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Original Article

Plastic Waste Management in Bac Ninh Province: Current Status and Policy Implications

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Abstract: Plastic waste has become a major environmental pressure in rapidly urbanizing and industrialized provinces of Vietnam. This study assesses the generation, composition, and spatial distribution of single-use plastics and non-biodegradable plastic bags in Bac Ninh Province through a large household, retail, and office survey (3,200 households and 400 establishments) and a waste audit of 675 samples. Average generation reached 17.14 kg/person/year (~23.5 thousand tons/year), with strong variation across administrative units. Industrial–urban areas such as Yen Phong, Tien Du, Tu Son, and Bac Ninh City recorded the highest loads and densities, while rural districts generated markedly less. Plastic bottles represented 39% of household plastic waste by mass, followed by plastic bags (24%), reflecting both the recycling potential of rigid plastics and the leakage risks of lightweight items. Survey findings show a clear perception–behavior gap: although over 70% of respondents acknowledged environmental and health risks, fewer than 20% frequently practiced reduction behaviors. GIS-based spatial visualization highlights pronounced spatial heterogeneity in plastic waste generation and identifies areas with comparatively high waste loads at the commune and district levels. These results indicate that plastic management should prioritize differentiated interventions tailored to both geographic hotspots and specific waste composition (e.g., focusing on recovery for high-mass items and leakage reduction for lightweight items), integrating economic instruments (plastic bag levy, deposit–return schemes, strengthened Extended Producer Responsibility) with targeted communication and improved access to alternatives, supporting provincial and national plastic reduction strategies.

Keywords: Plastic waste, single-use plastics, household plastic generation, plastic-reduction behavior, plastic policy, Bac Ninh province.

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1. Introduction

Single-use plastic waste has become a significant global environmental burden. Its persistence, rapid growth in consumption, and low recycling rates cause long-term impacts on terrestrial, freshwater, and marine ecosystems [1, 2]. Recent studies show that plastic waste generation is strongly shaped by demographic characteristics, urbanization levels, and consumption patterns. Spatially explicit assessments are therefore essential for identifying high-pressure areas and informing targeted policy interventions [3, 4]. Community awareness and behavioral responses also play a critical role in shaping waste generation and the effectiveness of mitigation actions, particularly in developing countries.

In Vietnam, per-capita plastic consumption has risen sharply over the past two decades, while waste management infrastructure has lagged behind, resulting in substantial plastic leakage to the environment [3]. Rapid urbanization, industrial expansion, and changing consumption patterns have accelerated the use of single-use plastics, particularly plastic bags and disposable packaging. Provincial studies from Phu Yen and Ha Tinh demonstrate clear intra-provincial variation in plastic generation and treatment, underscoring the value of spatial analysis for local decision-making [5, 6]. However, most existing studies focus on waste quantities or leakage pathways alone, and evidence on public awareness and plastic-reduction practices at the provincial scale remains limited and is rarely assessed alongside waste generation and spatial distribution.

Bac Ninh is a representative northern province featuring both intensive industrial development and interspersed rural areas. It hosts diverse sources of plastic waste, including households, commercial and service establishments, and industrial parks. As one of Vietnam's most industrialized inland provinces with high population density, Bac Ninh provides a critical case for examining plastic waste generation beyond coastal contexts. A large-scale survey across multiple communes and wards provides detailed data on plastic quantities, composition, and spatial differences. Coupled with surveys on public and vendor awareness and behavior, the dataset captures both physical waste flows and human dimensions, two components essential for effective policy design. GIS-based spatial analysis further clarifies distribution patterns and identifies local hotspots.

Against this background, this study addresses a key research gap by integrating waste audits, large-scale household and establishment surveys, and GIS-based spatial analysis at the provincial level. This study examines the generation and spatial distribution of single-use plastics and non-biodegradable plastic bags in Bac Ninh, incorporates community awareness and behavioral responses, and situates the findings within national and international research. Crucially, the study goes beyond identifying geographic hotspots by providing a composition-based analysis that distinguishes between different management priorities, such as high-mass and high-recycling-potential plastics versus high-frequency, low-recyclability items. The results provide evidence to guide provincial plastic-reduction strategies and support the development of context-specific management solutions.

2. Materials and Methods

2.1. Study area

The study was conducted in the former administrative boundary of Bac Ninh Province, located in the Red River Delta of Vietnam. The province covers 822.7 km² and had a population of approximately 1.5 million in 2021, characterized by high population density and rapid industrialization and urbanization. At that time, Bac Ninh comprised eight district-level units and 126 commune-level units. All analyses in this study follow the 2021 administrative boundaries to ensure consistency with the survey dataset.

2.2. Field Survey and Waste Audit

Field surveys were conducted from February to May 2021 across households, retail shops, and offices. Sampling locations were selected using a stratified random sampling approach to ensure representation of urban areas, rural areas, and zones adjacent to industrial parks.

The minimum sample size for the household survey was determined using Cochran's formula for large populations [7]:

$$n = \frac{Z^2 p(1-p)}{e^2} \quad (1)$$

where n is the required sample size, Z is the standard normal deviate (1.96 for a 95% confidence level), p is the estimated population proportion, and e is the margin of error (±5%). In the absence of prior province-level estimates of household plastic waste generation characteristics, p was conservatively set at 0.5, which yields the maximum required sample size. Based on this formulation, the minimum required sample size was approximately 384 households.

