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ACCUMULATION OF PLASTIC DEBRIS TRAPPED IN RIPARIAN VEGETATION OF THE BEDOG RIVER, INDONESIA, BASED ON COMPLEXITY OF THE PLANT STRUCTURE

ACCUMULATION OF PLASTIC DEBRIS TRAPPED IN RIPARIAN VEGETATION OF THE BEDOG RIVER, INDONESIA, BASED ON COMPLEXITY OF THE PLANT STRUCTURE

Inggita Utami[1,2]*, Nobuaki Tanaka[3]
[1]*Department of Ecosystem Studies, Graduate School of Agricultural and Life Sciences, The University of Tokyo, Japan*
[2]*Department of Biology, Faculty of Applied Science and Technology, Universitas Ahmad Dahlan, Yogyakarta, Indonesia*
[3]*The University of Tokyo Hokkaido Forest, The University of Tokyo Forest, Graduate School of Agricultural and Life Sciences, The University of Tokyo, Japan*
**Corresponding author:* inggitautami@g.ecc.u-tokyo.ac.jp

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Abstract

Plastic accumulation not only degrades water quality but also impacts riparian vegetation. Vegetation plays a key role in trapping plastic debris; however, the influence of plant structure and environmental factors on this process remains poorly understood. This study evaluates the trapping capacity of riparian vegetation along the Bedog River, Yogyakarta, and identifies the key factors controlling plastic accumulation. A riparian target map was first developed using satellite and drone imagery to classify land use and land cover. Trapping capacity was estimated based on vegetation structural parameters and validated through field surveys conducted across 20 plots, 3 m² each, distributed along the upstream-to-downstream gradient during both the dry and wet seasons. Plastic cover per unit area and environmental variables were analyzed using statistical approaches. The results show that bamboo exhibits the highest trapping capacity and plastic accumulation, followed by grass and arboreal vegetation, highlighting the importance of structural density and rigidity. Plastic cover was significantly higher during the dry season, indicating that riparian zones act as temporary storage under low-flow conditions. Environmental factors further influenced accumulation, with higher retention observed in low-elevation and low-slope areas, while flow velocity showed seasonal effects. These findings emphasize that vegetation structure and hydrodynamic conditions govern plastic trapping, positioning riparian zones as critical targets for plastic pollution management in tropical river systems.

Keywords: Bamboo; Plastic accumulation; Trapping capacity; Tropical river; Yogyakarta

Abstrak

Akumulasi plastik tidak hanya menurunkan kualitas air, tetapi juga berdampak pada vegetasi riparian. Vegetasi berperan penting dalam menjebak sampah plastik; namun, pengaruh struktur tanaman dan faktor lingkungan terhadap proses ini masih belum banyak dipahami. Penelitian ini mengevaluasi kapasitas penjebakan vegetasi riparian di sepanjang Sungai Bedog, Yogyakarta serta mengidentifikasi faktor-faktor utama yang mengendalikan akumulasi plastik. Target riparian terlebih dahulu dikembangkan menggunakan citra satelit dan drone untuk mengklasifikasikan tutupan dan penggunaan lahan. Kapasitas penjebakan diestimasi berdasarkan parameter struktur vegetasi dan divalidasi melalui survei lapangan yang dilakukan pada 20 plot pengamatan dengan luas 3 m² per plot yang tersebar sepanjang gradien hulu-hilir, baik pada musim kemarau maupun musim hujan. Tutupan plastik per satuan luas serta variabel lingkungan dianalisis menggunakan pendekatan statistik. Hasil penelitian menunjukkan bahwa bambu memiliki kapasitas penjebakan dan akumulasi plastik tertinggi, diikuti oleh vegetasi rumput dan arboreal, yang menegaskan pentingnya kerapatan dan kekakuan struktur vegetasi. Tutupan plastik secara signifikan lebih tinggi pada musim kemarau, yang menunjukkan bahwa zona riparian berperan sebagai tempat penyimpanan sementara pada kondisi aliran rendah. Faktor lingkungan juga memengaruhi akumulasi, dengan retensi yang lebih tinggi pada area dengan elevasi rendah dan kemiringan kecil, sementara kecepatan aliran menunjukkan pengaruh yang berbeda secara musiman. Temuan ini menegaskan bahwa struktur vegetasi dan kondisi hidrodinamika mengontrol proses penjebakan plastik, sehingga zona riparian menjadi target penting dalam pengelolaan sungai tropis.

