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Mapping plastic waste entry points into the riverine environment

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ABSTRACT

Mismanaged plastic waste (MPW) is a major source of plastic pollution in rivers, particularly in regions with insufficient waste management infrastructure. Despite prior studies on MPW drivers, the entry points of MPW into riverine environments across the lifecycle of specific plastic items have not been assessed. This study addresses this gap by analyzing the lifecycle of the three most polluting plastic items, drinking water sachets, small bottles, and expanded polystyrene (EPS) food packaging in the Odaw catchment, located in Accra, Ghana to identify their critical entry points into the riverine environment. The Odaw is known for its high contribution to environmental plastic pollution due to the high anthropogenic activities, coupled with its inadequate waste management systems. Using a qualitative methodology, interviews and focus group discussions were conducted with 15 stakeholders involved in production, retail, consumption, waste management, and regulation across the plastic lifecycle. Data collected through audio recordings, were transcribed and analysed through inductive content analysis approach in ATLAS.ti. The findings reveal that all MPW entry points occur during post-consumption stages, with four of eight identified practices classified as high-impact. EPS packs was not recovered for recycling, bottles were exported overseas for recycling, and water sachets recovery faced challenges due to the low market prices and limited recycling capacity. This highlights the catchment's limited recycling infrastructure. The study provides localized insights for targeted mitigation strategies and support targeted monitoring efforts. Furthermore, it offers a replicable methodological framework for regions with limited waste operations data, serving as a baseline for data-rich regions.

Introduction

Plastic pollution in rivers is an issue because rivers accumulate and transport them from terrestrial environments into the ocean. This problem is pronounced in regions with inadequate waste management, mostly Global South countries, where MPW is a primary source (Nyberg et al., 2023) of riverine plastic pollution, with hydrometeorological factors (rain, discharge) playing a minimal role in its absence (Meijer et al., 2021). Since most plastic pollution does not reach the ocean (van Emmerik et al., 2022), the entry of MPW into the riverine systems pose major environmental impacts, including reduced water quality, which harms aquatic life. Poor waste management systems are characterized by insufficient collection infrastructure (Lissah et al., 2021), and weak regulatory enforcement (Srivastava et al., 2014). High plastic consumption further strains waste management system (Jamal and El-Fattah, 2023), leading to plastic pollution in the riverine environment with substantial economic (Williams et al., 2016) and health impacts (Collard et al., 2019).

The global issue of plastic pollution is also evident at the local level, with small rivers in Southeast Asia and West Africa among the most polluted (Meijer et al., 2021). The Odaw river in Accra, Ghana, is estimated to transport 15.7 million items annually (Pinto et al., 2024) mainly due to MPW. Despite interventions like street bins provisions, awareness campaigns, and punitive measures, waste entry persists. Thus, identifying MPW entry points, which are defined as the stages in the waste management system where plastic waste escapes into the natural environment (eg. during collection, transportation or disposal), is crucial for targeted interventions. However, our understanding of MPW entry into the riverine environment remains limited, particularly in urban areas with weak waste management systems (Lebreton et al.,

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2017). Existing studies (Lobelle et al., 2023; Rinasti et al., 2022) analysed waste entry points using Material Flow analysis (MFA), considering plastics as a general category, and overlooking specific item entry pathways (Barkhausen et al., 2023). For example, Rinasti et al. (2022) assessed plastic leakage in Jakarta using the Waste Flow Diagram (GIZ, 2020) based on MFA. This broad approach results in generalized findings that may not address unique waste streams challenges. Therefore, an item-specific entry analysis can reveal distinct waste entry practices and support more effective mitigation strategies.

Previous studies in the Odaw and along the Accra-Tema coastline beaches have focused on littering behavioural intentions on plastic pollution (Abraham and Aniapam, 2016; Oduro-Appiah et al., 2024; Van Dyck et al., 2016). However, these studies focused on specific stakeholder groups, overlooking contributions from other stakeholders in the lifecycle. For instance, Van Dyck et al. (2016) engaged only beach users and some regulatory bodies, while Oduro-Appiah et al. (2024) focused solely on consumers. This narrow focus misses the importance of engaging stakeholders across lifecycle stages (Alhazmi et al., 2021) to understand MPW entry practices. Additionally, these studies did not identify MPW entry points, which are crucial for effective interventions.

Addressing these gaps, this research examines the lifecycle stages of three polluting plastic items, i.e. drinking water sachets, small PET bottles (≤ 0.5 liters), and EPS food packaging (Pinto et al., 2024). Fifteen stakeholder parties from manufacturing, consumption, to waste management were engaged through interviews and focus group discussions. Data was analyzed qualitatively to map practices and identify waste entry points across their lifecycle. By identifying plastic entry points, the study addresses the root causes of pollution, enhancing our understanding of MPW sources and entry processes. This holistic approach provides actionable insights for targeted mitigation strategies to riverine plastic pollution. It also aids monitoring programs by optimizing data collection at accumulation zones, improving resource allocation, and refining global pollution models.

Methods

Research design

The study employs a qualitative approach, using open-ended questions to collect detailed stakeholder perspectives on plastic entry points. A qualitative approach was used for this study because we wanted to understand the underlying reasons, attitudes, and beliefs that drive stakeholders waste practices and the eventual entry into the natural environment. Data was collected using a semi-structured interview which provided the flexibility to diverge into topics during the discussions. The study centres on the stakeholders in the lifecycle of three specific plastic items (water sachets, small PET bottles (≤ 0.5 l), and EPS packs) (Fig.1). Water sachets, commonly used in Ghana, are 500 ml machine-sealed plastic pouches of drinking water (Angnunavuri et al., 2022). Small PET bottles (≤ 0.5 liters) are PET bottles, referred as 'small bottles' in this study. EPS food packaging, commonly called 'takeaway packs' are expanded polystyrene food containers (Awodi and Adewumi, 2024), referred to as 'EPS packs' in this study. These plastic items account for 31 to 67 % of the plastic pollution in the catchment (Pinto et al., 2024), with water sachets being the most dominant (14 %–31 %), followed by EPS packs (9 %–23 %), and small bottles (8 %–13 %) (Pinto et al., 2024). Beyond their prevalence in the environment, these plastic items are also extensively used daily by stakeholders in the catchment. Thus, with their high consumption relating to their high prevalence in the environment, focusing on these plastics can provide valuable insights into the broader plastic pollution issue in the catchment.

Research location

The study focuses on the Odaw catchment (270 km^2) in the Greater Accra Metropolitan Area (GAMA), centred within Accra, Ghana (Appendix C, Fig. C1). This catchment is highly urbanised with a high population density and diverse economic activities including commerce and industries (Abraham et al., 2018). However, due to inadequate waste management infrastructure, the river is polluted by the direct disposal of household sewage, industrial effluents, and solid waste, with macroplastics being a major component of the river's pollution. Annually, 15.7 million macroplastic items are transported through the river (Pinto et al., 2024), highlighting the severity of plastic pollution in the catchment.

While the study focuses on the Odaw catchment, the activities of some stakeholders extend beyond this catchment. The geographical extent of stakeholders' activities range from the catchment (local) to international. Consumers, retailers, and recyclable waste pickers operate locally, though recyclable waste pickers may extend their services to the municipal level. At the municipal level are the services of the informal waste collector, recyclable waste distributor, and municipal regulator. Formal waste collector and environmental organisations operate at the regional level with the national regulator, consumer product manufacturer, and the industry association found at the national level. Recyclers operate either at the national or international level depending on the recyclable plastic item. Despite these varying geographical extents in stakeholder services, the study focused on the local practices to understand waste entry pathways within the catchment.

