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RESEARCH ARTICLE

Disposable diaper consumption in sub-Saharan Africa: Estimating the risks of associated unsafe waste

Mair L. H. Thomas-Possee[1¤], Peter J. Shaw[1], Robert E. S. Bain[2], Allan G. Hill[3], Joseph Okotto-Okotto[4], Lorna G. Okotto[5], Mawuli Dzodzomenyo[6], Jim A. Wright[1]*

1 School of Geography and Environmental Science, University of Southampton, Southampton, United Kingdom, **2** UNICEF Regional Office for the Middle East and North Africa, Amman, Jordan, **3** School of Economic, Social and Political Sciences, University of Southampton, Southampton, United Kingdom, **4** Victoria Institute for Research on Environment and Development (VIRED) International, Rabuor, Kenya, **5** School of Spatial Planning and Natural Resource Management, Jaramogi Oginga Odinga University of Science and Technology, Bondo, Kenya, **6** Ghana School of Public Health, University of Ghana, Accra, Ghana

¤ Current address: WaterAid UK, London, United Kingdom.
* j.a.wright@soton.ac.uk

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Abstract

Disposable diaper use is widespread in many low- and middle-income countries whilst waste collection services are scarce. Despite the potential environmental and public health impacts of disposable diaper consumption by households lacking waste services, an international system for monitoring such consumption is lacking. This study therefore aims to develop and evaluate a method for estimating disposable diaper use based on secondary data, specifically nationally representative household expenditure surveys. Disposable diaper expenditure reported via household expenditure surveys for Nigeria (from 2018–19), Kenya (2015–16) and Ghana (2016–17) was used to estimate national disposable diaper consumption among households lacking waste collection services. To assess plausibility of reported expenditure, consumption-smoothing was examined, and Receiver Operating Curve analysis was used to infer mean toilet-training age. In Ghana, Kenya and Nigeria, households lacking appropriately managed waste services consumed an estimated 19 million, 210 million and 285 million disposable diapers per year (292 child/year, 433 child/year and 59 child/year among nappy-consuming households), respectively. Mean toilet-training ages were 24 to 30 months. Disposable diaper purchasing patterns showed evidence of consumption-smoothing among poorer households. Where commodity coding allows, household expenditure surveys can be used to construct internationally comparable indicators depicting disposable diaper consumption among households lacking waste services. Such indicators could be used to advocate for accelerated diaper product innovation, and target areas with high disposable diaper consumption but low waste service coverage.

Kenya National Bureau of Statistics at https://statistics.knbs.or.ke/nada/index.php/catalog/13/study-description and the Nigerian National Bureau of Statistics https://www.nigerianstat.gov.ng/nada/index.php/catalog/68/study-description.

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Author summary

Rapidly changing urban lifestyles in low and middle-income countries are leading to greater consumption of many products that generate plastic waste including disposable diapers. Whilst convenient, disposable diaper consumption pose waste management challenges in cities where coverage of waste collection services is incomplete, risking their entry into the environment. In our study, inspired by our own field observations of discarded diapers, we used household expenditure surveys to estimate consumption of disposable diapers among households lacking waste services in Ghana, Kenya, and Nigeria. We find households without waste services consumed an estimated 19 million, 210 million and 285 million disposable diapers annually, reflecting higher waste collection coverage in Ghana. However, in Nigeria, since the survey asks respondents to recall diaper consumption over a longer period compared to Ghana and Kenya, it likely under-estimates diaper consumption. Since household expenditure survey data are available for many years and in many countries, these surveys could be used more widely for international monitoring of mismanaged disposable diaper waste and potentially also mismanaged waste from consumption of other products.

1. Introduction

Use of disposable diapers (DDs) across low- and middle-income countries (LMICs) is widespread [1]. Estimates of average DD use per child range from two to six per day [2,3], to over 4000 [4] during a child's diapering period. Consumers overwhelmingly cite convenience as the main motivation for using DDs, though a minority also cite skin rash prevention [5]. Thus, they can save care-givers' time and overcome water access issues preventing washing of reusable cloth diapers.

However, DDs are generally used once before disposal. Where DDs are not safely disposed of, there is a risk of higher greenhouse gas impacts from methane emitted as diapers decompose [6] and population exposure to faecal contamination [7]. Young children may experience more frequent diarrhoea and shed higher pathogen loads in faeces because of their underdeveloped immune systems [8], increasing the hazards associated with DDs. Unsafe disposal of child faeces is associated with diarrhoea, helminth infection, stunting, and vulnerable young children being exposed to faeces during play close to the home [7]. Where waste disposal systems are lacking, DD use poses environmental and public health risks additional to risks from other forms of unsafe disposal of child faeces.

