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Article

Rapid Characterization of Macroplastic Input and Leakage in the Ganges River Basin

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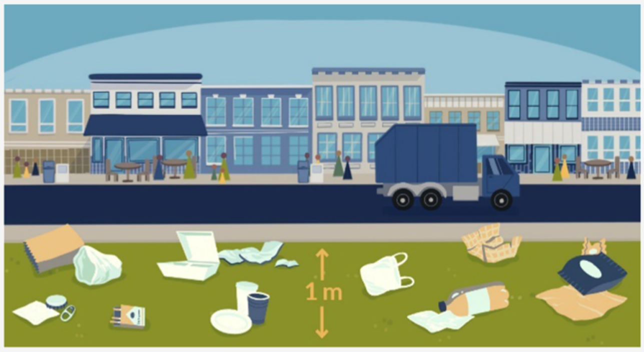

ABSTRACT: Efforts to understand macroplastic pollution have primarily focused on coastal and marine environments to the exclusion of freshwater, terrestrial, and urban ecosystems. To better understand macroplastics in the environment and their sources, a dual approach examining plastic input and leakage can be used. In this study, litter aggregation pathways at 40 survey sites with varying ambient population counts in the Ganges River Basin were surveyed in pre- and postmonsoon seasons. We examine active litter leakage using transect surveys of on-the-ground items, in conjunction with assessments of single-use plastic consumer products at the point of sale. We find that sites with low populations have a significantly higher number of littered items per 1,000 people than those with mid to high populations. Over 75% of litter items were plastics or multimaterial items containing plastic, and tobacco products and plastic food wrappers were the most recorded items. There was no significant variation of litter densities pre- and postmonsoon. Most single-use plastic consumer products were manufactured in-country, but approximately 40% of brands were owned by international companies. Stratified sampling of active litter input and consumer products provides a rapid, replicable snapshot of plastic use and leakage.

KEYWORDS: *plastic pollution, urban litter, circular economy, single-use plastic, informal recycling, Ganges River, India, Bangladesh, macroplastic*

INTRODUCTION

As plastic pollution has become an increasing concern on the global stage, remote accumulation sites (like Midway Atoll, Henderson Island, and the ocean gyres) have captured both public attention and scientific interest.[1−3] It has been estimated that a significant fraction of marine plastic originates from cities and communities on land. Data on abundance, distribution, and composition has primarily been collected in coastal and marine environments although some recent work has included freshwater and terrestrial ecosystems.[4,5] One data gap, therefore, is empirical data from many perceived land-based sources of litter from human activity like cities. Interestingly, a recent citizen science study of macroplastics in Denmark found higher litter densities in areas of human use like roadside ditches, parks, and rural roadsides, as compared to environmental reservoirs like streams, lakes, forests, beaches, and dunes, indicating that studies of plastic pollution focused solely on such reservoirs might not represent a worst-case scenario for litter.[6] As plastic is a manmade material, a logical connection exists between human activity and plastic in the environment, and many ocean and riverine models of plastic inputs have historically been driven by population.[7−11] However, more people living in an area do not necessarily implicate more litter on the ground in a local context.[12] There are other potential influencing factors such as availability of products and packaging, waste management capacity and design, governance and regulations, and cultural contexts.

Capturing a more comprehensive understanding of sources, fluxes, and fates which make up the "plastic cycle"[5] before loss to environmental reservoirs requires sampling of litter closer to the source, i.e., human activity. In colloquial use, the term "litter" often connotes a purposeful discarding of items into the environment. Here, we use litter (more accurately, anthropogenic litter) to refer to nonpoint source leakage of waste specifically tied to the processes of human society, whether intentional or unintentional.[13] Understanding the composition,

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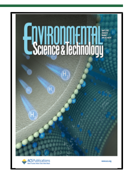

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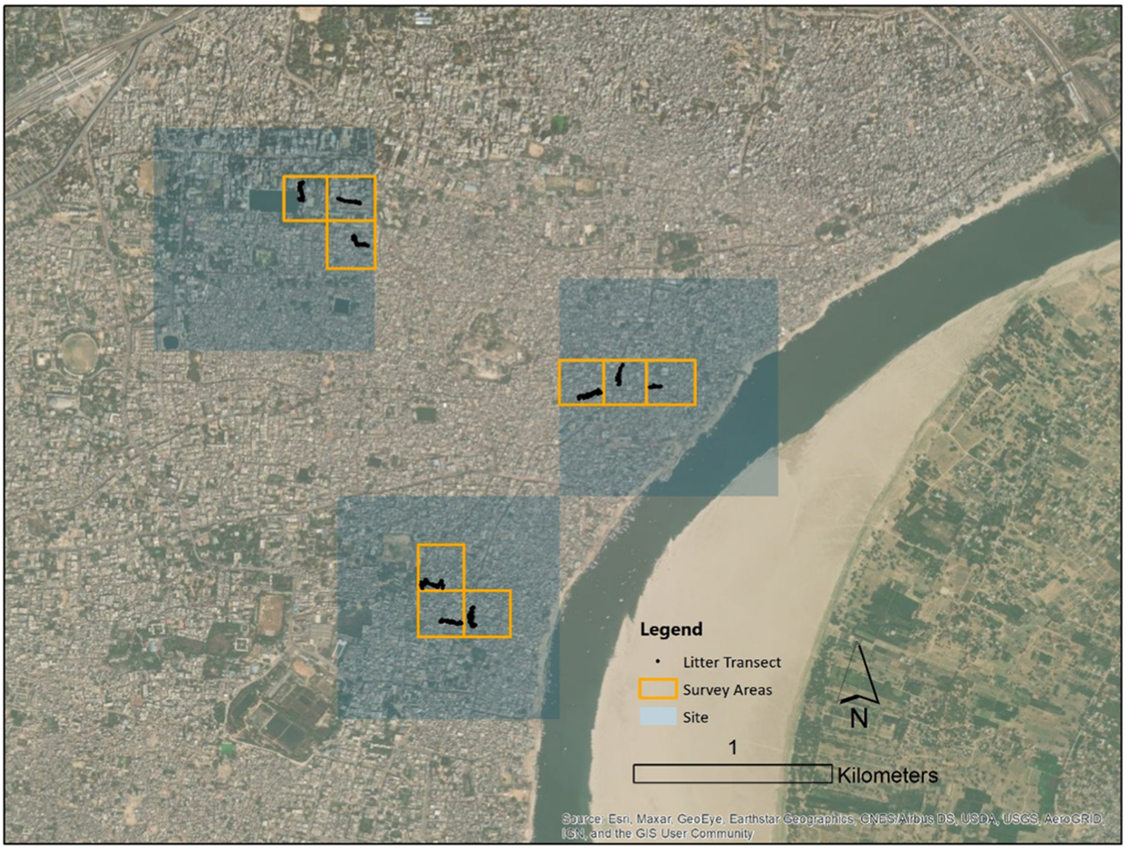