Although this minimum requirement was modest, a substantially larger sample was intentionally adopted to support spatially disaggregated analysis. An equal number of 100 households was surveyed in each selected commune/ward/town, regardless of population size, to ensure balanced representation across spatial units and enable meaningful comparisons among urban, rural, and industrial-adjacent areas. Differences in population size were subsequently accounted for during the analysis stage by weighting per-household and per-capita plastic waste generation coefficients using commune-level population data. This design resulted in spatial replication at multiple levels, with repeated household-level observations within communes/wards and replication across multiple communes/wards within each district.

In total, 3,600 survey units were included in the study, comprising 3,200 households (four communes/wards/towns per district across eight districts), 320 retail shops (10 shops per selected commune/ward/town), and 80 offices or tourism/service establishments (10 per district). A total of 675 household waste samples were audited, ensuring sufficient replication for spatial comparison at both commune/ward and district levels. This sample size exceeds the statistically required minimum by more than eight times and enhances the reliability of spatial analysis at both commune/ward and district levels. The surveyed locations in 2021 and their correspondence to administrative units following the 2025 restructuring are presented in Table 1.

The survey employed structured questionnaires to collect three main types of information: i) waste composition, sources of generation, and current handling practices of the surveyed groups; ii) data necessary for calculating plastic generation coefficients (for offices, shops, and households); and iii) stakeholders' awareness, attitudes, and behaviors (AAB) regarding single-use plastics and non-biodegradable plastic bags. The AAB indicators were measured using a five-point Likert scale.

Waste audit: A waste audit was conducted on a subset of the surveyed households to determine waste composition and generation rates. A total of 675 samples were analyzed. Participating households were instructed to separately collect all plastic waste generated within a 24-hour period in pre-labeled bags provided by the survey team. Waste collection was implemented in two separate one-week campaigns, conducted in January and May 2021, respectively, to capture short-term temporal variability and potential seasonal differences. Within each campaign, waste was collected over seven consecutive days, including both weekdays and weekends. Collected samples were retrieved daily, manually sorted, and weighed using a portable digital electronic scale (measurement accuracy ±1 g) following a standardized protocol applied consistently across all surveyed locations. Household plastic waste was classified into categories synthesized from approaches suggested in previous studies [8, 9]. These categories include plastic bags, plastic

bottles/containers, single-use plastic items (e.g., straws, spoons, cups), composite milk cartons, diapers, foam boxes, and other mixed or low-recyclability plastics, based on material characteristics, recyclability, and relevance to local waste management practices.

Table 1. Administrative units selected for the survey

No.	Commune/Ward (2021)	Population density, 2021 (persons/ha)	Main Activities & Primary Plastic Waste Sources	District/City/Town (2021)	Commune/Ward (2025)
1	Gia Binh Town	14.79	Commerce & services; domestic plastic waste.	Gia Binh District	Gia Binh Commune
2	Nhan Thang Commune	10.47	Agriculture; plastic bags & packaging residues.		Nhan Thang Commune
3	Lang Ngam Commune	13.0	Agriculture; domestic plastic waste.		Dong Cuu Commune
4	Van Ninh Commune	8.54	Agriculture; market-generated & household waste.		Cao Duc Commune
5	Binh Dinh Commune	9.59	Agriculture; fertilizer & pesticide packaging.	Luong Tai District	Lam Thao Commune
6	Thua Town	15.14	Retail & services; domestic & consumer plastic.		Luong Tai Commune
7	My Huong Commune	11.15	Small-scale farming; household packaging waste.		Trung Kenh Commune
8	Phu Hoa Commune	7.45	Agriculture; domestic plastic waste.		Luong Tai Commune
9	Bang An Commune	11.33	Agriculture; household plastic consumption.	Que Vo District	Que Vo Ward
10	Pho Moi Town	48.48	Commercial hub; retail & service-related packaging.		
11	Chi Lang Commune	10.2	Agriculture & services; local retail packaging.		Chi Lang Commune
12	Phu Lang Commune	8.42	Ceramic craft; packaging & transport plastic residues.		Phu Lang Commune
13	Song Lieu Commune	13.49	Agriculture; domestic plastic waste.	Thuan Thanh District	Song Lieu Ward
14	Ngu Thai Commune	13.39	Agriculture; agricultural supply packaging.		
15	Xuan Lam Commune	20.3	Agriculture; consumer-based packaging.		
16	Ho Town	30.15	Commercial services; single-use plastics & packaging.		Thuan Thanh Ward
17	Dai Dong Commune	34.97	Industry & services; worker residential plastic waste.	Tien Du District	Dai Dong Commune
18	Hoan Son Commune	39.02	Industry & services; high-density residential waste.		
19	Phat Tich Commune	14.82	Tourism & farming; tourism-related plastic waste.		Phat Tich Commune

