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Assessment and Sustainable Management Strategies for Plastic Waste in Can Tho City, Vietnam: A Circular Economy Approach

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Abstract: This study presents a comprehensive analysis of plastic waste accumulation in both terrestrial and aquatic environments in Can Tho city, Vietnam, a nation with high per capita plastic consumption and significant plastic waste discharge. Focusing on urban residential areas, riverside communities, suburbs, and rural regions, the research investigates the extent and impact of plastic waste in these diverse settings. Additionally, the study examines the accumulation of plastics at barriers, under bridges, and in the Hau River, identifying the predominance of single-use plastics and their environmental implications. The key findings indicate that the plastic waste leakage at land-based-source emission sites is substantial, with waste persisting for extended periods without effective clean-up. The study reveals a significant accumulation of plastics at barriers and bridge bases in aquatic environments, including along the river. The pollution level was observed to be more influenced by the quantity of waste rather than its mass per unit area, emphasizing the need for targeted waste reduction strategies. The study also identifies seven types of plastic, each associated with different sources of accumulation or settlement. This variety presents both challenges and opportunities for waste management and recycling. Significantly, the research underscores the potential of repurposing plastic waste into recycled products, aligning with the circular economy model. This approach not only extends the lifecycle of plastic products but also contributes to reducing plastic waste generation and minimizing the environmental impact. Overall, the findings highlight the urgent need for improved waste management practices in Vietnam, particularly in urban and riverside areas, and advocate for innovative recycling solutions to mitigate the environmental challenges posed by plastic pollution.

Keywords: accumulation; Can Tho city; circular economy; deposition; plastic waste; sustainability

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1. Introduction

The increasing global population, rapid urbanization, and economical expansion have led to a surge in the production of plastic waste. However, this escalation is not counterbalanced by the same development in the recycling, recovery, and treatment of plastic waste, thus posing a significant environmental crisis [1]. As of 2015, approximately 6.3 billion tons of plastic waste had been generated worldwide, with a staggering 79% accumulating in landfills, and the rest in natural environments [2]. This issue is aggravated by the fact that regulations governing the management, use, disposal, and consumption of plastics vary widely across different countries, resulting in its inefficient management [3]. Currently, one of the most pressing environmental concerns is plastic pollution in aquatic ecosystems. Plastic waste has directly resulted in the endangering of aquatic life and the exacerbation of flood risks by obstructing urban drainage systems [4,5]. Moreover, over time, exposure to sunlight results in the physical breakdown of plastic debris into microplastics [6]. These microplastics are ingested by aquatic organisms, subsequently entering human and animal food chains and, thus, posing a grave threat to human health and the integrity of global ecosystems [7,8].

Building on the global context of the plastic waste crisis, this study specifically focuses on Vietnam, particularly the Can Tho area. In Vietnam, the reported national average for solid waste collection is 85.5% in urban areas and between 40 and 60% in rural areas. Furthermore, plastic waste constitutes approximately 6–8% of this collected waste [9]. Notably, there has been a significant increase in the plastic content of household solid waste, rising from 5.5% in 2009 to 13.9% by 2017. The average per capita plastic consumption has increased dramatically, from 3.8 kg per person in 1990 to 41.3 kg per person in 2018 [10]. The majority of this plastic waste comprises items such as plastic bags, contaminated plastic bottles, single-use plastic products, and other plastics that pose challenges in the recovery and recycling processes. The sources of this waste are diverse, including domestic and consumption activities, socio-economic activities, and sectors like agriculture, tourism, construction, and the plastic recycling industry [10]. Approximately 10–12% of household solid waste in the country is made up of plastic waste and plastic bags. It has been estimated that Vietnam generated between 2.6 and 2.8 million tons of plastic waste in 2019, contributing significantly to the floating waste found in rivers, lakes, estuarine wetlands, and coastal areas [11].

This study investigates the plastic pollution crisis in Can Tho city, Vietnam. Can Tho, a major urban center, faces substantial environmental issues due to domestic waste. With a collection rate of 85–90%, the city generates approximately 650 tons of domestic waste daily [12,13]. As part of a strategic plan (Plan No. 66/KH-UBND, dated 3 April 2019), the authorities in Can Tho city aim to significantly improve the city's waste management by 2030, targeting the 100% collection of domestic solid waste in urban areas and 95% in rural areas [14]. Despite having numerous waste treatment facilities and the active promotion of the "anti-plastic waste" movement through various awareness programs to safeguard the environment [15], Can Tho still faces significant challenges in the collection and management of domestic waste. Waste accumulation and the clogging of land and water bodies is prevalent in many areas, resulting in the deterioration of the urban landscape [16]. These challenges underscore the need for a shift in public perceptions and habits regarding waste management and environmental stewardship [17]. Thus, there is a pressing need for Can Tho city to sustain and intensify the "anti-plastic waste" movement over the long term to effectively mitigate these environmental problems [18].

This study on the Can Tho region provides crucial insights into the implementation and impact of waste management strategies within the context of Vietnam's broader environmental challenges. Plastics from terrestrial sources inevitably find their way into river systems, a process influenced by land use patterns, wind, rainfall, river flow, and the efficiency of hydraulic infrastructure within the river catchment area [19–22]. Can Tho has a huge network of waterways which are ultimately connected with the Hau River. Therefore, plastics ultimately find their way into these water bodies of the river network. Once in the river system, plastic items may sink or become stranded, while others continue their journey to the river mouth [23–25]. Consequently, in this region, there is a clear need for a comprehensive evaluation of this problem to gain a complete understanding of its scope and impact. Hence, this study specifically aims to investigate the current state of plastic waste accumulation in the receiving environments of Can Tho city. Through this study, we aim to identify and propose effective solutions to mitigate plastic waste pollution sustainably, aligning with the broader environmental goals of the region and contributing to the global effort to tackle plastic pollution.

2. Materials and Methods

The primary objective of this study is to investigate the pathways and patterns of plastic waste leakage and accumulation in both terrestrial and aquatic environments within Can Tho city. Specifically, the focus is on illegal dumping sites on land, as well as the accumulation at various points in water bodies such as barriers, bridges, and along the Hau River. The research methodology encompasses several key areas of assessment: quantifying plastic waste leakage at illegal dumping sites located in urban residential areas, riverside residential areas, riverside suburbs, and rural localities; evaluating the accumulation of waste at water barriers; assessing waste deposition at the bases of bridges; analyzing waste accumulation along the Hau River, and proposing viable solutions for sustainable reduction of plastic waste pollution. These components of the study are illustrated in Figure 1.

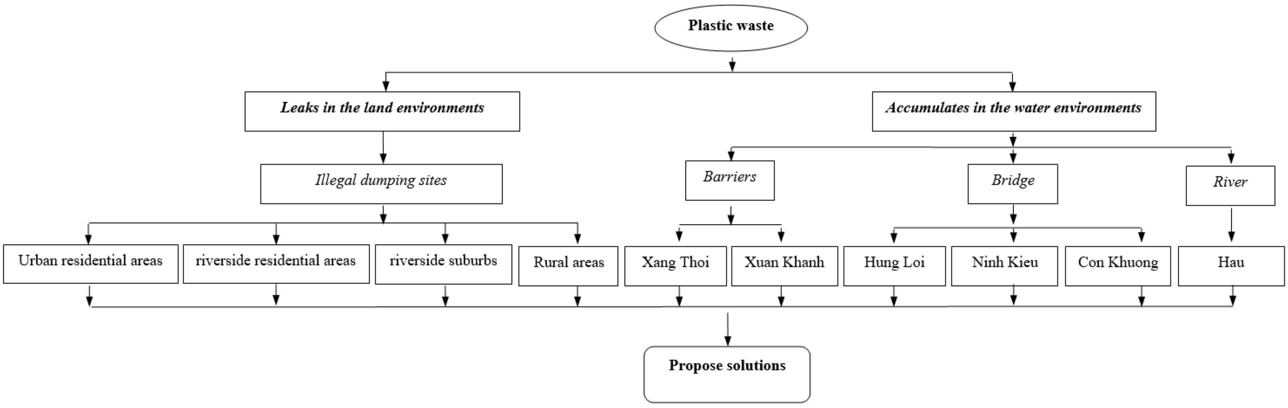

Figure 1. Schematic of research process.