***Kata Kunci**: Akumulasi plastik; Bambu; Kapasitas penjebakan; Sungai tropis; Yogyakarta*

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INTRODUCTION

Mismanaged plastic waste leakage from land into riparian zones has been increasingly studied in subtropical regions of Europe (Cesarini & Scalici, 2022; Gallitelli et al., 2025), although tropical Asia remains the largest contributor to global plastic pollution in ecosystems (Jambeck et al., 2015; Lebreton et al., 2017; Meijer et al., 2021). This study builds upon the work of Utami and Tanaka (2025) in August 2024, which provided one of the earliest assessments of plastic pollution affecting riparian vegetation in Indonesia, specifically in the Bedog River, Yogyakarta Province (Utami & Tanaka, 2025). Their findings revealed that bamboo communities in the Bedog riparian area exhibited the highest plastic coverage, reaching up to 80% per unit area. Species such as *Bambusa spinosa*, *Dendrocalamus asper*, and *Bambusa vulgaris* (bamboo community), *Cenchrus purpureus* (grass community), and *Ficus hispida* (tree community) showed the highest levels of plastic coverage, reaching up to 100%.

Plant structural characteristics, particularly within the range of water level fluctuations, play a crucial role in trapping riverine plastic debris (Gallitelli et al., 2023, 2024). Stems, roots, densely packed grass leaves, and specialized structures such as thorns can act as physical filters, retaining plastics for extended periods (Gallitelli et al., 2024; Utami & Tanaka, 2025). Tropical riparian zones, characterized by high vegetation density and diversity, are therefore expected to be highly effective in trapping plastic debris. However, Gallitelli et al. (2023) reported that plants with dense branching architectures and greater structural complexity intercept and retain more floating macroplastics, increasing the likelihood that plastic debris accumulates on branches where it can cover buds and flowers, thereby potentially reducing pollination success by up to 18.6%, resulting in an overall pollination success of approximately 81.4% (Gallitelli & Scalici, 2023). This study aims to evaluate the trapping capacity of riparian vegetation along the Bedog River and identify the key factors influencing this process. In addition, this study examines seasonal variations in plastic trapping and maps the distribution of plastic-trapping hotspots within vegetation based on structural characteristics. Ultimately, this research contributes to the development of strategies for mitigating plastic pollution in riparian zones, particularly in tropical Asian regions such as Indonesia.

MATERIALS AND METHODS

The study was conducted along the riparian zone of the Bedog River in Yogyakarta Province, Java Island, Indonesia, the most densely populated island in the country. The Bedog River flows through Sleman and Bantul Regencies, where population density exceeds 2,000 people/km² (Badan Pusat Statistik (BPS) DIY Province, 2024a). The river extends approximately 55 km, originating from Mount Merapi in the north and joining the Progo River, which ultimately discharges into the Indian Ocean in south part.

The primary dataset for the riparian Bedog network was generated using a 30 m buffer around the Bedog River polygon, in accordance with Indonesian government regulations (Dewan Sumber Daya Air Nasional (DSDAN), 2018). The riparian zone was classified into six land use/land cover (LULC) classes: water, bare land, and built-up areas (categorized as unvegetated), as well as arboreal, bamboo, and grass (categorized as vegetated). LULC classification was conducted using PlanetScope imagery (3 m resolution), supported by training data derived from drone imagery (0.5 m resolution), and processed in ArcGIS Pro. All imagery was acquired in August 2025 to ensure optimal conditions with minimal cloud interference. The resulting riparian target map was used to visualize vegetation patch distribution and to infer spatial patterns of plastic-trapping capacity. The distribution of trapping capacity was derived through raster calculations based on the average values of three vegetation structure parameters: species density, stem number, and species dominance. The trapping capacity map was then validated using field-based measurements of plastic cover along the river.

Field validation data were collected from 20 sampling plots randomly distributed across the riparian target map and vegetation patch (arboreal, bamboo, and grass) (Figure 1). Based on their structural characteristics, arboreal vegetation refers to tree-dominated woody vegetation characterized by a distinct main stem (trunk) and a well-developed canopy. Bamboo belongs to the grass family (*Poaceae*, subfamily *Bambusoideae*) but is characterized by dense woody culms. In contrast, grass patches consist of herbaceous vegetation dominated by non-woody grasses. At each site, a 25 m² plot (5 × 5 m) was established, with three 1 m² subplots used to quantify plastic cover following a modified approach from Gallitelli (Gallitelli et al., 2024). Vegetation was identified, and dominance was assessed using DBH for woody plants and percentage cover for grasses and herbs. The number of stems or branches up to a height of 4m was also recorded, representing typical water level fluctuations (Meijer et al., 2021). Data were collected during the wet (January 2025) and dry (August 2025) seasons. Abiotic parameters potentially influencing plastic trapping, including elevation, slope, and flow velocity, were measured at each sampling point. Population density at the sub-district level was also incorporated as an anthropogenic variable (Badan Pusat Statistik (BPS) DIY Province, 2024b). Statistical analyses were conducted to (1) assess differences in plastic cover (% per m²) between seasons and (2) evaluate relationships between plastic cover and environmental and anthropogenic factors. Differences among vegetation types and their structural characteristics were also analyzed. All statistical analyses were performed using RStudio (version 2025.09.2).