20	Lim Town	26.65	Festivals & retail; festival & service-related waste.		Tien Du Commune
21	Long Chau Commune	35.7	Industry & logistics; household & logistics packaging.	Yen Phong District	Yen Phong Commune
22	Dong Phong Commune	21.67	Agriculture; local retail packaging.		Tam Da Commune
23	Cho Town	23.25	Commerce & retail; urban consumer plastic waste.		Yen Phong Commune
24	Yen Trung Commune	35.67	Industry & services; residential & service packaging.		Yen Trung Commune
25	Phong Khe Ward	21.36	Paper recycling; feedstock packaging & industrial residues.	Bac Ninh City	Vo Cuong Ward
26	Ninh Xa Ward	128.84	Administration & services; office & domestic plastic.		Kinh Bac Ward
27	Suoi Hoa Ward	66.21	Offices & services; single-use plastic consumption.		
28	Vu Ninh Ward	24.01	Tourism & services; domestic & hospitality waste.		Vu Ninh Ward
29	Dinh Bang Ward	9.63	Woodcraft & services; commercial & household waste.	Tu Son Town	Tu Son Ward
30	Chau Khe Ward	26.6	Steel manufacturing; industrial & domestic plastic waste.		Phu Khe Ward
31	Phu Khe Commune	61.31	Woodcraft; protective films & packaging wraps.		
32	Dong Nguyen Ward	20.23	Retail & services; urban residential plastic waste.		Dong Nguyen Ward

2.3. Data Processing and Analysis

Generation coefficients: Per-household plastic waste generation rates were calculated from measured waste weights following standard solid waste characterization methods [10, 11] as:

$$G_i = \frac{W_i}{T} \quad (2)$$

where G_i is the household plastic waste generation rate (kg/household/day), W_i is the measured plastic waste weight (kg), and T is the sampling duration (days). Per-capita generation rates (kg/person/day) were obtained by dividing household generation by household size and annualized by multiplying by 365 (days).

Ward/commune-level load estimation: Total plastic waste generation was estimated using a population-scaling approach commonly applied in municipal solid waste studies [10, 12]:

$$L_j = G_j \times P_j \quad (3)$$

where L_j is the annual plastic waste load (kg/year) in ward/commune j, G_j is the average per-capita generation coefficient (kg/person/year), and P_j is the local population. Results were normalized by land area (kg/ha/year) to support spatial comparison.

Uncertainty: Variability was expressed using standard deviation from household-level measurements. Uncertainty sources include short-term sampling duration and weighing

precision (±1 g), which were mitigated through spatial replication and standardized audit procedures.

Statistical analysis: Data were processed using Excel and SPSS, and descriptive statistics (mean and standard deviation) were calculated for each plastic waste category and stratification group.

2.4. GIS-based Spatial Visualization

Administrative boundary data for 2021 (commune/ward shapefiles) were used as the base layer in ArcGIS 10.3 for spatial visualization of plastic waste generation. Input datasets included commune-level plastic waste generation estimates (total load, per-capita load, and area-normalized load), population data, land area, and administrative boundary shapefiles. The analysis included:

Attribute assignment: Plastic waste load data (total, per capita, and area-normalized) were joined to the shapefile using administrative codes, resulting in a spatial database linking plastic waste indicators to each commune/ward polygon.

Map visualization: Choropleth maps were produced to illustrate plastic waste generation by commune/ward and district. The Jenks Natural Breaks classification method (k = 5) [13] was applied to capture spatial variability in plastic waste loads. Color-based zoning represents classified ranges of plastic waste generation intensity, with darker colors indicating higher values and lighter colors indicating lower values. Map legends report the unit of measurement (kg/year or kg/ha/year) and the corresponding value ranges for each class.

3. Results and Discussion

3.1. Generation and Composition of Plastic Waste in Bac Ninh Province

The 2021 survey results show that the average generation of single-use plastics and non-biodegradable plastic bags in the former Bac Ninh Province reached 17.14 kg/person/year, equivalent to 23.5 thousand tons/year (~64 tons/day), accounting for 6.7% of the province's total municipal solid waste. Generation rates varied substantially across districts (Figure 1). Yen Phong recorded the highest value (26.51 kg/person/year), more than twice that of low-generation districts such as Gia Binh (12.18 kg/person/year) and Thuan Thanh (11.45 kg/person/year). This variation aligns with clear contrasts in population density and dominant activities (Table 1): Gia Binh communes exhibit low densities (8.54–14.79 persons/ha) and are primarily agricultural, whereas Yen Phong communes show substantially higher densities (21.67–35.7 persons/ha) and are dominated by industrial and logistics activities, including household and packaging-related services, which are associated with higher consumption of packaged and single-use products.