To achieve these objectives, the study measures the volume of waste leaking from illegal dumping sites on land and estimates the time required for clean-up operations. In aquatic environments, the waste collected at barriers, deposited at bridge bases, and found in the river is categorized by its composition and type of plastic, quantified by mass. The classification and quantification methodologies are detailed in Figure 2 and Table 1. This comprehensive approach aims to provide a clear understanding of plastic waste dynamics in Can Tho city and inform effective strategies for mitigating environmental pollution.

Table 1. Illustration of sampling locations.

1. Illegal dumping sites		
1.1 Urban residential areas		
1.1.1	Hung Phu 1 residential area (Cai Rang district)	
1.1.2	Hung Phu 2 residential area (Cai Rang district)	

Table 1. *Cont.*

1.2 Riverside residential areas		
1.2.1	Area 1 Tam Vu (Ninh Kieu district)	
1.2.2	Area 2 Tam Vu (Ninh Kieu district)	
1.3 Suburban riverside areas		
1.3.1	Thanh Hoa area (Cai Rang district)	
1.3.2	Embankment 586 (Cai Rang district)	
1.4 Rural areas		
1.4.1	An Binh area (Binh Thuy district)	
1.4.2	My Khanh area (Phong Đien district)	
2. Accumulation at barriers		
2.1	Xang Thoi	
2.2	Xuan Khanh	
3. Deposited at the foot of bridges		
3.1	Hung Loi	

Table 1. *Cont.*

3.2	Ninh Kieu	
3.3	Con Khuong	
4. Accumulation in the river		
4.1	Hau	

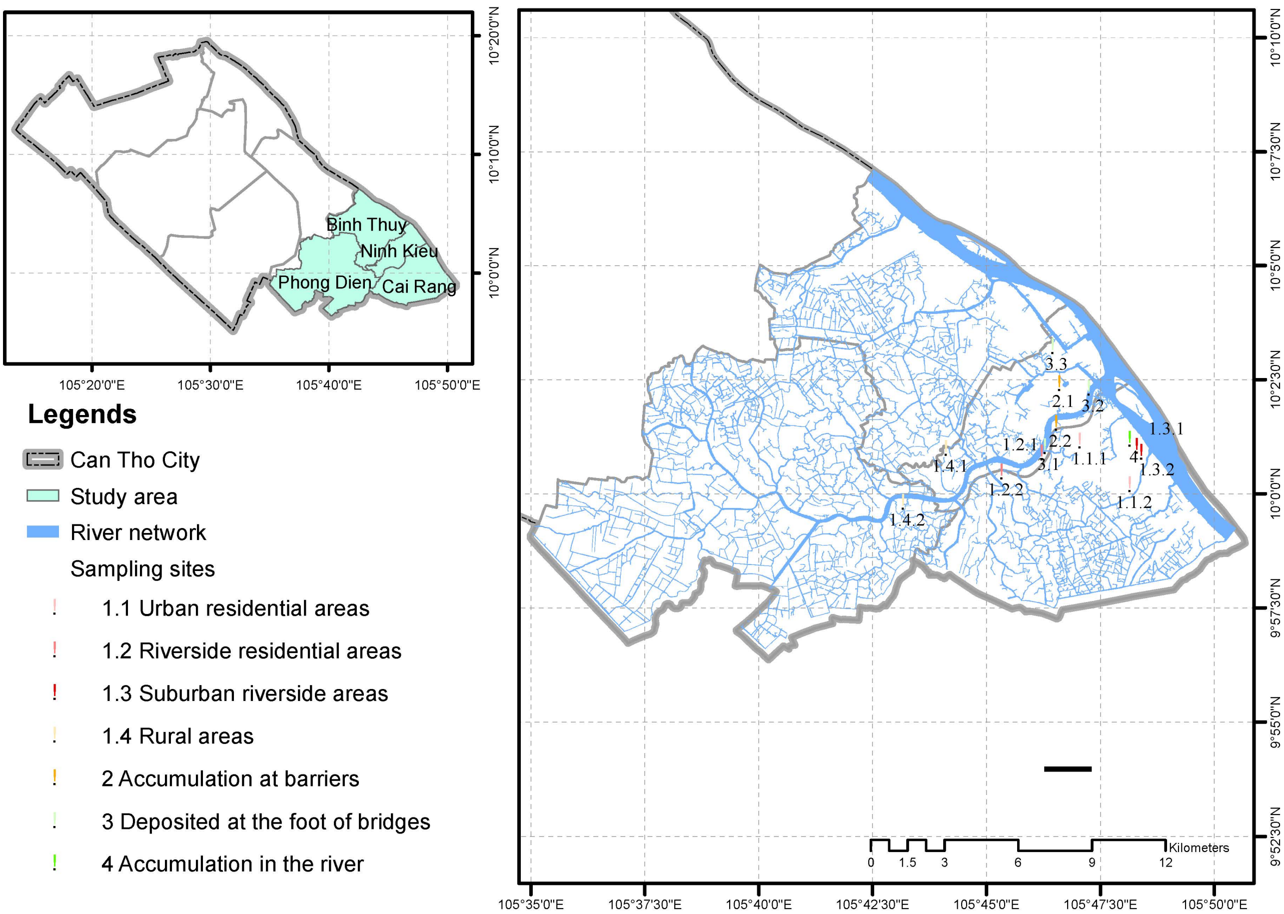

Figure 2. Location of the sampling locations in the study area.

2.1. Study Area

Can Tho city, covering an area of 1401 km^2, exhibits a diverse range of population densities across its districts. The overall population density is 848 people per km^2. Within the city, Ninh Kieu district reports the highest density with 8407 people per km^2, while Vinh Thanh district has the lowest at 274 people per km^2. Administratively, Can Tho comprises nine units: five urban districts (Ninh Kieu, Binh Thuy, Cai Rang, O Mon, Thot Not) and four rural districts (Vinh Thanh, Co Do, Thoi Lai, Phong Dien), encompassing a total of 85 communes, wards, and towns [26].

According to 2022 statistical data, the urban population of Can Tho city stands at 882,586 individuals across 266,872 households, representing 72.45% of the total population. Conversely, the rural population accounts for 27.55%, totaling 630,288 individuals in 101,497 households [27]. In 2020, the city achieved a notable urban solid waste collection rate of 98%. Of the districts, Ninh Kieu leads with a 98.5% collection rate, closely followed by Thot Not and Thoi Lai districts, each at 98%. The practice of waste classification at the source varies across districts: Thoi Lai district achieves over 97%, Ninh Kieu district 80%, Cai Rang district 65%, and Binh Thuy district 41% [15]. These detailed demographic and waste management data form the basis for understanding the varied challenges across Can Tho city in managing and mitigating plastic waste pollution.

2.2. Sample Collection

2.2.1. Illegal Dumping Sites

The geometry of illegal dumping sites is not specific. However, for the purpose of volume estimation, they are hypothesized as rectangular prisms. Based on this, the length (L) is defined as the longest side, the width (W) as the widest point across, and the height (H) as the peak height of the waste pile. The volume (V) of the dump is calculated using the formula V = L × W × H (in cubic meters). Additionally, brief interviews were conducted with nearby residents to gather information about the frequency and schedule of clean-up efforts at these sites.

2.2.2. Barriers

The barriers, constructed from steel and with a mesh size of 5 cm, are detailed in Figure 2. The Xuan Khanh barrier has a length of 22 m (Figure 3a), and the Xang Thoi barrier measures 25 m in length (Figure 3b). Plastic waste accumulation at these barriers is collected over a two-day period (14–15 January 2021) using rackets and is subsequently stored in nylon bags. The collected plastic waste is then dried to a constant weight at 85 °C (using a Memmert UN110 oven, Germany, with an accuracy of ±0.5 °C) before proceeding with counting, weighing, and classification.

Figure 3. (**a**) The Xuan Khanh barrier and (**b**) Xang Thoi barrier.

2.2.3. Bridge-Foot Waste Collection

Plastic waste accumulation at the bases of bridges was sampled from a randomly selected area of 15 m^2 (3 m × 5 m). The collected plastic waste was dried to a constant weight at 85 °C (using a Memmert UN110 oven, Germany, with an accuracy of ±0.5 °C). This process precedes sorting, counting, and weighing, which are conducted at the Solid Waste Treatment Laboratory of the Faculty of Natural Resources and Environment, Can Tho University.

