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From riverbank to the sea: An initial assessment of plastic pollution along the Ciliwung River, Indonesia

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ABSTRACT

This study presents the first comprehensive analysis of anthropogenic debris on the riverbanks of the Ciliwung River, covering upstream to downstream areas. The mean of debris found in each measurement was 32.79 ± 15.38 items/m^2 with a weight of 106.00 ± 50.23 g/m^2. Plastic debris accounted for over 50 % of all litter items identified and represents 55 % by weight, signifying a significantly high prevalence compared to global studies examining litter along riverbanks. The majority of the plastics found originated from Single-use applications and were predominantly made from Styrofoam. This investigation demonstrated the importance of actions to reduce single use applications and to improve waste management strategies. This can be achieved through proactive initiatives coupled with adaptable approaches, such as implementing effective urban planning and enhancing waste collection capacity.

1. Introduction

Plastic pollution caused by human activities is widespread in the natural environment and results in significant economic and ecological consequences. These consequences include negative impacts on tourism due to aesthetic degradation, as well as harm to ecosystems through ingestion or entanglement of wildlife (Lau et al., 2020). Anthropogenic debris refers to solid waste materials that are intentionally or unintentionally disposed of improperly, which leads to environmental pollution (Palmas et al., 2022). One of the most significant challenges caused by human-made debris stems from the adverse ecological impacts linked to plastics (Cordova et al., 2022a; Iskandar et al., 2022). Plastics, which are among the predominant forms of human-made debris, present a critical danger to rivers and oceans due to their long-lasting nature and resistance against natural deterioration (Baudena et al., 2022). The improper management of municipal solid waste leads to the introduction of anthropogenic debris into the natural environment (Lebreton and Andrady, 2019; Nurhasanah et al., 2021). The prevalence of plastic pollution can range from 13 to 25 million metric tons per year in terrestrial ecosystems and from 9 to 23 million metric tons per year in aquatic and marine ecosystems (Borrelle et al., 2020; Lau et al., 2020). Numerous authors argue that plastic pollution significantly threatens our planetary boundaries (Borrelle et al., 2020; Jambeck et al., 2015; Omeyer et al., 2023, 2022). The presence of larger plastics in rivers contributes significantly to the accumulation of microplastics (plastic size <0.5 cm) in these environments (Fan et al., 2019; Cordova et al., 2024). Ultraviolet light and mechanical forces can break down larger-sized plastics, leading to their transformation into smaller particles (O'Brine and Thompson, 2010; Song et al., 2017). However, there still needs to be more comprehensive knowledge regarding larger plastics' origins, destinations, and transport mechanisms within river systems despite their evident detrimental effects on the surrounding ecosystems (Andrady, 2017; De-la-Torre et al., 2021; Gardon et al., 2018).

Incipiently, the predominant focus has been on anthropogenic

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debris, specifically plastic litter, in marine ecosystems (Blettler et al., 2018). Rivers have increasingly been acknowledged as significant contributors of macroplastic (size >2.5 cm, (GESAMP, 2019)) debris to the oceans, with estimates suggesting that riverine inputs to the global ocean range from 800 thousand to 2.7 million metric tons (Meijer et al., 2021; van Emmerik et al., 2018). Nevertheless, recent research indicates that a considerable portion of macroplastic pollution remains within rivers for extended periods (Honingh, 2018; Tramoy et al., 2021). This prolonged presence of anthropogenic debris within river systems, including along riverbanks, exacerbates the detrimental impact of plastic litter on these environments.

To gain a comprehensive understanding of anthropogenic pollution in river ecosystems, it is essential to closely monitor and analyze its distribution patterns and accumulation zones (González-Fernández et al., 2018). Accurate and consistent observations of anthropogenic debris provide valuable insights for policymakers and facilitate the development of effective mitigation strategies (Cordova and Nurhati, 2019; Miller et al., 2021; Owens and Kamil, 2020). While studies have primarily focused on floating anthropogenic debris, there remains a need to quantify the presence of such litter in other regions within rivers (Dobler et al., 2022; González-Fernández et al., 2018; Iskandar et al., 2021; Kiessling et al., 2019; Seo and Park, 2020). Furthermore, standardized methodologies for monitoring litter are necessary to ensure harmonization across different research efforts (Bakir et al., 2024).

The collection of data on anthropogenic debris along riverbanks is a crucial step in developing effective strategies to mitigate marine plastic pollution (Battulga et al., 2019; Kiessling et al., 2019). While there have been documented efforts in scientific literature, there remains a significant amount of unreported information regarding the identification of riverbank debris in Asia, including in Indonesia (Owens and Kamil, 2020). Research on anthropogenic debris has predominantly focused on European rivers, such as the Adour River and Seine riverbank in France, the Elbe-Weser triangle rivers in Germany, 8 rivers in Central Italy, and the Rhine-Meuse River delta in the Netherlands (Bruge et al., 2018; Cesarini and Scalici, 2022; Roebroek et al., 2021; Schöneich-Argent et al., 2020; Tramoy et al., 2022). Studies have also been conducted on riverbank anthropogenic debris along the Selenga River in Mongolia (Battulga et al., 2019). The findings from these studies consistently highlight plastic as a dominant component of riverbank anthropogenic debris.

Understanding the composition and distribution of anthropogenic debris in rivers is crucial for identifying priority areas for intervention and developing effective strategies to reduce its presence in natural aquatic and marine ecosystems. Despite the lack of baseline data on debris items in many rivers, this study fills that gap by examining large-scale riverbank surveys conducted along the Ciliwung River, which has been heavily impacted compared to other Indonesian rivers.

The objective of this research is to firstly to identify the predominant types of anthropogenic debris found on riverbanks, and second, to analyze spatial variations in riverbank anthropogenic debris abundance within the Ciliwung River. Ultimately, these findings will inform local stakeholders on monitoring methods tailored to local conditions as part of a comprehensive strategy towards mitigating plastic pollution caused by human activity. We will examine two hypotheses in this study: a) the abundance of debris on river banks will be greater in areas with poor waste management, and b) single-use products will be the prevalent type of debris due to their widespread use.

2. Material and methods

2.1. Study sites

The Ciliwung River plays a vital role in providing water for fisheries, agriculture, and industry sectors in the upper region. Additionally, it serves as a source of drinking water for the communities living upstream and midstream. The Ciliwung River originates from Mount Pangrango, which sits at an altitude of 3020 m above sea level. The annual precipitation in the Ciliwung watershed varies between 1500 and 3500 mm.