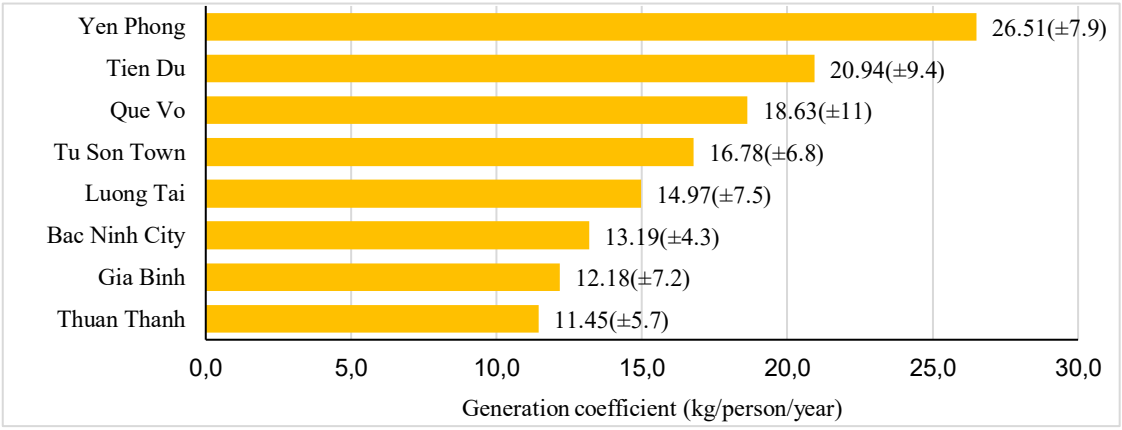


Figure 1. Generation coefficients of single-use plastics and non-biodegradable plastic bags (± SD).

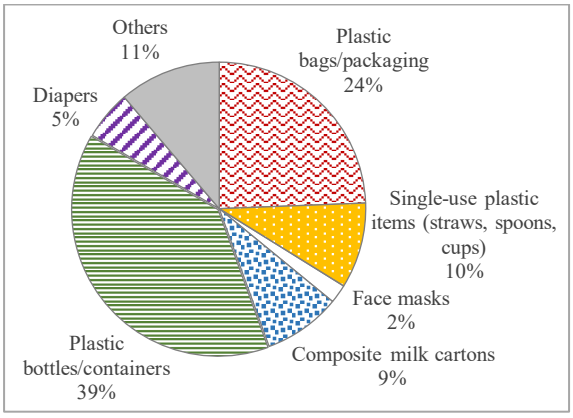


Figure 2. Composition of household plastic waste by mass.

Regarding composition, household plastic waste is dominated by plastic bottles (39% by weight), followed by plastic bags (24%), single-use items such as straws, cups, and spoons (10%), composite milk cartons (9%), diapers (5%), and other minor categories (Figure 2). Although plastic bags have the highest usage frequency (7.7 bags/household/day), plastic bottles account for a substantially larger mass (26.97 kg/household/year compared to 16.92 kg/household/year for plastic bags). This indicates that bottles constitute the primary mass fraction and hold high recycling potential, whereas plastic bags, despite their light weight, represent the waste stream most prone to environmental leakage.

3.2. Spatial Distribution of Plastic Waste

Total loads by administrative unit:

The total volume of single-use plastic waste, estimated from generation coefficients and population data, is illustrated in Figure 3. Yen Phong, Tien Du, and Que Vo districts exhibit the highest generation levels, with corresponding annual loads of 5,852, 3,979, and 3,703 tons, respectively. Other administrative units show decreasing totals, including Bac Ninh City (3,380 tons), Tu Son (3,003 tons), and Thuan Thanh (1,986 tons). In contrast, predominantly rural districts such as Luong Tai and Gia Binh generate substantially lower amounts, only 1,589 and 1,277 tons per year, respectively.

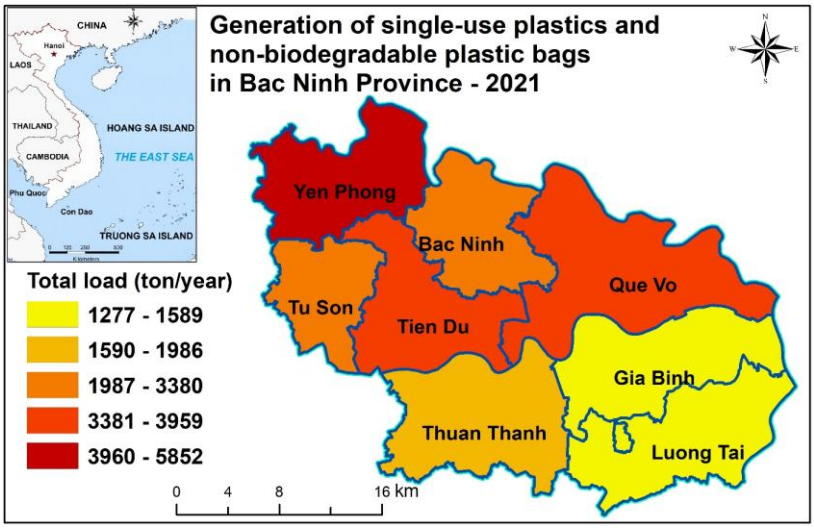


Figure 3. Total load of single-use plastic waste across Bac Ninh Province.

Waste generation density:

Yen Phong (606 kg/ha/year), Tu Son (489 kg/ha/year), Tien Du (414 kg/ha/year), and Bac Ninh City (413 kg/ha/year) exhibit the highest density of single-use plastics and non-biodegradable plastic bags. In certain urban wards and industrial-proximal communes, emissions exceed 1,000 kg/ha/year (Figure 4).

Several communes in adjacent districts also show exceptionally high densities, such as Yen Trung, Long Chau, and Van Mon, adjacent to Yen Phong I & II industrial zones (IZs); Hoan Son and Noi Due (near Tien Son and Dai Dong - Hoan Son IZs); and Phuong Lieu and Pho Moi (Que Vo I IZ area). These hotspots are characterized by limited land availability, concentrated worker housing, and economic activity servicing the industrial zones. In contrast, rural districts such as Luong Tai (227 kg/ha/year) and Gia Binh (312 kg/ha/year) display consistently low densities.