2.2.4. Hau River Waste Collection

To assess plastic pollution in the Hau River, a net with dimensions of 8 m × 9 m (width × height, with a mesh hole size of 1 cm^2) was used. This net is strategically placed on a boat near the junction where the Can Tho River discharges into the Hau River, approximately 500 m upstream from the Can Tho Bridge on the Mekong River (Figure 4). The Hau River has a total length of 65 km and an average width of about 1.6 km [13]. The average flow speed in this section of the river ranges from 0.60 to 0.80 m/s, with maximum speeds reaching up to 1.25 m/s [28]. The net is positioned perpendicular to and against the river flow, ensuring it remains submerged by more than 4 m.

Figure 4. Sampling plastic waste on Hau River: (**a**) sampling location, (**b**) sample collection net, (**c**) sample classification, and (**d**) seize plastic samples.

Sampling was conducted from 7:00 a.m. to 5:00 p.m. over two consecutive days (18–19 January 2021). Approximately every two hours, the net was retrieved, and the collected plastic waste was transported to the solid waste treatment laboratory, Faculty of Environment and Natural Resources at Can Tho University. Here, the waste was dried at 85 °C (Memmert UN110 oven, Germany, ±0.5 °C) to stabilize its weight before undergoing counting, weighing, and sorting. The classification of plastic types adheres to the consumable materials guidelines set by the United Nations Environment Programme (UNEP), 2018 [4]. This systematic approach to sample collection from both terrestrial and aquatic sources provides comprehensive data on plastic waste distribution and characteristics in the Can Tho region.

3. Results and Discussion

3.1. Waste Leaking into the Land Environment at Illegal Dumping Sites

A survey was conducted to assess the waste leakage at illegal dumping sites located in various areas, including urban residential areas, riverside residential areas, suburban riverside areas, and rural regions, as illustrated in Figure 5. The survey results indicated a significant variation in the volume of waste at these illegal dumping sites, ranging from 1.65 m^3 to 7.60 m^3. Specifically, in urban residential areas, the volume of waste at illegal dumping sites varied considerably, with a range from 6.30 m^3 in the Hung Phu 2 residential area to 7.60 m^3 in the Hung Phu 1 residential area of Cai Rang district. The average volume in these urban areas was calculated to be 6.95 m^3. These findings highlight the substantial issue of waste leakage into the land environment within residential areas. Additionally, in the suburban riverside area of Cai Rang district, notably at embankment 586, the volume of waste at an illegal dumping site was recorded at 1.66 m^3, whereas in the Thanh Hoa area, it reached 5.04 m^3, averaging 3.35 m^3 across these sites. Considering that Can Tho city achieves a 98% collection rate from urban solid waste and, specifically, Cai Rang district has a collection rate of only 65% [29], it is evident that a portion of the waste does not enter the formal collection system and instead leaks into the land environment, accumulating over time.

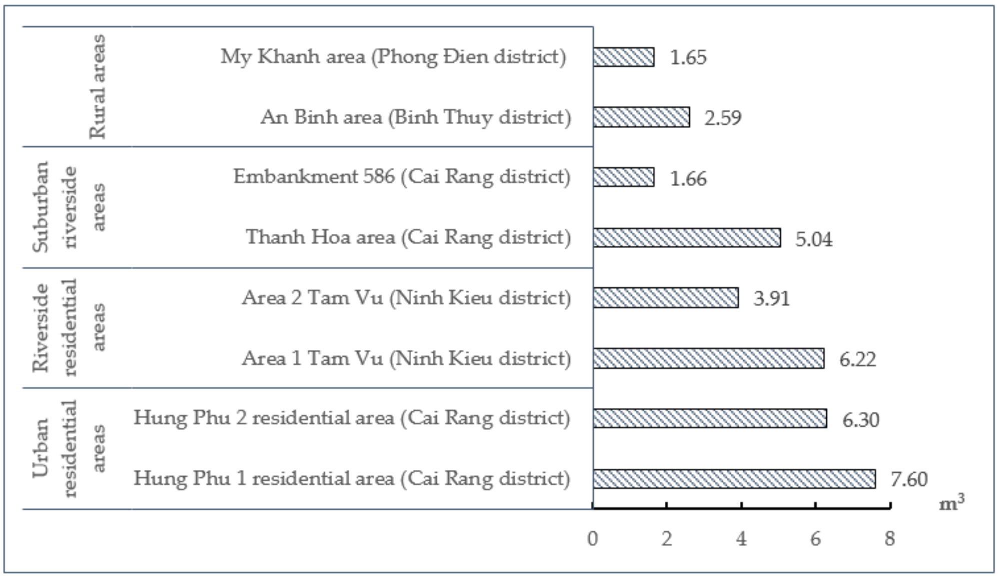

Figure 5. Volume of illegal dumping sites.

In the riverside residential areas of Tam Vu (areas 1 and 2) in Ninh Kieu district, the volume of waste at illegal dumping sites was found to range from 3.91 m^3 to 6.22 m^3, averaging 5.06 m^3. Despite Ninh Kieu district boasting the highest domestic solid waste collection rate at 98.5%, the rate of waste classification at the source is only 80% [29]. This discrepancy highlights a significant issue that a considerable amount of waste still escapes into the land environment, particularly along riverbanks, where it is at high risk of entering the water environment. In rural areas, the volume of illegal landfills ranges from 1.65 m^3 in the My Khanh area of Phong Dien district to 2.59 m^3 in the An Binh area of Binh Thuy district, with an average volume of 2.12 m^3. Notably, Binh Thuy district reports only a 41% rate of household waste classification at the source. There are also issues with indiscriminate and unsanitary waste disposal on roads, public works, and construction sites. Furthermore, the habit of directly discarding garbage into canals and rivers persists among local residents [29].

The results indicate that waste leakage into the land environment is considerably high, with illegal dumping sites ranging in volume from 1.65 m^3 to 7.6 m^3. These sites contribute to the accumulation of waste in aquatic environments, as debris is often washed from land into various water systems. These illegal dumping sites, resulting from human activities, are not part of the formal waste collection system. The frequency with which these sites is cleaned varies significantly across different locations (Figure 6a,b). For instance, Figure 6a shows that only 12.5% of sites are cleaned within 3 days, a rate similar to those cleaned after 14 and 30 days. In contrast, cleaning after 7 days occurs at twice this rate (25%). Notably, 37.5% of these sites are not cleaned regularly. This irregularity in waste management highlights the importance of effective management at the source. Even when these sites are cleaned, the process can be prolonged, with the fastest cleanup taking 3 days and the slowest 30 days. During this time, waste can further decompose, accumulate, or spread. The diverse origins of land-based waste emissions complicate the responsibility for cleanup. A survey of households near these illegal dumping sites revealed that 37.5% reported that no one cleans these sites. However, cleanup efforts are still undertaken by local government (12.5%), villagers (12.5%), and others (37.5%) (Figure 6b). These findings underscore that waste leakage into the land environment is significant, particularly at the points of emission, and that it persists in the environment for extended periods without effective cleanup measures.

