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Estimation of packaged water consumption and associated plastic waste production from household budget surveys

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Abstract

Packaged water consumption is growing in low- and middle-income countries, but the magnitude of this phenomenon and its environmental consequences remain unclear. This study aims to quantify both the volumes of packaged water consumed relative to household water requirements and associated plastic waste generated for three West African case study countries. Data from household expenditure surveys for Ghana, Nigeria and Liberia were used to estimate the volumes of packaged water consumed and thereby quantify plastic waste generated in households with and without solid waste disposal facilities. In Ghana, Nigeria and Liberia respectively, 11.3 (95% confidence interval: 10.3–12.4), 10.1 (7.5–12.5), and 0.38 (0.31–0.45) Ml day^{-1} of sachet water were consumed. This generated over 28 000 tonnes yr^{-1} of plastic waste, of which 20%, 63% and 57% was among households lacking formal waste disposal facilities in Ghana, Nigeria and Liberia respectively. Reported packaged water consumption provided sufficient water to meet daily household drinking-water requirements for 8.4%, less than 1% and 1.6% of households in Ghana, Nigeria and Liberia respectively. These findings quantify packaged water's contribution to household water needs in our study countries, particularly Ghana, but indicate significant subsequent environmental repercussions.

Introduction

Alongside its widespread consumption in high income countries, packaged drinking-water consumption has been growing in many low and middle income countries (LMICs) [1]. Packaged water comprises bottled, sachet and cooler water, sealed in plastic containers. In parallel with urbanisation and other socio-economic changes, discarded packaging raises particular challenges for solid waste collection [2] and disposal in resource-poor settings [3]. At times, this has resulted in widespread littering of used packaging, causing blocked gutters and flooding [4] and contributes to the global impact of plastics on marine and other environments [5]. In high income countries,

a growing literature has sought to quantify the environmental impact of packaged water consumption, such as those from different packaging alternatives and solid waste management options [6]. Given growing interest in the water-energy nexus [7], several studies in high income countries such as the USA [8] and Italy [9, 10] have also quantified the manufacturing and transportation-related energy costs of bottled water, alongside waste management. In LMICs, however, despite reported growth in packaged-water consumption, even basic data quantifying volumes of packaged water consumed at local or national scales remain scarce.

In LMICs, packaged water consumption is most common in urban areas lacking uninterrupted piped

water [11]. In urban West Africa, the industry emerged from street traders selling cups of water drawn from large containers to passers-by. In the 1990s, these traders began selling water in plastic bags tied at the corners and from 2000, affordable machinery enabled both small-scale entrepreneurs and large corporations to heat-seal water in plastic sleeves [12]. Ongoing issues of piped water coverage, quality, and continuity through this period meant consumer demand remained buoyant. From 2007, the subsequent policy response to this private sector-led phenomenon has variously included calls for an outright sachet ban in Nigeria, higher water tariffs and compulsory product registration for sachet producers in Ghana [13], and incentivisation of plastic recycling.

Given universal piped water services are unlikely in the short- to medium-term, comparatively low reported microbial contamination of packaged water in these countries [14, 15] and the perceived quality and convenience of packaged water among consumers [16], it seems that packaged water will remain a major drinking-water source in several countries. The long-term sustainability of this situation and the industry's environmental impacts thus need to be balanced against the potential public health benefit of contributing towards household water requirements.

The objectives of this study were to estimate:

1. Per household consumption of packaged water (bottled or sachet water, where sachet water refers to small volumes of water packaged in plastic sachets for drinking);

2. Packaged water use by type of water service;

3. Regional and urban/rural differences in packaged water consumption;

4. Sachet plastic waste generated by disposal method; and

5. The proportion of drinking-water needs supplied by packaged water.

Due to the lack of data regarding packaged water consumption in LMICs, we developed a method to quantify packaged water consumption via the novel utilisation of household expenditure survey data. Three case study countries in sub-Saharan Africa were selected based on the availability of micro-data from household budget surveys with information on quantities of packaged water purchased or consumed: Ghana, Liberia and Nigeria. The majority of the current literature on packaged drinking-water in LMICs is focussed on Ghana due to the relatively high rates of packaged water use in this country: here we also include Liberia and Nigeria to enable cross-country comparison.

Methods

Data
Data from the 2012–13 Ghana Living Standards Survey Round 6 (GLSS6), the 2012–13 Nigeria General Household Survey Panel Wave 2 (NGHS-panel) [17, 18] and the Liberia Household Income and Expenditure Survey 2014–15 (LHIES) were used. These countries were selected for analysis due to the availability of household survey data that explicitly capture packaged water purchasing or consumption. The purchasing or consumption data from household surveys are typically used to assess household consumption aggregates, which in turn are used to define poverty. The analysis presented here utilises these data in an innovative way to provide estimates of packaged water consumption in the study countries.

The GLSS6 and LHIES were designed to be nationally and regionally representative. In Ghana, 1200 enumeration areas (EAs) were selected from within 10 regions, using probability-proportional-to-population size, with fieldwork in each region over 12 months. Within each selected EA, 15 households were systematically selected, giving an overall sample size of 18 000 households. In Liberia, a sample of 836 EAs was planned with 10 systematically selected households per EA, but fieldwork was halted by the Ebola outbreak in August 2014 after only 409 EAs had been sampled. Although planned county-level representation was lost, the sample of 4090 households was reweighted to be regionally representative. The NGHS-panel was designed to be nationally representative: 500 EAs were selected using probability-proportional-to-size with 10 households systematically selected per EA, giving an overall sample size of 5000 households. The NGHS-panel was conducted in two rounds (post-planting and post-harvest). The surveys covered household demographic and socio-economic indicators, and expenditure (GLSS6 and NGHS-panel) or consumption (NGHS-panel and LHIES) relating to common commodities, including bottled and sachet water. All surveys also recorded commodity prices.

The authors estimated quantities of sachet plastic packaging by recording the weights of plastic sleeve rolls on sale and related numbers of sachet units per roll.