Interviewee selection

The research applied a combination of purposive and snowballing methods to ensure a comprehensive and diverse inclusion of relevant stakeholder parties across the lifecycle of plastic items and reduce

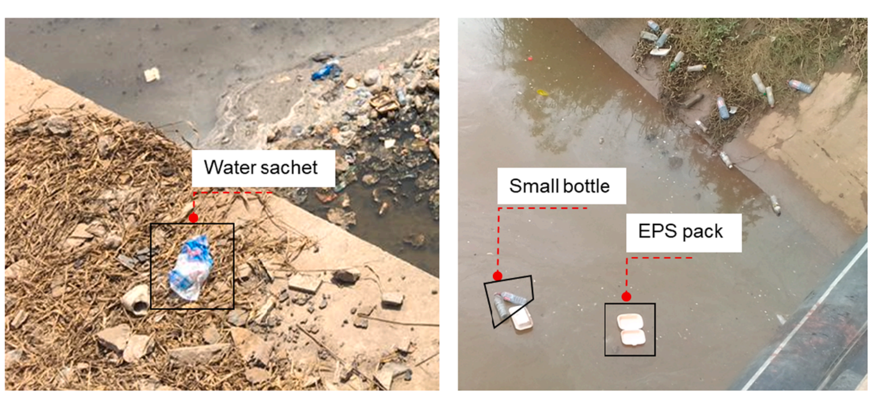

Fig. 1. Polluting plastic items in the Odaw catchment. L-R: water sachet at bridge location 7 riverbank and small bottles and EPS packs in transport in the river section at bridge 5 (Source: Rose Pinto 2021).

selection bias. Purposive sampling (Campbell et al., 2020) guided by literature review identified key stakeholders relevant to the study's objectives. Snowball sampling (Leighton et al., 2021) was used, where referrals from previously engaged stakeholders helped identify and include informal stakeholders, such as recyclable waste pickers and distributors.

Data was collected through interviews and focus group discussions (FGDs). The interviews lasting 30 to 60 min each were conducted with up to two representatives per stakeholder stage, while FGDs ranged from 45 to 90 min. The discussion lengths were carefully chosen to balance thorough data collection with the practical need to minimize interruptions, particularly for participants in the informal sector who rely on daily earnings. FGDs engaged consumers, informal waste collectors, recyclable waste pickers, and recyclable waste distributors. Gatekeepers, being well-known and respected in the community, facilitated participant recruitment, ensuring gender and age diversity (excluding children for ethical reasons). Each FGD consisted of 6–10 participants. Initial contact with institutions was via email, with phone calls and in-person visits facilitating engagement. During these visits, we delivered interview invitation letters (see supplementary material, Appendix C) and finalized arrangements for potential meeting dates. In total, 15 stakeholders were engaged, with each FGD counted as a single unit (Table 1). Interviews were tailored to stakeholders' role, with some questions consistent across all stages. The sampling strategy and interview protocols were approved by the Wageningen University's Review Ethics committee (see supplementary material, Appendix B).

Data collection and analysis

Data collection was done between September 28 and October 12, 2023, using interview and FGD questions (see supplementary material, Appendix A). Audio recordings and photographs were taken with participant consent. Data collection was assisted to help facilitate the sessions. Sessions were conducted in English or Twi based on participants' preferences. For the FGDs, efforts were made to ensure inclusive participation by inviting responses from each participant. The study ensured the confidentiality and anonymity of all participants who are addressed by pseudonyms (Table 1) in this paper.

All audio recordings were transcribed and translated for analysis. English interviews were transcribed using Whisper AI (https://github.com/openai/whisper), an AI transcription software with transcripts validated by listening to the full audio recording. Transcripts were then emailed to participants for verification. Twi interviews were manually transcribed to English by listening to the audio files twice. The research assistant validated the transcripts due to the low literacy rate of participants under the FGDs. Transcribed data was analysed in ATLAS.ti (ATLAS.ti Scientific Software Development GmbH, 2023) using an inductive content analysis approach (Kyngäs, 2019), allowing themes to emerge directly from the data. Codes were assigned to relevant text segments. For example, a code 'Organisational measures' for institutional operational measures. Other codes included operational activities, product preferences, motivations, waste management arrangements, bad waste practices, good waste practices, hindrances to good practices, and regulation, among others. These codes were grouped using the code manager in ATLAS.ti, organising codes according to overarching themes. For example, grouping codes 'bad waste practices',

Table 1
Participating institutions at each stakeholder stage in the lifecycle of each specific plastic item (water sachets, small bottles, EPS packs) in the Odaw catchment.

Role	People and Institutions	Pseudonyms	Activities geographical extent	Role of stakeholder in the context of the study	Method of data collection	Language of communication
Consumer product manufacturer	Water sachet and bottling company	COM(A)	National	Produces water sachets and small bottles.	Interview	English
	EPS-packs company	COM(B)	National	Produces EPS-packs.	Interview	English
Waste collector	Formal waste collector- A	FWC(A)	Regional	Responsible for waste collection services regulated by municipal and national regulator.	Interview	English
	Formal waste collector – B	FWC(B)	Regional		Interview	English
	Informal waste collector	IWC	Municipal	Independently provides waste collection services on a small scale with minimal national or municipal regulation.	Focus Group Discussion	Twi
Recycler	Recycling company	REC	National -International	Collects or buys recyclable waste for processing into raw materials for manufacturing new plastic items.	Interview	English & Twi
Retailer	Retailers	RET	Local	Sells plastic consumable items (water sachets, small bottles, EPS packs).	Interview	Twi
Consumer	Consumers	CON	Local	Uses purchased consumable plastic items	Focus Group Discussion	Twi
Recyclable waste picker	Recyclable waste pickers	RWP	Local - Municipal	Collects littered recyclables like water sachets and bottles from streets, rivers, dumpsites, and landfill.	Focus Group Discussion	Twi
Recyclable waste distributor	Recyclable waste distributors	RWD	Municipal	Purchases collected recyclable waste from various sources such as recyclable waste pickers and consumers, either by moving from place to place or from a stationary location, for sale to recyclers.	Focus Group Discussion	English & Twi
Industry association	Industry association	IDA	National	Advocates for the interest of consumer product manufacturers and provides advisory guidance on good manufacturing practices.	Interview	English
Regulatory bodies	Municipal regulator	MUN	Municipal	Enforces compliance to environmental laws and supervises waste management activities within a municipality.	Interview	English
	National regulator	NAT	National	Develops and regulates policies related to the activities of stakeholders in the plastic lifecycle, i.e., from production to disposal.	Interview	English
Environmental organisations	Environmental NGO	ENV	Regional	Promotes awareness on activities that reduces environmental pollution and advocates for the integration of the informal sector into waste management activities.	Interview	English
	Informal waste collectors' association	IWCA			Interview	Twi

'good waste practices', 'waste management arrangements', 'hindrances to waste management practices' under the theme 'Waste management practices'. We acknowledge that qualitative analysis is inherently context-dependent and shaped by researchers' positionality. To reduce this potential bias and enhance the reliability of the findings, codes, themes, and interpretations were discussed with co-authors during the analysis process. This collaborative discussions helped ensure that multiple perspectives were considered, and that the analysis remained grounded in the data collected.

Stakeholder mapping

Stakeholders in the plastic lifecycle were mapped based on collected data, illustrating their interactions throughout the lifecycle. Stakeholders were grouped into three sectors namely 'production and sales', 'consumption and waste management', and 'regulation and advocacy' based on their roles within the lifecycle. These sectors were arranged in concentric circles using the stakeholder onion diagram (Krkač, 2021). This diagram, a type of circular representation, consists of a core circle and concentric circles that look like the cross-section of an onion. This diagram visually represents dependencies along the lifecycle, where processes in each ring depends on the processes in the smaller inner rings (Odessa, 2024). The 'production and sales' sector, including the consumer product manufacturer (COM) and retailer (RET), were positioned at the core as they drive the market presence of these plastics (Kemper et al., 2023). The 'consumption and waste management' sector which includes consumer (CON), formal waste collector (FWC), informal waste collector (IWC), recyclable waste picker (RWP), recyclable waste distributor (RWD), and recycler (REC), occupies the middle circle, engaging in the consumption and post-consumption processes of the plastic item. The outermost circle, 'regulation and advocacy', includes national regulator (NAT), municipal regulator (MUN), environmental organisations (ENV), and industry association (IDA), guiding the activities of stakeholders in the inner circles. Relationships between stakeholders are shown with lines, indicating interactions and arrows showing service dependencies.