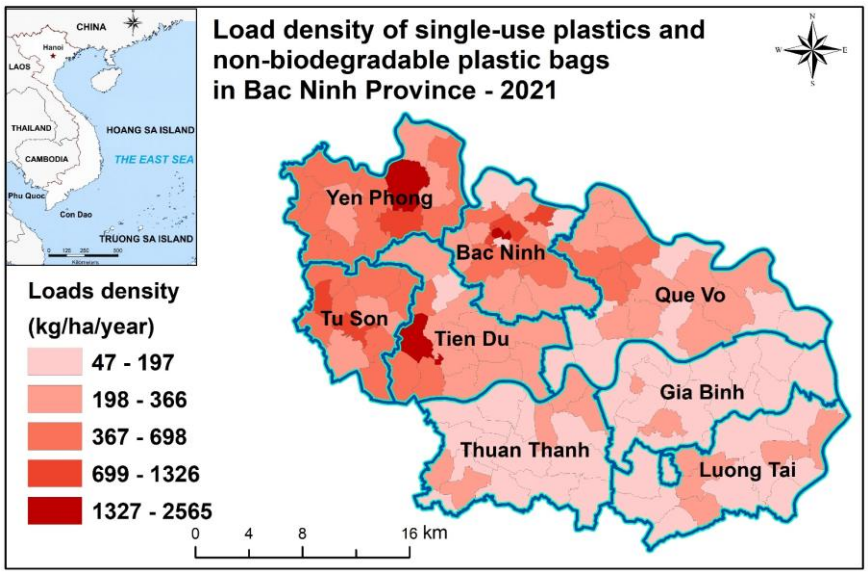


Figure 4. Density of single-use plastic waste per hectare.

The spatial analysis in Figure 4 reveals strong pressure from industrial-township areas, where hotspots show loads several times higher than surrounding communes. This highlights the need for waste management strategies to account for industrial population structures, particularly worker dormitories and logistics hubs. This pattern is supported by Table 1: Ninh Xa and Suoi Hoa Wards represent high-density urban hotspots; Yen Trung (35.67 persons/ha) and Hoan Son (39.02 persons/ha), dominated by IZ-related services, align with the major hotspots in Yen Phong and Tien Du. In contrast, agricultural communes like Phu Hoa and Nhan Thang consistently correspond to low-density areas.

These findings are consistent with observations in other provinces. Studies in Phu Yen and Ha Tinh using Waste Flow Diagrams reported high proportions of single-use plastics with clear urban–rural contrasts [5, 6]. Internationally, Jambeck et al. [1] identified single-use plastics as a major contributor to marine leakage, while the World Bank [3] highlighted plastic bags and flexible packaging as the most common waste streams in riverine and coastal systems. The results from Bac Ninh therefore demonstrate that single-use plastic pollution is not limited to coastal provinces but is also a critical issue in industrial inland regions.

An important finding is that approximately 58% of plastic waste in Bac Ninh consists of recyclable materials (bottles, cups, cartons, and part of the plastic bags). Optimizing sorting and collection systems could significantly increase recycling rates. Conversely, the extremely high consumption frequency of plastic bags makes them the most challenging stream to control, particularly around waste collection points and worker housing near industrial zones. This aligns with recent international evidence [1] indicating

that lightweight, thin, and frequently consumed products are the most prone to environmental leakage.

In summary, Bac Ninh generates a substantial amount of single-use plastic waste, with pronounced spatial and compositional differences. These findings underline the need for targeted, spatially differentiated plastic management strategies focusing on urban–industrial hotspots rather than uniform province-wide interventions.

3.3. Consumer Behavior and Public Awareness

Consumption of plastic products:

The survey of 3,200 households across 32 communes/wards shows persistently high use of plastic bags and single-use plastic products (Table 2). On average, each household uses 7.7 plastic bags per day, equivalent to more than 2,800 bags per year. Other frequently consumed items include plastic bottles (1.5 items/household/day), single-use cups (0.8 items/day), and straws (1.2 items/day). These constitute the main sources of lightweight plastics that are difficult to recover and highly prone to leakage.

Table 2. Annual consumption frequency of selected single-use plastic products in households

Product	Average (items/ household)	Mass (kg/ household)
Plastic bags	2,810	16.9
Plastic bottles/ containers	548	27.0
Single-use plastic cups	292	8.6
Plastic straws	438	1.2
Composite milk cartons	110	9.4

Awareness of environmental and health impacts:

Survey results indicate a relatively high level of public awareness regarding the health risks associated with plastic waste (Figure 5). Most respondents recognized that plastics may affect human health through drinking water (82%), food (79%), and air exposure (77%).

