of CBs and other plastic waste. Supplementary Figure 2

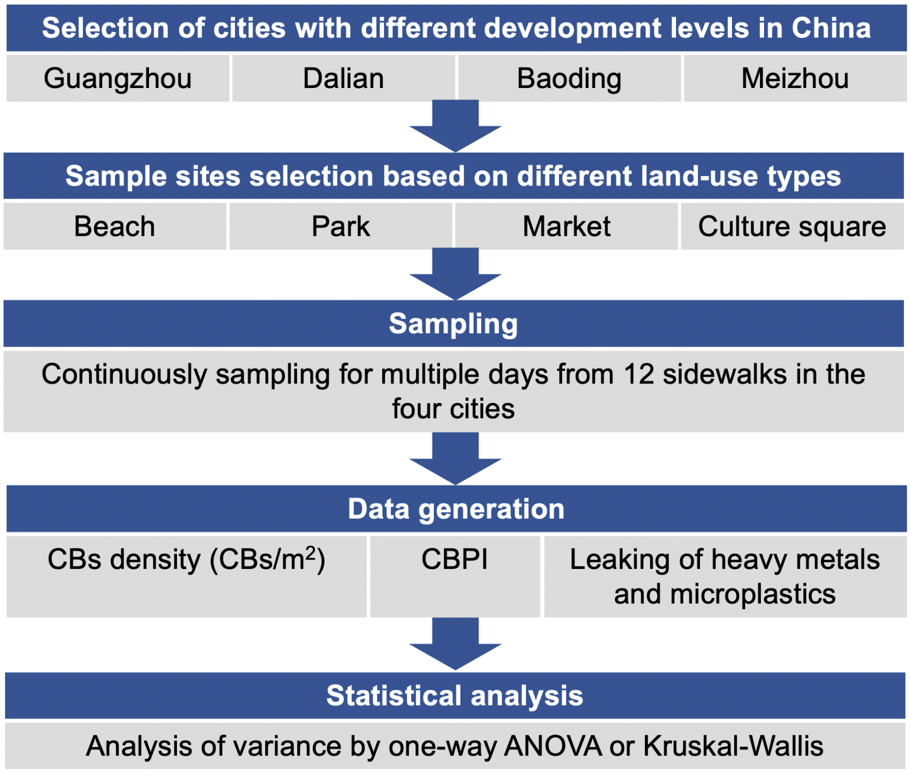

FIGURE 1
Flowchart depicting the conceptual framework of the sample design.

illustrates the state of CBs observed in the study areas and outlines the laboratory procedures used for sample processing.

2.2 CBs density

The density of CBs was derived from the ratio of CBs abundance in the previously measured area (m^2) at each site (Ribeiro et al., 2022). The total sampled area in Guangzhou, Dalian, Baoding, and Meizhou was 39,600 m^2, 27,590 m^2, 23,595 m^2, and 23,500 m^2, respectively.

2.3 CBs pollution index

Under the influence of specific human and environmental conditions, the contamination of CBs in different environments may result in varying levels of pollutants being released into the environment. In this study, we evaluated the pollution caused by CBs in urban and beach environments by calculating the CBs pollution index (CBPI) in each surveyed area. The detailed calculation of CBPI is shown in Equation (1). This index takes into account the CBs density in different surveyed environments, as well as soil status, path type, and rainfall conditions, as proposed by Torkashvand et al. (2021). The resulting CBPI values can indicate different levels of pollution, ranging from very low pollution (≤1), low pollution (1.1–2.5), pollution (2.6–5), significant pollution (5.1–7.5), high pollution (7.6–10), or severe pollution (>10).

$$CBPI = DCB \times E \tag{1}$$

where DCB represents the CBs density and E is a coefficient.

2.4 Reagent

The reagents used were of analytical grade. The HNO_3 employed for the digestion process was of ultra-trace pure quality (Guoyao Ltd., Shanghai, China). Prior to use, all glassware were subjected to cleaning by immersing them in a 10% (w/v) HNO_3 solution and subsequently rinsing them with deionized water.