Within waste management, stakeholders are classified into waste generation (COM, CON, RET), waste collection (FWC, IWC), waste recovery (RWP, RWD, REC), and waste regulation and advocacy (NAT, MUN, ENV) based on their waste management roles in the catchment.

Mismanaged plastic waste entry points and interventions

MPW entry practices along the lifecycle were identified from the interviews and focus group discussions. Identified waste entry practices were categorised as high, medium, or low impact based on their perceived relative contribution on MPW. For example, a MPW entry process involving stakeholders with large populations was considered high-impact since a greater proportion of waste is entering the environment. This classification was assumed since there was limited quantitative data on waste processes in the catchment.

To address these entry practices, mitigation strategies were recommended based on stakeholder input and existing literature. Strategies were self-assessed for environmental, social, and economic impact using the impact categories: positive high, positive low, neutral, unknown, negative low, and negative high (see supplementary material, Appendix D, Fig. D1). These assessments were discussed to ensure reliability. However, this paper does not extensively discuss these impact levels but mentions each strategy's effectiveness and feasibility. For each mitigation strategy, the waste entry practices it addresses was indicated. Strategies were prioritized based on their ability to address high-impact entry points and multiple entry rates. Additionally, the environmental, social, and economic impacts of these strategies on stakeholders were also considered in the prioritization process.

Results and discussion

The complexity of stakeholder dynamics in the plastic chain

The stakeholder mapping exercise in the Odaw catchment revealed interdependencies among stakeholders, highlighting both traditionally recognised (COM, RET, CON, FWC, REC, NAT, MUN) and underrepresented stakeholders (IWC, RWP, RWD), revealing their contributions to the plastic lifecycle. Stakeholders classification into sectors revealed distinct yet interdependent roles (Fig. 2a, b), showing how each sector's actions influence downstream activities, particularly how production-phase decision, influenced by profit and regulations, impact consumption and waste management practices.

Six key stakeholder interactions were identified, namely payment transactions, waste collection services, advocacy, plastic product sales, sale of plastic items (recyclable), and regulation (Fig. 2a, b). One-way interactions were from advocacy (orange arrows) and regulation (blue arrows) interactions. Regulatory interactions occurred between NAT/MUN and FWC, REC, and COM, while advocacy was from ENV targeting CON, IWC, RWP, and RWD. Two-way interactions involved monetary transactions for services, i.e. for product sales (violet arrows), recyclable sales (brown arrows), and waste collection (black arrows). For instance, payments from COM to RET and then to CON demonstrated plastic item flow into the market for use.

The results revealed economic-driven consumer choices. This behavior affects waste generation patterns, as cheaper products, often single-use, increases waste generation (Gomes et al., 2022; Vidal-Ayuso et al., 2023). For instance, RET noted water sachets sell faster than bottled water due to affordability (Quote 1).

'Now water sachet sells faster than bottled ones.' (Quote 1, RET)

Waste collection services also involved financial exchanges between collectors (FWC, IWC) and waste generators (CON, RET, COM), reflecting economic dependencies within this sector. This dependency extends to RWP and RWD, who engage in financial transactions with waste generators and collectors for recyclables, later sold to recyclers. These transactions highlight the economic linkages driving the recycling chain and emphasizes the informal sector's role in recycling. This indicates that the ability of FWC, IWC, RWP, and RWD to maintain operations relies on stable financial transactions. Economic pressures from payments fluctuations may impact their operations and willingness to collaborate, hindering effective waste management. This reveals the importance of a sound economic framework for waste management (Guerrero et al., 2013).

While stakeholder interaction patterns for water sachets and small bottles (Fig. 2a) are similar to that of EPS packs (Fig. 2b), differences exist in their recycling chain. Water sachets and small bottles engage all identified stakeholders, while EPS packs show no interaction with RWP, RWD, and REC, indicating they are not recycled in the catchment.

Limited current waste management practices

Waste generation

In industrial settings, waste management vary by organizational capacity. For instance, COM(B) implements an internal recycling system for production waste and contracts FWC for residual waste management. Conversely, COM(A) lacks on-site recycling facilities; instead, they store production and onsite-generated waste (water sachets, bottles, caps) for later sales to recyclers, while also relying on FWC to handle its residual waste. While both companies aim to minimize waste, their reliance on external services highlight inefficiencies and potential long-term costs in their waste management systems. Manufactured products are distributed to consumers via retailers (supermarkets, street hawkers, small shops). Stationary retailers, support waste management by collecting consumer-generated plastic waste (water sachets, bottles), and selling

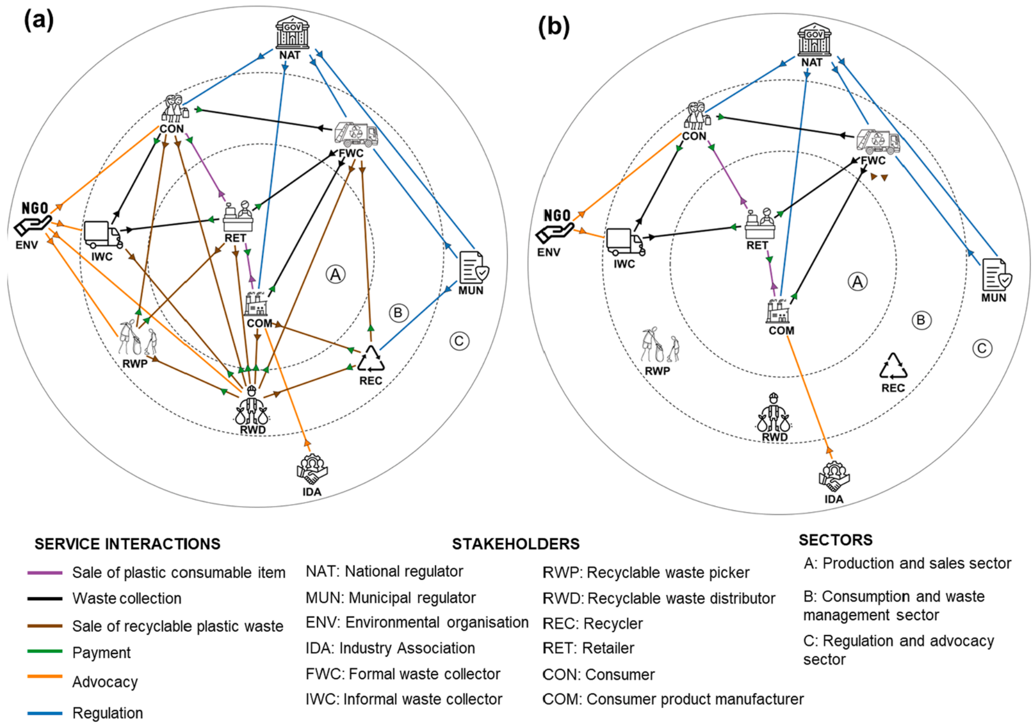

Fig. 2. Stakeholder mapping of stakeholders in the lifecycle of (a) water sachets and small bottles (b) EPS packs in the Odaw catchment shown in the black solid circle. The indicated circular bands A, B, and C show the sectors each of the stakeholders are involved in namely 'production and sales', 'consumption and waste management', and 'regulation and advocacy' which are represented in the dashed circles. The lines represent the service interactions between the stakeholders with the arrows showing the direction of service between stakeholders (see legend for the colour use for the lines and arrows).

approximately two 240l bags of water sachets monthly to RWD. Residual waste is managed by FWC and IWC.