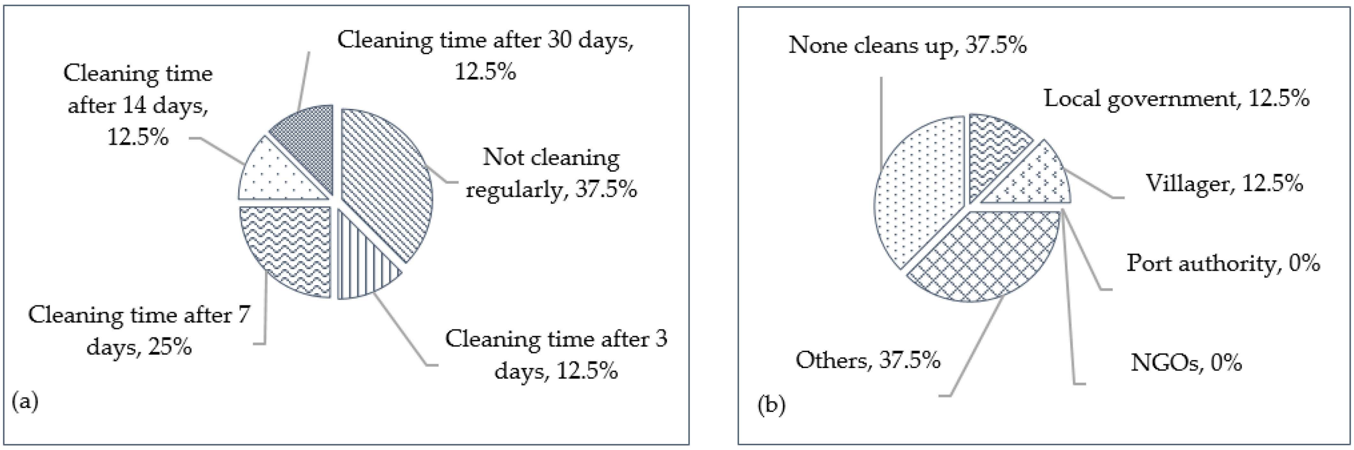

Figure 6. Status of illegal landfill cleaning: (**a**) frequency of cleanup, (**b**) who cleaned up.

3.2. Garbage Accumulates at the Barrier

After two days of collecting floating trash at the Xuan Khanh and Xang Thoi barriers, as depicted in Figure 7, significant findings were observed. The majority of the floating debris at these barriers consisted of plastic items, including plastic bottles, cups, and foam takeout containers. The presence of these items was consistent over the two days of sample collection.

At the Xuan Khanh barrier, the total weight of floating waste collected amounted to 1845 g on the first day and 1660 g on the second day. In addition to plastic, other types of floating waste, such as glass and metal, were also found. Despite their higher density, these materials floated due to features like sealed glass bottles and metal cans. The statistical results covering two days showed that the plastic component ranged from 89.97% to 93.37%, with an average of 91.67%. Although the number of hard plastics is smaller than others in total plastic waste, they have the largest volume, including sandals and baskets. Meanwhile, take out/away containers (foam) are available in large quantities, but they have a low density, so their collected volume is smaller than that of hard plastic, but more than those of plastic bottles, plastic cups, and other plastic bags.

At the Xang Thoi barrier, the total waste collected was 2640 g on the first day, with plastic constituting 540 g (20.45%). On the second day, the total collection was 850 g, with plastic accounting for 760 g (89.41%). The first day saw a higher volume of entangled trash, largely due to the significant weight of a glass bottle (1500 g), resulting in a lower percentage of plastic. On the second day, the proportion of plastic was higher, at 89.41%.

Foam takeout containers were more prevalent in quantity and volume compared to other plastic items at both barriers.

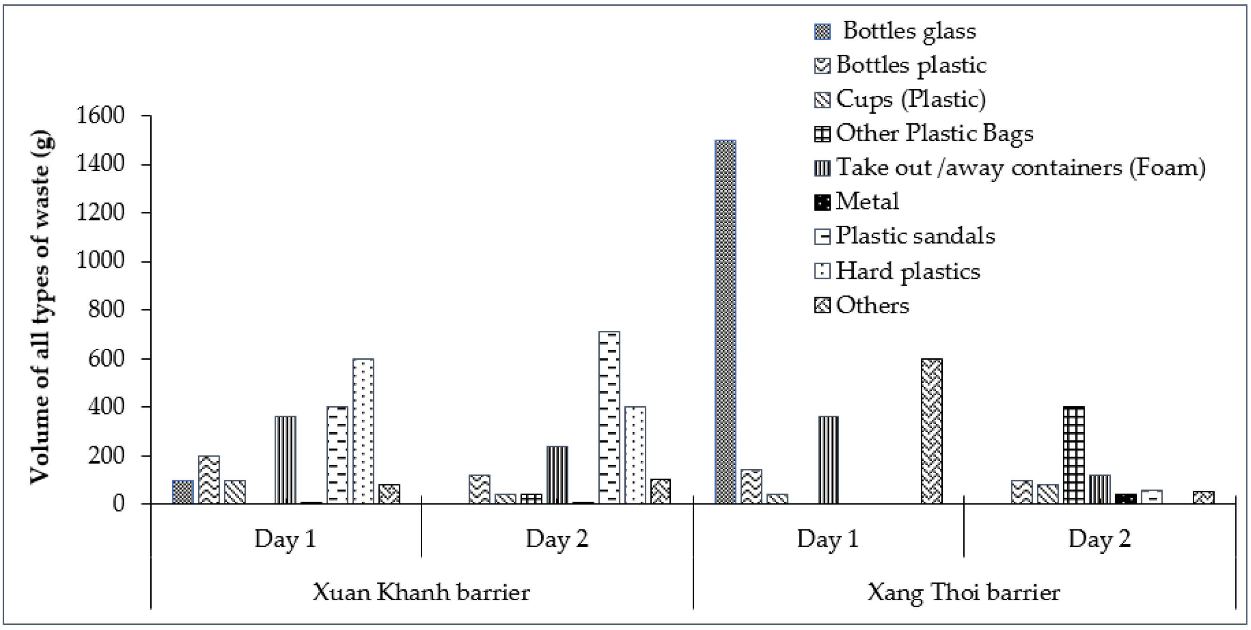

Figure 7. Garbage accumulation at the barrier.

The results indicated that the floating plastic waste was more entangled in the Xuan Khanh barrier compared to the Xang Thoi barrier, despite the fact that the former is smaller (Figure 8). This can be attributed to the Xuan Khanh barrier's proximity to the Can Tho River and a nearby market. Additionally, the entanglement of plastic in barriers is influenced by various factors, including water currents, objects like water hyacinths, wind, and river activities. The findings highlight the significant presence of various types of plastic waste in the river, with foam takeout containers posing a particular concern due to their abundance, fragility, and potential to pollute the water environment. The classification of plastic types at the Xuan Khanh and Xang Thoi barriers is detailed in Figure 9.

Figure 8. (**a**) Total amount of plastic waste at Xuan Khanh barrier and (**b**) Xang Thoi barrier.

On the first day of the sample collection at the Xuan Khanh barrier, the composition of the collected plastics varied significantly. High-density polyethylene (HDPE) was the most prevalent, constituting 34.48% of the total. This was followed by a category labeled as "other plastics," which made up 27.59%. Polystyrene (PS) was the third most common, accounting for 20.69% of the plastics. The remaining plastics included polyethylene terephthalate (PETE), at 11.49%, and polypropylene (PP), at 5.75%. Notably, low-density p(LDPE) was absent in the samples collected on this day. On the second day, the distribution of plastic types changed. 'Other plastics' emerged as the most abundant category, representing

49.24% of the collected materials. This was followed by HDPE, comprising 24.17% of the plastics. Furthermore, PS accounted for 14.50%, which was double the amount of PETE plastic, at 7.25%. The PP and LDPE plastics were also present, but in smaller quantities, accounting for 2.40% of the total.