Figure 1. Example of a sampling strategy for a city (Varanasi) along the Ganges River. Three square kilometers (sites) in the top fifth of population counts were isolated and gridded with 200 m × 200 m survey areas; three clustered survey areas were selected; 100 m × 1 m litter transects were conducted within each area (black points indicate litter items). Data Sources: LandScan 2019,[21] Marine Debris Tracker, and ArcGIS World Imagery Basemap.

abundance, and distribution of litter can be instrumental in informing upstream and tailored community solutions rooted in the local context although methods have been inconsistent for data collection that can be conducted by both trained researchers and/or citizen scientists.[14−16] A more recent work has focused on randomized transect methods that, along with incorporation of geospatial data, can be comparable across study locations and potentially combined for extrapolation purposes or to inform current and future models of plastic inputs into the environment and aquatic systems.[12] The need for replicable baseline data on plastic input and leakage is especially important in the context of rapidly developing economies. In this context, policy and waste management strategies for reducing land-based inputs of marine debris are rapidly evolving as waste characteristics change and generation rates increase with economic growth.[17]

Since what does, or does not, end up as litter is inherently related to the products and packaging we use, litter is closely tied to consumption, as demonstrated by unprecedented observations of littered personal protective equipment since the onset of the COVID-19 pandemic.[18] Some organizations have conducted brand audits of litter as a citizen science tool to increase producer accountability (often following protocols outlined in Break Free from Plastic's Brand Audit Toolkit). Multinational companies often sell products through distributors, leading to a potential disconnect from product design within the local context and from responsibility for waste management. While brand audits have been a successful tool in engaging stakeholders with the issue, exploration of producers tied to litter has been limited in the scientific literature, potentially because of confounding factors in conducting brand litter audits like variability in recognizable brands and package durability. Surveying single-use plastic consumer products at the point of sale and in conjunction with litter surveys in the same geographical area can facilitate a comparison of products that are sold with items that are littered, providing a more holistic picture of community circular material management through not only examining what ends up in the environment but also what does not.

Here, we present results of conducting litter and product surveys in communities with a stratified sampling design compared to the ambient population, which was piloted as part of National Geographic Sea to Source Ganges Expedition (hereafter, the Sea to Source Expedition). Sampling was conducted in Bangladesh and India within the Ganges River basin, which is known as the Ganga in India and Padma and Meghna in Bangladesh, hereafter referred to as the Ganges. This study focuses on the plastic cycle at the point closest to the source to examine (1) the input of consumer plastic products at the point of sale and (2) active litter leakage (litter that is not yet in environmental reservoirs) in cities and communities.

METHODS

In 2019, the Sea to Source Expedition team traveled along the Ganges from the Bay of Bengal to the Himalayas in the premonsoon season (May–June) and in the postmonsoon

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season (November–December). Pre- and postmonsoon surveying periods were selected based on a hypothesis that litter would be seasonally influenced by the heavy monsoon rains in India and Bangladesh during June–September. Eleven cities and seven villages were selected for sampling along the river; they spanned a wide variety of population sizes and community characteristics from rural fishing villages to urban and industrial centers. The sampling design presented here is derived from the Circularity Assessment Protocol (CAP), a diagnostic tool developed by the Jambeck Research Group at the University of Georgia New Materials Institute to characterize what the circular economy looks like within a geographically delineated community.[19] Incorporating material flow models and complex systems thinking, the CAP is a holistic assessment of plastic use in a community, disposal to waste management systems, and leakage to the environment, along with various factors affecting these metrics. In this study, we focus on the two bookends of the CAP, input and leakage.