The findings reveal diverse consumer waste practices that strain the waste management system. While some consumers recycle by reusing bottles or selling sorted water sachets, others resort to open dumping or burning near the river, particularly in areas with limited formal waste collection (Quote 2). Similar practices are common in densely populated Lagos communities (Kofoworola, 2006) and across sub-Saharan Africa, where open dumping, accounts for 75 % of waste disposal (Folarin, 2021). Additionally, other consumers who sorted their plastic waste preferred burning, with the motivation to reduce littering of this non-degradable waste (Aliu et al., 2014). These inconsistent practices reduce recyclable recovery rates, as contaminated recyclables are often rejected by FWC, IWC, RWP, and RWD, affecting the efficiency of stakeholders in the recycling chain.

'We mostly dispose it off at the dumpsite close to the river.' - (Quote 2, CON)

Waste collection

Waste collection in the catchment involves both formal and informal waste collectors. Formal waste collectors (FWC), regulated by national (NAT) and municipal (MUN) bodies, operate under franchise agreements. They provide door-to-door waste collection in middle-to-high income areas and institutions and communal container collection services in low-income, densely populated communities. This system is common in many African countries as seen in Nigeria (Aliu et al., 2014) and Cameroon (Parrot et al., 2009). In Greater Accra, the door-to-door system, franchised to around 16 companies, offers weekly or bi-weekly services. FWCs also engage in waste recovery programs for recyclables like organics, paper, and plastic, offering incentives to clients. The communal container system, a government initiative, places containers within a 200-meter radius in densely populated communities and commercial centres (markets, bus stations). Site attendants supervise disposal, collect fees, and coordinate with FWCs for collection. During waste collection, truck workers sometimes recover recyclables and sell them to RWDs at landfill sites, who later sell to recyclers. Waste is transported to transfer sites, engineered landfills at Adipa (Nsawam, ~46.2 km from city centre), Kpone (Tema,~35.2 km from city centre] or material recovery facilities such as ACARP (Medie,~36.5 km from city centre) and IRECoP (Korle-bu,~7.7 km from city centre) (see supplementary material, Appendix C (Fig. C2)).

Despite structured services, FWCs struggle to serve urban-poor areas due to poor access routes and operational financial risks. These limitations create opportunities for the informal waste collectors (IWC), who independently serve these underserved areas without franchise agreements, using handcarts and motorised rickshaw. IWCs set fees based on waste quantity collected and bargaining power. They also recover recyclables (water sachet, bottles) based on cleanliness, either reusing or selling them to RWDs. Typically, IWCs dispose of waste in skip containers, but recently, they dump waste at landfill sites, transfer stations, or unengineered dumpsites managed by the municipality. Some consumers also prefer unorganized informal waste collectors due to lower costs, though they often resort to open dumping.

The results reflect a fragmented waste management system with varying operations and efficiency levels between FWCs and IWCs, each serving different populations. The mix of FWC and IWC in the Odaw catchment follows trends in many developing countries like Indonesia (Damanhuri and Padmi, 2012), Uganda (Katusiimeh et al., 2013), and Côte d'Ivoire (Andrianisa et al., 2015). This co-existence arises when FWC services are inadequate, prompting IWC to fill in the gap, especially in underserved areas. Andrianisa et al. (2015) found that 86.5 % households in such communities indicate IWC as an important link to city waste management. While some recyclables are recovered, the collect-transport-dispose system (Nnaji, 2015), limits recycling rates. However, the lack of regulation on IWC activities sometimes lead to illegal dumping in open areas.

Waste recovery

At landfill sites, recyclable waste pickers (RWP) recover recyclable materials like plastic bottles, water sachets, HDPE and PP containers, bottle caps, and metal scraps. Their activities extend to streets, rivers, dumpsites, and commercial centres using sacks or handcarts. Recycler demand drives their choices, with water sachets being the most collected due to high market value. RWPs focus in high-activity commercial centres and work early mornings (5:00am-7:00am) or late evenings (after 9:00pm), before cleaning activities by individuals or FWCs. This timing reveals a competitive dynamic approach, similar to practices in Indonesia, where waste pickers start at 3:00/4:00am (Damanhuri and Padmi, 2012). Many RWPs are rural migrants from Ghana or neighbouring countries seeking jobs (Quote 3). Due to limited education, they engage in informal activities like waste picking for economic survival in high-unemployment countries (Mensah and Nalumu, 2023). Thus, immediate income needs restrict their ability to invest in better equipment, affecting service quality.

> *'We do this as an alternative of a proper way of working for money due to unemployment- (Quote 3, RWP(D))*

Collected recyclables are sold to stationary RWDs (three hubs in Accra) or mobile RWDs, who travel to clients (CON, COM, RET) to purchase recyclables. These stakeholders clean and sort the recyclables before selling to recyclers, as quality affects sale prices. Damanhuri and Padmi (2012) note that initial processing increases recyclables' selling value by 10 %. Despite improving plastic recovery, RWPs contribute to poor environmental hygiene by leaving non-recyclable waste unmanaged, prioritizing market demand over environmental concerns (Chung and Lo, 2004).

Recyclers process recyclables into raw materials like pellets. While items like water sachets, gallons, caps, are processed locally, plastic bottles, are often exported for recycling. Clean plastics are prioritised, while contaminated recyclables are rejected and added to the general waste for FWC collection. Despite these efforts, gaps remain, with some plastics like EPS packs, commonly unmanaged, excluded from current recycling processes. Additionally, exporting plastic bottles for recycling further reveals capacity, machinery, and economic constraints within the local recycling system. Additionally, recycled plastics are not reintegrated into local manufacturing, reflecting a linear waste management approach that limits circular economy progress.

Waste regulation and advocacy

NAT and MUN regulate waste management practices. NAT provides and enforces manufacturing and waste management policies, including promoting sustainable waste management initiatives. One ongoing initiative is a segregation program piloted in collaboration with FWC(B) in some educational and governmental institutions. This initiative involved the provision of colour-coded bins, training participants, and monitoring progress (Quote 4). Results showed a material recovery success rate of 89–92 % in the educational institutions (NAT). However, expanding such small-scale initiatives to diverse urban areas, where waste handling practices are variable remains a challenge. This therefore highlights the need for a robust stakeholder integration and participation to ensure the sustainability of such initiatives on a wider scale.

> *'Colour-coded bins were provided to participants to segregate their waste for further processing.'- (Quote 4, NAT)*

MUN ensures policies compliance through supervision of waste collection, transport, and disposal at the municipal level. MUN also supports IWCs through their associations, by facilitating their access to transfer stations and landfill sites and providing vehicle riding licenses. This demonstrates a progressive inclusive approach toward formalizing IWCs, which promotes better regulatory compliance. Environmental organisations also support the underrepresented stakeholders (RWP, RWD, and IWC) by offering capacity-building programs, storage spaces, and facilitating market access for recyclables collection and sales. They also collaborate with MUN on cleanup exercises, encouraging responsible waste disposal practices (Parrot et al., 2009). This multi-stakeholder effort bridges gaps between policy, enforcement, waste collection, and recovery, ensuring a more sustainable waste management system.

Seasonal waste practices dynamics

Seasonal variations impact waste management practices, influencing waste quantity and type. During the dry season (December to March and July to August), increased water consumption increases water sachets and small bottles waste. In the wet season (April to June and September to November) bottled energy drinks and fruit juices waste are more common, likely due to consumers preference for these beverages during this season to help maintain their energy levels for daily activities. This reflects variable consumption patterns across the two seasons. Despite these, waste composition remains relatively consistent year-round. However, the quantities of water sachets, peak in the dry season. The abundance of water sachets in the dry season reduces recyclers' market price, while its scarcity in the wet season increases prices. These fluctuations highlight the financial instability faced by stakeholders in the recycling sector, driving them to adapt their operational strategies to avoid financial losses. One approach is storing recyclables for later sales at better prices, though this poses risks such as theft or loss during floods if not safely stored. Seasonal variations also impact recyclers' operations. During periods of high water sachet influx, they often struggle to process collected waste, leading to storage overflow and increasing littering risks.