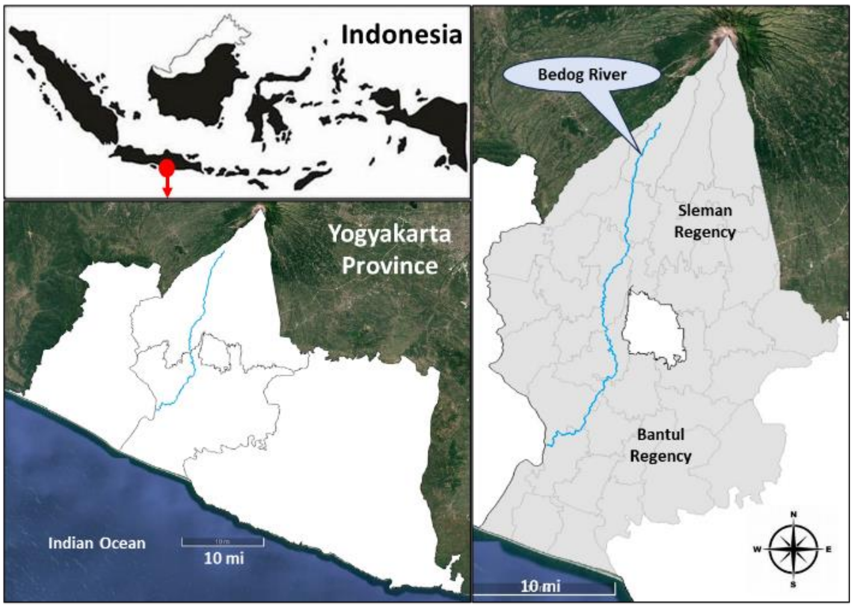

Figure 1. River Bedog in tropical Yogyakarta, Indonesia

RESULTS

Trapping Capacity of Various Vegetation Patches

Target riparian mapping along the Bedog River resulted in a total riparian Bedog area of 242.34 ha (Table 1). Based on supervised analysis with random forest classification, the vegetated area (198.82 ha) in the Bedog riparian zone was larger than the unvegetated area (43.53 ha), with a ratio of 82.04% and 17.96%. Arboreal patches and bamboo dominated the vegetated areas. Upstream, arboreal and bamboo dominate the riparian area, with built-up areas, such as settlements, beginning to fill the riparian zone (30 m from the riverbank) (Figure 2). In the central riparian zone of the Bedog River, settlements increasingly occupy the riparian area. Downstream, the river becomes wider and is increasingly dominated by grass vegetation. The classification achieved an acceptable level of accuracy (OA= 85.9%, Kappa coefficient (κ)= 0.79), which is considered sufficient for landscape-scale analysis.

Table 1. Area of the six land use/land cover (LULC) classes in the Bedog riparian zone

Classes	Number of pixels	Area (ha)	Cover area (%)	
Water	17.39	15.65	6.46	Unvegetated
Bare land	6.66	5.99	2.47	43.53 ha= 17.96%
Built up	24.31	21.89	9.03	
Arboreal	98.88	88.99	36.72	Vegetated:
Bamboo	91.99	82.80	34.17	198.82 ha= 82.04 %
Grass	30.03	27.03	11.15	
Total	269.27	242. 34	100.00	