Survey Site Selection. In each city, a stratified random sampling method was applied to select transect locations in a 5 km × 5 km area, which was delineated in the city area directly adjacent to the Ganges River, using ArcMap 10.7. To capture relevant human activity within each study area, rasterized population data for the sites was sourced from the Oak Ridge National Laboratory's 2017 LandScan[20] dataset (https://landscan.ornl.gov/), which provides the ambient population per raster cell at approximately 1 km spatial resolution. The top fifth of cells with the highest ambient population were isolated. Of these, three 1 km^2 survey sites were then randomly selected; each selected survey site was overlaid with a 200 m × 200 m grid, and three 200 m × 200 m locations were randomly selected as a cluster using the National Oceanographic and Atmospheric Administration (NOAA) Sampling Design Tool to conduct 100 m × 1 m litter transect paths in situ, as shown in Figure 1. Transect paths were selected upon arrival at the 200 m × 200 m site in a visually evident litter aggregation pathway (along a walkway or an open gutter along the side of the road) based on access and safety considerations. Data was also collected in seven villages near the cities. Due to the small area of the villages (most less than 1 km^2), site selection based on LandScan data was not possible; instead, local guides assisted in identifying various land use areas for surveying. All site names and types are listed in Table S2.

Data Collection in the Field. In total, transect surveys of litter (n = 99 city transects at 33 sites) were collected in 11 cities. During the premonsoon expedition (May–June), nine litter transects (three transects in each of three 1 km^2 population-based survey sites for a total of nine transects for each city) were surveyed in 10 cities. In the 10th city in the Himalayas, resurveying during postmonsoon was not possible due to winter weather conditions. An additional city in the region was selected and surveyed with nine transects at three sites in December using the same methods. Additionally, during the postmonsoon expedition (November–December), three of the nine original transects at nine cities were resurveyed for comparison, where logistical constraints allowed (n = 26 replicated transects; in three cities, a full site was resurveyed, and in the remaining cases, one transect per site was resampled). In the postmonsoon expedition, litter transect surveys were additionally completed at seven villages near the cities previously sampled. In each village, three transects were conducted, one at a relatively commercial site (the main market center, which typically comprised three to five small grocery shops and/or a school) and two at more residential sites (n = 21 village transects at 7 sites). In the field, transect locations in each village area were chosen similarly to in the cities.

The transect length of 100 m was measured using a distance wheel, and the transect width of 1 m was measured once and then visually estimated by trained researchers. Transects followed along the side of a road or pathway and, while continuous, were not necessarily linear. Litter item type and Global Positioning System (GPS) coordinates of all visible litter items (observed by looking down at the ground) within the transect were recorded using the National Geographic Sea to Source list on the Marine Debris Tracker mobile application (https://debristracker.org/). The list of items used to tag litter was developed during a scoping trip to India in April 2019 (Table S1). It was adapted from the NOAA Marine Debris Shoreline Survey to reflect the local land-based litter characteristics (i.e., common regional product types) in collaboration with Indian and Bangladeshi team members (Table S1). For uncommon litter items not included in the list, researchers tagged the item as "other" and typed a description of the item.

All team members collecting litter data received individual training from the lead author in the field on litter characterization. The tracking team included researchers based in the United States of America (US), India, and Bangladesh; the in-field input from local partners was critical to identifying unfamiliar items to ensure accuracy of the litter data. To reflect upstream sources of plastic pollution, the team members recorded fragmented items as their associated item of origin if visually identifiable by the trained surveyors, for example, a fragment of a chip or crisp bag was recorded as a plastic food wrapper.

In both the city and village sites, in-store visual assessments of the most common brands for sale were conducted across the following categories: tobacco (e.g., cigarettes or chewing tobaccos like gutka), beverages (e.g., soda or juices), snack foods (e.g., chips/crisps, candy, and cookies/biscuits), and personal care products (e.g., shampoo sachets or hair oil packets). These product categories were intended to represent consumer products often packaged in single-use plastics that are commonly littered and were selected with Indian and Bangladeshi partners during the earlier scoping visit. Stores were assessed within each selected 200 m × 200 m site, where possible, though the prevalence of stores varied depending on the land use and site type. Most shops offered only a small number of brands for sale, and common brands were visually identified with local partners and recorded to obtain manufacturer and parent company information. In addition, researchers purchased samples of common brands in each category to reference the packaging information, categorize the material type, and weigh the plastic packaging generated for each product.

Analysis Methods. For each survey site, an average litter density was calculated by averaging the litter densities in the three 100 m × 1 m transects. To explore other influencing factors, litter densities for each square kilometer were normalized by 2019 LandScan[21] ambient population data. One-way ANOVA presented throughout this work was conducted using Excel. Statistical significance was set at a probability level (α) of 0.05.

For consumer plastic products surveyed at the point of sale, manufacturing and parent company information was obtained