2.5 The leakage of microplastics and heavy metals

A total of 20 CBs randomly selected from the collected samples were immersed in 1 L of deionized water and gently stirred to mimic the disturbance of water environment. After 12 hours, the 1 L sample was filtered three times through a 125 µm mesh filter and subsequently filtered using a 0.22 µm polycarbonate (PC) membrane (Merck Millipore, Ireland). After completion, the membrane was dried at 50°C for 2 hours and subjected to microplastics detection using SEM and EDS. Simultaneously, the same procedure was performed on a blank sample containing only 1 L of deionized water to collect filter membrane for microplastics detecting. The filtrate was used for heavy metals detection. In this process, a 10 mL sample was first acidified using 1 mL of 1 M HNO_3 and subjected to analysis using the Perkin Elmer ICP-MS NexIon 350D instrument. To identify and eliminate any potential interference, procedural and reagent blanks were implemented. The multielement calibration standards were made by diluting PerkinElmer Pure standards in a 5% HNO_3 solution, spanning a calibration range from 0.1 μg/L to 100 μg/L, with a regression statistic requirement exceeding 0.9990. Quality control samples met <5% accuracy and precision criteria. Instrument parameters were optimized according to Hineman et al. (2010) for the analysis.

2.6 Statistical analysis

To determine if there are significant differences in CBs density, CBPI, and other data among different groups, we employed one-way ANOVA analysis or Kruskal-Wallis analysis, which was performed using GraphPad Prism 9 (GraphPad Software, San Diego, CA, USA; http://www.graphpad.com).

3 Results

3.1 Plastic littering

During the investigation, the number and distribution of plastic litter varied across different surveyed areas (Figure 2A). The highest flux of plastic litter was observed in Dalian city, ranging from 766.3 to 1281.8 items/day. Meizhou followed with a flux of 520.8 to 619.4 items/day, Baoding had 398.0 to 484.0 items/day, and Guangzhou had 351.0 to 382.0 items/day. This indicates that Guangzhou, as a first-tier city with a significantly larger population than the other cities, exhibited the lowest plastic litter flux.

Among the plastic litter, CBs were the predominant type, accounting for 86.0% to 97.4% of the total plastic waste across all sampled sites. This indicates that CBs are the most prevalent form of plastic litter in Chinese cities. In various sampled locations across different cities, a lower percentage of CBs was observed on market sites compared to park, beach, or cultural area sites (Figure 2B). This suggests that in the agricultural market area, activities such as grocery shopping may contribute to a higher prevalence of plastic waste.

3.2 CBs density and CBs pollution index

There were significant differences ($P<0.001$) in the density of CBs among different cities (Figure 3A), and it followed a pattern similar to plastic littering. The highest density of CBs was observed in Dalian (0.10 ± 0.03 CBs/m^2), followed by Meizhou (0.07 ± 0.02 CBs/m^2), Baoding (0.06 ± 0.02 CBs/m^2), and Guangzhou (0.03 ± 0.02 CBs/m^2) (Figure 3A). Moreover, the density of CBs in second, third, and fourth-tier cities is 2-3 times higher than in first-tier cities. Considering the different land use types, we found that there were no significant differences in the density of CBs between leisure and commercial areas in Guangzhou and Dalian (Figures 3C, E). However, in Baoding and Meizhou, the density of CBs was significantly correlated with land use type ($P<0.05$) (Figures 3D, F). This suggests that there are different patterns of CBs occurrence among different cities.

The CBPI in Dalian was classified as high pollution (CBPI=9.0), Meizhou as pollution (CBPI=3.4), and Guangzhou and Baoding as low pollution (CBPI=2.0 and CBPI=1.4, respectively) (Figure 4A). There was a significant difference in CBPI among cities ($p<0.0001$). The CBPI in Chinese cities had not been assessed prior to this study, making it the first evaluation of CBPI in Chinese urban areas. When considering land usage types, there were no significant differences in CBPI among different land types in this study (Figure 4B). However, for specific cities, different land types showed distinct patterns in CBPI. For example, in Guangzhou, there were no significant differences among different land types (Figure 4C), while in Dalian, Baoding, and Meizhou, CBPI was significantly correlated with land type (Figures 4D–F).