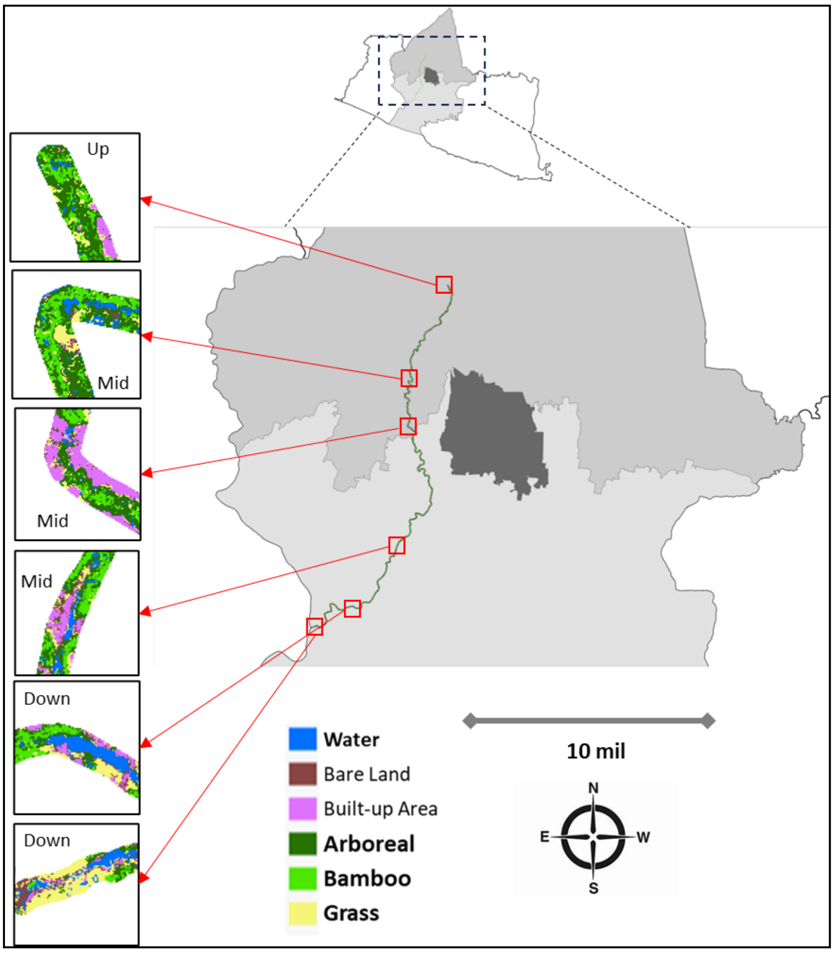

Figure 2. Distribution of riparian target areas in the Bedog River based on vegetated and unvegetated classes

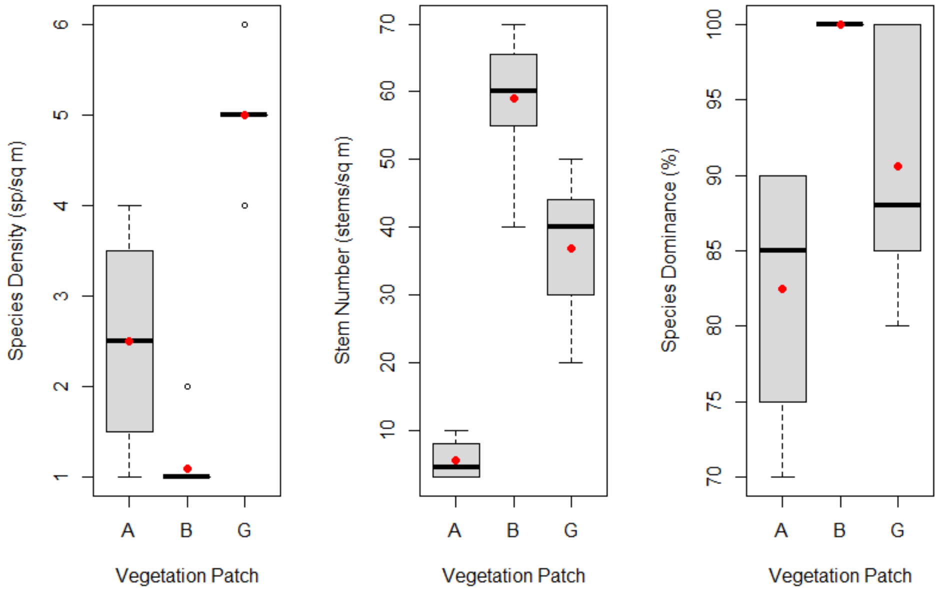

Figure 3. Differences in structural characteristics of arboreal (A), bamboo (B), and grass (G) vegetation based on species density, stem number, and species dominance

The ecological structure of different vegetation patches underlies variations in plastic cover patterns within riparian areas (Figure 3). Species density was highest in grass (mean= 5.00 species/m^2, red dot), followed by arboreal (mean= 2.50 species/m^2), and lowest in bamboo (mean= 1.09 species/m^2). In contrast, stem density and species dominance were highest in bamboo (mean= 59.09

stems/m²; 100%/m^2), followed by grass (mean= 36.80 stems/m²; 90.60%/m^2) and arboreal (mean= 5.50 stems/m²; 82.50%/m^2). Kruskal-Wallis tests indicated significant differences among vegetation patches for species density (P <0.001), stem number (P <0.001), and species dominance (P= 0.001). Dunn post hoc tests showed that bamboo differed significantly from arboreal vegetation in species density (P= 0.001) and dominance (P= 0.002), while differences involving grass were not significant, although a marginal trend was observed between bamboo and grass (P= 0.07).