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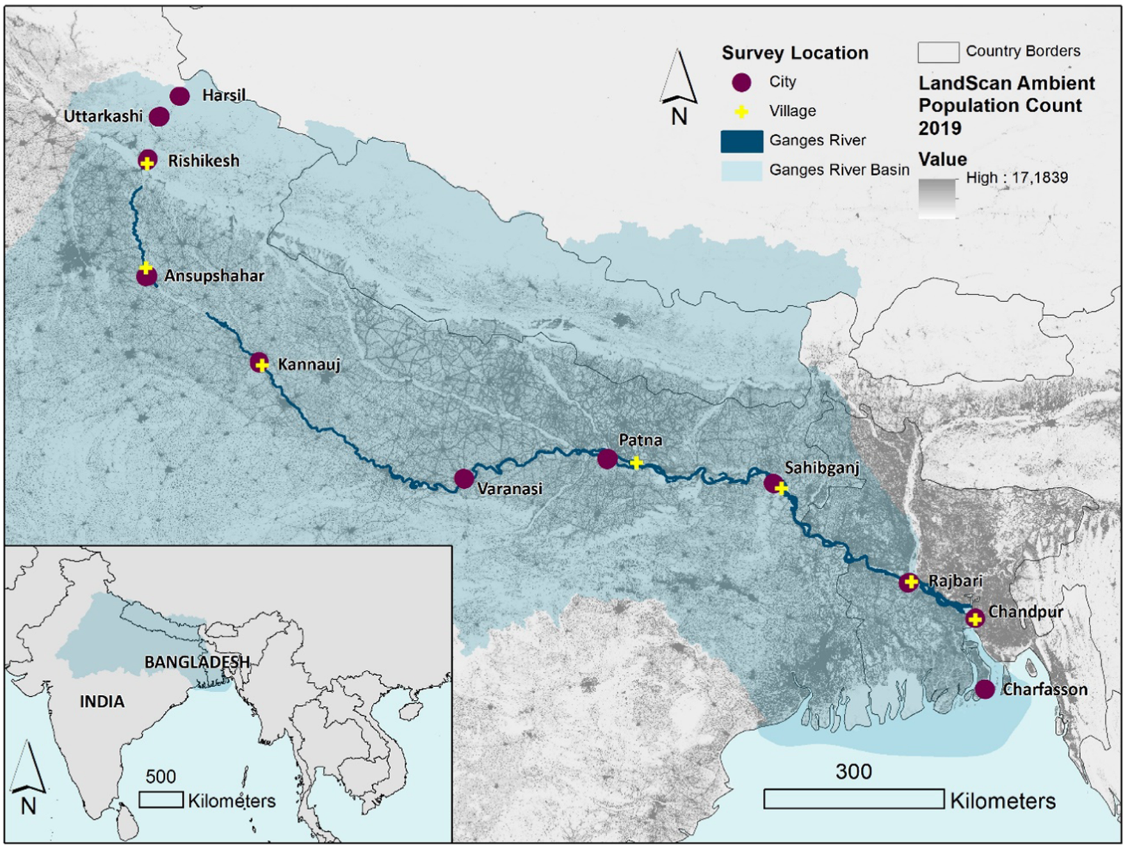

Figure 2. Sampling sites including city names along the Ganges River. Data Sources: LandScan 2019[21] and Digital Atlas of Earth 2019.

through a combination of information available on the packaging and desktop research. Samples of packaging were weighed to the nearest 0.1 g when clean and dry. Product weights were determined based on the manufacturer's information listed on the packaging. To approximate distances between the point of sale and manufacturers and parent companies, distances were calculated taken based on geodesic lines from the center of each site to the center of the city, where the company is headquartered or where the manufacturing facility is located, projected using an azimuthal equidistant projection.

Maps throughout this research article were created using ArcGIS software by Esri. ArcGIS and ArcMap are the intellectual properties of Esri and are used herein under license. Maps contain information from OpenStreetMap and OpenStreetMap Foundation, which is made available under the Open Database License.

RESULTS AND DISCUSSION

In total, 40 survey sites, each 1 km^2 in area, with varying ambient population counts were assessed along the Ganges River, with 33 sites surveyed in 11 cities and 7 sites surveyed in seven villages (city and village names are contained in Table S2). Sampling sites spanned the length of the river, as shown in Figure 2. In addition, 26 transects across nine cities were resurveyed in the postmonsoon period for seasonal comparison. Briefly, 70,696 litter items were logged in cities and villages, and 18,995 litter items were logged in replicated transects for a total of 89,691 litter items recorded during the Sea to Source Expedition.

Transect Litter Density. Average litter densities for each 1 km^2 survey site (three transects in each) ranged from 2.4 to 14.7 items/m^2, with a mean value of 5.9 items/m^2 (SD $\pm$ 2.6) (histogram of all transect densities is shown in Figure S1). While there was variability within the transects of each sampling area as is typical of environmental sampling, only five of the 40 surveyed sites had standard deviations greater than the mean litter density for that site (transect litter density data provided in Table S2; scatterplot of the litter density and ambient population is shown in Figure S2). When examining the litter density relative to ambient population in the Ganges River basin, sites fell into three groupings, below 2,000 people (group A, $n = 14$), between 2,000 and 10,000 people (group B, $n = 16$), and above 10,000 people (group C, $n = 10$) (Figure 3).

Sites with an ambient population above 10,000 people tended to be dense urban areas (average per capita litter density = 0.19 items/m^2 per 1,000 people, Table S3). Sites with an ambient population between 2,000 and 10,000 people were still primarily urban but less dense areas (average per capita litter density = 1.59 items/m^2 per 1,000 people). Sites with an ambient population under 2,000 people were typically small villages or the outskirts of less dense urban areas (average per capita litter density = 6.43 items/m^2 per 1,000 people). Per capita litter densities were significantly different at the p 0.5 level across the three site groupings [ANOVA, F (2, 37) = 21.52, p = <0.001].