The Ciliwung River covers a vast area of >476 km^2 and has a length of approximately 119 km. It flows through the administrative boundaries of West Java Province, DKI Jakarta Province, and Banten Province. The mismanagement of plastic waste in these territories is a significant concern, with an estimated annual accumulation of ~5900 t (Kementerian Lingkungan Hidup dan Kehutanan, 2023). This number includes both floating and non-floating debris, contributing to the pollution levels in Jakarta Bay and The Java Sea. These seas have become heavily affected by marine plastic debris, specifically from the Ciliwung River, with estimates of 255.5–365 t per year for floating plastic debris alone (Cordova and Nurhati, 2019). The province of DKI Jakarta accounts for the largest portion (40 %) of the Ciliwung Watershed. Land use patterns differ significantly across different parts of the river; upstream includes a mix of natural forest, agricultural land, and settlements, while midstream and downstream primarily consist of more developed areas including settlements and commercial infrastructure (Fig. 1). The land cover within the Ciliwung watershed has undergone significant changes, mainly due to the conversion of agricultural and forest lands into built-up areas. This transition has been occurring at a rapid pace, with an annual increase of over 100 % since 1990 (Abighail et al., 2022). In order to ensure the appropriateness and suitability of the sampling locations, a pre-survey was conducted prior to beginning the actual sampling process. This involved taking aerial photographs as a means of assessment. The results of this pre-survey, along with a brief analysis, are available in the supplementary materials (Figs. S1–S3).

The selection of study sites was based on three factors: the presence of a riverbank that is prone to submersion during periods of high water levels, legal accessibility for team members, and representation of various land uses (such as vegetation, agriculture, built up area or mixed area) along the river. In total, there were 33 research locations identified

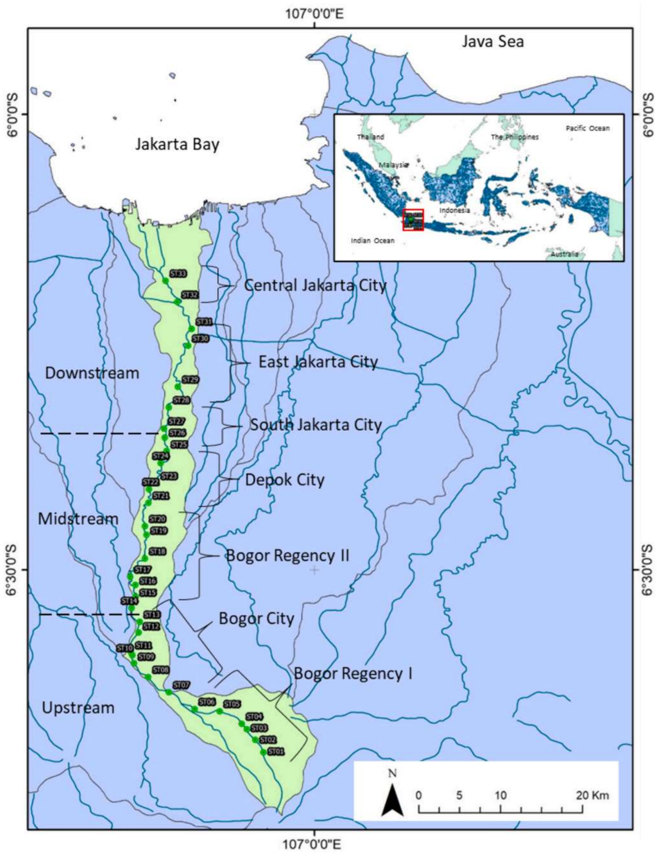

Fig. 1. Study sites in Ciliwung Watershed.

as potential study sites (Fig. 1). These locations included 11 in the upstream region, 17 in the midstream region, and 5 in the downstream region. Out of the total 33 locations, there are seven areas that are surrounded by vegetation and two areas in close proximity to agricultural lands. Additionally, there are ten mixed-use locations and 14 built-up areas. In terms of river morphology, the majority of these locations exhibit a curved shape (25) while the remaining have a straight shape (8). Notably, curved river sections tend to have a higher litter density compared to straight sections (Schneider et al., 2021). From an administrative standpoint, it is found that among these locations, Bogor Regency has the highest number with 13 survey sites, followed by Bogor City with seven survey sites. Meanwhile, Depok City has five survey sites, whereas South Jakarta City along with East Jakarta City also has three survey sites; Central Jakarta City merely appears twice.

2.2. Sampling procedure

During the sampling period spanning from October to September 2021, a comprehensive analysis was conducted on riverbank debris items. The riverbank survey sites ($n = 33$) ranged from 30 to 50 m and were situated parallel to the low waterline mark, as depicted in Fig. 2. The width of the sampling area was determined by measuring the distance between the waterline (the point at which the water meets the bank) and the high-water line, with a maximum allowance of 20 m from the waterline to ensure sampling was the same in each survey site. To identify this high-water line accurately, researchers look for evidence, such as debris, litter, and organic matter left behind during previous flood events. A quadrant measuring 100 × 100 cm within each sampling area is established near where deposition occurs parallel to the waterline. Data collection focuses on collecting visible debris items found within both surface layers and those buried up to five centimeters. All collected pieces are categorized based on predefined classifications. It is imperative to acknowledge that the absence of a systematic classification system for plastic litter in rivers necessitates the adoption of beach debris categorizations from reputable sources such as NOAA and UNEP shoreline debris assessments (Cheshire et al., 2009; Lippiatt et al., 2013). Consequently, we proceeded to classify the collected riverbank debris into six distinct categories: plastics and rubber, metal, glass, processed wood, cloth, and others. These categories were further divided into subcategories for more accurate classification. Any food waste or animal waste found during our assessment was classified within 'other' including any small or unclassifiable debris. Moreover, among all the riverbank debris sub-categories (57 in total), we further divided plastics and rubber into 30 different sub-categories using established classifications from previous studies (Cheshire et al., 2009; Cordova et al., 2022a; Kumar et al., 2016; Lippiatt et al., 2013; Simeonova and Chuturkova, 2019).

The debris found on the riverbank was meticulously rinsed and cleaned and left to dry under the sun for 10–15 min. Once dried, it was counted and weighed using a Harnic Heles HL-340 digital scale capable of holding up to 5 kg with an accuracy of 0.1 g. To determine the density of the debris along the riverbank, transects were utilized alongside a specific formula:

$$D = \frac{n}{\omega \times l}$$

where D represents the debris density measured as number or weight per-square meter, n, denotes the observed count (frequency) or weight (kg) of debris items, ω representing transect width (expressed in meters), and l indicating transect length (measured in meters).

2.3. Plastic debris chemical composition analysis

This study used a Fourier Transform Infrared (FT-IR) spectrometer to analyze chemical compounds in plastic debris collected from various riverbank sampling locations. Specifically, 9156 plastic items from 27 sub-categories were carefully selected for analysis using the FT-IR instrument (Agilent Cary 630), which was equipped with an Attenuated Total Reflection diamond crystal. The experimental setup involved utilizing an 8 cm single-reflection resolution mode within the wavenumber range of 600 and 3800 cm^{-1} with 16 scans conducted per analysis. We meticulously cleaned each plastic item's surface before conducting any FT-IR analysis by gently applying a sterile ethanol solution (96 %) to avoid contamination. The identification of polymer types in the analyzed samples relied on distinct peaks observed at specific bands as described previously by Käppler et al. (2015), Löder et al. (2015) and Cordova et al. (2023). Three separate tests were performed on different areas of each plastic surface for enhanced consistency in our findings. For quality control, an assessment was conducted by comparing the particle spectrum with predetermined reference standards provided by Thermo-scientific, Shimadzu, and the Research Center for Geosciences at the University of Bayreuth in Germany. By comparing the properties