Consumer disposal practices, such as dumping waste into rivers during the rainy season (COM, RET, MUN, IWC), increase plastic pollution. Twaibu and Okidi (2021) noted similar behaviours in Kampala in anticipation of the rains washing the waste away. While this creates economic opportunities for RWPs to recover recyclables in the river, they face health risks. Owusu-Sekyere (2014) found in Kumasi that RWPs often suffer from back pains, skin infections, diarrhoea, and malaria due to the unsanitary working conditions. These unsafe working conditions highlight the vulnerabilities of RWPs who risk their health on waste recovery to sustain their livelihood. The rainy season poses operational challenges to IWCs, such as delays and accidental spills due to poor road conditions (Quote 5). These seasonal shifts create both opportunities and challenges for stakeholders in the waste sector, requiring adaptive strategies to sustain operations year-round.

> *'Sometimes in the rainy season, due to the potholes covered by water, we accidentally fall in and lose some of the collected waste.'- (Quote 5, IWC)*

Where does waste enter the riverine environment?

Figs. 3 and 4 illustrate the flow path of water sachets and small bottles, and EPS packs respectively from production to waste management, highlighting key waste entry practices in their lifecycle. In the Odaw catchment, plastic waste is generated from production and distribution, retailers, and consumers. Waste is managed in several ways. One approach involves sorting recyclable plastics (water sachets and small bottles) (Fig.3) for sale to RWD. Another option is open dumping in streets, drains, or open spaces (Fig. 3 and 4). The other option involves adding plastic waste to the general waste for collection. Collection ranges from formal waste collectors (FWC), organized informal waste collectors (IWC), and unorganized informal waste collectors. In the services of FWC and IWC, some recyclables, mostly water sachets and small bottles (Fig. 3) are recovered and sold to RWD. If recovery is not possible, the plastic waste is added to the general waste for disposal. During transportation to either the landfill site or transfer station, losses

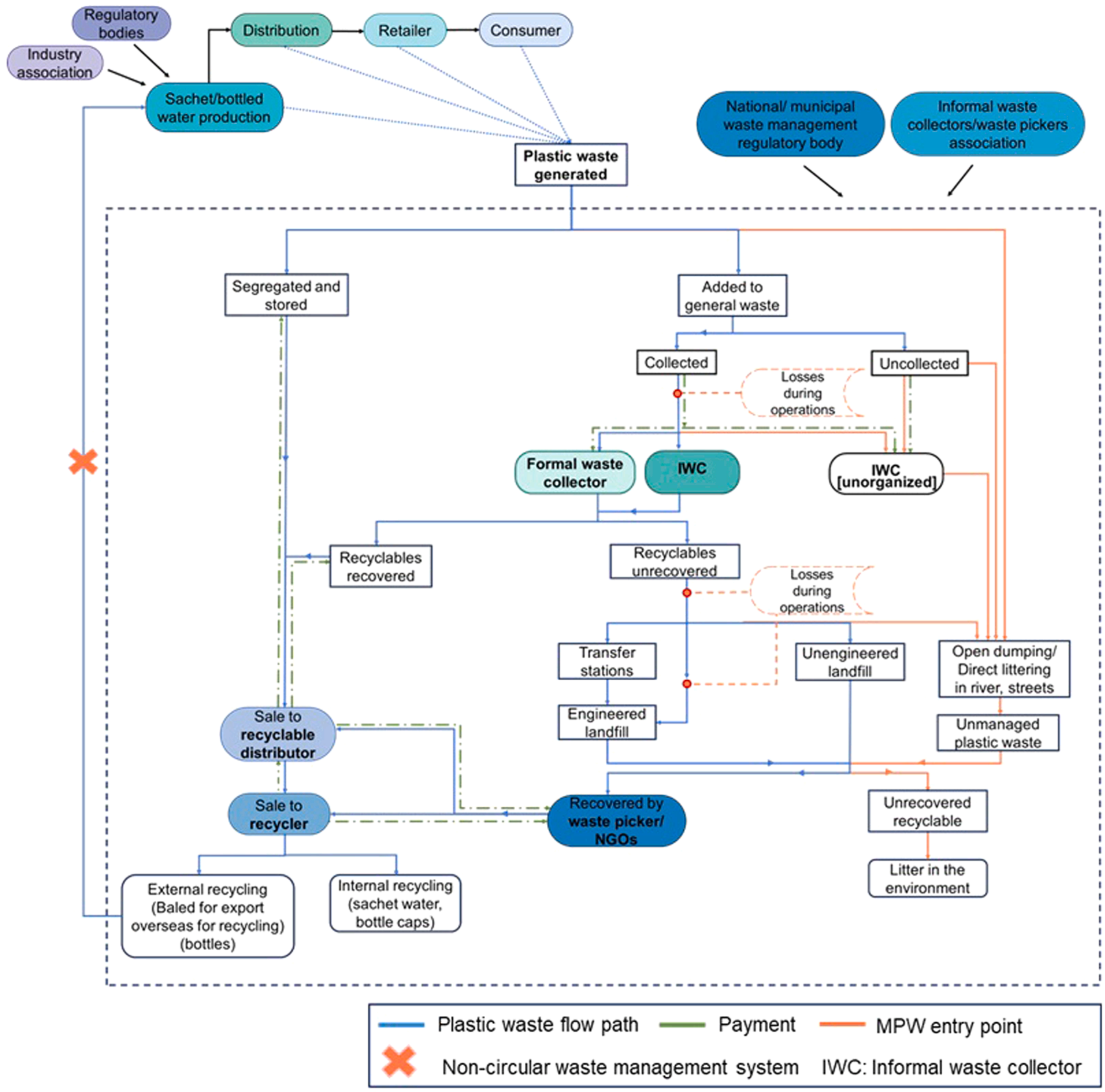

Fig. 3. Flow diagram illustrating the lifecycle and waste management pathway of water sachets and small bottles in the Odaw catchment. The flow is represented in different line colours to show the pathway of the plastic items. The dashed black box shows the waste management processes of generated water sachets and small bottles waste. The blue dashed lines indicate the sources of waste generation, while the blue solid lines represent the flow of the waste practices indicated in the rectangular boxes. The green dashed lines show the monetary flow associated with waste management (collection, recovery, and recycling). The orange solid lines highlight the entry points of these plastic items into the environment, resulting from open dumping, uncollected waste or unrecovered recyclables. The orange dashed lines shows losses during waste transport by the waste collectors. The orange X symbol marks the non-circular waste management system in the catchment. The oval rectangles represent the stages in the plastic lifecycle, and the rounded rectangles indicate the outcome of the waste item.

(wind blowing uncovered collected waste and accidental spills due to bad road) are observed by both FWC and IWC (organized).

Additionally, some organized IWC engage in intentional open dumping on the streets and highway. Uncollected household waste by FWC and organized IWC is either openly dumped by consumers or handed to unorganized IWC, whose services, despite being cheaper, dispose of waste indiscriminately. Waste at landfill sites, openly dumped in the streets or dumpsites attract the work of RWPs who recover recyclable plastics (water sachets and bottles) and other non-plastic recyclables. Unrecovered (EPS packs) or degraded recyclables (unclean or damaged) remain in these sites, which are dispersed to other environmental compartments by wind or surface runoff, further spreading the pollution of these plastic items. Eight waste entry practices (Fig. 5) were identified (highlighted in orange in Figs 3 and 4) with four being high-impact.