The results of plastic trapping capacity measurement across vegetaton types/patches showed that bamboo had the highest trapping capacity (mean= 53.39), followed by grass (mean= 44.13) and arboreal (30.17) (Table 2). This indicates that bamboo traps more plastic debris due to its dense and rigid structure, including thick stems and, in some cases, thorny features that resist river flow. Bamboo covers approximately 34% of the Bedog riparian zones (red color in Figure 4) and is most widely distributed upstream to the midstream sections.

Table 2. Trapping capacity values for each riparian vegetation type in the Bedog River

Vegetation types	Species density (species/m^2)	Stem number (stems/m^2)	Species dominance (%/m^2)	Average	Capacity trapping level
Arboreal (n= 12)	2.50	5.50	82.50	30.17	Low
Bamboo (n= 33)	1.09	59.09	100.00	53.39	High
Grass (n= 15)	5.00	36.80	90.60	44.13	Medium

Note: Non-vegetated (water, bare land, built-up areas) value= 0

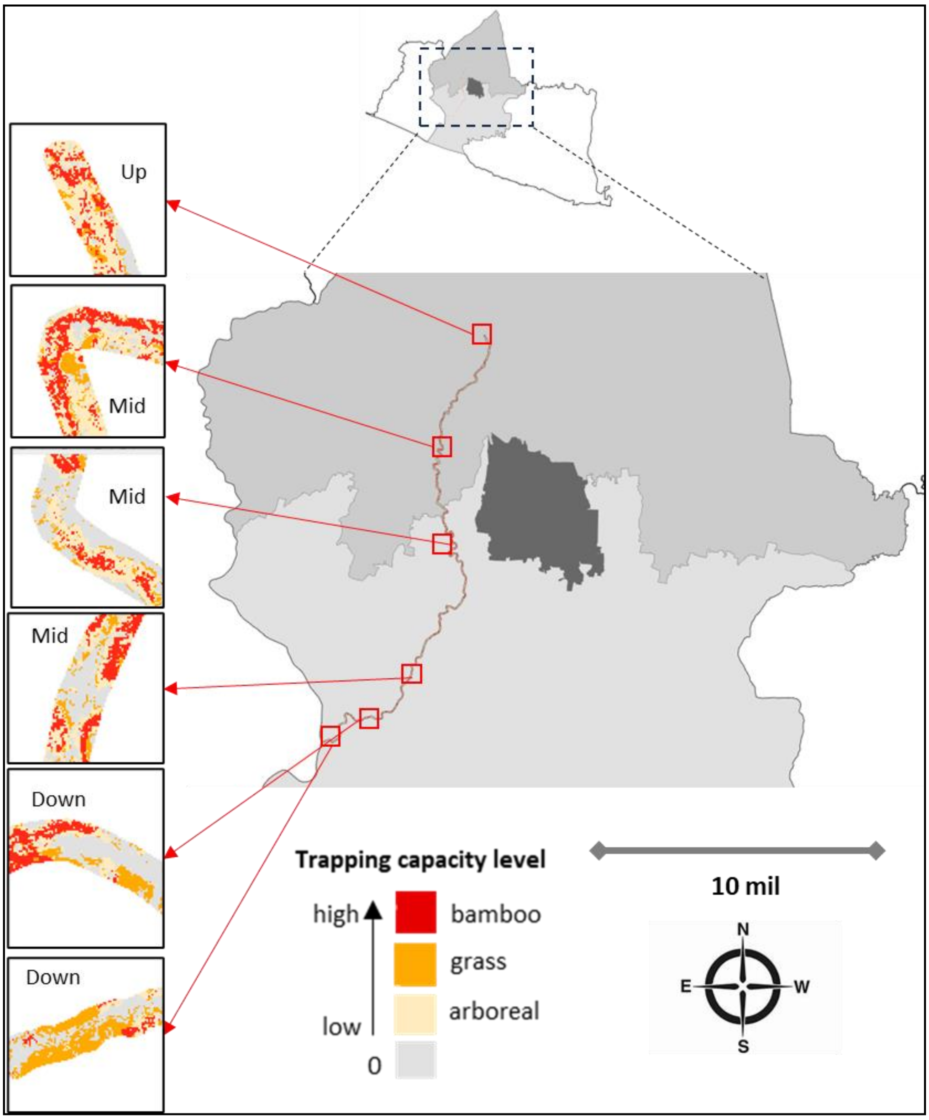

Figure 4. Spatial distribution of trapping capacity across riparian vegetation in the Bedog River

Plastic Cover Variation Across Vegetation Patches

Plastic cover was measured across vegetation patches along the riparian zone to validate the trapping capacity assessment. Vegetation type significantly affected plastic cover during the dry season (ANOVA, P= 0.0499), with bamboo-dominated sites exhibiting the highest accumulation (mean= 53.60%/m^2), followed by arboreal (27.00%/m^2) and grass (19.00%/m^2) (Figure 5). Although pairwise comparisons were not statistically significant, bamboo consistently showed higher plastic retention. A similar pattern was observed during the wet season, with bamboo retaining the highest plastic cover (33.60%/m^2), followed by arboreal (20.50%/m^2) and grass (8.00%/m^2), although the effect was not statistically significant (P= 0.081), suggesting reduced vegetation control under high-flow conditions. Overall, plastic cover per unit area in Bedog riparian vegetation was substantially higher during the dry season (mean= 39.65%/m^2) compared to the wet season (mean= 24.60%/m^2). A Wilcoxon signed-rank test revealed a significant difference between seasons (P <0.001), with higher values observed during the dry season.