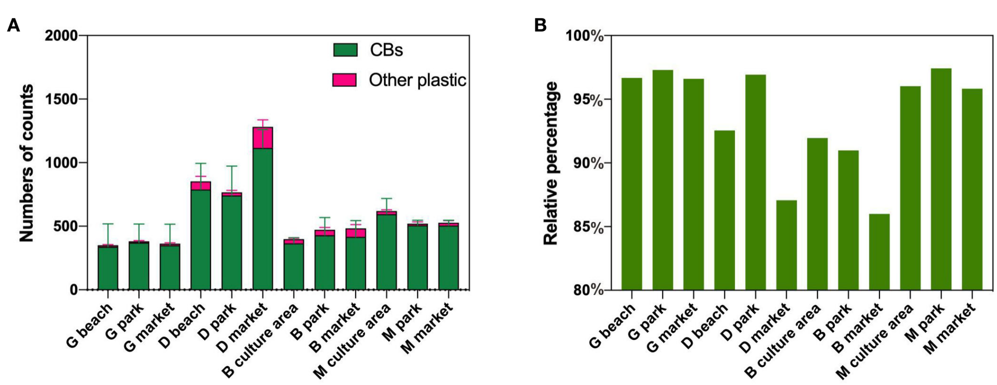

FIGURE 2
The average daily quantity of plastic collected at sampling sites **(A)** and the proportion of CBs collected on average at sampling sites to the total plastic waste **(B)**.

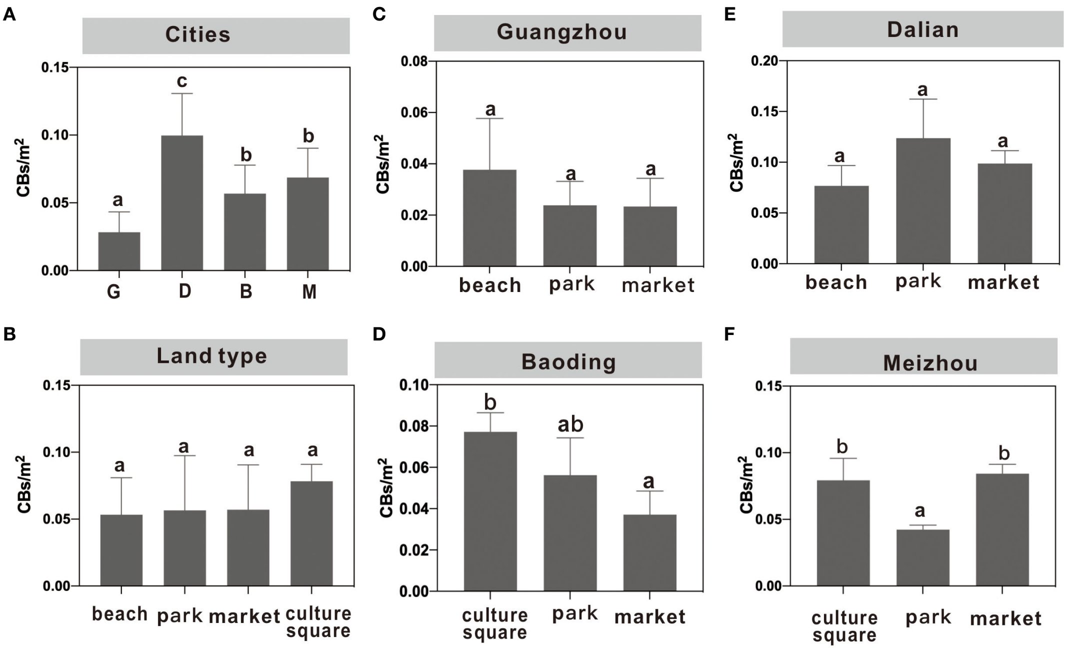

FIGURE 3
CBs density in China cities **(A)** and CBs density in China cities by specific land usage types **(B)**, and CBs density in different development cities by specific land usage types **(C–F)**. G, D, B and M denote Guangzhou, Dalian, Baoding, and Meizhou, respectively. Significance of differences was analyzed using the criteria "a, b, c", with no common superscript indicating significance (p<0.05).