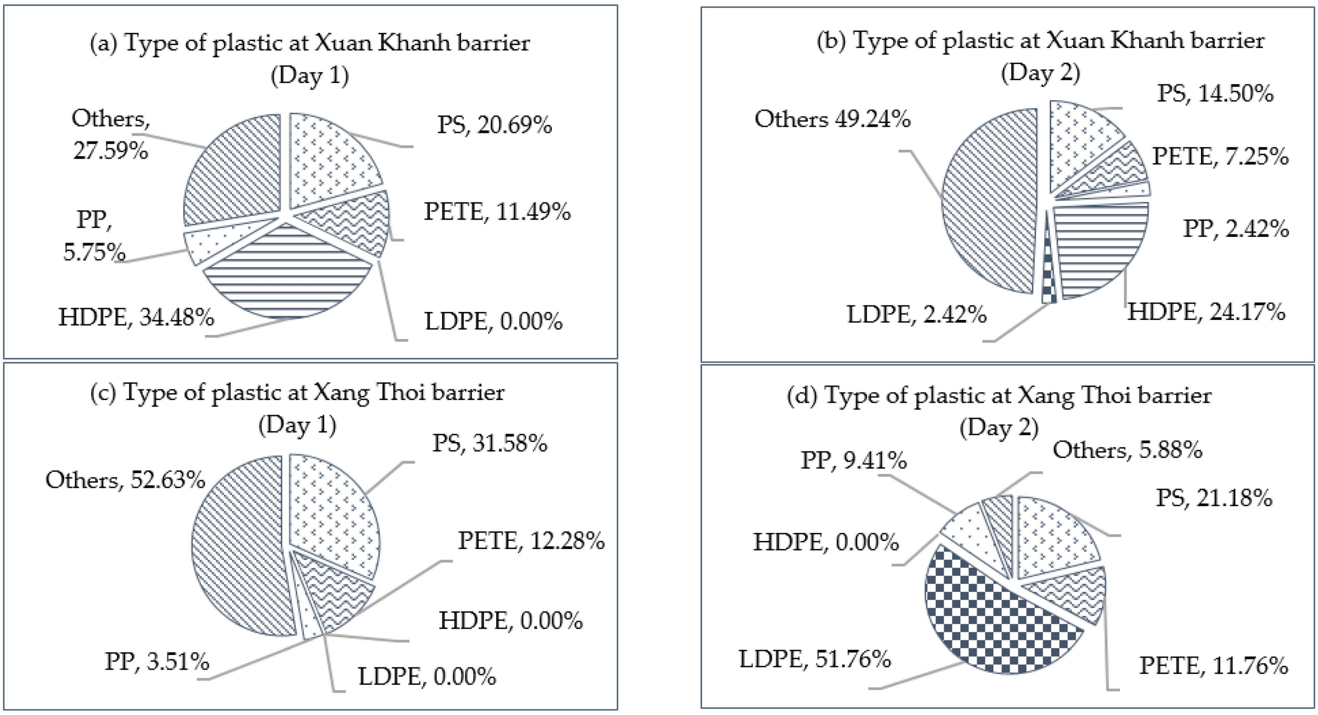

Figure 9. (**a**,**b**) Proportion of types of plastic at Xuan Khanh barrier on day 1 and day 2 and (**c**,**d**) Xang Thoi barrier on day 1 and day 2.

At the Xang Thoi barrier, the composition of plastics varied notably over the two-day sampling period. On the first day, the category of "other plastics" comprised the largest portion of the collected material, accounting for 52.63%. However, this category was not present in the samples collected on the second day. In contrast, low-density polyethylene (LDPE) was the predominant plastic type on the second day, making up 51.76% of the plastics, but it was not detected on the first day. Polystyrene (PS) consistently ranked as the second most abundant type on both days, ranging between 21.18% and 31.58%. The proportion of polyethylene terephthalate (PETE) resin remained relatively stable during the two days, fluctuating between 11.76% and 12.28%. Polypropylene (PP) also maintained a lower percentage in the overall composition, varying from 3.51% to 9.41%. Interestingly, high-density polyethylene (HDPE) was not found in the samples from the Xang Thoi barrier on either day of observation.

These findings indicate that the composition of plastics at the barriers is subject to significant daily fluctuations. At the Xang Thoi barrier, "other plastics" and PS were the most prevalent on average. Meanwhile, at the Xuan Khanh barrier, the categories of "other plastics" and HDPE were found to have the highest average content. This variation in plastic types highlights the dynamic nature of plastic pollution at these sites and underscores the need for adaptable and comprehensive waste management strategies.

3.3. Garbage Deposited at the Foot of the Bridge

In this study, we also investigated the accumulation of waste, particularly plastics, deposited at the bases of bridges, as depicted in Figure 10. The figure illustrates the diversity of waste deposited at the bridge bases, with a predominant presence of plastic waste. At Hung Loi bridge, the entire collection of waste (totaling 37 pieces) from an area measuring 15 m^2 was composed of various plastics. The most common type was "other plastic materials" (seven pieces), followed by plastic beverage bottles (six pieces), and takeout plastic containers (five pieces). There were equal quantities (four pieces each) of food wrappers, foam takeout containers, and bottle caps and lids. Additionally, the collection included straws/stirrers (three pieces), plastic cups and plates, and other plastic/foam packaging (two pieces each).

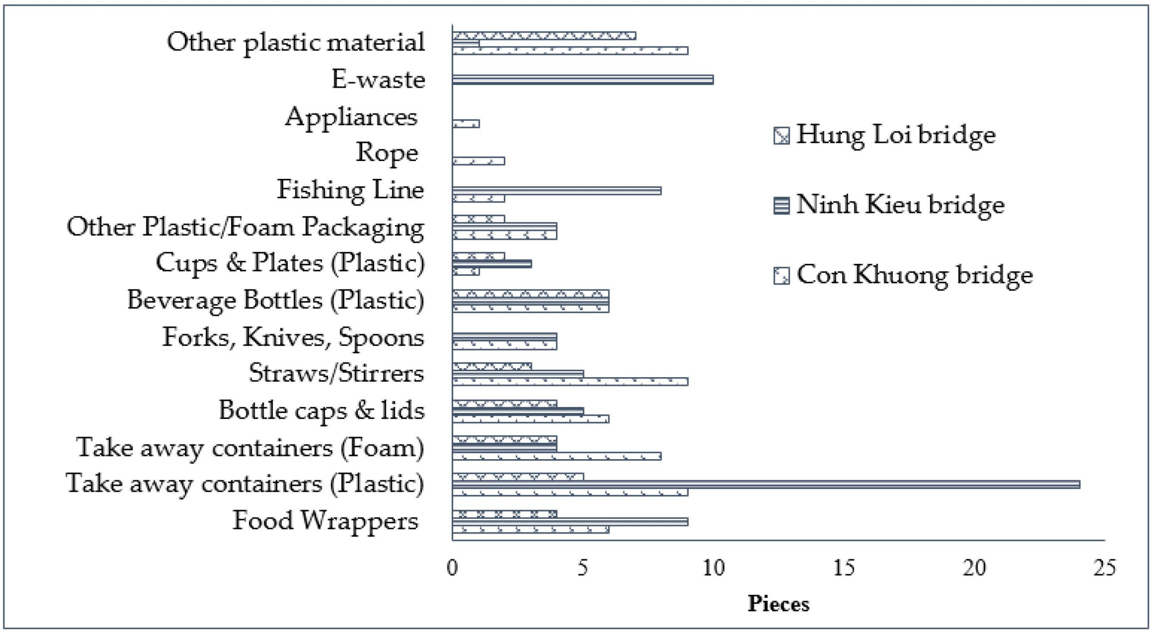

Figure 10. Garbage accumulates at the foot of the bridge.

At Ninh Kieu bridge, the deposited plastic waste constituted 87.95% of the total debris (73 out of 83 pieces) in a similarly sized area of 15 m^2. The most numerous items were plastic takeout containers (24 pieces), followed by food wrappers (nine pieces) and fishing line (eight pieces). Other items included plastic beverage bottles (six pieces), bottle caps, lids, straws, and stirrers (five pieces each). There were also four pieces each of foam takeout containers, plastic utensils (forks, knives, and spoons), and other plastic or foam packaging. Plastic cups and plates accounted for three pieces, while "other plastic materials" were found in one piece. Notably, electronic waste (e-waste) was also present, amounting to 10 pieces at the base of Hung Loi bridge.

The survey of waste accumulation extended to the Con Khuong bridge, where the same area (15 m^2) as the previous bridges was examined. At this location, a total of 67 pieces of debris were identified, with 66 pieces (98.51%) being plastic. The most abundant items were takeout plastic containers, straws/stirrers, and other plastic materials, each category comprising nine pieces. This was followed by eight pieces of foam takeout containers and six pieces each of food wrappers, bottle caps and lids, and plastic beverage bottles. Additionally, there were four pieces each of plastic utensils (forks, knives, and spoons) and other plastic or foam packaging. The lesser quantities included one piece each of plastic cups and plates and appliances, and two pieces of fishing line and rope.

Figure 11 presents the volume of garbage deposited under the bridge. E-waste was found to have the largest volume among all the types, totaling 911.05 g at the Ninh Kieu bridge, consisting of 10 pieces. Appliances followed in volume, with the largest single item weighing 460.15 g, found at the Con Khuong bridge. This item ranked second in volume after e-waste across the three bridges surveyed. In third place was "other plastic material," comprising six pieces totaling 216.14 g, with the largest volume of this category found at the Hung Loi bridge.