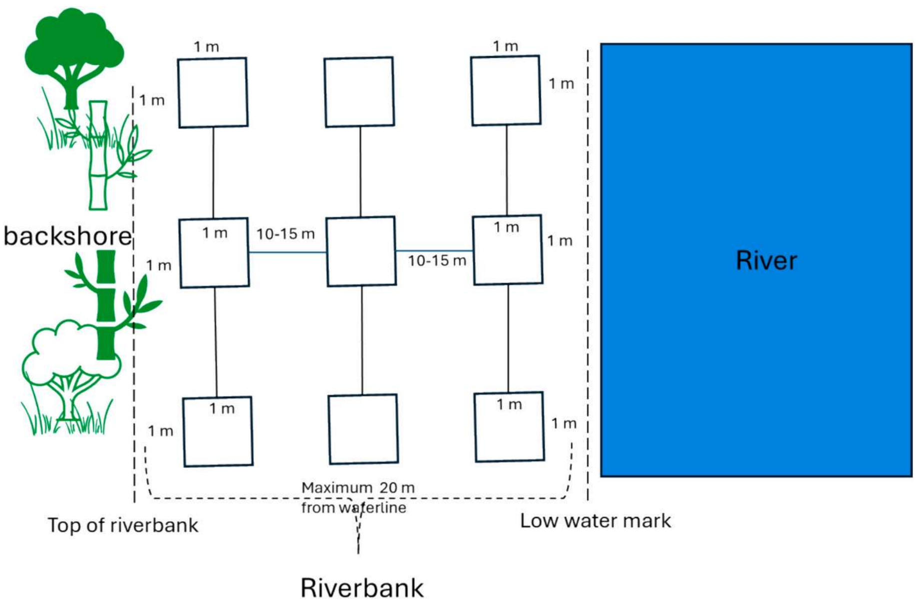

Fig. 2. Overview of sampling procedure in the riverbanks.

of the tested plastic polymers with these established benchmarks, an evaluation could be made regarding their adherence to desired quality criteria.

2.4. Statistical analysis

Statistical analyses were conducted to assess potential variations in each sampling areas and type of riverine debris collected. The Kruskal-Wallis test and Mann-Whitney pairwise test functions, offered by PAST software version 4.03, were employed for this purpose. A significance level of $p < 0.05$ was utilized throughout these analyses as a threshold for determining statistical significance.

3. Results

3.1. Quantities of riverbank debris

A total of 87,656 riverbank debris items, weighing 283.34 kg, were sampled and evaluated in this study (Fig. 3). The mean abundance of debris across all measurements was 32.79 ± 15.38 items/m^2 (106.00 ± 50.23 g/m^2). Notably, the highest concentration of riverbank debris was observed at ST 19 (mean: 56.85 ± 8.71 items/m^2 and 150.92 ± 38.70 g/m^2), followed by ST 17 (mean: 49.74 ± 6.88 items/m^2 and 136.92 ± 50.397 g/m^2), and ST 18 (mean: 48.79 ± 5.41 items/m^2 and 122.22 ± 33.08 g/m^2. In comparison, the minimum abundance value was identified at ST 30 (mean: 9.30 ± 2.93 items/m^2 and 53.76 ± 13.09 g/m^2), followed by ST 26 (mean: 9.47 ± 3.19 items/m^2 and 50.18 ± 20.43 g/m^2), and ST 28 (mean: 9.64 ± 2.77 items/m^2 and 43.32 ± 13.97 g/m^2).

There was a significant variation ($p < 0.05$) in the amount and weight of riverbank debris in different areas (Fig. 4). The upstream area exhibited the greatest abundance and weight of debris (mean: 38.33 ± 8.19 items/m^2 and 124.79 ± 46.40 g/m^2), followed by the midstream region (mean: 35.83 ± 15.37 items/m^2 and 109.22 ± 48.94 g/m^2). Conversely, relatively lesser amounts of riverbank debris were found downstream, with an mean density of approximately 10.30 ± 2.80 items/m^2 (53.73 ± 16.64 g/m^2).

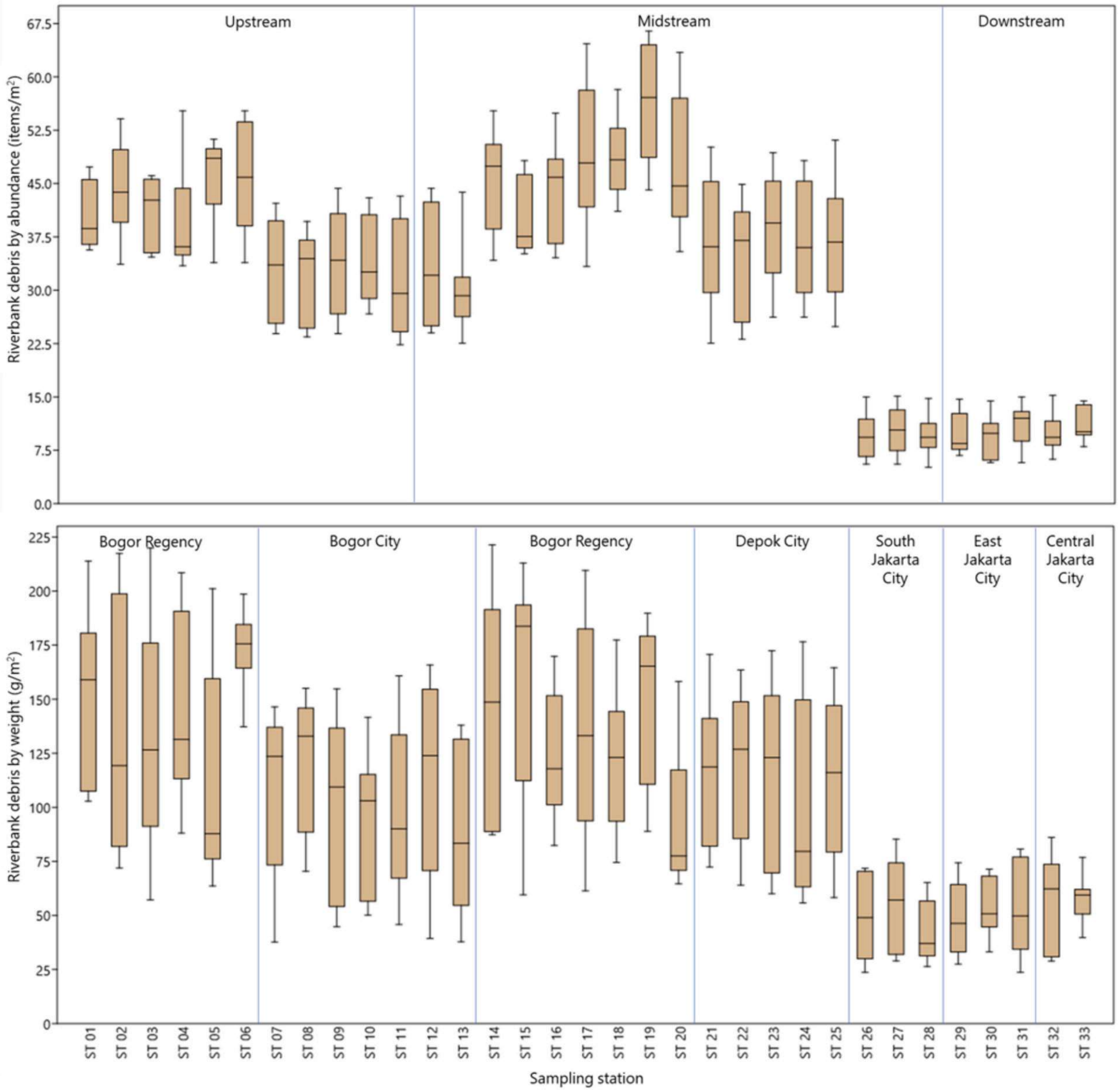

Fig. 3. Riverbank debris by abundance (top) and weight (bottom) in each sampling station that divided based on the nature of the river (top) and administrative area (bottom).