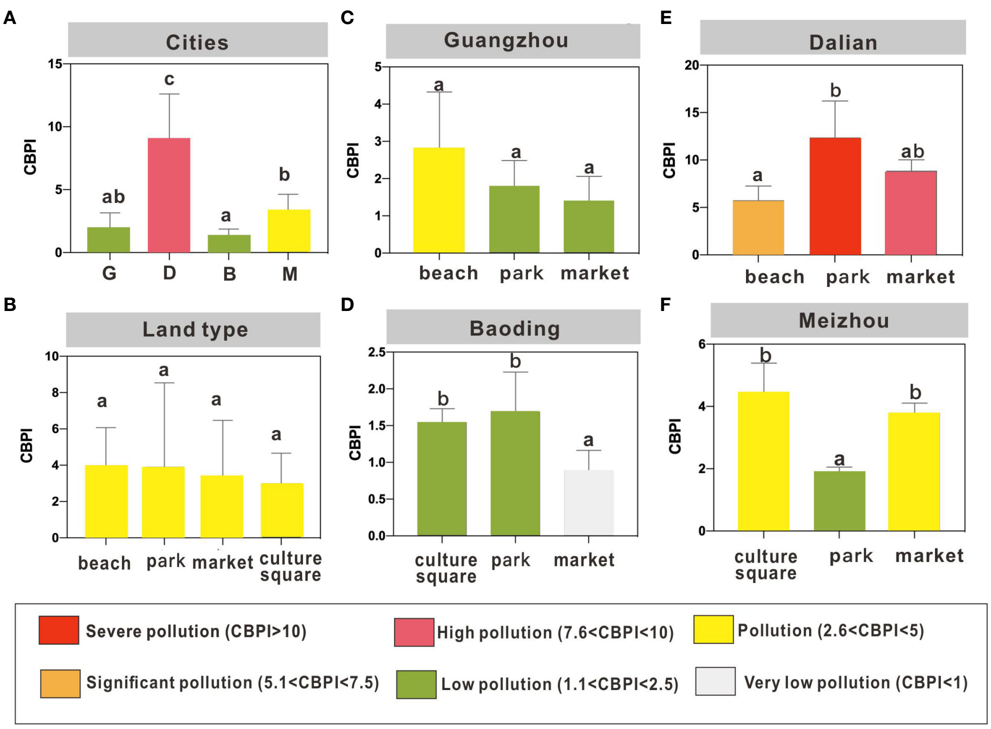

FIGURE 4
CBPI in cities across China **(A)** and CBPI in China cities by specific land usage types **(B)**, and CBPI in different development cities by specific land usage types **(C–F)**. G, D, B and M denote Guangzhou, Dalian, Baoding, and Meizhou, respectively. Significance of differences was analyzed using the criteria "a, b, c", with no common superscript indicating significance (p<0.05).

3.3 The leakage of microplastics and heavy metals from CBs

The microplastics leached into the water environment from both blank sample and sample containing CBs were observed (Figures 5A–C). SEM images indicated that the surfaces of microplastics often exhibit rough, porous, cracked, and torn characteristics (Figures 5B, C). Fragmented microplastics show an irregular layered structure and irregular cracks, while fiber-like microplastics have grooves and raised small bubble-like structures of varying shapes on their surfaces. EDS analysis reveals that the surfaces of microplastics contain elements C, O, Ca, and K, with the detection of heavy metal elements Fe, Al, Si, and Pt on the surfaces of fragmented microplastics (Figure 5D). The total spectrum also includes heavy metal elements Mg and Zr. This may indicates that microplastics with different structures have varying abilities to adsorb heavy metals. Meanwhile, the leachate from CBs was detected using ICP-MS, revealing the presence of 14 different heavy metals with a total concentration of 629.7 μg/L (Figure 5E).

4 Discussion

4.1 Current occurrence of CBs in different cities of China

Previous research has indicated that CBs are the most prevalent type of litter globally in terms of item count (Veiga et al., 2016). For example, in 2017, volunteers worldwide collected over 2 million CBs, surpassing other common plastic wastes such as straws, plastic bags, bottle caps, and food wrappers. In this present study, the collected plastic waste primarily consisted of CBs, disposable masks, plastic bags, plastic bottles, and bottle caps. Among these, CBs accounted for 86%-97.4% of all plastic litter across all sampled sites (Figure 2B), which is consistent with previous research findings. Moreover, in various sampled locations across different cities, a lower percentage of CBs was observed on market sites compared to park, beach, or cultural area sites (Figure 2B). One possible explanation for this phenomenon is that parks and beaches are popular leisure and tourism areas that typically have signage prohibiting littering (Driedger et al., 2015). Furthermore, as people become more environmentally conscious, they may be less likely to discard common plastic waste, resulting in a lower prevalence of such litter in these areas. In contrast, in the agricultural market area, activities such as grocery shopping may contribute to a higher prevalence of plastic waste (Ammendolia et al., 2021). However, regardless of the specific reasons, CBs account for over 80% of the litter, indicating the need for further efforts to promote proper CBs disposal in Chinese cities. In this context, public policies that emphasize raising awareness of the importance of proper CBs disposal and its impact on coastal and urban environments are crucial for reducing human waste in the city. Similar actions have been successfully implemented in cities such as Chile (Eastman et al., 2013).