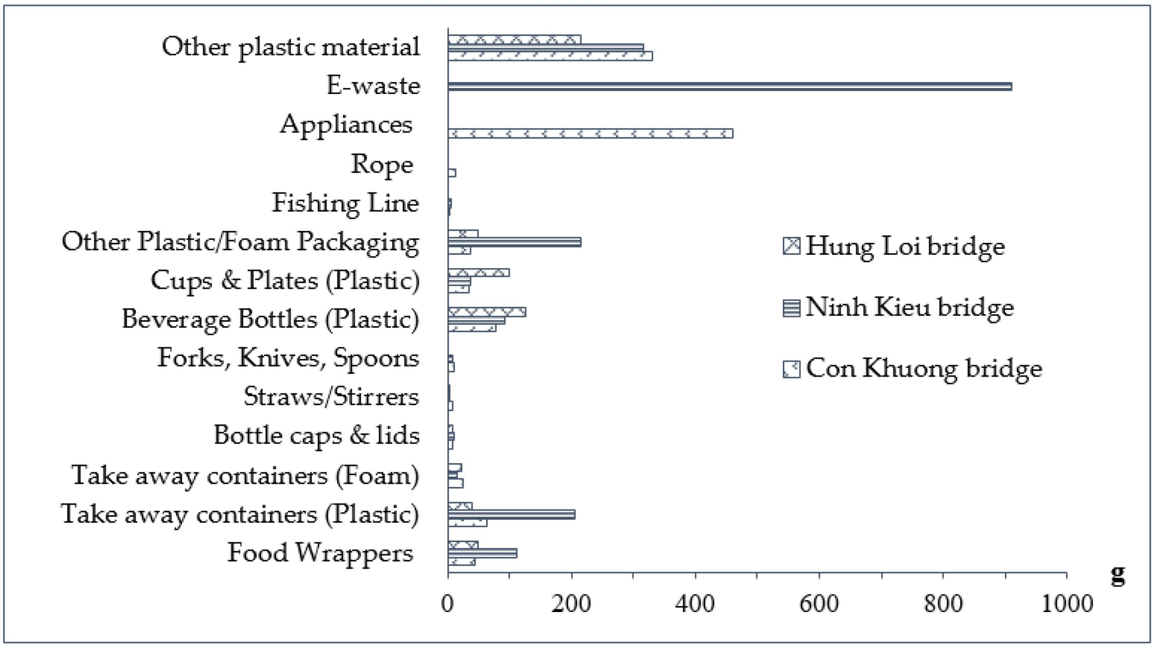

Figure 11. The volume of garbage accumulates at the foot of the bridge.

The density of various items found under the bridges significantly influenced their mass, despite variations in quantity. For example, at the Ninh Kieu bridge, the collected e-waste comprised 10 pieces but had the highest total mass, of 911.05 g. In comparison, takeout plastic containers, totaling 24 pieces, were 2.4 times more numerous than the e-waste but had a total mass that was approximately 4.4 times smaller. Additionally, a single piece of “other plastic material” weighed 315.23 g, which, although lower in number compared to the 23 pieces of takeout plastic containers, was 1.5 times heavier. A similar trend was observed at the Con Khuong bridge. A single appliance item, although significantly less in quantity than the takeout plastic containers (nine pieces), foam takeout containers (eight pieces), and straws/stirrers (nine pieces), had a mass that was 7.2 times, 18.4 times, and 62.9 times heavier than those respective items.

Figure 12a illustrates the proportions of different types of plastic, based on the number of pieces found per unit area of 15 m^2. At the Con Khuong bridge, all seven identified types of plastic were present. Polystyrene (PS) plastic was the most prevalent, accounting for 37.88%, followed by polypropylene (PP) at 24.24%, and high-density polyethylene (HDPE) at 13.6%. Low-density polyethylene (LDPE) and polyethylene terephthalate (PETE) each constituted 9.09%, while polyvinyl chloride (PVC) and other plastics together accounted for 3.03%. At the Ninh Kieu bridge, PP plastic was predominant, representing 43.84% of the total number of pieces, followed by PS plastic, at 23.29%. Notably, PVC plastic, particularly in fishing lines, comprised 10.96% of the total. Similarly, at the Hung Loi bridge, PP plastic was the most abundant (29.73%), followed by PS plastic (24.32%). The LDPE, PETE, and HDPE plastics accounted for 10.81%, 16.22%, and 18.92%, respectively.

Figure 12b presents the proportions of various plastic types based on their weight per item. The data reveal that high-density polyethylene (HDPE) plastic constituted the highest percentage of weight at the Con Khuong bridge, accounting for 50.7%. This percentage ranged from 30.81% at the Ninh Kieu bridge to 35.06% at the Hung Loi bridge. Polypropylene (PP) plastic followed, with its proportion varying between 16.21% and 2.88%. Polystyrene (PS) plastic was the third most significant component, representing 12.11% to 23.87% of the plastic weight.

These results suggest that within the same area, the extent of the waste pollution deposited under bridges is more influenced by the quantity of waste items rather than their volume. Essentially, the number of waste pieces is a more accurate indicator of the density of the pollution covering the surveyed area, as opposed to the total volume of waste. This distinction is important for understanding the impact and distribution of waste in these environments, emphasizing the need for waste management strategies that address both the volume and the quantity of debris.

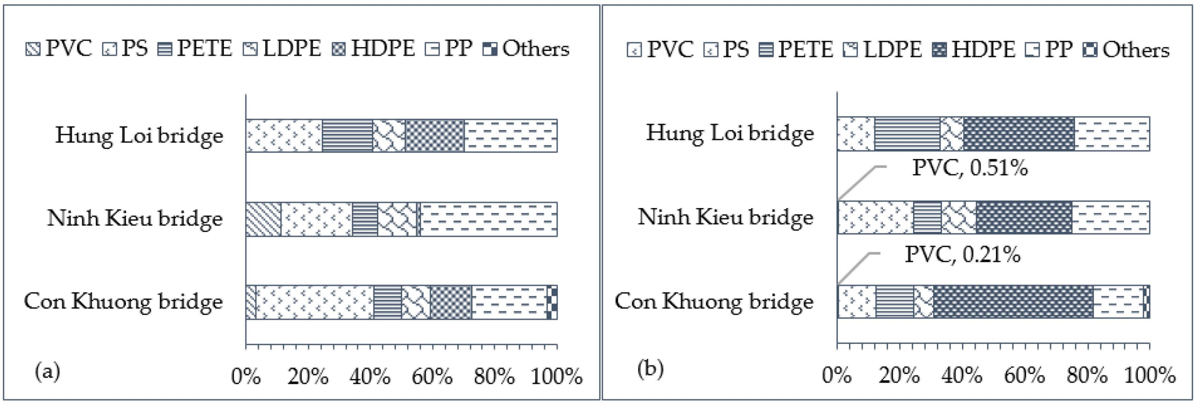

Figure 12. Proportion of types of plastic deposition at the foot of the bridge: (**a**) by quantity and (**b**) by volume.

3.4. Waste Accumulation on the Hau River

In this study, we investigated the accumulation of plastic waste in the aquatic environment of the Hau River, as depicted in Figure 13. The total weight of the waste collected on the first day was 1160 g, increasing to 1470 g on the second day. Over the two-day monitoring period, a substantial quantity of items such as plastic bags, cups, grocery bags, and other plastic types was observed (Figure 13a). These items probably originated from direct discharge into the river or from their accumulation on land, before their subsequently washing into the aquatic environment. Figure 13a illustrates the diversity of the plastic items found in the Hau River. Plastic bags were the most prevalent on both days, with an average weight of approximately 710 g, accounting for 53.99% of the total. Plastic cups followed, with an average weight of 185 g (14.07%), and plastic grocery bags averaged 135 g (10.27%). Additionally, a significant volume of other plastic items was detected, totaling 230 g and representing 17.49% of the collected waste. The remaining 3.42% comprised foam takeout containers (3.04%) and foam cups and plates (0.38%). Metal components were also present, accounting for 0.76% of the total waste.