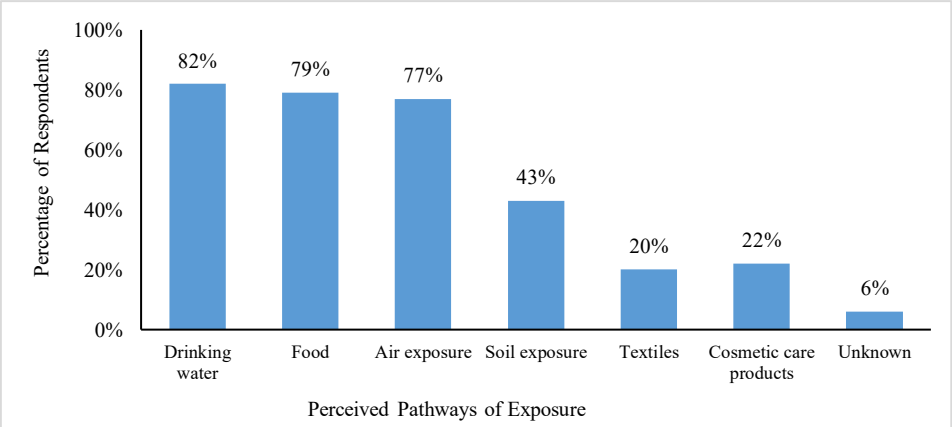


Figure 5. Survey responses on perceived pathways through which plastic waste affects human health.

These findings are consistent with the review by Caminiti et al., [14], which reports that most community surveys in Asia and Europe reveal high levels of concern regarding microplastic exposure through food and drinking water; however, understanding of less common exposure pathways remains limited. In line with this awareness–action gap, previous behavioral research has shown that risk perception alone is insufficient to trigger behavioral change when perceived behavioral control and enabling conditions are weak [15, 16].

In addition, foundational knowledge about plastic properties and life cycles is low. Only 9% of respondents correctly identified the primary raw materials used to produce plastics (natural

gas and petroleum), 21% were aware of Vietnam's position among the world's top five plastic polluters, and 18% correctly stated the degradation time of a plastic bottle (100–500 years) (Figure 6). These results align with Walker et al., [17], who note that global public awareness tends to emphasize "risk perception", whereas scientific understanding of plastic origins, characteristics, and life cycles remains relatively weak.

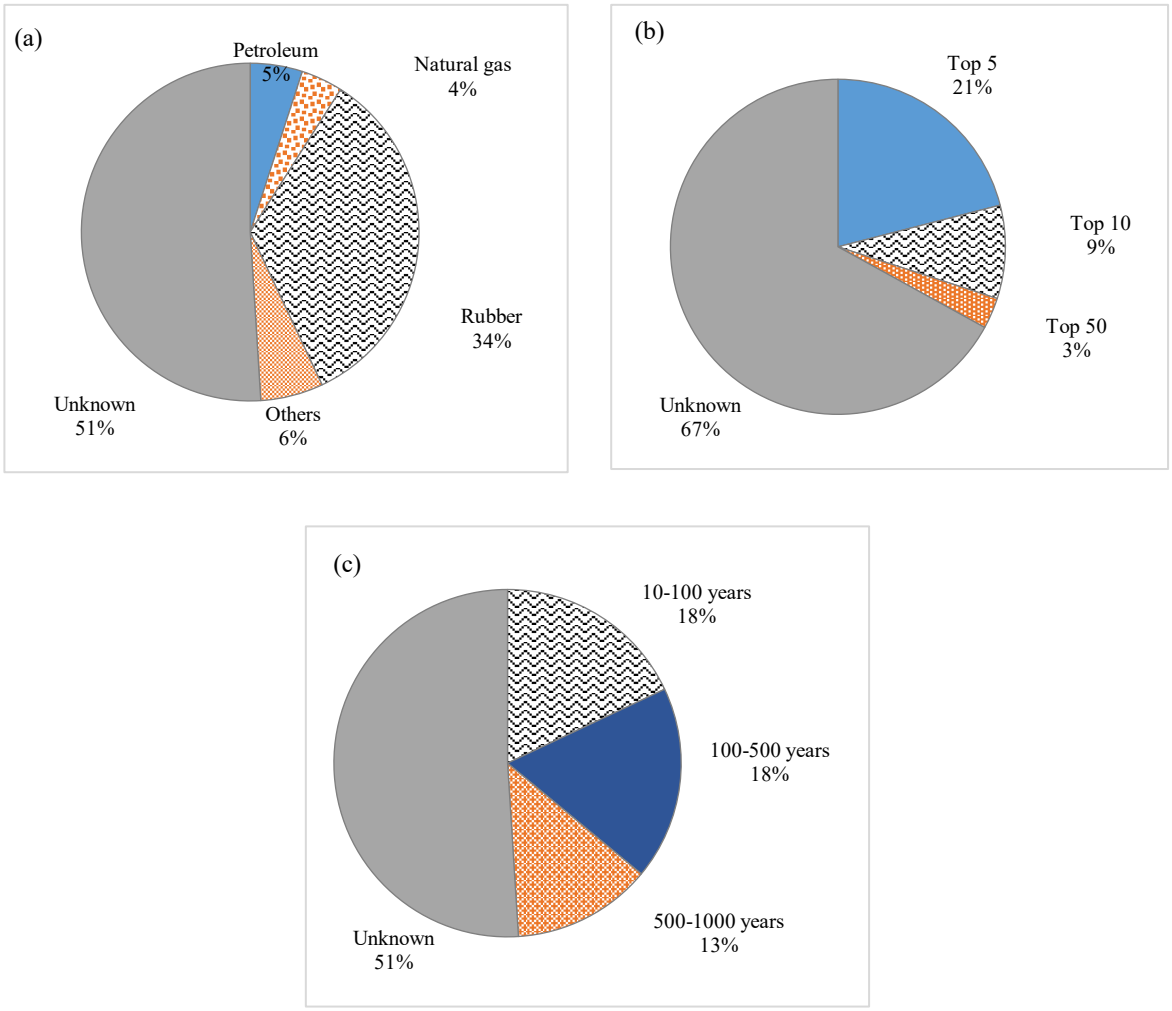


Figure 6. Basic public knowledge about plastic waste: (a) Raw materials used for plastic production; (b) Vietnam's plastic emissions relative to other countries; (c) Degradation time of plastic bottles.