Estimation of per household consumption of packaged water
In the Ghanaian GLSS6, packaged water expenditure and unit prices were recorded, but not volumes consumed or purchased, so we calculated volumes purchased by dividing expenditure by the appropriate price. Since the survey recorded household expenditure via six separate visits, we calculated average daily packaged water expenditure across all six visits. Up to three prices were recorded during the survey for sachet

and bottled water products in 118 market places across Ghana, along with measurement units. Outliers (>GH¢2.5 per litre for bottled water and >GH¢0.5 per litre for sachet water) were excluded. Since bulk sachet purchases (bags of 30×500 ml sachets rather than individual 500 ml sachets) are discounted, we calculated separate prices per litre for small (<2 litre; i.e. single sachets purchased) and large volume (bulk purchase) transactions. The price per litre was calculated for each market observation. Median national prices were then used to convert packaged water expenditure into volumes, separately for water sachets versus bottles and single versus bulk purchases (≥GH¢2.0 for bottled water and ≥GH¢1.50 for sachets).

The Nigeria survey directly recorded volumes of packaged water purchased and consumed per household during the seven days prior to interview: volumes purchased were analysed for consistency with Ghana (where purchases were also recorded). The Liberian survey recorded packaged water volumes consumed per household during the seven days prior to interview. Hereafter we will use the terms 'consume' and 'consumption' for simplicity, which encompasses both purchases and direct oral consumption.

For all surveys, we divided the daily volume of water consumption by household size to estimate daily litres consumed per person. To estimate the number of sachets consumed by households, we multiplied the daily volume in litres of sachet water consumed (total of bulk and single purchases) by households by two (each sachet contains 500 ml). The number of bottles consumed was not calculated due to variation in the volumes of bottled water on the market.

Estimation of packaged water use by type of water service

The data were summarised to estimate the percentage of households who consume packaged water (sachet or bottled water) by reported primary drinking-water source.

Estimation of regional differences in packaged water consumption

We summed the number of sachets consumed by households for each study country, accounting for the survey design, to estimate the daily number of sachets consumed nationally, regionally (with the exception of Nigeria, as the survey used was not designed to be regionally representative) and by urban versus rural areas.

Estimation of sachet plastic waste generated by disposal method

We multiplied the estimated national number of sachets consumed by the estimated weight of primary packaging to estimate the total weight of plastic waste generated by sachet water consumption in each study country. Due to variation in bottled water volumes

sold and the potential reuse of water bottles, this was not undertaken for bottled water. The estimated weight of plastic waste generated was also summarised by the main waste disposal method used by households. All data analyses accounted for the survey design using the *svy* commands in Stata [19]. Strata with a single sampling unit (NGHS-panel and LHIES) were treated as certainty units, scaled by average within strata variance.

Estimation of the proportion of drinking-water needs supplied by packaged water

Recommended daily water requirements (from beverages) developed for temperate climates, by gender and age group [20], were adjusted upwards by 20% to account for the West African climate. This increase was based on total liquid recommendations for adult males in a 30 °C environment, under non-active work conditions [20]. We then applied Loess smoothing, conducted in the R statistical software [21], to provide estimates of daily drinking-water requirements for males and females aged 1 to 19 years (see figure 1). We assumed that children under six months of age were exclusively breastfed based on current recommendations for infant feeding. We recognise exclusive breastfeeding rates in the study countries are not 100% (52% in Ghana, 55% in Liberia and 17% in Nigeria) and, thus, our estimates of drinking-water requirements will be underestimates [22–24]. We applied these age- and gender-specific drinking-water requirements to survey household members to estimate household daily drinking-water requirements. Where the daily volume of packaged water consumed was at least one litre less than the estimated daily household requirement, a household was classified as consuming insufficient packaged drinking-water to meet daily drinking-water requirements.
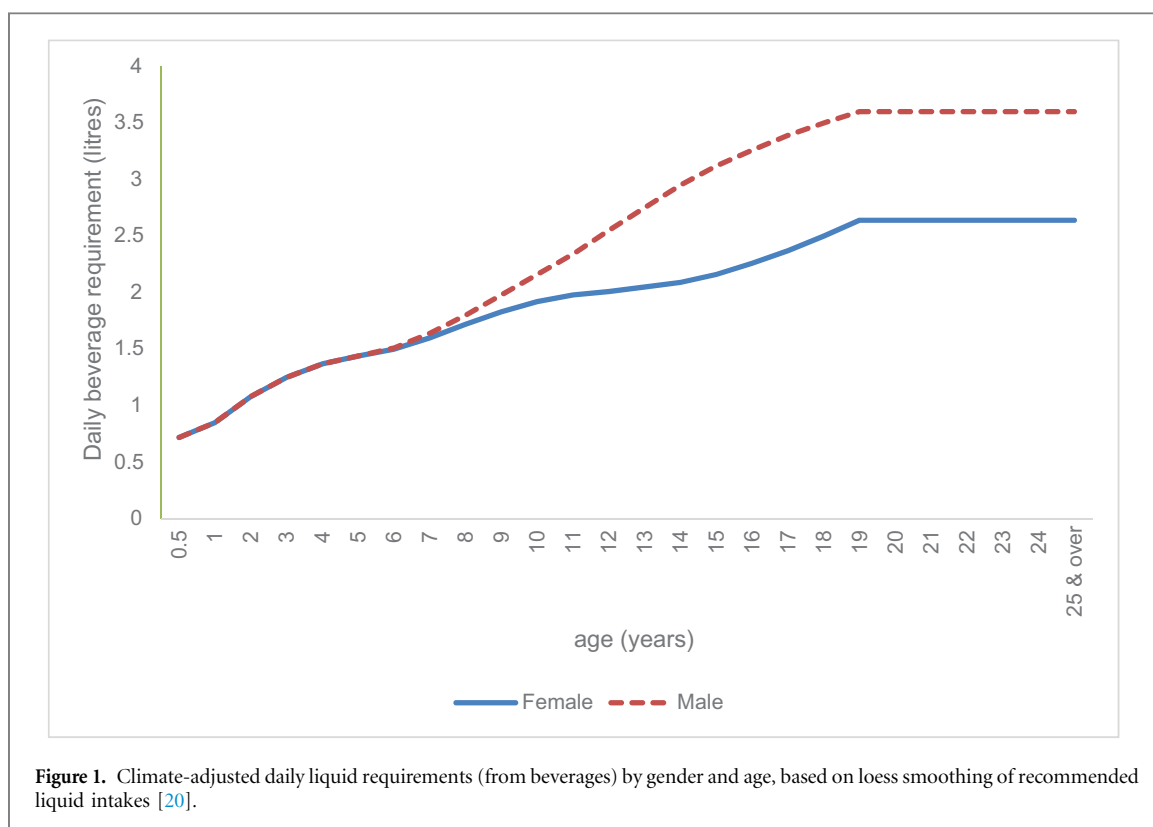
See also table 1 for a summary of the analysis steps undertaken for each of the three study countries.