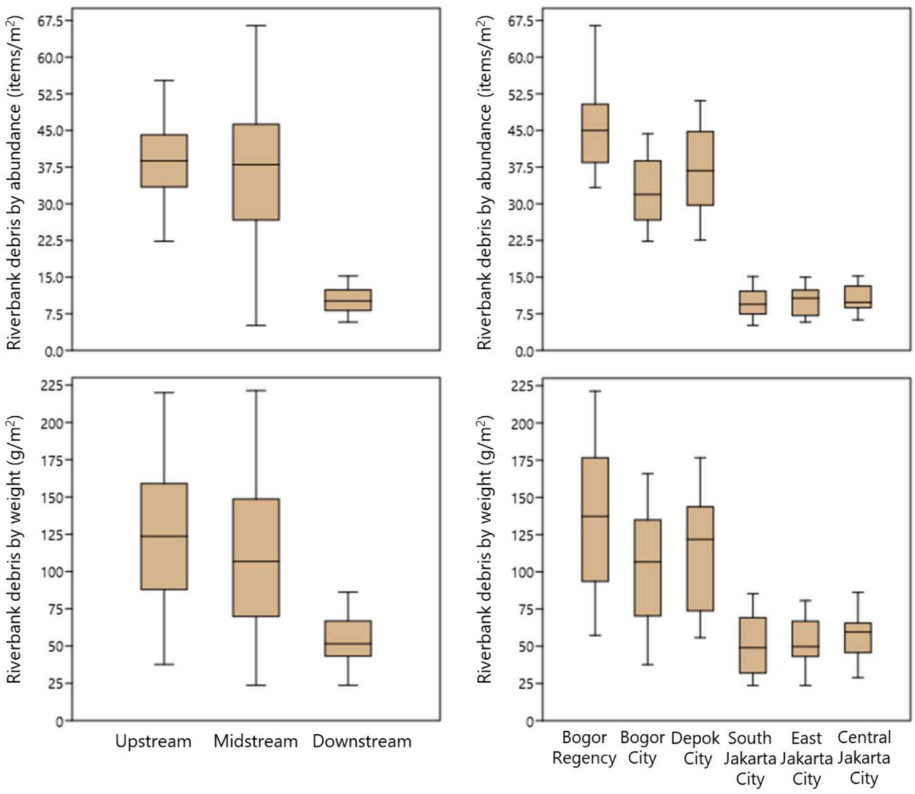

Fig. 4. Riverbank debris by abundance (top) and weight (bottom) based on the nature of the river (left) and administrative area (right).

An intriguing aspect of this study pertains to the examination of riverbank debris based on the jurisdictional boundaries set by local government administration (Fig. 4). In Bogor Regency, specifically in two particular areas (ST 01–06 and ST 14–20), there is a noticeably high abundance (42.82 ± 6.40 items/m^2; 142.59 ± 46.65 g/m^2 and 47.41 ± 8.91 items/m^2; 133.44 ± 45.25 g/m^2, respectively) of riverbank debris compared to the other locations. Followed by Depok City (36.89 ± 8.02 items/m^2 and 113.92 ± 37.79 g/m^2) and Bogor City (32.56 ± 6.87 items/m^2 and 102.89 ± 37.94 g/m^2). Conversely, South Jakarta City (9.84 ± 2.98 items/m^2 and 49.99 ± 18.89 g/m^2), East Jakarta City (10.13 ± 2.98 items/m^2 and 51.89 ± 16.83 g/m^2), and Central Jakarta City (10.56 ± 2.56 items/m^2 and 56.49 ± 16.43 g/m^2) had the lowest levels of riverbank debris among all sampling areas.

3.2. Riverbank debris composition

Most debris collected along the riverbank consisted of plastic, accounting for 53.65 % by count and 54.82 % by weight (Fig. 5). The mean density of debris stranded on the Ciliwung riverbank was 32.79 ± 14.27 items/m^2, with a total mean weight of 106.00 ± 36.52 g/m^2. Among all types of debris, plastic had the highest contribution by count (17.59 ± 7.83 items/m^2) and weight (58.10 ± 20.51 g/m^2), followed by textiles which accounted for a mean abundance of 7.00 ± 3.48 items/m^2 and an mean weight of 19.60 ± 8.26 g/m^2. Although, there were notable variations observed among the different categories of debris found along the riverbanks. Plastic material exhibited the highest prevalence across all categories, indicating a statistically significant difference ($p < 0.05$). On the other hand, textiles displayed notable high distinctions in terms of metals, glass, lumber, other forms of debris, and hazardous waste ($p < 0.05$). A consistent presence of plastic litter was observed along the riverbanks at all sampling points, with proportions ranging from 47.43 % to 64.35 % based on count and from 46.64 % to 64.15 % based on weight. The greatest count of plastic litter was found at ST 12 (upstream in Bogor City), while the highest proportion based on weight was found at ST20 (midstream in Bogor Regency). Conversely, the lowest proportions were recorded for both abundance and weight at ST26 (downstream in South Jakarta City).

Table 1 highlights Styrofoam (cushion) was the most abundant material among all sampling areas along the Ciliwung riverbank, accounting for 10.13 % of all collected plastic debris. This was followed closely by plastic shopping bags (10.11 %), cigarette butts (10.04 %), disposable medical masks (9.93 %), and Styrofoam used for food packaging (9.90 %). Other notable categories included food wrappers, nonfood plastic sachet packaging, disposable cups, pieces such as straws and cotton buds (3.76 %), and miscellaneous types of plastic bags (3.78 %). Interestingly, the most prevalent category differs along both administrative areas and natural water flow in the Ciliwung riverbank (Table 1). Furthermore, the seven aforementioned types of debris collectively account for >60 % of each area surveyed. In addition, the composition of the top 10 items differed across different sampling areas, but single-use plastic items were consistently found to be the most prevalent category of debris on riverbanks, accounting for over 80 % of all collected plastic debris.