From Figure 13b, the chemical composition analysis of the plastics accumulated in the Hau River over the two-day monitoring period reveals a predominance of low-density polyethylene (LDPE) plastic, ranging from 59.18% to 71.93%. Polypropylene (PP) plastic comprised between 12.24% and 16.67%, while the proportion of other types of plastics varied from 7.02% to 25.85%. Notably, polystyrene (PS) plastic accounted for 2.72% to 4.39% of the total. High-density polyethylene (HDPE) and polyethylene terephthalate (PETE) plastics were not detected on either day of monitoring. These findings indicate that the most abundant type of plastic waste in the Hau River is LDPE, primarily in the form of plastic bags and PP plastic, which was mainly found in plastic cups (Figure 14).

In summary, we observed that in aquatic environments, a variety of trash types accumulate at barriers, predominantly consisting of floating plastics with low density. Among these, PS plastic items, mainly foam takeout containers, tend to fragment under external influences, losing their original shape and forming smaller, amorphous pieces. Conversely, the accumulation of litter under bridges suggests that the extent of plastic pollution is related more to the quantity of items rather than to their volume. A significant number of items were found to be LDPE plastics, corresponding to takeout containers. In the river, LDPE and PP plastics were mainly found in plastic bags. It is estimated that the waste in the Mekong River passing through Can Tho city, including areas like the Cai Rang floating market and Con Son Island, amounts to approximately 300–400 tons per year [30]. This comprehensive analysis underscores the diverse nature of plastic pollution in riverine environments and the importance of targeted waste management strategies to address this issue.

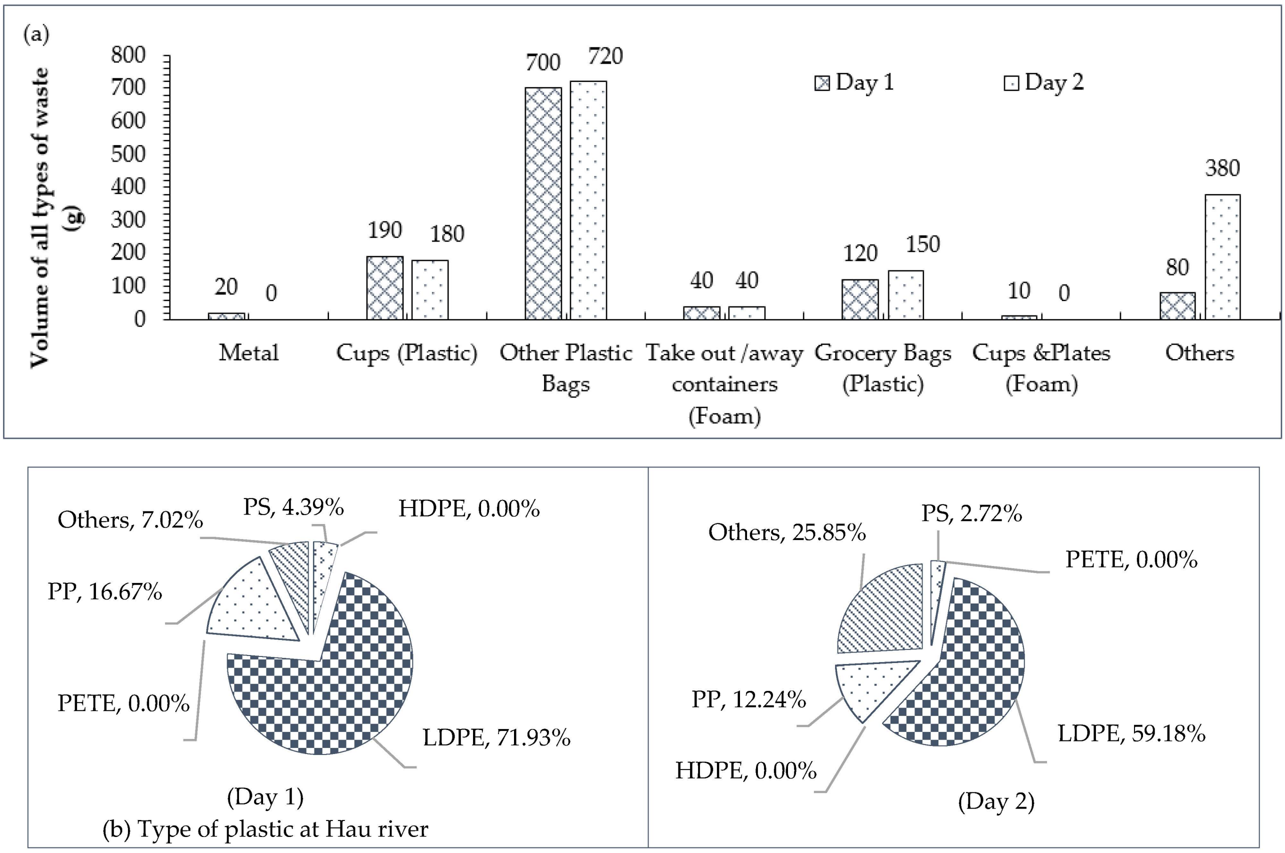

Figure 13. Plastic accumulation on the Hau River: (**a**) volume of all types of waste and (**b**) type of plastic.

Figure 14. Total types of plastic waste accumulated in Hau river.

3.5. Proposed Solutions to Limit Plastic Waste

The research findings on the leakage and accumulation of plastic waste in terrestrial and aquatic environments reveal a diverse array of plastic items persisting in the environment. These items encompass nearly all seven non-degradable plastic types: PETE, HDPE, PVC, LDPE, PS, PP, and other plastics. Notably, some of these plastics, like PETE and HDPE, are fully recyclable, while others, such as PVC and LDPE, are recyclable under specific conditions. However, PS, PP, and other plastics present significant recycling challenges, as indicated in Table 2. According to Figure 15, fully recyclable plastics, such as PETE, account for approximately 10.70% to 13.79%, and HDPE ranges from 14.66% to 38.87%. Plastics like LDPE and PVC, which are recyclable under certain conditions, range from 13.55% to 65.56% and about 0.2%, respectively. The remaining categories, including non-recyclable plastics like PP (5.27% to 21.8%), PS (3.55% to 21.99%), and other plastics (0.68% to 33.84%), pose greater challenges.

Table 2. Types of plastic that can be recycled (source: [31]).

Symbol	Abbreviation	Polymer Name	Uses	Repurposed to Make	Recyclable
1 PETE	PETE or PET	Polyethylene Terephthalate	Soda bottles; water bottles; salad dressing bottles; medicine jars; peanut butter jars; jelly jars; combs; bean bags; rope; tote bags; carpet; fiberfill material in winter clothing	Textiles, carpets, pillow stuffing, life jackets, storage containers, clothing, boat sails, auto parts, sleeping bags, shoes, luggage, winter coats	Yes
2 HDPE	HDPE	High-Density Polyethylene	Milk jugs; juice containers; grocery bags; trash bags; motor oil containers; shampoo and conditioner bottles; soap bottles; detergent containers; bleach containers; toys	Plastic crates, lumber, fencing	Yes
3 PVC	PVC	Polyvinyl Chloride	Some tote bags; plumbing pipes; grocery bags; tile; cling films; shoes; gutters; window frames; ducts; sewage pipes	Flooring, mobile home skirting	Yes—but call your recycler
4 LDPE	LDPE	Low-Density Polyethylene	Cling wrap; sandwich bags; squeezable bottles for condiments such as honey and mustard; grocery bags; frozen food bags; flexible container lids	Garbage cans, lumber	Yes—but call your recycler
5 PP	PP	Polypropylene	Plastic diapers; tupperware; kitchenware; margarine tubs; yogurt containers; prescription bottles; stadium cups; bottle caps; take-out containers; disposable cups and plates	Ice scrapers, rakes, battery cables	No
6 PS	PS	Polystyrene or Styrofoam	Disposable coffee cups; plastic food boxes; plastic cutlery; packing foam; packing peanuts	Insulation, license plate frames, rulers	No
7 OTHER	N/A	Miscellaneous Plastics (polycarbonate, acrylic, polyctide, acrylonitrile butadiene, styrene, fiberglass, and nylon)	Plastic CDs and DVDs; baby bottles; large water bottles with multiple-gallon capacity; medical storage containers; eyeglasses; exterior lighting fixtures	Plastic lumber (which is often used in outdoor decks, molding, and park benches)	Not usually—call your recycler to verify

The overall average of fully recyclable plastics (PETE and HDPE) at all the surveyed sites was found to be 39.01% [31]. Furthermore, LDPE and PVC, commonly used in plastic and grocery bags, are also recyclable, averaging 43.93%, although they require specific conditions, as outlined by Mertes (2017) [31]. Consequently, the total proportion of recyclable plastics could be as high as 82.84%. A World Bank report (2019) indicates that Vietnam recycles about 33% of its plastic waste, with PETE packaging achieving the highest recycling collection rate among plastic types [32]. The Global Plastic Action Partnership (2022) reported that approximately 10% to 15% of Vietnam's plastic waste is collected for recycling [33]. The recycling of plastic waste has garnered attention globally. For instance, the recycling rate of PETE beverage bottles in California is 74%, which is significantly higher than the US average [34].