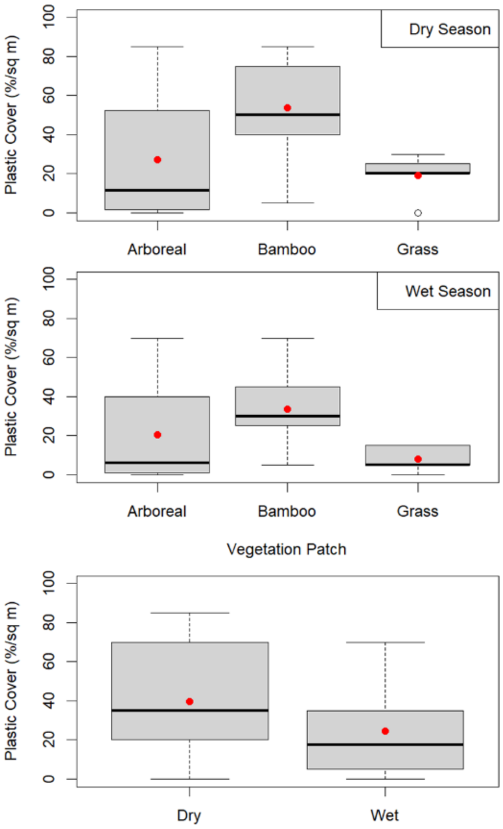

Figure 5. Comparison of plastic cover across vegetation types and seasons

Environmental Controls on Plastic Trapping

The environmental and anthropogenic parameters tested against plastic cover across two seasons showed variable relationships (Figure 6). Elevation showed a significant negative relationship with plastic cover in both dry (β= -0.42, P= = 0.002, R^2= 0.42) and wet seasons (β= -0.30, P= 0.003, R^2= 0.39), indicating that plastic accumulation increases toward lower elevation areas. Slope exhibited a strong and consistent negative relationship with plastic cover in both dry (β= -6403, P <0.001, R^2= 0.57) and wet seasons (β= -4630, P <0.001, R^2= 0.54), indicating that steeper river sections significantly reduce plastic accumulation. Flow velocity showed a strong and significant positive relationship with plastic cover during the dry season (β= 9.14, P <0.001), explaining nearly half of the observed variation (R^2= 0.48). In contrast, no significant relationship was observed during the wet season (P= 0.704, R^2= 0.008), indicating that increased discharge and turbulence likely reduce plastic retention within riparian zones.

Population density showed no significant relationship with plastic cover in both dry (P= 0.353, R^2= 0.05) and wet seasons (P= 0.173, R^2= 0.10). The consistently negative relationship suggests that higher population density does not necessarily correspond to higher local plastic accumulation. This indicates a spatial decoupling between plastic sources and accumulation zones, where plastics are transported downstream and retained in riparian vegetation rather than accumulating near their points of origin.