Population density is a common input into models of mismanaged waste, where mismanaged waste is a percentage of waste generation made up of inadequately managed waste and litter;[7,10,11] however, empirical data has been lacking to be able

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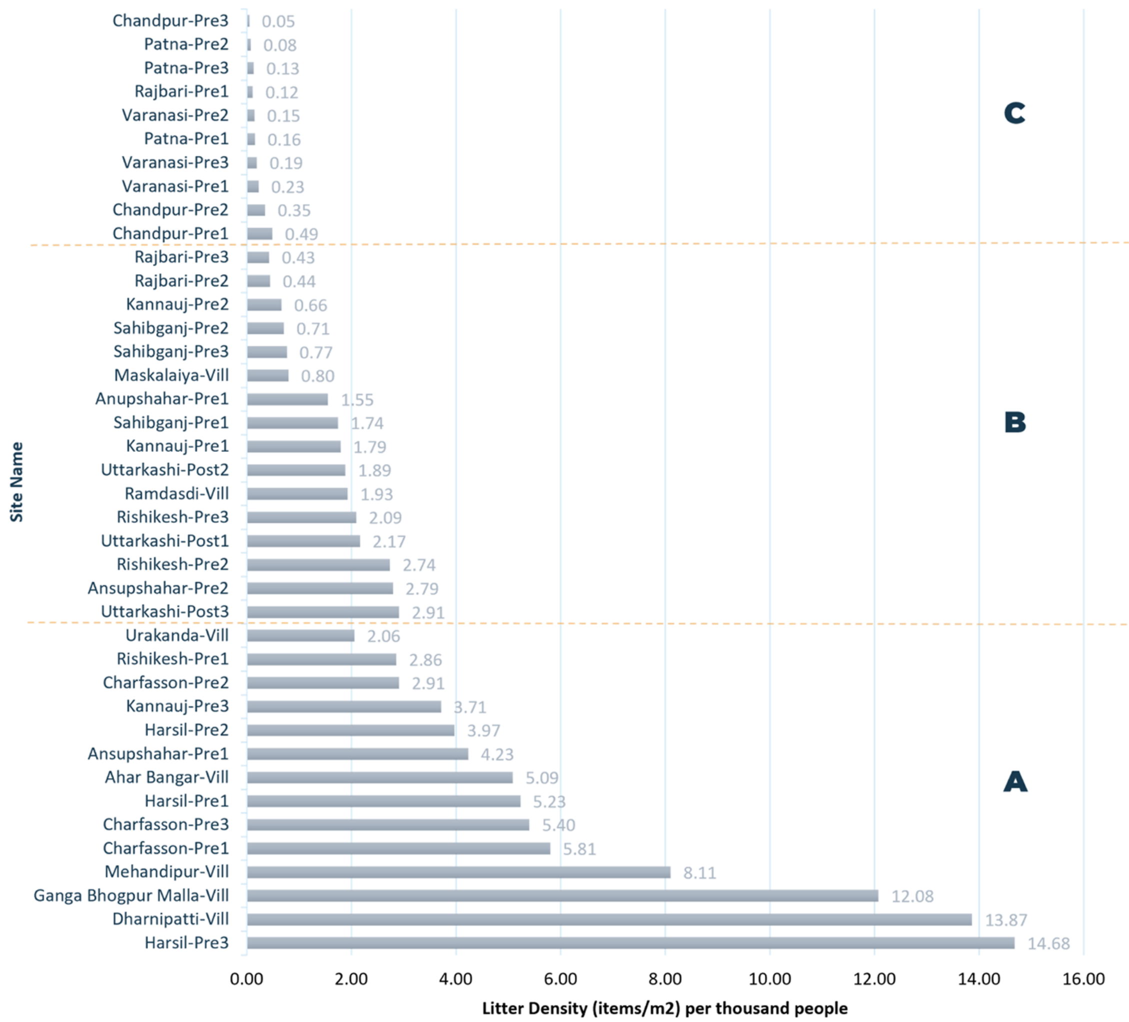

Figure 3. Litter densities in 40 survey sites normalized by LandScan 2019[21] ambient population. Site names indicate the city name, followed by "-Pre" (premonsoon) or "-Post" (postmonsoon) and the site number. Villages are indicated by "-Vill"; only one site was sampled in each village and all villages were surveyed postmonsoon. Dashed lines represent approximate natural breaks observed in the dataset that corresponds to three groupings (A) (below 2,000 people), (B) (between 2,000 and 10,000 people), and (C) (above 10,000 people). Sites are sorted with a higher ambient population at the bottom.

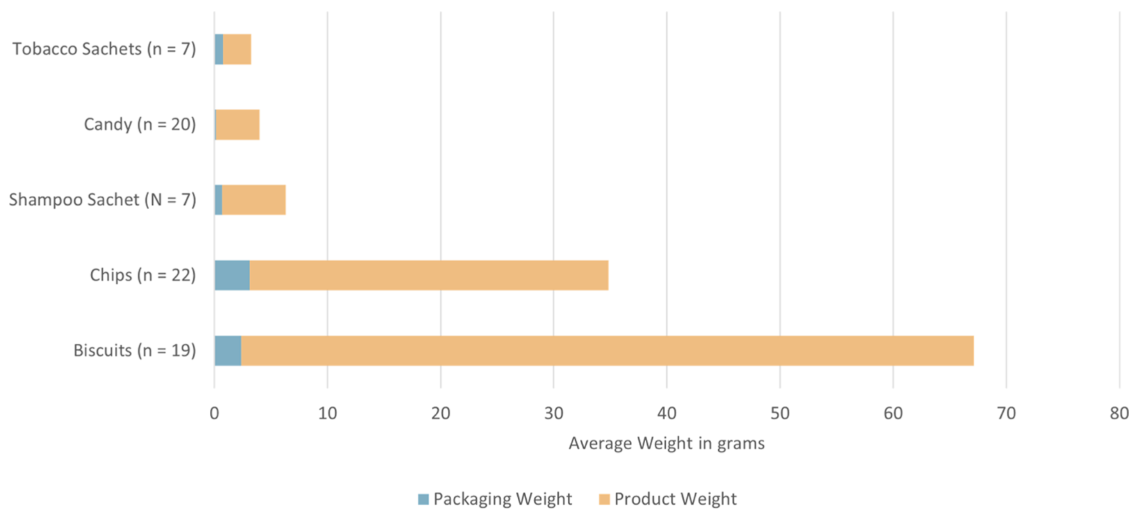

Figure 4. Average plastic packaging weights and product weights for common consumer products.