Previous studies indicate that the density of CBs is higher on beaches than in urban areas (Table 1). Beaches typically

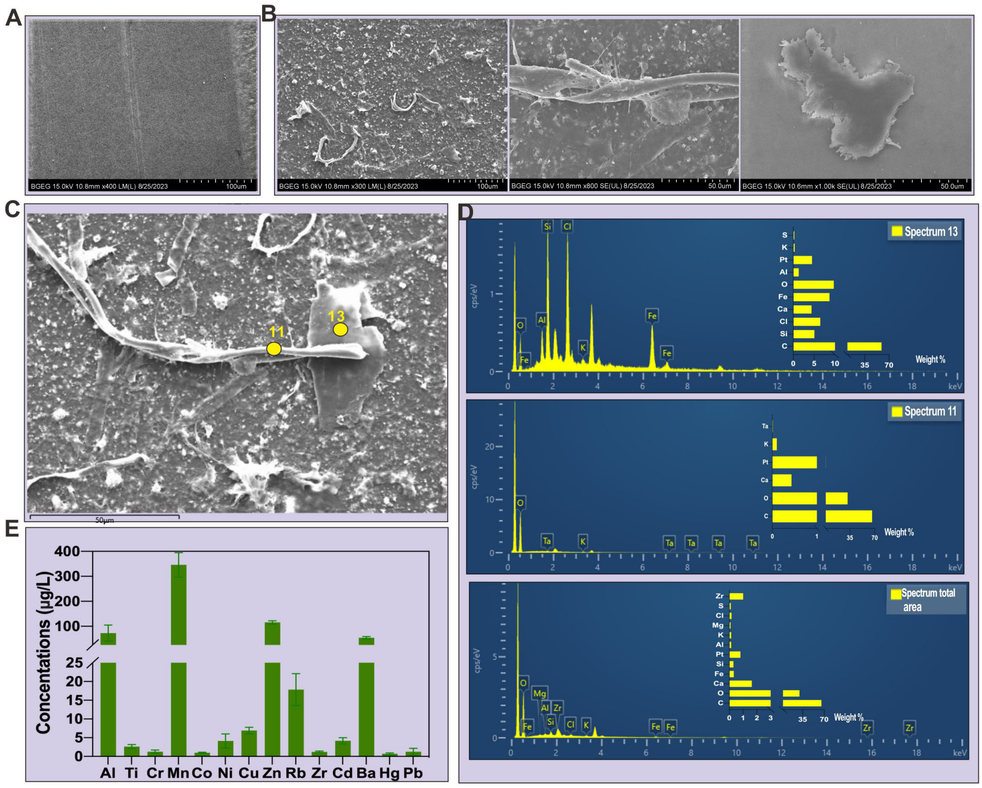

FIGURE 5
SEM-EDS analysis results of blank sample **(A)** and CBs in water environment after 12 hours **(B–D)**, as well as the corresponding concentrations of released heavy metals **(E)**.

accumulate more anthropogenic litter (Geyer et al., 2017). This may be because more waste flows into the oceans through rivers, leading to higher beach litter due to fluid dynamics. Additionally, coastal areas often have poorer solid waste management capabilities (Esquinas et al., 2020; Okuku et al., 2022; Xiong et al., 2022). While we observed this phenomenon on beaches in Guangzhou (Figure 3C), in Dalian, the urban areas showed a higher CBs density compared to the beaches (Figure 3E). This finding is consistent with the findings observed in Santos city, Brazil, where urban areas exhibited a higher CBs density of 0.25 items/m^2 compared to beaches with 0.20 items/m^2 (Lima et al., 2021). A similar pattern was also observed in Mazandaran city, Iran (Yousefi Nasab et al., 2022). However, it is important to note that there were no significant differences in CBs density between different land use types in Guangzhou and Dalian. On the other hand, Baoding and Meizhou exhibited significant differences. Previous research on CBs pollution has shown both correlated and uncorrelated relationships with land use types, suggesting that the relationship between CBs and land use types requires specific analysis based on local urban activities. It is crucial to investigate the underlying mechanisms behind CBs pollution levels and recognize that there might not be a universal pattern.