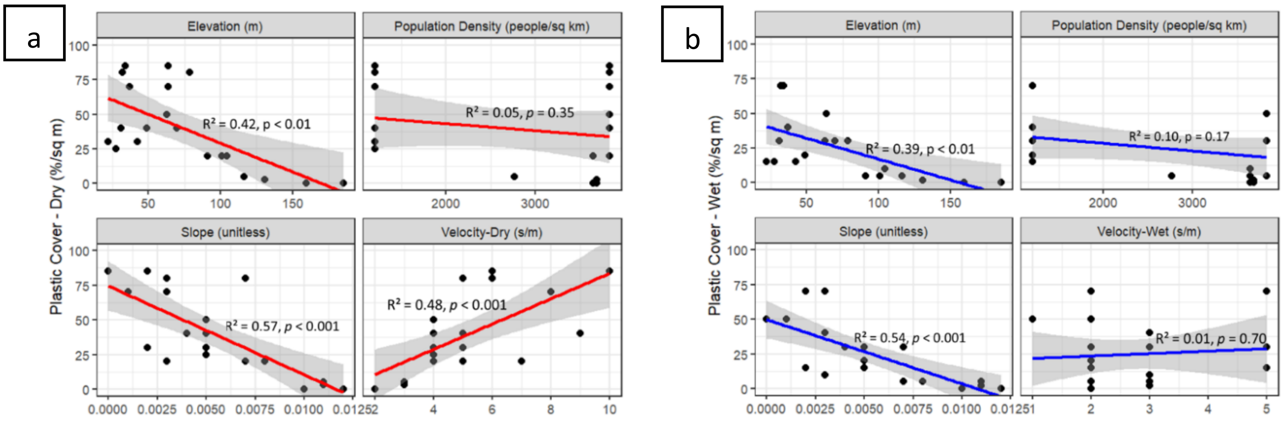

Figure 6. Relationship between environmental parameters and plastic cover across seasons, dry season (a) and wet season (b)

Plastic trapping capacity across vegetation types reveals a clear structural control, with bamboo exhibiting the highest trapping capacity, followed by grass and arboreal (Figure 7). This pattern is consistent with the observed plastic cover, where bamboo-dominated patches also show the highest accumulation.

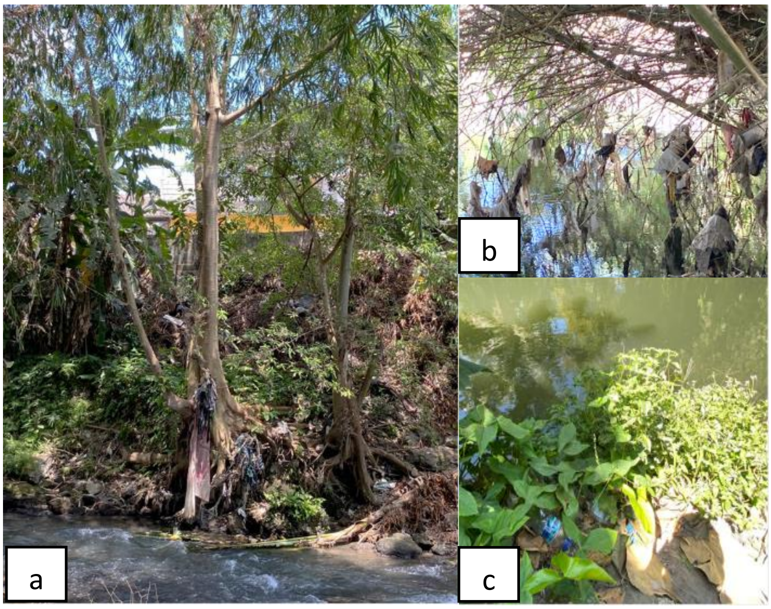

Figure 7. Plastic retention across vegetation types: arboreal (a), bamboo (b), and grass (c)

DISCUSSION

Dynamics of Plastic Trapping Across Riparian Vegetation Structure

The riparian zone of the Bedog River is predominantly composed of vegetated areas (82%), indicating that vegetation plays a major role in shaping the physical river corridor. This high proportion is likely influenced by the relatively narrow width of the Bedog River (average 3.26 m (Utami & Tanaka, 2025) and extensive canopy cover from arboreal and bamboo vegetation, which can obscure the water surface in remote sensing classification. In small tropical rivers, vegetation structure may dominate the physical interface between land and water, creating extensive zones for potential plastic retention (Bauer-Civiello et al., 2019; Meijer et al., 2021; Utami & Tanaka, 2025). Field observations across the 20 riparian plots supported the structural-based assessment of vegetation trapping capacity. Plots characterized by greater vegetation complexity generally retained higher amounts of macroplastic debris, whereas structurally simpler vegetation exhibited lower macroplastic accumulation. These observations indicate that vegetation structural characteristics provide a reliable indicator of macroplastic retention under natural field conditions. Figure 7 shows plastic trapping capacity across vegetation types. The strong agreement between structural metrics (stem density and dominance) and field-based plastic cover indicates that vegetation structure directly regulates plastic retention efficiency (Gallitelli et al., 2025).

Bamboo stands function as highly effective natural barriers due to their dense culm arrangement, high stem density, and structural rigidity (Buziquia et al., 2019; Pioquinto-Laguardia et al., 2025). The presence of closely spaced stems and low-height branches acts as a porous obstacle, increasing flow resistance, enhancing drag and reducing local flow velocity (Boothroyd et al., 2018; Gallitelli et al., 2024; Mossa et al., 2017), thereby increasing the likelihood of plastic entrapment. Similar mechanisms have been reported in studies on sediment transport (Ahmed & Mohanadhas, 2025; Huai et al., 2021) and debris accumulation (Amina et al., 2024). Grass-dominated patches, despite high species density and moderate stem abundance, show lower plastic accumulation than bamboo due to their flexible structure, which reduces flow resistance and promotes remobilization under variable hydrodynamic conditions (Owowenu et al., 2023). Arboreal vegetation accumulates more plastic than grass despite lower density, as its stable structures (trunks, roots, and branches) provide more effective and persistent trapping than flexible grass (Cesarini & Scalici, 2022). This supports the broader conceptual framework that physical structure, rather than species richness, is the dominant driver of microplastic retention in riverine ecosystems.