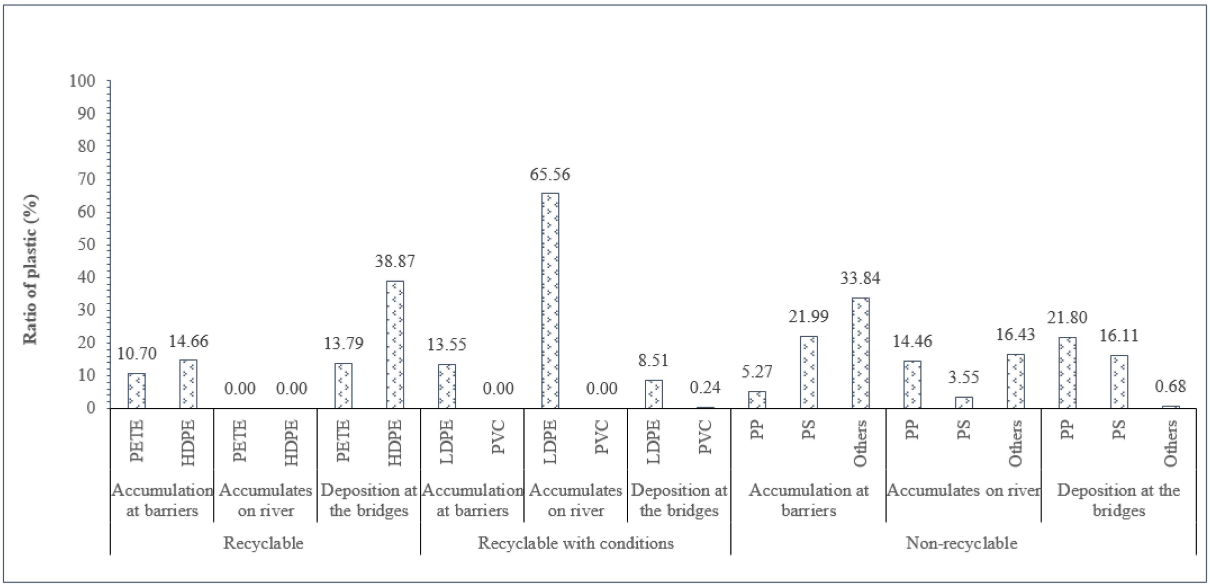

Figure 15. Ratio of recyclable plastic and non-recyclable plastic.

In Vietnam, innovative recycling efforts have been made with LDPE plastics, which are commonly derived from plastic bags. One notable example is the recycling of LDPE to produce a "plastic stone," an alternative to traditional green stone, which is used in construction projects. This process has been copyrighted under Nguyen Dinh Duong (No. 2927/2012/QTG) [35]. Furthermore, research is being conducted on utilizing LDPE in the production of hot asphalt concrete in the laboratory [36]. Studies are also exploring the use of plastic waste as an additive to enhance the mechanical properties of asphalt concrete [37] and investigating the impact of waste nylon on the elastic modulus of asphalt concrete [38]. Additionally, PETE waste plastic is utilized in hot asphalt mixtures in Ho Chi Minh City, with the aim of improving the properties of the mix and the overall quality of asphalt pavements [39,40].

The study's findings on plastic waste management in Vietnam reveal a complex landscape, necessitating multifaceted strategies to address the challenges effectively. Firstly, there is a critical need to enhance recycling infrastructure. Investment in and the upgrading of recycling facilities are essential, specifically for plastics that are currently very challenging to recycle. This step is pivotal in broadening the scope of recyclable materials and enhancing the efficiency of the recycling process. Moreover, public awareness and education also play a critical role in the success of recycling programs. Educating the public about the importance of recycling and proper waste segregation can significantly increase the collection rate of recyclable waste. This approach is fundamental in ensuring the efficacy of recycling efforts from the grassroots level. Another key area is innovative repurposing, where encouraging research and development in the repurposing of plastic waste can open avenues for novel uses, especially for plastics that are not traditionally recyclable. The ongoing initiatives with LDPE and PETE plastics serve as exemplary models in this context. The implementation of effective policies and regulations is also vital. These must aim to incentivize recycling activities while imposing penalties for the improper disposal of plastic waste. Such policy measures will significantly boost recycling rates and ensure compliance with environmental standards. In addition, collaboration and partnerships form the basis of innovation in recycling technologies and strategies. The building of robust partnerships between the government, private sector, and research institutions is critical for advancing innovation and developing sustainable solutions in waste management. Targeted interventions for high-impact plastics, particularly those constituting a larger portion of the waste stream, like LDPE in plastic bags, is also essential. Focusing on such materials will yield substantial benefits in reducing environmental pollution and managing waste more effectively.

Despite these strategies, the study features certain limitations and gap areas. For instance, the lack of comprehensive data on the lifecycle of all the plastic types in the study area limits the ability to suggest tailor-made solutions effectively. Furthermore, the study's geographic focus on Can Tho city does not fully encapsulate the diverse waste management practices across different regions of Vietnam. Future research shall aim to address these limitations by encompassing a broader geographic scope and delving deeper into the lifecycle analysis of different plastics. Studies exploring the long-term environmental effects of various waste management strategies would also be very valuable. Additionally, research into emerging recycling technologies and innovative waste-to-resource methods would further advance the field. The task of managing plastic waste in the study area currently has significant challenges but also offers considerable opportunities for meaningful solutions. Through a combination of improved recycling processes, innovative repurposing methods, public education, policy support, and strategic partnerships, it is practical to significantly mitigate the environmental impact of plastic waste. These efforts, coupled with targeted research and development, are key to advancing sustainable waste management practices in Vietnam and other developing regions of the world.

4. Conclusions

This study analyses the plastic waste leakage and accumulation in Can Tho city, Vietnam, providing crucial insights into their environmental impact and potential mitigation strategies. Notably, the leakage of waste into terrestrial environments, particularly at emission points, is a significant concern. This waste remains in the environment for extended periods, often without effective clean-up measures, indicating a need for enhanced waste management practices in these areas. In the aquatic environments in the study area, the accumulation of plastic waste at barriers, bridge bases, and within rivers was observed. The study found a high occurrence of single-use plastic items, stressing the urgent need to address this source of pollution. Notably, the study showed that the level of pollution in these environments depends more on the quantity of waste items than their mass per unit area. This finding suggests that interventions targeting the reduction in the number of disposable plastics could be particularly effective. The diversity of the plastic types found in these environments was also noteworthy. Seven different types of plastic were identified, each originating in various sources of waste accumulation or settlement. This diversity presents both challenges and opportunities in recycling and waste management. Importantly, the results of this study underscore the potential of recycling plastic waste into new products. This approach is deemed to extend the lifecycle of the products, as well as reducing the generation of plastic waste. It will also minimize the environmental impact and aligns with the principles of the circular economy. The possibility of using plastic waste to create recycled products represents a sustainable solution that could significantly contribute to environmental protection and waste management efficiency. The findings from this research emphasize the need for comprehensive strategies to manage plastic waste in Can Tho city. These strategies should include enhancing waste collection and recycling infrastructure, promoting public awareness and education, and implementing policies that encourage the reduction in and recycling of plastics. Furthermore, innovative recycling initiatives, as observed in the study, can offer promising avenues for transforming plastic waste into valuable resources, thereby contributing to a more sustainable and circular economy.

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