3.3. Chemical composition of riverbank debris

A total of 9156 random plastic samples were analyzed, accounting for approximately 10.45 % of the 87,656 litter items studied. Fig. 6 presents data on eight confirmed polymer groups that were identified in these samples. The dominant synthetic polymer group was polyethylene, representing 31.75 % of the total items analyzed (including low- and high-density polyethylene). Following this, polypropylene accounted for 25.78 %, while polystyrene items comprised 19.17 %. Other identified polymers included cellulose acetate (9.58 %) and polyethylene terephthalate (8.41 %) and a smaller fraction of polyurethane (2.99 %), cellophane (1.89 %), and lastly, polyacrylate (0.44 %). In addition, the distribution of polymer types across different regions aligns with the overall dominance. However, there are specific

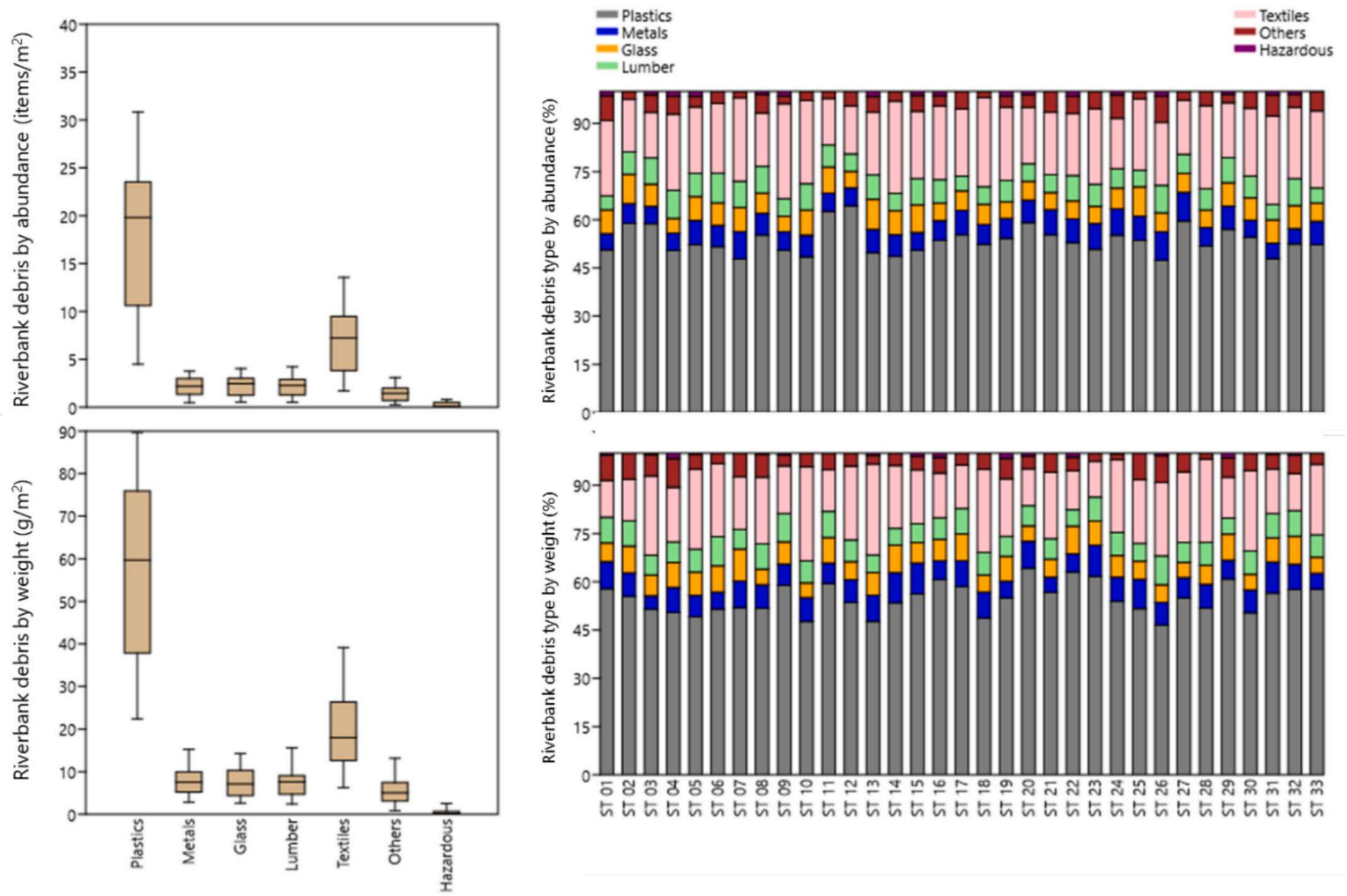

Fig. 5. Riverbank debris composition and its percentage by abundance (top) and weight (bottom) in each sampling station.

areas, such as South Jakarta City, where the polyethylene group (48.6 %) and polyacrylate group (9.64 %) constitute a higher portion of the polymers found. Similarly, in the Depok city area, cellophane accounts for a considerable proportion (9.02 %).

4. Discussion

4.1. Distribution and origin of riverbank litter

Here we present the first study of the spatial distribution of riverbank debris along Indonesia's most densely populated river, spanning from its upstream region to downstream. Due to the lack of comprehensive investigations quantifying and characterizing debris on riverbanks in Indonesia, comparing the results directly is challenging due to variations in methodologies and a lack of harmonization across studies. Yet, riverine plastic pollution is a widespread and presents a cross-border issue that necessitates globally standardized monitoring efforts for effective mitigation. Our research findings revealed a significantly higher accumulation of debris on riverbanks compared to similar studies in Germany, the Netherlands, Albania, and Vietnam (Table 2).

The amount of riverbank debris observed was up to 30 times greater in our study area (Table 1). Several factors may account for the significant presence of macrodebris on the riverbanks of the Ciliwung River. These include a lack of awareness regarding environmental concerns, and inadequate government focus on proper waste management practices (Ali and Shams, 2015; Santos et al., 2009; Thushari et al., 2017). Additionally, the excessive litter observed along the riverbank can be attributed to illegal dumping at unauthorized sites and unintentional disposal of waste in areas near the riverbank (Gasperi et al., 2014; Kiessling et al., 2019). The accumulation of litter in the riverbanks is exacerbated by wind or rainfall-driven surface runoff (Dris et al., 2015; Roebroek et al., 2021). Most of the litter items observed in this study likely originated from local sources.

During our research, observations were found indicating that residents in the Bogor Regency area were directly disposing of their garbage into the river. This finding aligns with similar research conducted along riversides in Wales (mean of 5.84 Items/m) and Chile (0.14–3.42 Items/m^2), which identified illegal dumping as a prominent source of litter (Rech et al., 2015; Williams and Simmons, 1999). While other studies have suggested additional sources of river debris, such as household waste from residents (Bruge et al., 2018; Franz and Freitas, 2012) or industrial-related pollution (Cordova et al., 2022b; Deng et al., 2020; Lechner and Ramler, 2015), these were not extensively studied in the current investigation. Please refer to Table 2 for a comparison of the average riverbank debris from previous studies. It is worth noting that industry-related litter may contribute considerably to microplastic pollution, an aspect that was not specifically addressed in this study as we aimed to identify whole litter items to help identify where targeted interventions are needed.

Once in the river system, litter items can be transported downstream and may temporarily accumulate in lower areas (Hohenblum et al., 2015; van Emmerik et al., 2019). Nonetheless, this study discovered a lower amount of waste in the downstream region. Besides improved waste management practices in these areas, it is possible that there has been an underestimation of litter accumulation along the riverbanks upstream due to most research focusing solely on river litter. Ideally, this

Table 1
Top-10 stranded riverbank debris in administrative area and in each location.