Regarding awareness of regulatory frameworks, only 45% of respondents reported having heard of national or local regulations on waste segregation, reduction, or recycling, and merely 7% were able to identify a specific measure. This trend is consistent with findings by Baechler et al. [18], which indicate that in many countries, public understanding of environmental policies remains substantially lower than concern about health-related risks. Low policy awareness has been widely identified as a barrier to pro-environmental behavior, as regulations fail to act as effective behavioral signals when they are not salient to households [19].

Overall, the results reflect a pattern commonly observed in international studies: while the public expresses strong concern about the health impacts of plastics, foundational and system-level knowledge related to plastic life cycles, emissions, and management policies is limited [14, 17, 18]. These gaps are key contributors to the well-documented discrepancy between perception and actual behavior.

Perception–behavior gap:

Despite high levels of concern about health and environmental impacts, actual adoption of plastic-reduction practices remains low. Fewer than 20% of households regularly engage in measures such as waste segregation, recycling, carrying reusable bags, or refusing single-use plastics, and the uptake among vendors is even lower (Figure 7).

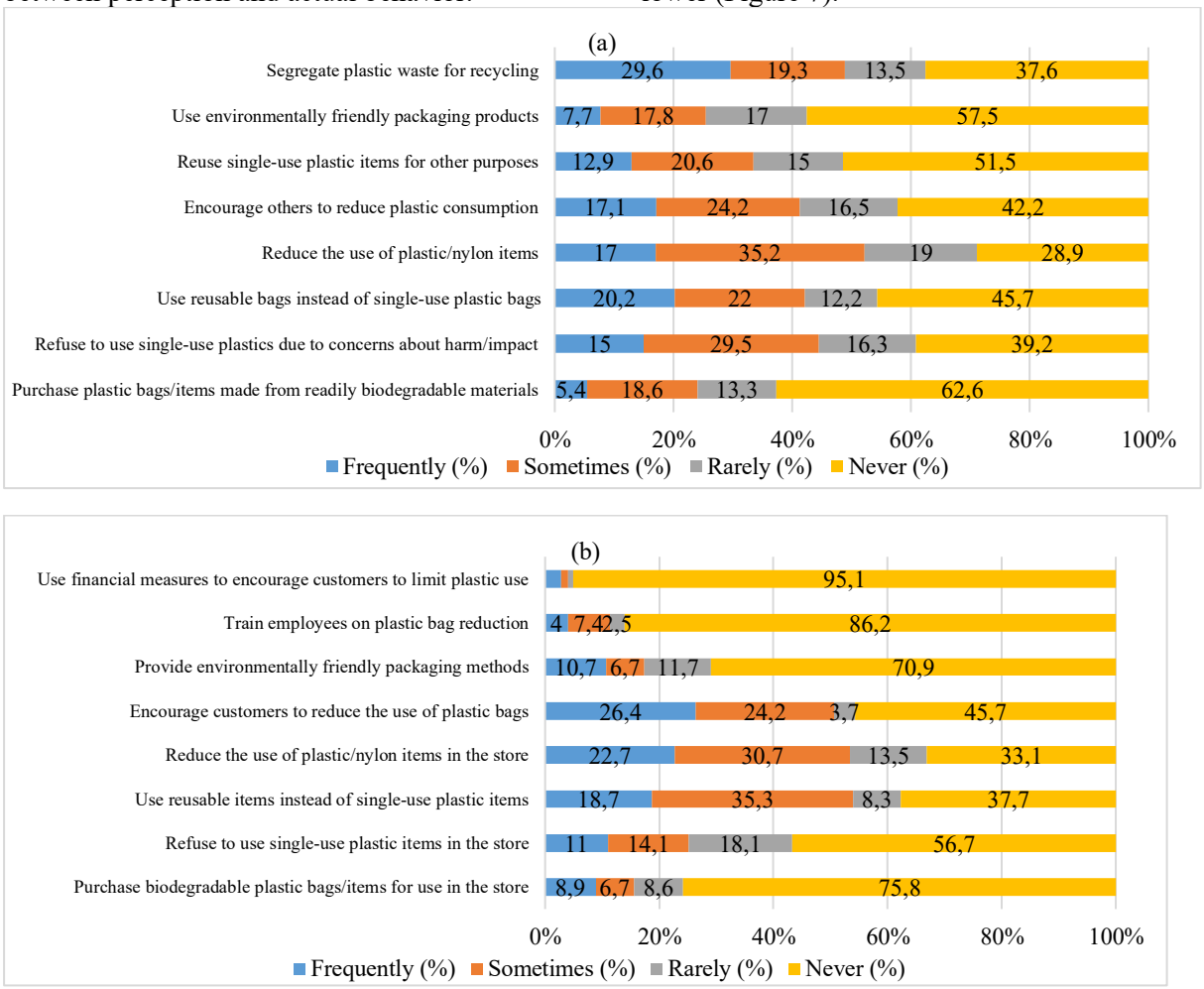


Figure 7. Frequency of plastic-reduction practices: (a) Consumers; (b) Vendors.