Environmental and Anthropogenic Drivers of Plastic Accumulation

The Bedog River serves as a fishing area for local communities and tourists, as a receiving body for treated industrial discharge and illegal waste dumping, and as a source of drinking water for Sleman Regency (Jumiati et al., 2024), although high concentrations of microplastics have also been reported in river sediment (Utami et al., 2021a; Utami et al., 2021b). Land use within the river basin is dominated by rice fields (45%), followed by vegetation (30%), settlements (20%), and other uses (5%). Municipal solid waste generation in Sleman and Bantul exceeds 1,000 tons/day, with disposal primarily occurring at the overloaded Piyungan open dumping landfill (Dinas Lingkungan Hidup (DLH) Sleman, 2023), which is prone to leakage into nearby river systems. Riparian vegetation along the Bedog River is dominated by bamboo, which is considered a native tropical riparian species in Indonesia, followed by economic timber trees, fruit trees, and grasses and herbs, particularly in areas disturbed by infrastructure development such as dams and bridges (Adhitama et al., 2022). The complex vegetation structure, combined with significant water level fluctuations, is expected to enhance the trapping of plastic debris within the riparian zone.

Higher plastic accumulation during the dry season indicates that riparian zones function as temporary storage systems under low-flow conditions, whereas increased discharge during the wet season promotes remobilization and downstream transport (Manners et al., 2013). Geomorphological factors further control this pattern, with lower elevation and low-slope areas acting as convergence zones that enhance deposition and interaction with vegetation, while steeper sections facilitate rapid transport and limit trapping (Brooks & Hopkins, 2025). The study rivers originate from the volcanic slopes of Mount Merapi and flow through alluvial lowlands before discharging into the Indian Ocean. During the wet season, increased rainfall substantially elevates river discharge and flow velocity, enhancing the transport and remobilization of macroplastic debris. Conversely, lower discharge during the dry season reduces transport capacity, allowing floating plastics to remain trapped within riparian vegetation for longer periods. Flow velocity shows a seasonal shift in influence, enhancing delivery and trapping under low-flow conditions (Van Emmerik et al., 2023), but becoming less significant during high-flow periods due to increased turbulence and discharge, indicating that plastic accumulation reflects longer-term transport–retention dynamics rather than instantaneous flow conditions. Additionally, the lack of a significant relationship between population density and plastic accumulation suggests a spatial decoupling between sources and sinks, where plastic is transported along the river network and retained in areas with favorable hydrodynamic and structural conditions, emphasizing the dominant role of transport processes and vegetation trapping capacity over local waste generation.

Despite these insights, this study is limited to a single river system, which may constrain the generalizability of the observed patterns. Expanding the analysis to multiple rivers with varying geomorphological and land-use characteristics would provide a more comprehensive understanding of plastic trapping dynamics. Furthermore, future research should integrate spatial modelling of plastic leakage, incorporating both environmental drivers and anthropogenic inputs, and overlay these with vegetation trapping capacity maps. Such an approach would enable the identification of priority riparian zones for targeted management and intervention. Vegetation roughness can also be analyzed with terrestrial laser scanning (TLS) using LiDAR to measure the porosity and volume of plants as porous obstacles (Manners et al., 2013; Penman et al., 2023). Furthermore, integrating porosity parameters derived from TLS point cloud data can significantly enhance the accuracy of vegetation trapping capacity estimations in spatial analyses.

CONCLUSION

Plastic accumulation in the Bedog River riparian zone is primarily controlled by vegetation structure and hydrodynamic conditions rather than biodiversity or proximity to sources. The dominance of vegetated areas (82%) provides extensive zones for plastic retention. Bamboo exhibits the highest trapping capacity and plastic accumulation due to its dense, rigid, and monodominant structure, while grass shows lower retention despite higher species density due to its flexible form. Arboreal vegetation provides moderate trapping through more stable but less dense structures. These results confirm that structural complexity and dominance, rather than species richness, govern plastic trapping. Environmental controls further shape this pattern, with higher accumulation occurring in low-elevation and low-slope areas. Flow velocity is significant only during the dry season, while its effect diminishes under high-flow conditions. The lack of correlation with population density indicates that plastic accumulation is driven more by transport and retention processes than by local sources. Overall, riparian zones function as dynamic systems that store and release plastic depending on hydrological conditions, highlighting their importance for targeted plastic management strategies.

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