In this study, despite Guangzhou being a first-tier city with a significantly larger population than other cities, both its plastic litter quantity and CBs density were lower compared to other cities by 2-3 times. This disparity may suggest a poorer urban cleanliness mechanism in these cities, or it could indicate that a disproportionate number of smokers in these areas improperly dispose of CBs. Considering that Dalian experiences a peak tourist season, it may imply that tourists contribute significantly to the CBs litter in the city. Therefore, it is advisable to conduct more CBs monitoring activities and questionnaire surveys in these cities to better understand the background factors related to CBs disposal behaviors.

TABLE 1 CBs densities in beach and urban environments.

Environment	CBs density (CBs/m^2)	Location	Reference
Beach	0.11	Mazandaran, Iran	Yousefi Nasab et al. (2022)
Beach	0.20	Santos, Brazil	Ribeiro et al. (2021)
Beach	0.87	Northeast Brazil	de Araújo and Costa (2021)
Beach	0.06-0.10	Dalian, China	This study
Beach	0.02-0.07	Guangzhou, China	This study
Urban	0.08	Niterói, Brazil	Ribeiro et al. (2022)
Urban	0.03–1.2	Qazvin, Iran	Gholami et al. (2020)
Urban	0.25	Santos, Brazil	Ribeiro et al. (2021)
Urban	0.08-0.17	Dalian, China	This study
Urban	0.01-0.03	Guangzhou, China	This study

4.2 Current degree of CBPI in different cities of China

CBs pollution can result in the leakage of various pollutants into the environment, to varying degrees, under specific anthropogenic and environmental conditions. In order to compare the extent of CBs pollution in different environments, Torkashvand et al. (2021) introduced the CBPI as a qualitative and comparable criterion for cities contaminated with CBs. By calculating the values of CBPI for different cities and land use types within cities, significant differences in CBPI were found among various cities in China (Figure 4A). For specific cities, different land use types exhibited distinct patterns in the CBPI (Figures 4C–F). Previous studies observed a correlation between CBPI and land types, but the results showed heterogeneity in identifying which land types had higher CBPI. For instance, a study in Qazvin, Iran, reported a significantly higher CBPI value in commercial areas compared to other land use types (Torkashvand et al., 2021), while on the south coast of the Caspian Sea in Iran, higher CBPI values were reported in beach areas (Yousefi Nasab et al., 2022). This aligns with the results present in this study, indicating that CBPI varies among different land types in different cities, with numerical differences influenced by urban characteristics.

4.3 The leakage of microplastics and heavy metals from CBs

While CBPI can serve as an indicator of the extent of CBs pollution in the environment, it does not provide a qualitative and quantitative analysis of the pollutants leached from CBs. As hazardous waste, CBs have the potential to release various pollutants, including heavy metals and PAHs, especially in water environments. These pollutants can have adverse effects on the environment and human health (Kermani et al., 2021; Yang Q. et al., 2023). Therefore, it is important to characterize the pollutants leached from CBs under simulated environmental conditions. Our results demonstrate that CBs can release microplastics of different morphological structures into the aquatic environment and have the ability to adsorb heavy metals. The diverse morphological features of microplastics surfaces facilitate an increased surface area, enhancing their adsorption capacity for heavy metals (Gao et al., 2019). Although there has been limited research on the identification of microplastics released specifically from CBs, our results provide data on the release of microplastics from CBs.

Previous research has indicated that CBs release various heavy metals in different aquatic environments, with concentrations ranging from 0.005 to 142 μg/cig (Soleimani et al., 2023; Yang et al., 2023a).