Many high-impact waste entry practices result from voluntary actions by stakeholders, particularly consumers (Appendix C, Fig. C3). This practice, referred to as diffuse voluntary waste entry, involves the often-intentional release of waste into the environment through littering and illegal dumping. A major contributor to these voluntary waste entry practices in the Odaw is the presence of slums near the river, characterized by high population density and inadequate waste collection services. Due to this, direct waste disposal into the river or along its banks is a common practice, increasing pollution levels in the river. Similar trends are observed in Nigeria (Nnaji, 2015) and Indonesia (Rinasti et al., 2022), where poor urban regulations further compound the issue, allowing poor waste disposal habits to persist.

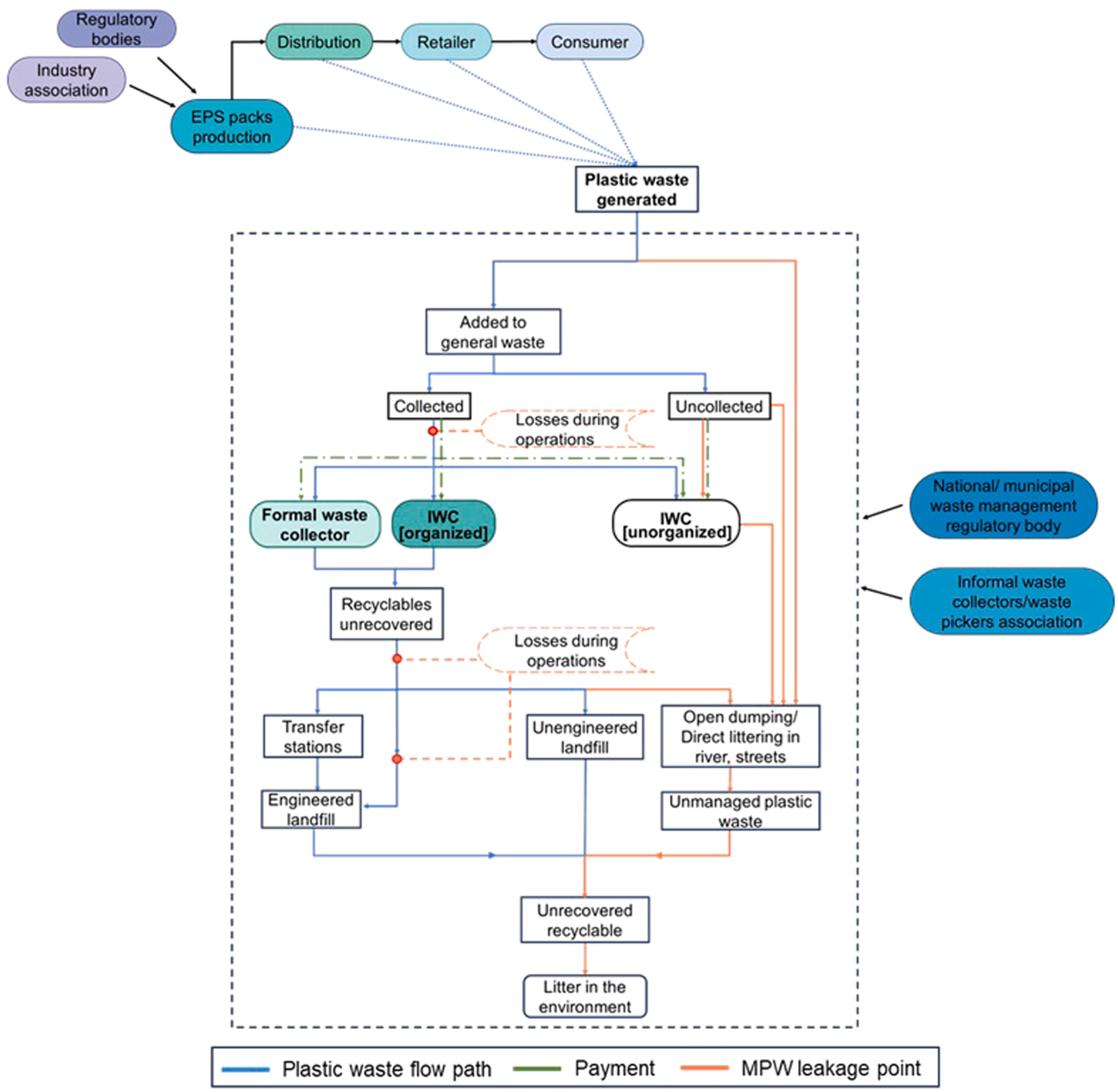

Fig. 4. Flow diagram illustrating the lifecycle and waste management pathway of EPS packs in the Odaw catchment. The flow is represented in different line colours to show the pathway of the plastic items. The dashed black box shows the waste management processes of generated EPS packs waste. The blue dashed lines indicate the sources of waste generation, while the blue solid lines represent the flow of the waste practices indicated in the rectangular boxes. The green dashed lines show the monetary flow associated with waste management (collection). The orange solid lines highlight the entry points of these plastic items into the environment, resulting from open dumping or uncollected waste. The orange dashed lines shows losses during waste transport by the waste collectors. The oval rectangles represent the stages in the plastic lifecycle, and the rounded rectangles indicate the outcome of the waste item.

Drivers to plastic waste entry

Governmental and institutional factors

Policy and implementation challenges contribute to waste management inefficiencies. Weak government intervention and enforcement, as noted by ENV, IWC, and CON, undermine accountability and proper disposal. Insufficient funding strains policy implementation, as inadequate financial resources limit waste infrastructure development, personnel training, and public awareness campaigns (Gurevich, 2023). The absence of an Extended Producer Responsibility (EPR) system, leaves COM unaccountable for its products' waste (Compagnoni, 2022). This, coupled with unregulated small-scale businesses that evade taxes, drives the fast sales of single-use products, increasing daily waste volumes which burdens the under-resourced FWCs and municipalities.

Waste infrastructure has not kept pace with population growth, hindering proper waste management. Ghana's urban centres lack sufficient infrastructure to handle growing waste volumes (Lissah et al., 2021), a challenge also in Nigeria (Akeh and Shehu 2018). Rapid urbanisation, especially in slums without municipal services like skip containers, force residents into open dumping, a key driver of mismanaged waste in developing countries (Akindele and Alimba, 2021). The absence of skip containers also strains IWC operations, forcing long disposal trips (~35–46 km from city centre). These journeys are hindered by poor roads, vehicle breakdowns, and unexpected closures or equipment failures at landfill sites, reducing collection efficiency (Quote 6). Lagos faces similar issues, where long disposal distances and poor road conditions limit collection trips (Kofoworola, 2006). This strain leads to uncollected waste and discourages proper disposal practices among IWC (Tilaye and van Dijk, 2013).

> *'For a year now, there is no skip container on site, so we ride to IRECOP to dispose of collected waste.' - (Quote 6, IWC)*

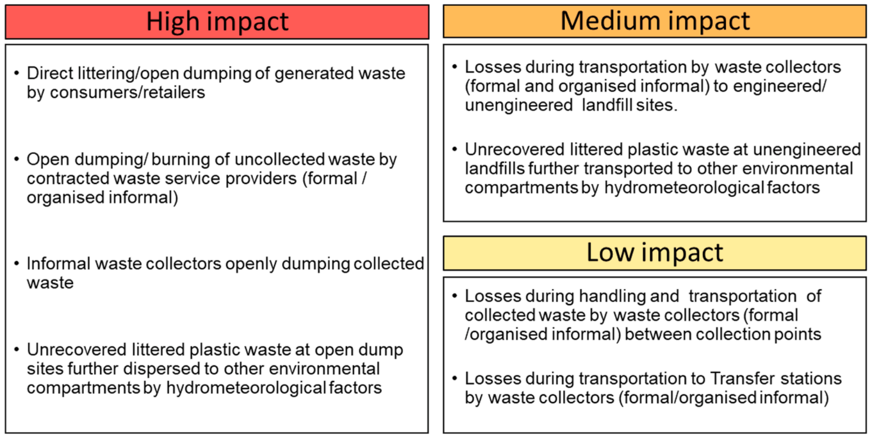

Fig. 5. Waste entry practices identified within the plastic lifecycle of water sachet, small bottle, and EPS pack waste and their impact on the presence of mismanaged plastic waste in the Odaw catchment.