to validate models.[12] While there is a significant difference between the litter density observed in the three ambient population groupings, it is likely that discrepancy in access to waste management is a driving factor, which was also suggested

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Table 1. Summary of Approximate Geodesic Distances From Stores to Parent Companies and Manufacturers by Product Type

	distance: store to parent company (km)			distance: store to manufacturer (km)		
	minimum	maximum	average	minimum	maximum	average
beverages (n = 183)	0	20,681	9,962	0	1,774	588
personal care products (n = 242)	24	20,094	8,386	15	2,211	672
snacks (n = 444)	28	28,346	3,322	6	1,996	508
tobacco (n = 124)	93	17,058	3,613	78	1,715	439

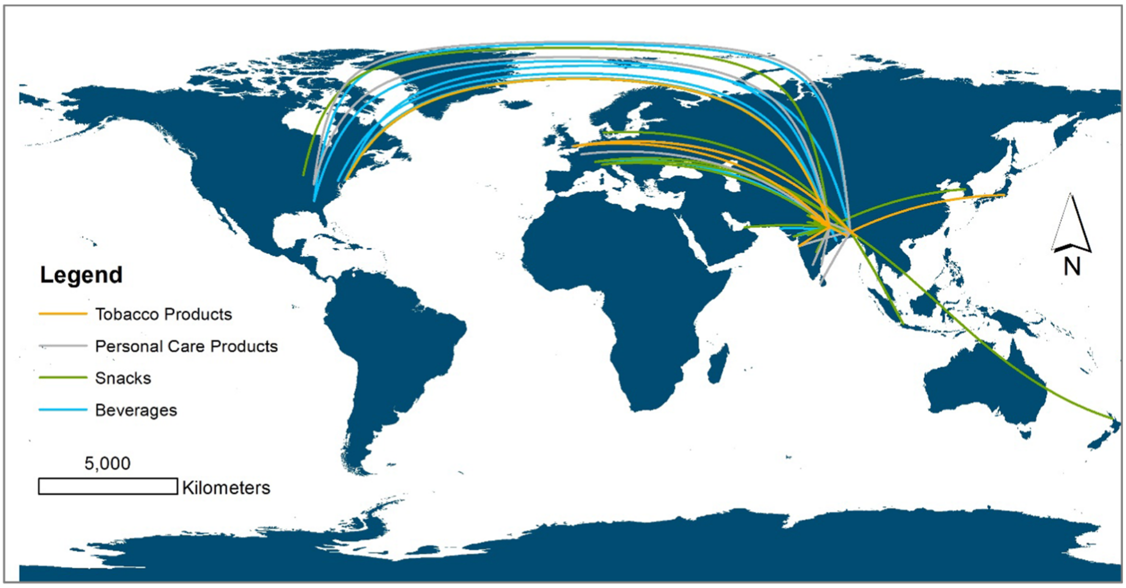

Figure 5. Headquarter locations of parent companies for consumer products in relation to central sites in India and Bangladesh visualized by product type.

to be an influencing factor in Schuyler et al., 2021. Sites in the low population group across the region tended to have little to no access to formal waste management services based on field observations and local knowledge held by the researchers involved in this study, while sites in high population areas did have some systems of management in place. Mid-population sites varied in this regard, and several had recently established waste management systems that may contribute to decreased leakage of waste in those areas. Waste management infrastructure, whether formal or informal, often relies on population concentration—and the resulting waste concentration—to achieve economic viability, so the disparity in access to such systems in low- and mid-population sites could, in part, explain higher per capita litter densities surveyed there.

Litter surveys were conducted pre- and postmonsoon; litter densities between these sampling events were similar despite heavy monsoon rains in the interim (Table S4). There was no significant difference at the $p < 0.5$ level between litter densities for transects surveyed in the pre- and postmonsoon periods [ANOVA, F (1, 50) = 0.22, p = 0.64]. The lack of significant difference between pre- and postmonsoon litter densities along the same transects suggests that there is a turnover of litter items surveyed in the litter aggregation pathways, in this case, likely due to reaccumulation after the monsoon rains in the region. Postmonsoon surveying occurred approximately one month prior to the end of the monsoon season in most sites. Similar litter densities also suggest that the sampling design succeeds in capturing active litter inputs from human consumption and disposal practices, rather than eventual environmental reservoirs.

Packaging Origin. Seventy-five product samples of common consumer products using the plastic film and multimaterial film packaging were obtained during store surveys. These included shampoo sachets (n = 7), tobacco sachets (n = 7), candies (n = 20), chips (n = 22), and biscuits (n = 19). Of the products sampled, tobacco sachets (0.30 g plastic packaging/g product) and shampoo sachets (0.12 g plastic packaging/g product) had the highest packaging to product ratio (Figure 4). These products are therefore producing the most plastic packaging waste per unit of product delivery. Packaging efficiencies remain a complex issue. Buying larger quantities of products, when possible, or designing minimal packaging for desired quantities of products makes the product delivery more efficient in terms of waste generation. In addition, packaging with more weight is typically more valuable to recyclers than lightweight packaging (more recyclable material per item), but heavier plastics can have a higher carbon footprint during transport.