Results

Estimation of per household consumption of packaged water and packaged water use by type of water service

In Ghana, the median prices for single and bulk sachet water purchases were GH¢0.2 per litre (equivalent to approximately £0.04 or $0.05; mean = GH¢0.2) and GH¢0.1 per litre (approximately £0.02 or $0.03; mean = GH¢0.1) respectively. The median price for single purchases of bottled water was GH¢1 per litre (£0.19 or $0.25; mean = GH¢1.14) and GH¢0.40 (£0.08 or $0.10; mean = GH¢0.38) for bulk purchases.

Sachet water was consumed by 63% and bottled water by 4.1% of households in Ghana, based on GLSS6 data. Amongst households consuming bottled or sachet water, the mean volume consumed was 0.97 l/person/day (pppd; median = 0.51,

Figure 1. Climate-adjusted daily liquid requirements (from beverages) by gender and age, based on loess smoothing of recommended liquid intakes [20].

Table 1. Summary of analysis steps undertaken for each study country (X indicates that the analysis step was carried out for the country in question).

	Ghana	Nigeria	Liberia
Raw data	Expenditure unit prices	Volume purchased	Volume consumed
Data processing	Expenditure/price per litre = volume purchased	None required	None required
Calculate daily household consumption of packaged water	X	X	X
Estimate packaged water use by type of water service	X	X	X
National estimates of sachet water consumption	X	X	X
Regional estimates of sachet water consumption	X	Not possible as survey was not regionally representative	X
Urban vs rural estimates of sachet water consumption	X	X	X
Estimate packaged waste generated by disposal method	X	X	X
Estimate proportion of drinking-water needs supplied by packaged water	X	X	X

range = 0.001 to 42.83; see table 2). Although the mean volume consumed was considerably higher for those reporting bottled or sachet water as their main drinking-water source (1.63 l pppd), 8.5% of these households did not consume any packaged water during the survey.

In Nigeria, sachet water was consumed by 23.4% and 24.8% of households during the post-planting and post-harvest rounds respectively, whilst bottled water was consumed by 2.0% in both seasons. Only 14.63% of households consumed packaged water during both survey rounds, with 21.3% consuming

packaged water in one survey round only. Within households that consumed packaged water, a mean of 0.25 l pppd was consumed during the post-planting round (median = 0.05) and 0.37 l pppd during the post-harvest round (median = 0.04; see table 3). Households reporting bottled or sachet water as their main drinking-water source had the highest mean and median values for litres of packaged water consumed pppd (mean = 0.51 l pppd; median = 0.36 l pppd during the post-planting round and mean = 0.88 l pppd; median = 0.48 l pppd during the post-harvest round). Of the households that reported

Table 2. Percentage of Ghanaian households consuming packaged water, and summary statistics for volumes of water consumed (excluding non-consuming households).

Main source of drinking-water	Consumed packaged water		Litres of packaged water consumed pppd		
	%	Households	Mean	Median	Range
Piped to premises	71.2%	421 394	1.07	0.65	0.006–42.83
Piped–neighbour	68.4%	331 947	0.87	0.54	0.005–13.63
Public tap, standpipe or tanker	67.8%	577 188	0.65	0.30	0.003–35.67
Borehole, pump, or tube well	44.5%	785 315	0.42	0.17	0.002–20.35
Protected well or spring	62.5%	149 612	0.56	0.31	0.006–5.27
Unprotected well or spring	30.8%	59 516	0.35	0.16	0.002–3.87
Surface water or other	30.9%	177 699	0.29	0.14	0.001–4.0
Rainwater	43.5%	12 183	0.71	0.25	0.005–13.33
Bottled or sachet water	91.5%	1 710 000	1.63	1.14	0.006–30.0
Total	**64.1%**	**4 230 000**	**0.97**	**0.51**	**0.001–42.83**

Table 3. Percentage of Nigerian households consuming packaged water, and summary statistics for volumes of water consumed (excluding non-consuming households), for both post-planting and post-harvest rounds.

Main source of drinking-water[a]	Consumed packaged water		Litres of packaged water consumed pppd		
	%	Households	Mean	Median	Range
Post-planting					
Piped	31.9%	1 200 000	0.35	0.15	0.0005–2.86
Borehole or hand pump	28.9%	3 240 000	0.22	0.03	0.0005–11.43
Protected well or spring	16.0%	723 166	0.20	0.12	0.0004–1.51
Unprotected well or spring	11.4%	416 100	0.15	0.09	0.001–1.02
Surface water or other	9.7%	344 267	0.10	0.01	0.001–1.43
Rainwater[b]	30.1%	63 915	0.09	0.05	0.005–0.29
Tanker, truck or vendor	21.3%	156 983	0.20	0.02	0.001–2.35
Bottled or sachet water	67.9%	883 848	0.51	0.36	0.0003–2.86
Total	24.5%	7 170 000	0.25	0.05	0.0003–11.43
Post-harvest					
Piped	31.0%	1 200 000	0.42	0.18	0.001–5.0
Borehole or hand pump	30.3%	3 460 000	0.19	0.02	0.0003–5.71
Protected well or spring	19.0%	878 561	0.20	0.04	0.0003–3.57
Unprotected well or spring	15.0%	555 794	1.19	0.02	0.0003–71.43
Surface water or other	9.8%	348 268	0.11	0.02	0.001–2.86
Rainwater[b]	22.1%	55 568	0.06	0.02	0.002–0.36
Tanker, truck or vendor	29.9%	224 377	0.11	0.02	0.0007–1.43[a]
Bottled or sachet water	71.7%	956 116	0.88	0.48	0.008–28.57
Total	**26.0%**	**7 680 000**	**0.37**	**0.04**	**0.0003–71.43**

[a] Main dry season drinking-water source.

[b] Note small number of households who consumed water in this category, hence summary statistics are based on $n < 10$.

packaged water as their main drinking-water source, 32.2% and 28.3% did not report consuming any packaged water during the post-planting and post-harvest rounds respectively.