Area	Top-10 plastic debris category									
	1	2	3	4	5	6	7	8	9	10
Ciliwung riverbank	Styrofoam (cushion)	Plastic shopping bags	Cigarettes butts	Disposable medical mask	Styrofoam (food wrapper)	Food wrappers	Plastic sachet (non-food pack/ wrapper)	Plastic cups	Straw, cotton buds, pieces	Other plastic bags
% share	10.13	10.11	10.04	9.93	9.90	9.87	9.85	3.79	3.78	3.78
Bogor Regency	Cigarettes butts	Styrofoam (cushion)	Plastic shopping bags	Disposable medical mask	Plastic sachet (non-food pack/ wrapper)	Styrofoam (food wrapper)	Food wrappers	Other plastic bags	Plastic cups	Drinking plastic bottles
% share	10.68	10.31	9.73	8.96	8.94	8.78	8.02	3.85	3.66	3.62
Bogor City	Food wrappers	Disposable medical mask	Styrofoam (food wrapper)	Plastic sachet (non-food pack/ wrapper)	Plastic shopping bags	Cigarettes butts	Styrofoam (cushion)	Straw, cotton buds, pieces	Plastic cups	Drinking plastic bottles
% share	10.8	10.04	9.9	9.41	9.37	9.2	8.97	3.78	3.59	3.24
Bogor Regency	Cigarettes butts	Plastic sachet (non-food pack/ wrapper)	Food wrappers	Styrofoam (cushion)	Plastic shopping bags	Styrofoam (food wrapper)	Disposable medical mask	Plastic cups	Other plastic bags	Shoes, sandals, gloves, cuts
% share	9.83	9.63	9.6	9.59	9.49	9.21	9.06	4.21	3.51	3.17
Depok City	Styrofoam (cushion)	Disposable medical mask	Plastic sachet (non-food pack/ wrapper)	Styrofoam (food wrapper)	Food wrappers	Cigarettes butts	Plastic shopping bags	Drinking plastic bottles	Straw, cotton buds, pieces	Other plastic bags
% share	10.55	9.51	9.5	9.32	9.22	9.06	8.35	4.28	3.94	3.83
South Jakarta City	Food wrappers	Styrofoam (food wrapper)	Styrofoam (cushion)	Disposable medical mask	Cigarettes butts	Plastic shopping bags	Plastic sachet (non-food pack/ wrapper)	Other plastic bags	Diapers	Plastic label, plastic lids
% share	9.84	9.35	9.3	8.77	8.71	8.66	8.56	4.85	4.27	3.86
East Jakarta City	Plastic shopping bags	Styrofoam (food wrapper)	Styrofoam (cushion)	Disposable medical mask	Food wrappers	Plastic sachet (non-food pack/ wrapper)	Cigarettes butts	Drinking plastic bottles	Plastic utensil	Plastic cups
% share	10.52	9.97	9.49	9.31	9.19	8.92	8.58	4.27	4.25	4.24
Central Jakarta City	Disposable medical mask	Plastic shopping bags	Cigarettes butts	Plastic sachet (non-food pack/ wrapper)	Food wrappers	Styrofoam (cushion)	Styrofoam (food wrapper)	Straw, cotton buds, pieces	Other plastic bags	Drinking plastic bottles
% share	10.44	10.19	9.63	9.47	8.84	8.75	8.5	4.55	4.04	3.99
Upstream	Cigarettes butts	Styrofoam (food wrapper)	Plastic shopping bags	Disposable medical mask	Styrofoam (cushion)	Food wrappers	Plastic sachet (non-food pack/ wrapper)	Straw, cotton buds, pieces	Drinking plastic bottles	Diapers
% share	10.47	9.4	9.37	9.31	9.28	9.06	8.99	3.76	3.45	3.42
Midstream	Styrofoam (cushion)	Plastic sachet (non-food pack/ wrapper)	Styrofoam (food wrapper)	Disposable medical mask	Plastic shopping bags	Food wrappers	Cigarettes butts	Other plastic bags	Plastic cups	Straw, cotton buds, pieces
% share	10.14	9.83	9.79	9.79	9.55	9.5	8.89	3.86	3.81	3.63
Downstream	Plastic shopping bags	Disposable medical mask	Cigarettes butts	Styrofoam (cushion)	Styrofoam (food wrapper)	Food wrappers	Plastic sachet (non-food pack/ wrapper)	Drinking plastic bottles	Plastic cups	Straw, cotton buds, pieces
% share	9.98	9.43	9.43	9.23	9.11	9.08	9.03	3.99	3.9	3.86

transportation process involves floating debris at the water's surface, suspended particles along with the water column, as well as movement over the river bed (Siegfried et al., 2017; Tramoy et al., 2022). Litter deposition occurs on aquatic organisms, riparian vegetation, sediment, and alongside riverbanks (Cordova et al., 2022b; Emmerik and Schwarz, 2020; Sadri and Thompson, 2014).

Through additional analysis, we have made estimations regarding the potential amount of litter on riverbanks that could enter the sea. Utilizing satellite images to identify riverbanks along the Ciliwung River, a total area of 13.31 ha was determined (Please refer to Table S3 Supplementary Material 2 for the analysis). Taking into account the average accumulation rate of debris on these riverbanks (as depicted in Figs. 3 and 4), it is projected that approximately 4.95 to 18.82 tons of litter annually may accumulate on the riverbank with potential for flow into the sea; within that range, roughly 2.71 to 10.32 tons would consist specifically of plastic litter. However, this calculation assumes no entanglement in vegetation or structures along the riverbank and considers litter accumulation as temporary before being washed away during periods of increased water flow in the river, which results in a potential discrepancy between the estimated and actual amounts of litter that ends up in the sea. Furthermore, our findings indicate that most of the litter observed from upstream locations to downstream sampling points consists mainly of relatively new plastic litter. This was evident by conducting analysis using carbonyl index calculations (Please refer to Supplementary Material 3 for the analysis), determining that plastic litter at Ciliwung River's bank is not older than two years. In-depth research and comprehensive monitoring are necessary to effectively address this issue, as it can contribute to improved waste

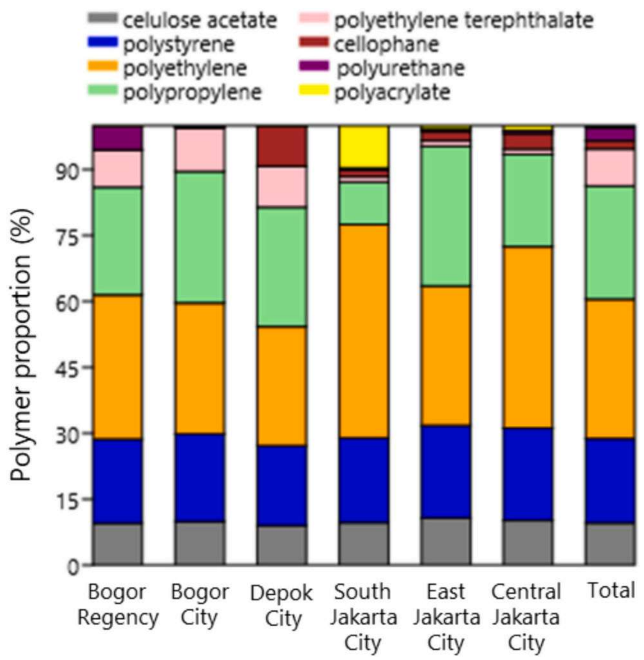

Fig. 6. Proportion of polymer types in each administrative sampling area.

management practices in rivers.