For the origin of products surveyed in stores, the mean distance to the parent companies is over 6,000 km, while the average distance to the manufacturers is about 500 km (Table 1). Many of the brands of consumer plastics surveyed were owned by companies with headquarters located both regionally and internationally (Figure 5). Of the 993 brands recorded, most products are manufactured in-country (99.7% in both Bangladesh and India), but a substantial portion of brands is owned by international companies (46.1% in Bangladesh and 40.8% in India). In both countries, the United States and the United Kingdom were the most represented parent company

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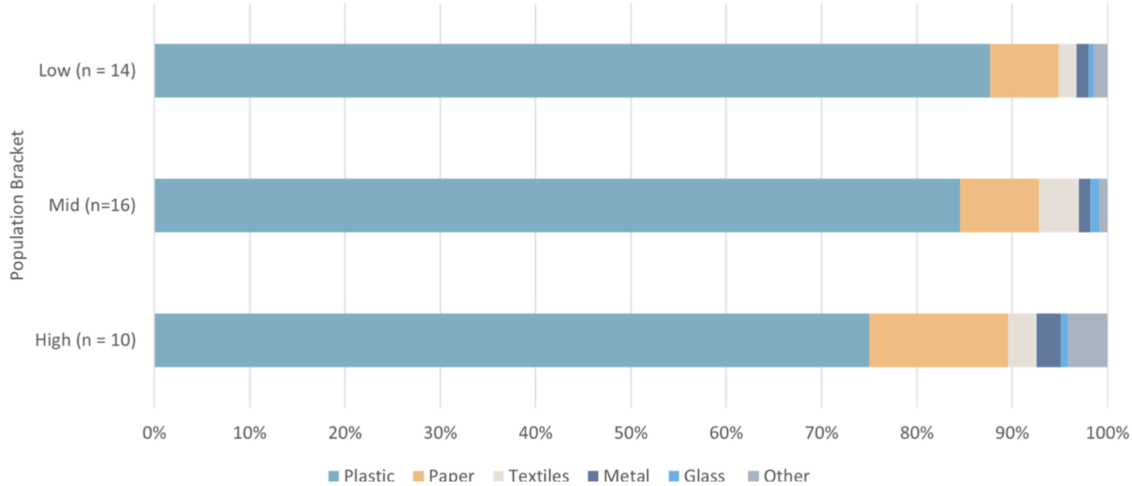

Figure 6. Litter characterization by material type.

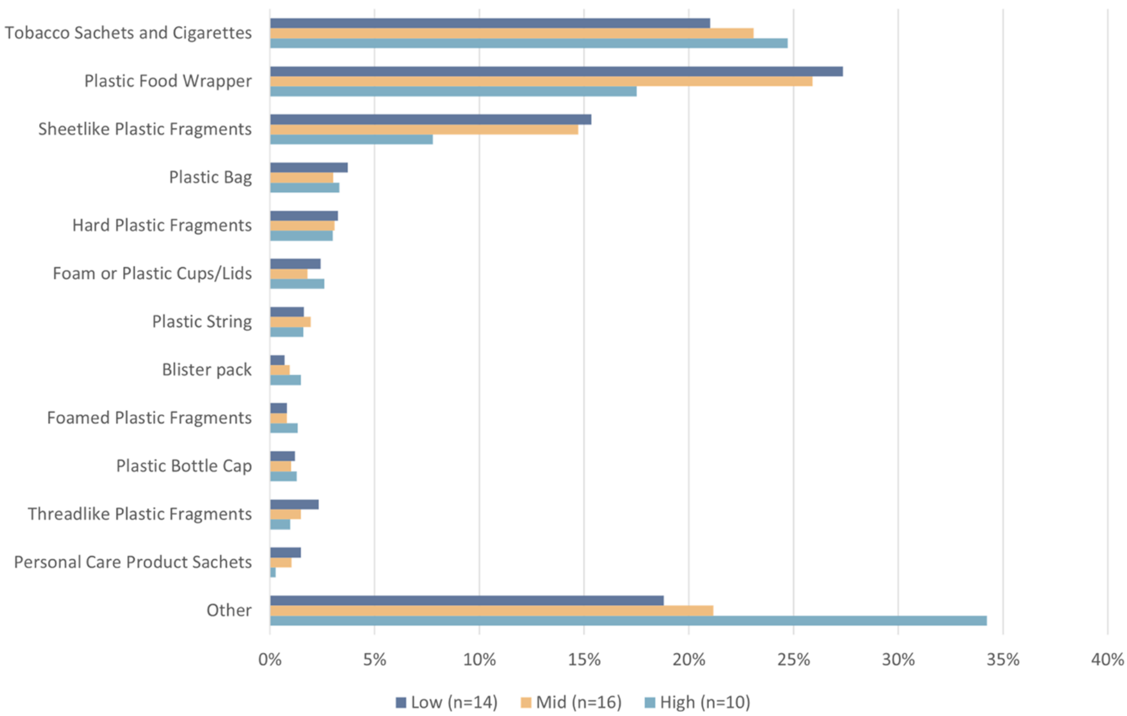

Figure 7. Proportion of the most common plastic items in low, mid, and high population groups.

locations, with 17.9 and 19.3% of the company headquarters for all brands surveyed (Table S7).

The prevalence of international parent company ownership, with company headquarters often located in high-income countries like the US and the UK, means that brand decisions are both physically and conceptually distant from the resulting waste management challenges, especially, since these brands often sell through distributor channels and may not have data on the fate of their products. The shorter "plastic mile" distance from the site to the manufacturer suggests that there may be opportunities for policy intervention at the manufacturing level on a local or regional scale. Sachets could be a target of such interventions—with high packaging to product ratios, they are an inefficient mechanism for delivering the product to a community in terms of plastic waste generation.