In Liberia, 19.5% of households reported packaged water consumption (table 4), of whom 1.0% consumed bottled water. Among those reporting consumption of packaged water, an average of 0.791 pppd (median 1.07) was consumed. Although, volumes consumed were greatest (1.431 pppd) amongst households that reported mineral water (a sub-type of packaged water, although after reviewing this survey's implementation, we assume it would report all packaged water as mineral water) as their main drinking-water source, 38.3% of these households did not report any packaged water consumption during the survey period.
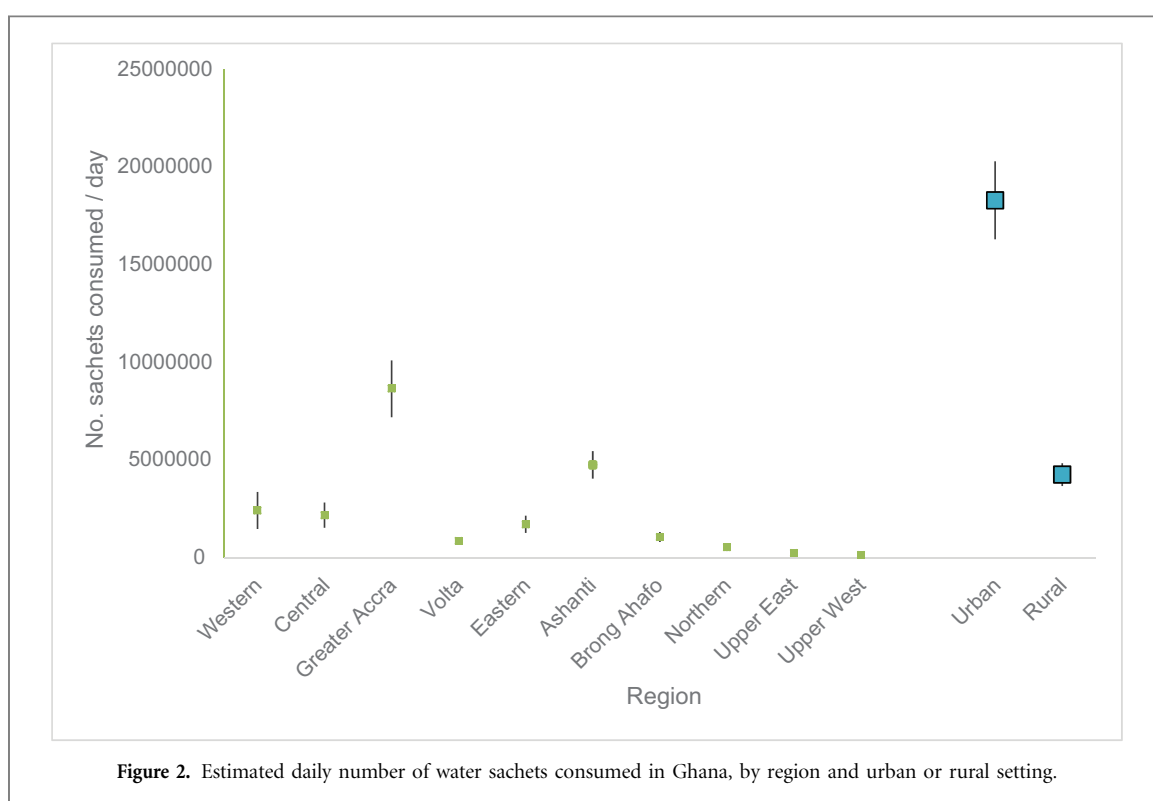
Estimation of regional differences in packaged water consumption

We estimate that from 2012 to 2013, 22.5 million water sachets were consumed daily in Ghana (95% confidence interval [CI] = 20.5 million to 24.7 million). Greater Accra contributes the largest number (just over 8.5 million), and Upper East and Upper West contribute the smallest numbers (see figure 2). Most sachet water consumption occurred in urban areas (18.3 million, compared to 4.26 million in rural settings).

In Nigeria, we estimate that over the same period approximately 20 million drinking-water sachets were consumed daily (95% CI = approximately 15 million to 25 million; see figure 3), predominantly in urban areas (16.5 million, compared to 3.6 million in rural settings based on the post-planting round).

Table 4. Percentage of Liberian households who consumed packaged water, and summary statistics for volumes of water consumed (excluding non-consuming households).

Main source of drinking-water	Consumed packaged water		Litres of packaged water consumed pppd		
	%	Households	Mean	Median	Range
Indoor pipe or pump	12.9%	4425	0.82	0.54	0.06–3.00
Outdoor pipe or pump	19.1%	49 076	0.72	0.43	0.02–3.75
Public standpipe or tap	25.2%	41 293	0.71	0.36	0.02–3.00
Borehole or tubewell	18.3%	33 550	0.44	0.25	0.02–2.14
Neighbouring household	28.4%	2082	0.77	0.75	0.75–0.8
Water vendor	47.7%	6399	0.99	1.00	0.14–2.14
Closed well	16.0%	9882	0.46	0.14	0.02–2.14
Open well	8.6%	2777	0.10	0.04	0.01–0.5
River, lake or creek	3.0%	4135	0.35	0.14	0.03–1.5
Mineral water	61.7%	28 567	1.58	1.43	0.07–4.29
Other	40.1%	917	0.45	0.31	0.31–0.71
Total	**19.5%**	**183 103**	**0.79**	**1.07**	**0.01–12.86**

Figure 2. Estimated daily number of water sachets consumed in Ghana, by region and urban or rural setting.

In Liberia, we estimate that from 2014 to 2015, 0.76 million drinking-water sachets were consumed daily (95% CI 0.62–0.90 million), overwhelmingly in urban areas (0.74 million, compared to 0.04 million in rural settings). The largest volume consumed was in Montserrado, the region incorporating the capital, Greater Monrovia (0.6 million; see figure 4).

Estimation of sachet plastic waste generated by disposal method

A typical sachet sleeve roll weighing 16–18 kg produced 9600 sleeves, implying 1.67–1.85 g of plastic per sachet: we used a weight of 1.7 g for the calculation of plastic waste generated. Applying this figure to total sachet consumption suggests