Economic factors

Financial challenges faced by FWC and IWC hinder effective waste management. Government-fixed waste service rates, unreviewed since 2018, limit FWCs' ability to maintain operations, as increased fuel prices, maintenance costs, and inflation (37.53 % in 2023) (Statista, 2024) strain operational budgets. Additionally, government's failure to assist in payment collection despite an agreement, forces FWCs to chase payments, resulting in revenue losses. IWC also struggles with irregular payments, charging upon collection with no fixed rates and often receiving less than needed to cover costs. This is worsened by disputes over tariffs, especially in lower-income areas, reflecting a low consumer responsibility toward waste management (Lissah et al., 2021). Similar trends in Lagos (Nigeria) show clients expect government-funded waste management (Aliu et al., 2014; Nnaji, 2015). In GAMA, fee collection rates range from 1–4 % in low-income areas to 50 % in high-income areas (Oteng-Ababio, 2009). Even in Bahir Dar (Ethiopia), 50 % collection rate proved insufficient to cover costs (Lohri et al., 2014), leading to yearly deficits. This unwillingness to pay leaves collectors financially under-resourced, limiting service expansion, such as purchasing more collection vehicles or integrating recycling (Breukelman et al., 2022). Furthermore, FWCs and IWCs face high costs in procuring a waste collection equipment ($\geq$ \$50,000), worsened by the absence of tax waivers and port delays. IDA, COM, and MUN also highlighted misallocated waste levies by NAT, impeding local waste management efforts and undermining trust in government's waste management.

Stakeholder behavioural factors

Consumer attitudes limits waste management efforts by regulatory bodies and ENV. Despite initiatives like waste segregation programs and street bins, non-compliance remains a major issue. Street bins are often damaged or filled with household waste, leading to overflows. Similar misuse occurs in Kampala, where bins are filled with inappropriate waste like faecal waste (Twaibu and Okidi, 2021).Additionally, in segregation programs, consumers mix waste items, reducing recycling efficiency (Henry et al., 2006). These demonstrate that infrastructure alone is insufficient, education is crucial for responsible consumer behavior (Jigani et al., 2020). However, education alone does not guarantee compliance, as Chung and Lo (2004) found no direct link between environmental literacy and littering. A holistic approach, including stricter enforcement, is needed to encourage long-term change.

Additionally, consumers choice for engaging the services of unorganized IWC is often a response to delayed or missed collection services from FWCs. This delayed collection is mostly due to the narrow access roads to these communities by FWCs. Owing to this, skip container sites are messy, consistent with findings by Amoah & Kosoe (2014) mentioning the issue of overflowing waste in urban-poor communities. IWC expressed concerns on limited stakeholder support and the dominance of a single private company with substantial government support, marginalising their operations. They also noted the difficulty in securing franchise agreement which is costly for them to afford. Additionally, RWPs face social stigma due to the dirty nature of their work. They are often viewed with suspicion as thieves and even face physical confrontations (Mensah and Nalumu, 2023), which limits their access to areas and engagement with communities for recyclable recovery (Schenck and Blaauw, 2011).

The future to reduced mismanaged plastic waste

Mitigation strategies (Table 2) suggested aim to address waste management challenges and improve sustainability. Their environmental, social, and economic impacts, as detailed in supplementary material, Appendix D (Fig. D1), provides a holistic assessment of their effectiveness in the lifecycle.

Strategies 6, 8, 10, and 11 were identified as particularly effective, especially in addressing high-impact waste entry practices 1, 2, and 3 (Fig. 6). These strategies, especially, 6, 8, and 10, also address a wide range of entry practices, making them comprehensive solutions. However, their (strategies 6,8,10, and 11) impact varies across stakeholders (see supplementary material, Appendix D (Fig. D1)).

For example, strategy 6, shows high positive environmental impact but imposes a high financial burden on NAT and MUN due to infrastructure provision cost, including street bins, landfills, and recycling facilities. As Guerrero et al. (2013) noted, waste infrastructure development accounts for 80–95 % of the total budget. Therefore, to ease this financial burden, funding options like public-private partnerships and international collaborations can be explored (Srivastava et al., 2014), to improve financial sustainability (Lohri et al., 2014).

Similarly, strategy 8 yields positive environmental impact, with low negative financial impact on CON, RWP, and RWD. Formalizing IWC activities can have greater impact if skip container sites are provided within communities for disposal. This strategy also offers social benefits by ensuring economic stability for IWCs potentially alleviating poverty (Aparcana, 2017; Jayasinghe et al., 2019). The low negative financial impact on consumers may reduce their preference for this collection system, highlighting the need for microfinancing and subsidies for low-income areas (Aparcana, 2017).

In contrast, strategy 10, offering technical and infrastructure support, shows no negative social or financial burdens on stakeholders. Capacity building through workshops and field visits improves service

Table 2
Suggested mitigation strategies (1–12) for waste entry practices of the specific plastic item (water sachets, small bottles, EPS packs) in the Odaw catchment.

ID	Mitigation strategies	Category	Adapted from (Ref:)
1	Enforcement of taxes or levies on plastic product manufacturing to reduce plastic production and use.	Legislative and regulatory measures	(Romer and Tamminen, 2014)
2	Providing a comprehensive reward and incentive program on proper waste management practices among consumers aimed at promoting responsible disposal habits.		(Kibria et al., 2023)
3	Implementation of buy-back collection points by manufacturers to recycle their waste products and encourage the design of environmentally friendly products.	Extended Producer Responsibility	(Quartey et al., 2015)
4	Launching education campaigns aimed at consumers to promote sustainable plastic use and reduce plastic waste.	Awareness and Education	Interview and (Anuardo et al., 2022)
5	Educational campaigns targeting consumers, retailers, consumer product manufacturers and other commercial businesses on effective waste segregation practices to enhance recycling rates.		Interview and (Yalwaji et al., 2022)
6	Expansion and enforcement of waste management infrastructure by the municipal and national regulator to enhance the efficiency of waste collection services by waste collectors.	Organised waste management	Interview and (Salvia et al., 2021)
7	Establishing and enforcing centralized government billing on formal waste collection from waste generators (consumers, retailers, and consumer product manufacturrers) to provide consistent funding for waste collectors, thereby enhancing waste services reliability.		Interview
8	Engagement of informal waste collectors in formal waste management practices by municipal regulatory bodies to promote responsible disposal practices.		Interview and (Sharholy et al., 2008)
9	Engagement of waste pickers in formal waste management activities by waste collectors (formal and informal) to enhance visibilty, further reduce littered recyclables in the environment.		Interview and (Mensah and Nalumu, 2023)
10	Provision of technical and infrastructure support by municipal and national regulators to the informal sector (informal waste collector, recyclable waste picker and distrbutor) in waste management to enhance their collection performance and knowledge capacity on good waste practices.	Capacity building	Interview and (Zhu et al., 2007)
11	Enforcement of community sanitation taskforce by municipal regulator to ensure compliance to waste management regulations and promote responsible waste practices.	Community involvement & monitoring	Interview and (Dillon, 2020)
12	Institution of monthly communal cleaning coordinated by national and municipal regulators and Environmental organizations, involving consumers, retailers, waste collectors, waste pickers, and consumer product manufacturers to promote collective responsibility to waste management.		(Rangeti and Dzwairo, 2021)

delivery, fostering greater responsibility among stakeholders, leading to reduced plastic waste entry. Thus, given its broad positive impact and minimal downsides, this strategy is foundational for mitigating plastic waste entry in the Odaw catchment.