Product and Litter Characterization. Common types of consumer plastic products were surveyed at 79 stores across four major categories: beverages (n = 183), personal care products (n = 242), snacks (n = 444), and tobacco products (n = 124). Most products surveyed were packaged in multilayer films (57%), which was also the packaging of many top items in the litter. Other common product packaging types included aseptic cartons (18%), coated paper or paperboard (12%), PET (12%), and other plastics like HDPE (1%) (Figure S3).

Across all sites, most litter items recorded were plastic. Plastic made up a higher proportion of the total litter items logged in low-population sites (87.7%) when compared to mid- and high-population sites (84.5 and 75.0%, respectively), as shown in Figure 6.

Of the plastic proportion recorded, tobacco products (typically, tobacco sachets made of film plastic in India and cigarette butts in Bangladesh), food wrappers, and plastic

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fragments were similarly documented across all sites (Figure 7). Film and multimaterial items were predominant in-stores and in the litter (tobacco sachets, plastic food wrappers, sheet-like (flexible, such as film) plastic fragments, plastic bags, blister packs, personal care product sachets), and this material type holds little to no value for recycling.

The higher proportion of plastics in the litter recorded in low population areas is potentially related to economic constraints with lack of access to alternatives and bulk buying in rural communities. Tobacco products were more prevalent in the litter in high-population sites (more urban and commercial) than low-population (more rural) sites. Personal care product sachets, typically shampoo sachets, were in the top 10 litter items in low- and mid-population sites but not in high-population sites. The proportion of "other" plastic items was the highest in high-population sites, indicating greater variability in the litter in these sites possibly related to more diverse economic activity (proportion of all litter items is shown in Table S5). Variation in litter composition among the site grouping shows that context-specific drivers for litter items, including access to waste management and alternatives to single-use plastics, should be explored in future work.

Although plastic beverage bottles were surveyed in stores across all sites, less than 2% of the items logged across the sites were plastic bottles or caps, with plastic bottles (<0.7%) found at a lower frequency across the site groupings compared to bottle caps (<1.2%) (Table S6). This stands in contrast to results in coastal and marine debris environments in Ocean Conservancy's International Coastal Cleanup, where plastic bottles and caps consistently rank in the top five litter items.[22] In contrast to films and multilayer films, poly(ethylene terephthalate) (PET), the predominant polymer in plastic bottles sold in stores, is a more recyclable and thus more valuable polymer. Because of this material value, plastic bottles are often collected by the informal recycling sector in Bangladesh and India, which was evident in the litter survey results, with relatively low quantities found across all site types. Additionally, the higher counts of bottle caps (generally made of polypropylene (PP) based on in-store surveys) relative to PET bottles support that the bottles are likely being collected for processing and recycling. For valuable polymers, the informal recycling sector plays a critical role in preventing leakage through a collection or recapturing leakage before it enters environmental reservoirs.[23]

SCALING AND LIMITATIONS

On a microscale, litter concentrations can fluctuate due to influences like the proximity of commercial businesses or waste collection receptacles, leading to variability within and between sites. Although litter accumulation is not uniform in a given site, we assumed that the average of three transects, normalized by the ambient population count, provides a meaningful approximation of per capita litter density.

Some sites, notably high population urban sites, sweep streets along litter aggregation pathways as a form of waste management. While some street sweeping was observed during sampling, the frequency and thoroughness of this activity were difficult to determine given logistical constraints. As the proposed sampling method is designed to capture active litter input, additional steps in the plastic cycle should be investigated to quantify the amount of plastic that travels to environmental or human-made reservoirs of waste.

Additionally, while we have indicated access to waste management as a probable variable in explaining differential per capita litter densities, there are additional influences, such as local education and awareness, access to alternative products and product delivery systems, policies and policy enforcement, and household consumption and waste management practices. These may also broadly vary with population.

Lastly, sampling methods that examine litter on the ground in populated areas rather than in their eventual environmental reservoirs can provide snapshots that yield a baseline understanding of plastic pollution in its socioeconomic and cultural context. Because there are local and regional influencing factors, it is not recommended that the calculated litter densities are extrapolated outside of this region, where other influencing factors could drive the results.

FUTURE DIRECTIONS

Litter, if not the biggest source of mismanaged waste along the Ganges River, is nonetheless prevalent in many communities. Within the per capita litter densities calculated for each site, factors such as economic development, availability, and access to waste management infrastructure, and cultural attitudes about plastic pollution are embedded. The sampling method developed here is being replicated to assess active litter input in other cities in various countries (https://www.circularityinformatics.org/urban-ocean). While population density has been shown to have an inconsistent influence on litter densities across multiple diverse countries,[12] this dataset was derived from sites with varying ambient population counts in one river basin, and we propose that future work could use ambient population quantiles to stratify randomized surveying locations for rapid baselining within a local context.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.1c04781.

Contains list of litter items and potential influencing factors; histogram of litter densities of all transects; scatterplot of the ambient population count and average litter density for each site; population, litter density, and per capita litter density for all sites; ambient population per capita litter densities across site groupings; pre- and postmonsoon litter densities for resurveyed transects; count and proportion of litter items across high-, mid-, and low-population site groupings; count and proportion of bottles and caps found across each site grouping; distribution of packaging types of products surveyed in stores; and manufacturing and parent company countries for common consumer plastics (PDF)

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