14 000 tonnes of HDPE or LDPE primary packaging were generated annually in Ghana from sachet use. The majority (80%) of this was among households whose solid waste was mainly collected or taken to a public dump (see figure 5). In Nigeria, we estimate that 13 600 tonnes of plastic waste from sachet primary packaging was generated annually. In contrast to Ghana, however, 63% of this was generated by households with no solid waste disposal facilities or whose main solid waste disposal was indiscriminate dumping at unauthorised refuse sites or burning (see figure 6). In Liberia, 474 tonnes of plastic waste from sachet primary packaging were produced annually, with most (57%) of this being generated by households lacking publicly or privately organised solid waste collection (see figure 7).
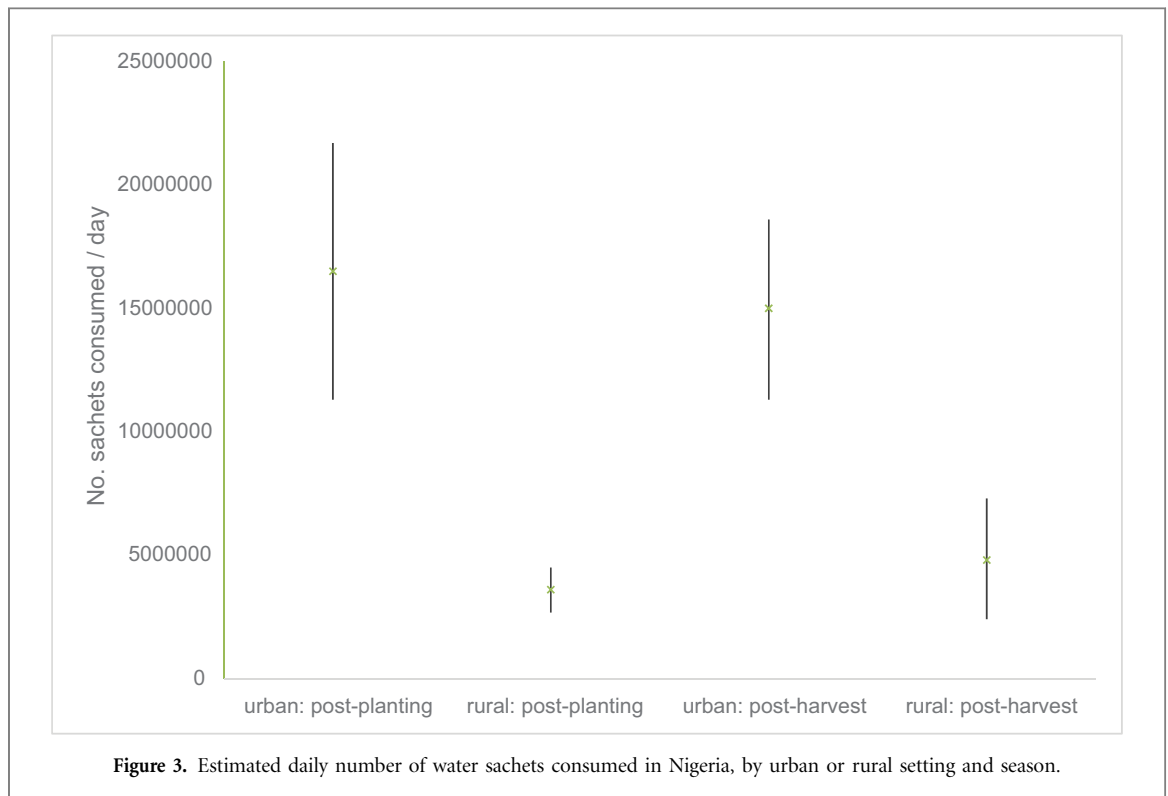
Figure 3. Estimated daily number of water sachets consumed in Nigeria, by urban or rural setting and season.
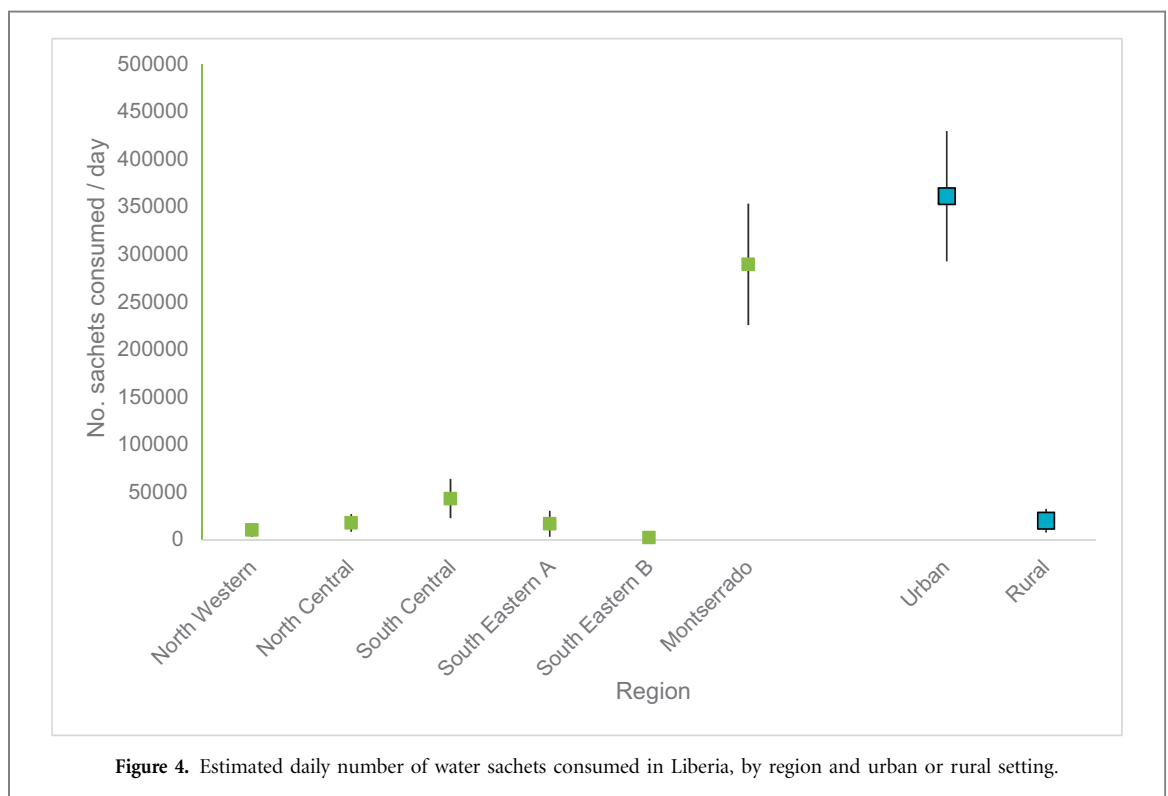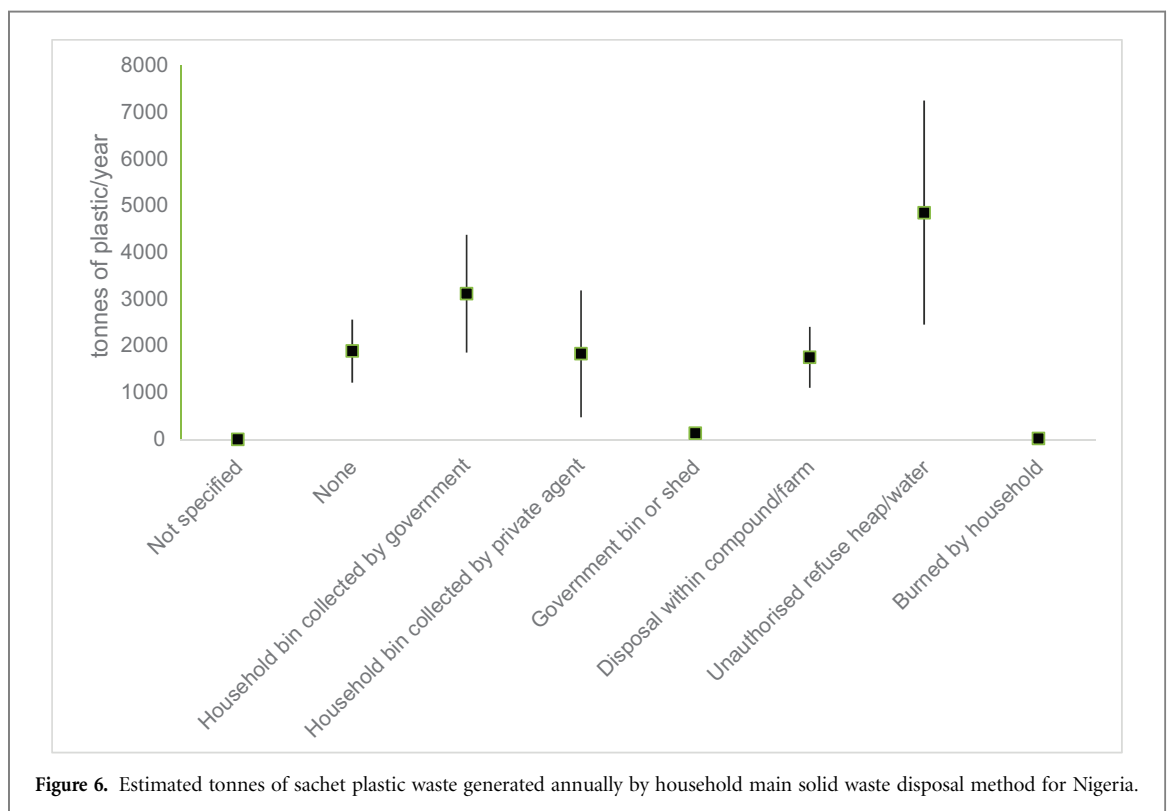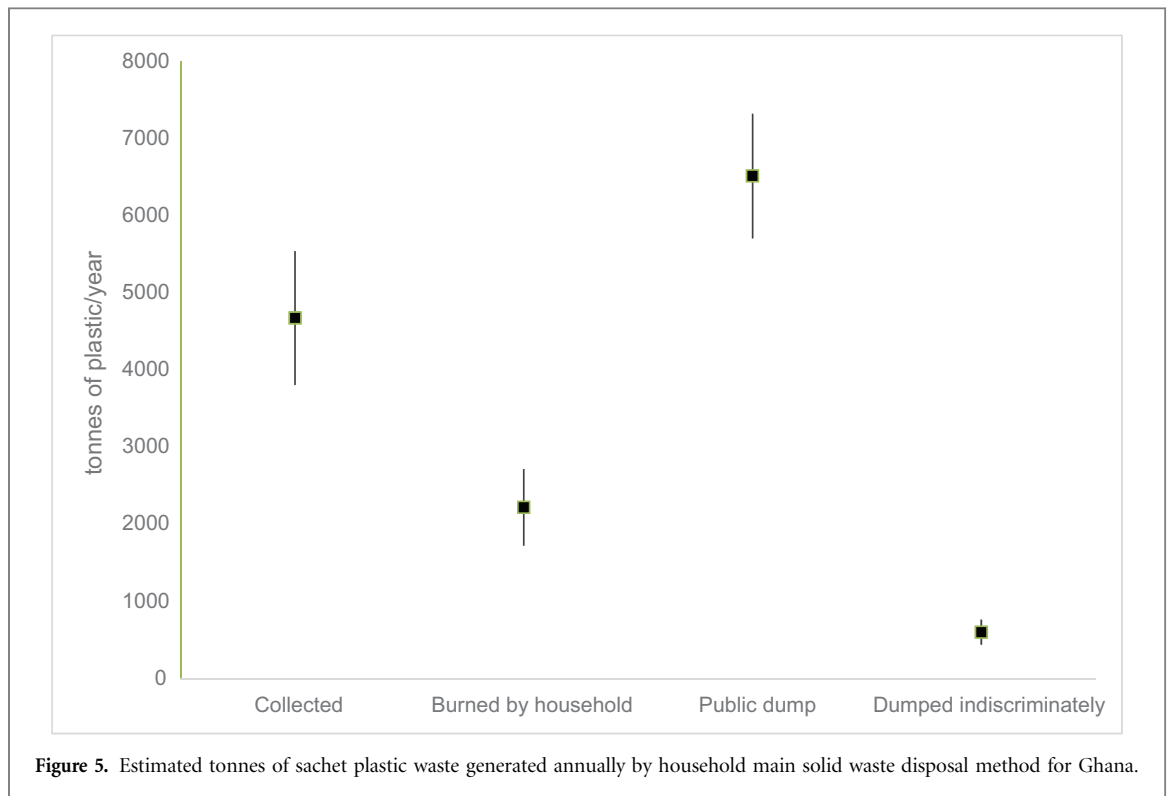