Study's limitations

While the study relied on qualitative data to identify MPW entry points within the life cycle of three highly polluted plastic items in the Odaw catchment, we acknowledge several limitations. First, time and resource constraints impacted the study's sample size. Due to the short timeframe of the study, combined with then resource-intensive nature of qualitative data collection and analysis, it was impossible to engage all intended individuals and organizations within certain stakeholder groups. Additionally, some stakeholders declined participation and others were unresponsive despite follow-up efforts, further limiting participation. Although the original plan was to interview at least two individuals per stakeholder group to ensure diversity of perspectives, in practice, this was reduced to one participant per stakeholder group.

Also, we were unable to engage consumers, retailers, informal waste collectors, from different neighborhoods along the river. Engaging these stakeholders from different neighborhoods in the catchment could have provided valuable insights into localized waste management practices dynamics. Their perspectives might have revealed whether waste practices and challenges vary across neighborhoods, and how these unique practices influence the broader waste management system in the catchment.

Another limitation was the study's inability to quantify the mass flow of plastic waste entering the environment. This would have helped illustrate the magnitude of waste entry into the environment at the various identified MPW entry points. Additionally, the study could not quantify the mismanaged plastic waste that eventually flows into the river. This could have provided a clearer understanding of the proportion of waste that accumulates on land and that which enters the river, thereby informing where mitigation strategies should be targeted. Despite these limitations, the study provides valuable insights into the MPW entry points of three highly polluted plastic items in the catchment and highlights stakeholder practices that contribute to their entry into the environment.

Implications and future directions

Stakeholder inclusive approach for improved waste management systems

The inefficiencies in the current waste management system, particularly the limited government intervention and inadequate waste infrastructure, highlight challenges common in Global South countries (Akeh and Shehu 2018; Rinasti et al., 2022). These gaps suggest the need for significant financial investment and stronger regulatory frameworks.

No.	Waste (plastic) entry practices	Impact to presence of MPW	Mitigation strategies											
			1	2	3	4	5	6	7	8	9	10	11	12
1	Direct littering or open dumping of generated waste by consumers or retailers.	High		✓	✓	✓	✓	✓		✓		✓	✓	✓
2	Open dumping or burning of uncollected waste by contracted waste service providers (formal or organised informal)							✓		✓		✓	✓	
3	Informal waste collectors openly dumping collected waste.							✓		✓		✓	✓	
4	Unrecovered littered plastic waste at open dump sites further dispersed to other environmental compartments by hydrometeorological factors.													✓
5	Losses during transportation by waste collectors (formal and organised informal) to engineered or unengineered landfill sites.	Medium						✓		✓		✓		
6	Unrecovered littered plastic waste at unengineered landfills further transported to other environmental compartments by hydrometeorological factors.													
7	Losses during handling and transportation of collected waste by waste collectors (formal or organised informal) between collection points.	Low										✓	✓	
8	Losses during transportation to Transfer stations by waste collectors (formal or organised informal).							✓		✓		✓		

Fig. 6. Mitigation strategies to the entry practices in the lifecycle of water sachets, small bottles, and EPS packs in the Odaw catchment. A '✓' in a box indicates that the mitigation strategy targets the specific waste entry practice. The green highlights identify mitigation strategies that effectively address a broad range of the entry practices across the different waste entry severity levels.

Such improvements address plastic waste entry and enhance public compliance, leading to reduced environmental pollution. The study also emphasizes the importance of stakeholder engagement in the design and implementation of waste management policies. An inclusive approach ensures that all relevant actors are considered, leading to more effective and sustainable solutions.

Insights from item-specific analysis

This study's item-specific waste entry approach, focusing on water sachets, small bottles, and EPS packs, provided detailed insights into the entry practices of these items. This offers a more nuanced understanding of how waste management practices for each specific item contribute to plastic pollution in the Odaw catchment. Unlike other waste entry studies (Rinasti et al., 2022) that used Material flow analysis to assess a broader category of plastic waste, our approach highlights the unique entry practices across the life cycle of these specific plastic items, which contribute to MPW. These findings suggest that more targeted strategies are needed, focusing on the specific plastic items prevalent in the environment. Expanding this item-specific approach to other prevalent plastic items in the environment could reveal additional critical entry points and inform targeted interventions. Moreover, this item-specific waste entry approach could also be adapted for other river systems globally, providing insights into the entry points of their prevalent plastic items.

Mass flow item-specific waste entry analysis

Because our study relied only on qualitative data to identify entry points in the lifecycle, a mass flow analysis (Lobelle et al., 2023) of the waste processes could help quantify the waste entry practices at the specific lifecycle points (Rinasti et al., 2022). Such an approach could provide a clearer understanding of entry magnitudes and impact on the environment. Moreover, the inclusion of mass flow data within the lifecycle could feed into global databases, contributing to a broader understanding of plastic waste flows, enhancing global analysis on plastic pollution sources in the terrestrial environment. Also, combining qualitative insights with mass flow data strengthens the robustness of identified plastic entry points. However, in data-scarce regions, where quantitative data on waste flows are unavailable or limited, the methodology developed in this study could serve as a useful framework to assess stakeholder involvement and identify plastic waste entry points. This approach can also serve as a methodological framework and baseline guide for data-sufficient areas.

Local insights for global research and policy

Our findings on identifying waste entry points offer valuable insights for global plastic pollution research by highlighting the local practices and factors contributing to MPW along the lifecycle. These localized insights are essential for policymakers to design targeted strategies that effectively address plastic pollution. Without this contextual understanding, global strategies may overlook local challenges, leading to inefficient solutions (Tallman & Cuervo-Cazurra, 2021). These insights also guide researchers in designing monitoring campaigns that target areas with high entry rates, allowing researchers to quantify the specific sources and pathways of plastic pollution more efficiently. Furthermore, incorporating such context-specific data into global models improves their accuracy by refining assumptions on the sources and entry practices of MPW, leading to more reliable predictions of macroplastic pollution.

Conclusions

This study highlights the roles and interdependencies of stakeholders across the specific plastic items' lifecycle in the Odaw catchment, revealing insights into informal waste collectors', recyclable waste pickers', and distributors' roles. Our approach to mapping stakeholder interdependencies and waste entry practices provides a foundational understanding of waste management challenges, particularly in underserved areas where formal systems may fall short. The study highlights the insufficient local recycling system, with EPS packs not recovered and small bottles though recovered not processed locally. Most entry practices occur post-consumption, with four of the eight waste entry practices identified as high-impact due to the large amount of waste they contribute. These practices are primarily driven by voluntary actions of consumers and some informal sector stakeholders, such as open dumping waste. Systemic inefficiencies linked to governmental and institutional, economic, and behavioural factors also contribute to plastic waste entry. We emphasize that formalizing informal waste collectors' roles and providing them with technical and infrastructure support improves operational performance and waste management practices, reducing plastic waste entry. These findings are crucial for policy development in the Odaw catchment and provides insights for other regions facing similar challenges. The methodology applied in this study could also serve as a model in these regions for identifying polluting plastics entry points. Future research should explore stakeholder dynamics in different geographical contexts while quantifying the magnitude of plastic waste entry practices and exploring other dominant polluting plastics in the environment.

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CRediT authorship contribution statement

Rose Boahemaa Pinto: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Makrita Solitei:** Writing – review & editing, Methodology, Conceptualization. **Martine van der Ploeg:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Janneke J.O. E. Remmers:** Writing – review & editing, Methodology. **Remko Uijlenhoet:** Writing – review & editing, Supervision. **Ivy Akuoko-Gyimah:** Methodology, Investigation. **Tim H.M. van Emmerik:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

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

Data availability

Processed data for this study will be available on 4TU Research repository [doi will be provided later].

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.envc.2025.101259.

Data availability

Processed data will be made available on a data repository

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