In our study, we detected a total of 14 different heavy metals with a cumulative concentration of 629.7 μg/L (Figure 5E). Among them, manganese (Mn) has the highest concentration, followed by zinc (Zn), aluminum (Al), and others. In comparison to other metals, there was more research on chromium (Cr) and lead (Pb), which may deposit in body tissues and fluids (Pinto et al., 2017). Cr is a common environmental pollutant and a known human carcinogen (Fowles and Dybing, 2003). Pb is also one of the most toxic metals, and even at low concentrations, it can have harmful effects on humans. It has been shown to be detrimental to various organs such as the liver, musculoskeletal system, and hematopoietic system. Pb exposure increases the risk of diabetes and impacts fetal growth and development. Copper (Cu)is a recognized environmental pollutant that can induce toxic effects in various organisms, including humans (Rehman et al., 2019). These heavy metals can be introduced in cigarettes through various substances used in tobacco cultivation and factory processing, such as herbicides, pesticides, and moisturizers.

The disposal of CBs presents a major challenge in solid waste management, and the extent of pollutant leakage from them remains largely unknown on a global scale (Ghasemi et al., 2022). According to the survey results, the average daily density of CBs in all surveyed areas across the four cities was 0.06 ± 0.03 CBs/m^2, equivalent to 6×10^^{4} ± 3×10^^{4} CBs/km^2. Assuming this can represent the CBs density in Chinese cities daily, based on the concentration data of heavy metals in leachate, it can be inferred that approximately 1.9 ± 0.9 g/km^2 of heavy metals may leach out in Chinese cities every day. However, the accuracy of this data requires further investigation and confirmation. Considering China's vast land area and large smoking population, the heavy metal leakage caused by indiscriminate disposal of CBs could pose a serious threat to soil and water safety.

5 Perspective and best practices

This study marks the first report of widespread CBs pollution among cities of varying development levels in China. Notably, second, third, and fourth-tier cities exhibit higher CBs pollution compared to first-tier cities, indicating the differences in cleanliness mechanisms among different urban settings. This disparity suggests a lack of public awareness regarding the proper disposal of CBs and a deficiency in stringent management systems in China.

Given that CBs can release microplastics and heavy metals into the environment, posing adverse effects on terrestrial and aquatic ecosystems, as well as on human health, urgent action is required in China to reduce CBs pollution. To mitigate the hazards associated with CBs, China should take comprehensive actions in education, legislation, and research. Widespread education campaigns can raise public awareness about the responsible disposal of CBs, encouraging individuals to refrain from littering. Legislation should be enacted to impose fines or penalties for irresponsible CBs disposal. Additionally, scientists and industries should focus on developing environmentally friendly cigarette filters through research initiatives. This multifaceted approach is crucial for addressing CBs pollution and promoting sustainable practices in China.

6 Conclusions

In the surveyed areas of four Chinese cities with different levels of development, over 80% of plastic waste was identified as CBs. Alarmingly, second, third, and fourth-tier cities exhibited CBs density 2-3 times higher than that of first-tier cities. This disparity indicates a close correlation between CBs pollution and the development level of cities. Interestingly, the relationship between CBs density, CBPI, and land-use types varied across different cities, emphasizing the need for specific analyses based on local urban activities. Notably, Dalian City demonstrated an overall higher CBPI compared to other cities, possibly associated with its tourism industry. Experimental findings revealed that CBs release microplastics and heavy metals into water environments. Estimated results indicated a potential daily leakage of approximately 1.9 ± 0.9 g/km^2 of heavy metals in Chinese cities, posing severe threats to both human health and ecosystems. These research outcomes unequivocally underscore the urgent need for proactive measures to reduce CBs pollution in Chinese urban areas. In future research and actions, emphasizing interdisciplinary collaboration can drive solutions to address CBs pollution, steering Chinese cities towards cleaner and more sustainable development.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding authors.

Author contributions

QY: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing. WZ: Data curation, Formal Analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. YJ: Data curation, Formal Analysis, Investigation, Writing – original draft, Writing – review & editing. YZ: Investigation, Resources, Validation, Writing – original draft, Writing – review & editing. LC: Data curation, Investigation, Writing – original draft, Writing – review & editing. YR: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. SY: Conceptualization, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Visualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

Authors LC and SY were employed by the company Shenzhen Yuchi Inspection & Testing Technology Co., Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2024.1388631/full#supplementary-material

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