Figure 4. Estimated daily number of water sachets consumed in Liberia, by region and urban or rural setting.

Estimation of the proportion of drinking-water needs supplied by packaged water

In Ghana, 8.4% of households were estimated to consume sufficient packaged water to meet their daily household drinking-water requirements (see table 5). This proportion was greatest (22.3%) amongst households who report bottled or sachet water as their main source of drinking-water, but for all

reported main drinking-water sources, small proportions of households consumed sufficient packaged water to meet daily household drinking-water requirements. Based on the NGHS-panel data, less than 1% of households are estimated to consume sufficient packaged water to meet household drinking-water requirements in Nigeria. This percentage is low for all reported main sources of drinking-water, but slightly

Figure 5. Estimated tonnes of sachet plastic waste generated annually by household main solid waste disposal method for Ghana.

Figure 6. Estimated tonnes of sachet plastic waste generated annually by household main solid waste disposal method for Nigeria.

higher in the post-planting period and among households reporting bottled or sachet water as their main source of drinking-water. In Liberia, an estimated 1.6% of households reported consumption of sufficient packaged water to meet daily drinking-water requirements, rising to 12.0% among households whose main drinking-water source was recorded as mineral water.

Discussion

There is a growing body of evidence highlighting increased packaged water consumption in LMICs, particularly in urban areas. Despite national and international concern about the unsustainable nature of packaged water and subsequent environmental impacts, there have been few attempts to quantify the
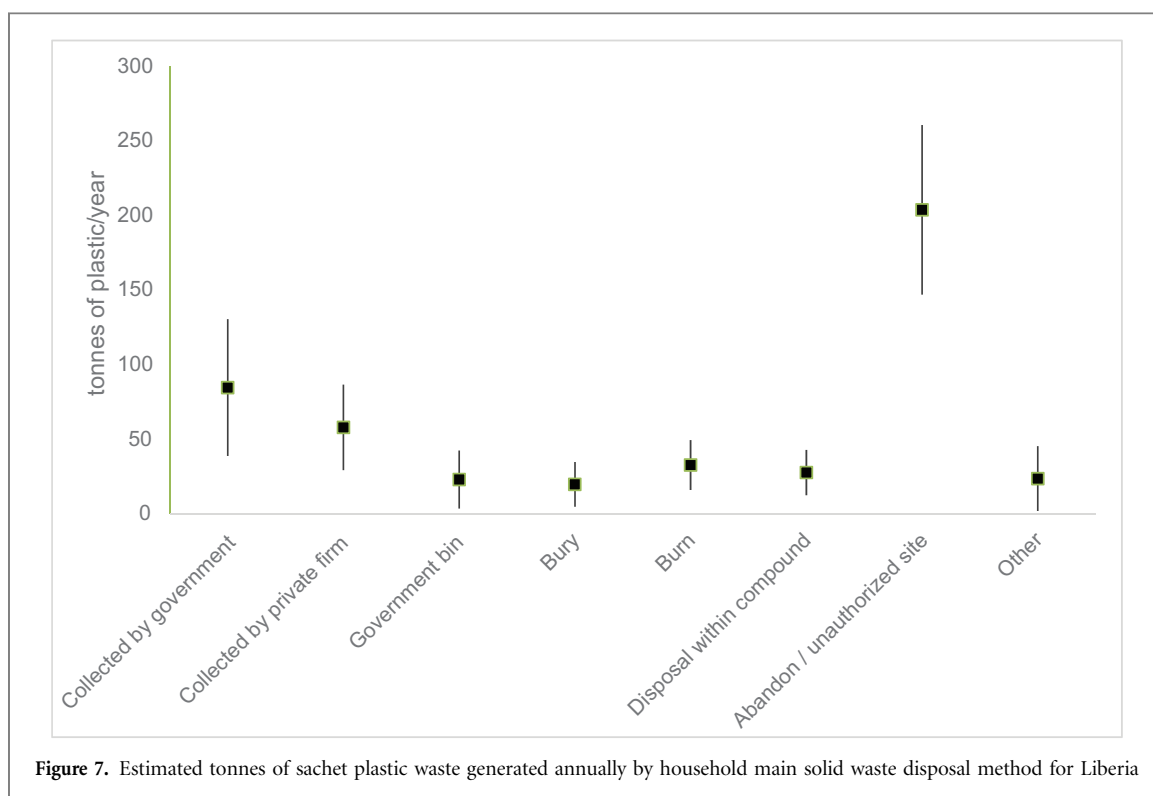
Figure 7. Estimated tonnes of sachet plastic waste generated annually by household main solid waste disposal method for Liberia

Table 5. Percentage of households that consume sufficient packaged water to meet daily household drinking-water requirements in Ghana, Nigeria, and Liberia, by main drinking-water source and season.

Water source	Ghana	Nigeria: post-planting	Nigeria: post-harvest	Liberia
Piped to premises	8.6%	–	–	4.8%
Piped to neighbour	5.9%	–	–	0%
Public tap, standpipe or tanker	3.2%	–	–	2.4%
All piped water (in Nigeria)	–	0.6%	1.5%	–
Tanker, truck or vendor	–	0.4%	0%	0%
Borehole, pump, or tube well	1.3%	0.7%	0.1%	0.1%
Protected well or spring	2.6%	0%	0.2%	0%
Unprotected well or spring	0.7%	0%	0.7%	0.8%
Surface water or other	0.3%	0.2%	0.1%	0.1%
Rainwater	1.0%	0%	0%	–
Bottled or sachet water	22.3%	4.3%	1.0%	12.0%
Total	**8.4%**	**0.6%**	**0.4%**	**1.6%**

scale of the problem in LMICs and to explore links to water service provision and solid waste disposal. Based on the novel application of nationally representative household budget survey data, we estimate that in Ghana, Nigeria and Liberia, 8.2 billion, 7.3 billion and 277.4 million water sachets respectively are consumed annually. This represents 14 000, 13 600, and 415 tonnes yr^{-1} of plastic waste from primary high-density polyethylene (HDPE) and low-density polyethylene (LDPE) packaging in Ghana, Nigeria and Liberia respectively, totalling over 28 000 tonnes yr^{-1} from these three countries, posing a significant environmental challenge. This consumption is largely urban, reflecting the macro-economic association between urbanisation and consumption-related environmental impacts [25].

Based on 2015 national population estimates [26], annual per capita sachet water consumption was 149.8 l in Ghana, 20.0 l in Nigeria and 30.9 l in Liberia. Annual bottled water sales in the United States and the United Kingdom from 2013 amounted to 143.0 and 36.5 l per capita respectively, comparable to annual per capita consumption in Ghana and Liberia respectively [1, 27]. This confirms high levels of overall packaged water consumption in West Africa, and particularly in Ghana. For context, the Ghana Water Company Limited was estimated to have provided 338 million litres of water per day in 2012 (based on simple linear extrapolation of data from 2001 to 2009), 30 times the volume provided by water sachets, and in Nigeria, water utility companies provide approximately 1.38 billion litres per day,

138 times the volume provided by water sachets [28]. The financial cost of sachet water is also substantially higher, per unit, than piped water.