4.2. Single-use products, the prevalent type of debris

The results of our study reveal that plastic litter is the predominant type of litter found on the riverbanks of the Ciliwung River, with styrofoam being the most common form within this category. This emphasizes the critical need to implement systematic measures aimed at reducing plastic and Styrofoam usage in both the Ciliwung watershed and Greater Jakarta area. This study identified two types of styrofoam litter, namely cushions (most abundant) and food wrappers (5th most abundant item), which accounted for nearly 20 % of the overall plastic litter observed. Foam materials have gained popularity across various industries due to their exceptional shock absorption properties, making them highly versatile in many applications (Knoblauch and Mederake, 2021). In particular, styrofoam is commonly used as a replacement for traditional organic food wraps like banana or teak leaves in packaging (Cordova and Nurhati, 2019). Once discarded in the environment, single-use styrofoam undergoes fragmentation caused by mechanical processes, UV exposure, or oxidative, leading to a decrease in its size (Andriolo et al., 2020; Chubarenko et al., 2020). Consequently, there has been an escalation in the presence of this form of plastic debris, in smaller sizes, along the riverbanks of the Ciliwung River.

The abundance of plastic litter on riverbanks is primarily attributed to the widespread production and use of single-use plastics worldwide (Adam et al., 2020). For example, single-use plastic items such as shopping bags, cigarette butts, disposable medical masks, food wrappers, non-food sachet packaging, cups, straws, and cotton buds are manufactured in large quantities globally (Quartey et al., 2015). The global production of plastic has drastically increased where approximately 360 million metric tonnes was produced in 2018; with half being accounted for by single-use plastics (PlasticsEurope and EPRO, 2021). These types of plastics often contain organic additives that have been found to contribute harmful chemicals into the environment and subsequently can be distributed throughout multiple ecosystems (Tun et al., 2023). Currently, only a small percentage (100 out of 514) of regencies and cities in Indonesia have implemented regulations to ban single-use plastics including plastic shopping bags (Cordova et al., 2023). This environmental initiative should be adopted by more areas across the country in order to address the issue effectively.

A crucial initial step towards better understanding the distribution of various plastic types along coastlines is identifying the most prevalent polymer types and the environmental impacts they may cause. This information can then be compared with findings from studies measuring the abundances of marine microplastics, supporting the hypothesis that fragmentation is the primary source of microplastics in oceans (Dimassi et al., 2022; Thompson, 2015). The composition of riverbank plastic debris discussed in this study is linked to the large-scale plastics entering Jakarta Bay (Cordova and Nurhati, 2019) and the presence of microplastics in the Ciliwung river (Cordova et al., 2022c, 2020). The predominant synthetic polymers found in this study are polyethylene, polystyrene, and polypropylene which are commonly used materials for single-use plastic products (PlasticsEurope and EPRO, 2021). In addition, Joly and Coulis (2018) stated the amounts of cellulose acetate polymers found are often derived from discarded cigarette butts.

The improper disposal of cigarette butts, which are commonly discarded worldwide without specific disposal systems, poses significant environmental concerns; particularly, the presence of microfibers made from cellulose acetate as the main component (Green et al., 2019; Haske-Cornelius et al., 2017; Yogaswara et al., 2024). These microfibers contain toxic chemicals such as persistent organic pollutants and heavy metals that have the potential to cause genetic mutations and cancerous

Table 2
Comparison of riverbank debris with previous reports.

Sampling area	Study year	Riverbanks sampling number	Method	Riverbank debris mean	Unit	References
Ciliwung River, Indonesia	2021	33	3 level of 1 m^2 quadratic transect	32.79 ± 15.38	Items/m^2	This study
the Rhine, Weser and Elbe river systems, Germany	2016, 2017	250	1.5 m circle transect	0.54 ± 1.20	Items/m^2	(Kiessling et al., 2019)
The Elqui, Maipo, Maule, and BioBio rivers, Chile	2014	55	3 m radius circle transect	0.14–3.42	Items/m^2	(Rech et al., 2015)
The River Taff, South Wales, United Kingdom	1996	50	5 m line transect	5.84	Items/m	(Williams and Simmons, 1999)
Ishëm River, Albania	2020	2	100 m line transect	1.66–2.69	Items/m^2	(Gjyli et al., 2023)
Saigon River, Vietnam	2022	1	100 m line transect	0.06–0.21	Items/m^2	(Nguyen and Bui, 2023)
Nederrijn River, Netherlands	2017, 2019	192	100 m line transect	3.99	Items/m	(Roebroek et al., 2021)
Meuse River, Netherlands	2017, 2019	93	100 m line transect	2.43	Items/m	(Roebroek et al., 2021)
Waal River, Netherlands	2017, 2019	6	100 m line transect	1.55	Items/m	(Roebroek et al., 2021)
Erzen River, Albania	2020	2	100 m line transect	2.42	Items/m	(Gjyli et al., 2022)

effects to wildlife (Rebischung et al., 2018; Shen et al., 2021; Torkashvand et al., 2020). Moreover, knowledge about specific polymers and their associated additives can prove beneficial in terms of assessing environmental risk and ecotoxicology. Conducting thorough back tracing to identify sources of marine plastic debris becomes more feasible when considering these unique characteristics inherent to different polymers (Int-Veen et al., 2021).

4.3. The relationship between riverbank litter and local waste management

The findings of this study reveal a strong relationship between waste management services (Collection rate based on SIPSN data (2023)) and the presence of riverbank debris (please see Supplementary materials Table S3 and Figs. S4–S5). The data indicates a positive correlation between the rate of waste collection in each region and both a lower the abundance and weight of debris found on riverbanks ($R^2 = 0.934$ for abundance, $R^2 = 0.948$ for weight, $p < 0.05$). Regions with higher waste collection rates tend to have lower levels of riverbank debris which indicates waste management services can help reduce the debris accumulations along the riverbank. Bogor Regency has the lowest waste collection rate at 41.4 %, while areas in Jakarta, i.e., South Jakarta City, East Jakarta City, and Central Jakarta City boast rates exceeding 95 %.

Waste management in Indonesia is primarily the responsibility of local governments. However, their expenditure on waste management is generally low, with an average of 0.07 % of the regional budget allocated for this purpose (Wardhana, 2020). Ideally, allocating around 3–4 % of the total regional budget would ensure adequate resources for managing municipal solid waste effectively (Cordova et al., 2022a). Moreover, there is a significant disparity in budget allocation for waste management across different regions. For instance, Jakarta has allocated >5 % of its regional budget towards waste management, whereas Bogor Regency, Bogor City and Depok City have allocated <1 % (Kementerian Lingkungan Hidup dan Kehutanan, 2023). To effectively manage municipal solid waste and improve waste management practices, it is crucial to increase the budget dedicated to transportation and infrastructure facilities (Damanhuri and Padmi, 2009).