This perception–behavior gap aligns with trends reported in international studies. Walker et al., [17] showed that although people in many countries hold positive attitudes toward plastic reduction, actual behaviors are often constrained by convenience, habits, and the lack of accessible alternatives. Similarly, the systematic review by Caminiti et al., [14] found that communities typically "recognize risks but act little", particularly where enabling factors such as infrastructure, economic incentives, or policy frameworks are insufficient.

Baechler et al., [18] also noted that public understanding of environmental policies frequently lags behind concern about health risks, contributing to a perception that "individual actions have limited impact" which in turn reduces motivation to change behavior. These observations are consistent with the survey results in Bac Ninh, indicating that meaningful shifts in plastic-reduction behavior are unlikely without adequate support mechanisms and appropriate incentives.

3.4. Policy and Management Implications

The results indicate that Bac Ninh faces substantial pressure from single-use plastics and non-biodegradable plastic bags, particularly in urban–industrial areas such as Bac Ninh City, Tu Son, Yen Phong, and Tien Du. These districts exhibit the highest loads and densities and also show low adoption of reduction practices (Figure 7), whereas rural districts such as Luong Tai and Gia Binh generate considerably lower amounts. This spatial heterogeneity suggests that plastic management policies should adopt a differentiated, hotspot-focused approach rather than uniform province-wide measures, consistent with international recommendations emphasizing areas with high leakage risk [3].

The composition of household plastic waste further informs policy design. Plastic bottles account for nearly 40% of total mass and have high recycling value, whereas plastic bags are consumed most frequently and present the greatest leakage risk. International experience shows that plastic bag levies or taxes have reduced consumption by over 90% in Ireland and by similar magnitudes in Tokyo and several European cities [20, 21]. However, outright bans may generate unintended effects where affordable alternatives and enforcement capacity are limited [22]. Given Bac Ninh's reliance on low-cost daily transactions in traditional markets and worker canteens, moderate levies calibrated to local purchasing power are likely more appropriate than uniform bans.

For recyclable plastics such as PET bottles, Deposit–Return Schemes (DRS) have increased recovery rates to 70–90% in Europe and North America [22, 23]. Bac Ninh's concentration of supermarkets and industrial parks provides favorable conditions for piloting a DRS with relatively low logistical costs. Extended Producer Responsibility (EPR), mandated under Decree 08/2022/ND-CP, can further mobilize financial contributions from packaging producers located in industrial zones to support local collection and recycling systems, as demonstrated in Korea and Japan [24].

A persistent challenge is the perception–behavior gap identified in Section 3.3. Although more than 70% of households recognize plastic-related risks, only >20% regularly adopt reduction practices, with even lower uptake among vendors. Similar patterns have been reported in major Vietnamese cities, where limited economic incentives and affordable alternatives constrain behavior change [25]. International evidence also shows that information alone has limited impact unless combined with economic and regulatory nudges [24]. Within this broader context, in Bac Ninh, such nudges could be embedded at the market level through requirements and targeted subsidies rather than relying solely on voluntary household actions.

Ultimately, effective implementation requires an integrated management framework involving provincial authorities, producers, distributors, and communities. Upgrading sorting and recycling infrastructure and strengthening monitoring mechanisms are essential to prevent leakage and non-compliance. With these conditions in place, Bac Ninh can reduce local plastic pollution and contribute to Vietnam's national target of reducing marine plastic waste by 75% by 2030.

4. Conclusion

This study assessed the generation, composition, and spatial distribution of plastic waste in Bac Ninh Province, revealing a relatively high per-capita level (17.14 kg/person/year) with pronounced variation

across administrative units, particularly in urban–industrial areas. Household plastic waste is dominated by bottles and plastic bags, reflecting both significant recycling potential and substantial leakage risk. Community surveys highlight a considerable perception–behavior gap: although awareness of environmental and health impacts is high, only 15–30% of households (and even fewer vendors) regularly adopt plastic-reduction practices, indicating that communication alone is insufficient.

These findings underscore the need for spatially and compositionally differentiated plastic management strategies that prioritize high-pressure hotspots and account for specific waste types. Effective policy responses should combine economic instruments, such as plastic bag levies, Deposit–Return Schemes (DRS), and strengthened EPR, with targeted communication efforts and expanded access to affordable alternatives to reduce single-use plastics and enhance material recovery.

This study has several limitations. The analysis is based on data collected at a single time point and focuses mainly on household and small commercial waste sources. The GIS component is intended for spatial visualization rather than causal or geostatistical modelling and does not control for confounding socio-economic or land-use factors. In addition, the awareness–attitude–behavior assessment relies on descriptive statistics without advanced behavioral or multivariate analysis. Future research should incorporate updated datasets, extend coverage to industrial and commercial waste streams, and apply more advanced analytical and spatial modelling approaches to support provincial plastic management planning.

Acknowledgments

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