Our analysis suggests that sachet water consumption generates over 28 000 tonnes yr^{-1} of plastic waste from primary HDPE/LDPE packaging in Ghana, Nigeria and Liberia. An attempt to quantify the energy footprint of the bottled water industry estimated that 1 million tonnes of polyethylene terephthalate (PET) plastics were required in the United States in 2009, equating to approximately 50 million barrels of oil [8]. Relative to this, the West African waste stream is comparatively small, reflecting the smaller quantities of plastic used in sachets rather than PET bottles. However, 20%, 63% and 57% of this consumption in Ghana, Nigeria, and Liberia respectively was among households lacking formal waste disposal facilities, which clearly represents a major challenge in these countries. Until substantive improvements in piped water supplies can be made in these countries, consumer demand for packaged drinking-water will continue to rise and emphasis should be placed on collection and recycling activities to prevent accumulation in the environment. Currently, rates of recycling in Ghana, Nigeria and Liberia are low, although reliable data are not available [29, 30]. For example, in Ghana it has been estimated that only 2% of plastic wastes are currently recycled [31]. In addition, while plastic bottles may be reused, there is no way to reuse a water sachet, and the HDPE/LDPE plastic is of lower value for recycling than PET plastics. Much waste sorting (which allows recycling of materials such as plastics) in LMICs is carried out by itinerant waste pickers (scavengers), mainly at refuse dumps [32]. Our previous work in Greater Accra established that household collection of used water sachets had been developed through the government-industry Plastic Waste Management Project initiative, whereby householders could sell packaging to door-to-door waste collectors [33]. There is scope for informal waste collectors to be included in an integrated waste management system to tackle the problem of environmental pollution [34].

Our analysis highlights the widespread sachet consumption in both Nigeria and Ghana, despite their very different strategies for urban water service provision. In Nigeria, service provision is private sector-led and large contracts awarded to private utilities (e.g. the Borno water supply project) have been criticised for their ineffectiveness and lack of transparency [35]. In Ghana, a single state-owned company, the Ghana Water Company Limited, is responsible for urban water supply, but coverage gaps and piped supply interruptions remain widespread [36]. Despite these differing service provision policies, in both countries the packaged water industry has emerged to fill the gap. As figures 2 to 4 suggest, if the entry of plastic waste into the urban environment is to be minimised, particularly in Nigeria, there is an urgent need for solid waste management investment by government.

Our analysis suggests that for some households, packaged water is an important ancillary drinking-water source. Given that population censuses and surveys typically only record primary drinking-water source [37], such data may understate the importance of packaged drinking-water. In countries where sachet water is widely used (e.g. Ghana and Nigeria), there have been proposed bans on sachet water or associated plastics to prevent littering, and planned tax increases to fund waste collection efforts [16]. However, in contrast to the situation in high income countries, many packaged water consumers in LMICs lack uninterrupted piped water to the home. Our comparison of volumes of packaged water consumed with estimated household drinking-water requirements suggests a significant proportion of the population, particularly in Ghana, is dependent on this industry for their drinking-water. The increasing reliance of low income households on sachet water means that the introduction of any such policies would disproportionately impact water access and financial stability for the poorest sections of society [38, 39]. Further policy proposals to tackle associated waste management must be balanced against the potential public health impacts on consumers. So far, these public health benefits remain unquantified [33] but if shown to be substantial, they need to be considered when framing taxation and regulation policies which could have a regressive income effect on the poor.

Our study highlights the potential to utilise household expenditure surveys to understand patterns of packaged water consumption and to quantify their environmental impacts in LMICs. By providing subnational estimates of packaged water consumption and the availability of solid waste disposal facilities, the findings enable targeting of areas where the environmental impact is expected to be largest. Such budget surveys, which record solid waste disposal as well as household consumption, are typically collected by national government statistical agencies rather than via industry and have been conducted for many LMICs (e.g. the Gambia, Sierra Leone). Packaged water purchases or consumption are explicitly included in a small number of national surveys currently: as trends in drinking-water availability change in additional LMICs, inclusion of packaged water within these budget surveys could provide the means to monitor volumes used and subsequent plastic waste production from these lifestyle changes. Micro-data at the household level are often accessible, facilitating in-depth and transparent analysis of packaged-water consumption patterns with estimation of confidence intervals to account for sampling design. Our methodology should be transferable to

other countries where appropriate household budget survey data are available, allowing the quantification of lifestyle-related consumption patterns and domestic waste streams in LMICs, including products of relevance to water, sanitation and hygiene; for example soap or sanitary products. Alternative data sources, such as market research reports (often generated via the packaged water industry itself) can provide data on quantities of packaged water consumed nationally (e.g. Rodwan [1]). However, because of their commercial value, these remain comparatively costly and the underlying raw data inaccessible. Field-based quantification of solid wastes from individual households or waste management facilities can be used to estimate solid waste volumes, by type of waste [31, 40–42]. In practice, the assessment of specific waste types (e.g. packaged drinking-water related waste) has rarely been conducted, with most studies focussing on broader categories (e.g. paper; plastic etc). In addition, data generated via this method are typically not comparable between studies due to varying waste characterisation categories, and studies mainly focus on subnational levels (e.g. within specific cities or states) and particular solid waste disposal systems, limiting their utility for national level estimates of consumption and waste production.

There are several sources of uncertainty inherent in the data and analysis. Responses to retrospective budget surveys implicitly focus on consumption in the home rather than elsewhere and can be subject to recall bias. The recall periods in the surveys were 14 days or less, which should minimise this issue [43], although the use of a single seven day recall period in the NGHS-panel survey may not capture irregular bulk purchases by households, thus potentially resulting in underestimation of packaged water consumption. We also do not include secondary packaging in estimating plastic waste. Household waste disposal data will not reflect domestic waste separation of used sachet packaging, which is known to take place in parts of Accra [33]. In addition, there is uncertainty around estimated household water requirements (and subsequent assessments of sufficiency of consumed water for household requirements), as individual requirements vary depending on environmental conditions, activity levels, food intake and physiology [44–46].

In conclusion, high rates of packaged water consumption were evident in our study countries, particularly Ghana, which has important environmental repercussions. Our methodology enables the quantification of packaged water consumption and associated plastic waste at the national and subnational levels. If a private packaged water industry is to continue to fill coverage gaps left by both public and private water utilities there is a requirement for public investment in integrated waste management and recycling solutions to reduce the entry of plastic waste into the environment.

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