Collaboration with private sector entities can also play a role in enhancing waste management efforts (Damanhuri, 2017; Nurhasanah et al., 2021). The relatively lower number of debris on the riverbanks in Jakarta, compared to neighboring municipalities during our study period, cannot be solely attributed to variations in river discharge. This suggests that improved river cleanup programs implemented by the capital city in 2015 may have contributed to this outcome. For example, the introduction of specialized cleaning teams, such as the 'orange troops' or 'pasukan oranye' and 'blue troops' or 'pasukan biru,' through Jakarta Governor Regulation No. 169/2015 has proven effective in maintaining cleanliness along rivers within Jakarta.

In addition to implementing high waste collection rates, it is also crucial to implement measures aimed at controlling waste entering river areas, including the riverbank zone (Cordova and Nurhati, 2019). Such measures should encompass efforts to change public attitudes and habits regarding proper waste disposal while also bolstering land- and water-based cleaning personnel (Simmons and Fielding, 2019; Williams and Rangel-Buitrago, 2019). Moreover, implementing regular and ongoing monitoring of river debris using reproducible methods, like the one utilized in this study, can serve as a valuable tool for evaluating the efficacy of river clean-up initiatives. Replicating similar monitoring efforts within the region, particularly in cities with major rivers and in developing countries, can provide policymakers with scientifically-backed and evidence-based information to address waste management issues that ultimately contribute to ocean pollution.

Similar patterns of riverbank debris distribution were observed at all the sampling locations along the Ciliwung River. The dominant proportion of macroplastic debris on the riverbank, both in terms of abundance (53.65 %) and weight (54.82 %), is consistent with other regions globally (de Lange et al., 2023; Gjyli et al., 2023; Kiessling et al., 2019; Nguyen and Bui, 2023; Roebroek et al., 2021). For instance, comparable proportions (Table 2) have been reported in the Rhine, Weser, and Elbe River systems in Germany (50.5 %), the Dutch Rhine-Meuse River system (55.8 %), the Rhine, IJssel, and Meuse River systems (70 %), Ishëm and Rhone River in Albania (77 %), as well as in Vietnam's Saigon River (86.54 %). The findings of this study, along with other literature (Ali and Shams, 2015; Battulga et al., 2019; Cordova et al., 2021; Eerkes-Medrano et al., 2015; Palmas et al., 2022), confirm that plastic litter is the predominant form of debris in aquatic ecosystems, although there may be slight variations depending on where the samples were collected.

Based on the enduring nature and wide distribution of plastics in aquatic and marine habitats, it can be inferred that these materials have a cumulative effect (Int-Veen et al., 2021). This includes adverse effects on water quality, endangerment of plant and animal species, and pollution of outdoor spaces vital for tourism and recreation (Beaumont et al., 2019; Gall and Thompson, 2015). Additionally, macroplastic debris contributes to the issue of small-sized plastic particles known as microplastics, whose hazards remain largely ambiguous but nonetheless concerning (Bucci et al., 2020; Toussaint et al., 2019; Wright and Kelly, 2017).

4.4. Way forward

The results of this study will provide valuable insights into the fate and distribution of litter on riverbanks, aiding waste management processes in Indonesia. Moreover, the riverbank debris dataset provided in this research has the potential to serve as a foundational resource for a global database. The establishment of such a database is crucial for enhancing monitoring and modeling initiatives focused on litter assessment. However, conducting comparative studies on different regions of Indonesia presents challenges due to variations in approaches and classifications used. Additionally, there is inconsistency in the measurement units for litter densities among various studies, and some research has yet to undergo peer-reviewed publication. Therefore, it is recommended to establish standardized methods that will enable better comparisons and understanding of anthropogenic debris contamination along riverbanks in Indonesia. This local data can subsequently be expanded to encompass regional or even global contexts. Effective waste management is a long-term process requiring proactive measures rather than reactive actions. In the context of this Indonesian riverine region, it is important to adopt flexible solutions for litter control to improve environmental quality. The presence of litter has negative consequences that affect various sectors interconnected with economic activities throughout the study area (Watkins et al., 2015). These impacts, directly and indirectly, affect local and national revenues, underscoring the critical nature of effective litter control for economic development in the region (McIlgorm et al., 2022; Omeyer et al., 2022). While completely eliminating waste and litter may be challenging given current production and consumption patterns, reducing inputs into the environment is a feasible goal that requires global efforts towards innovative management strategies and solutions. Hence, implementing effective urban planning and enhancing waste collection capacity are vital approaches to mitigate plastic leakage. Additionally, prioritizing direct river cleanup initiatives is crucial in eliminating the current presence of plastic litter. All proposed solutions should aim to minimize the significant negative effects of littering, while also delivering various benefits that contribute to positive outcomes.

5. Conclusion

This study presents the first quantitative and descriptive analysis of anthropogenic debris items on the riverbanks of the Ciliwung River, spanning from upstream to downstream. Plastic debris constitutes approximately 53.65 % of all litter items found, indicating a notable high abundance, by up to 30 times greater, compared to previous similar studies on riverbank litter globally. The presence of riverbank debris has the potential to contribute between 4.95 and 18.82 tons per year towards marine pollution, with an estimated 2.71 to 10.32 tons being plastic waste specifically. Riverbank debris is more prevalent in upstream areas compared to other locations along the river, and it tends to accumulate in regions with low collection rates for waste management practices. Among various types of litter, single-use plastics are dominant, particularly Styrofoam products. The riverbank debris dataset presented in this research holds great potential as a foundational resource for a waste management database within Indonesia and on a global scale. This dataset can be utilized to pinpoint the specific sources of anthropogenic debris and provide valuable support to policymakers in implementing targeted prevention measures. Additionally, the establishment of such a comprehensive database plays a critical role in enhancing monitoring and modeling initiatives focused on litter assessment. Furthermore, this locally derived data has the ability to extend its scope to regional or even global contexts. The framework provided by riverbank debris analysis serves as an invaluable tool for academia and stakeholders seeking assistance in developing and optimizing effective strategies for monitoring riverbank debris that align with local conditions and aspirations.

CRediT authorship contribution statement

Muhammad Reza Cordova: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Resources, Supervision, Visualization, Writing – original draft, Writing – review & editing. **Max R. Kelly:** Data curation, Formal analysis, Visualization, Writing – original draft. **Singgih Prasetyo Adi Wibowo:** Investigation, Resources, Validation. **Yaya Ihya Ulumuddin:** Investigation, Resources, Validation. **Triyoni Purbonegoro:** Investigation, Resources, Validation. **Deny Yogaswara:** Investigation, Resources, Validation. **Muhammad Taufik Kaisupy:** Investigation, Methodology, Resources, Validation, Visualization. **Riyana Subandi:** Investigation, Resources, Validation. **Sofia Yuniar Sani:** Investigation, Resources, Validation. **Richard C. Thompson:** Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing. **Susan Jobling:** Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at https://doi.org/10.1016/j.marpolbul.2024.116662. These data include the Google map of the most important areas described in this article.

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