DDs typically comprise a polypropylene top sheet, a cellulose pulp and polyester acquisition and distribution layer, an inner core (superabsorbent polymer encapsulated in cellulose), and a polyethylene back-sheet [2,3]. The complex composition waste of DDs hinders recycling or reuse [9]. Their hazardous nature poses additional occupational health risks for waste collectors. Inappropriate DD disposal may block storm-drains or sewers, leading to localised flooding [10] and associated impacts [11]. Conventional DDs contain polypropylene and polyethylene, plastics that can adversely affect aquatic wildlife [12]. When degraded into micro-plastics [13], these can be assimilated by marine organisms [14] and humans [15].

Use of DDs potentially undermines efforts to achieve the UN's Sustainable development Goals (SDGs), notably SDG 11 and target 11.6 addressing the inclusivity, safety, resilience and sustainability of human settlements with specific reference to 'municipal and other waste management' [16]. Progress towards target 11.6 is determined, in part by the 'proportion of municipal waste collected and managed in controlled facilities out of total waste generated by cities'

[16]. Across LMICs in sub-Saharan Africa (SSA), rapid urbanisation, population growth and changes in consumption patterns create challenges in providing municipal waste disposal services that meet demand [17]. Resource-poor settings lacking formal waste management systems are of particular concern where the burning, burying and indiscriminate dumping of waste are common [18]. If DD use increases in such settings, progress towards SDG target 11.6 will likely be inhibited.

DD use also affects progress towards SDG target 6.2, concerning sanitation and hygiene [19]. DDs are considered safe for child faeces disposal, depending on access to systems for their hygienic collection and disposal [20]. An extended household survey question [20] concerning unsafe child faeces disposal has been implemented in some recent Demographic and Health Surveys (DHS), alongside a question on solid waste disposal in some recent Multiple Indicator Cluster Surveys (MICS): both have been the subject of recent research [7,21]. Ideally, household survey questions would explicitly differentiate DDs from other forms of unsafe child faeces disposal. There is not currently an internationally harmonised monitoring methodology for assessing the extent of inadequate disposal of DDs.

Whilst there are national data and methods for quantifying DD use in high income countries, limited data availability inhibits country-scale quantification of DD use in LMICs. For example, the UK's Environment Agency conducted consumer surveys of DD use by child age to inform material flows within a DD life cycle assessment [22]. However, equivalent bodies in LMICs lack resources for such data collection, leading to waste management data gaps [23]. Several studies have suggested that over the past century [24,25], there has been a worldwide trend towards a later age of toilet training, which may increase both DD waste over a child's lifetime and parental anxiety over delayed toilet training. However, there are few studies assessing toilet-training age in LMICs.

Given the environmental and public health risks of inadequate DD disposal, their widespread use in LMICs with inadequate solid waste disposal systems, and lack of an international monitoring approach, our study aims to implement and evaluate a methodology for estimating DD use among populations lacking waste services at national level. Specifically, we aim to evaluate the plausibility of using data from household expenditure surveys in relation to DD consumption and waste, by examining evidence for consumption-smoothing [26] and inferred toilet-training age via DD purchases. Our study focuses on Nigeria, Kenya, and Ghana as countries with suitable household expenditure surveys. These form contrasting case studies, since Nigeria has lower waste collection service coverage and literacy rates than Kenya or Ghana, but safely managed sanitation is lower in Ghana than the other two countries.

2. Results

More households in Nigeria (14.0%) reported purchasing DDs than in Ghana (5.0%) or Kenya (6.4%) (Table 1). Some 22.1% of Ghanaian households had a child of diaper wearing age (DWA) (<30 months) in 2016–2017, compared with 20.6% in Kenya in 2015–2016 (<24 months) and 25.5% in Nigeria in 2018–2019 (<24 months). Of these, 19.4% bought DDs in Ghana, compared with 26.7% in Kenya and 47.8% in Nigeria. In all countries, 0.7% to 1.8% of surveyed households bought DDs and did not have a child of DWA (see S1–S3 Tables and Supporting Information for full details).

Logistic regression indicated no significant difference in DD purchase reporting by GLSS7 survey visit, suggesting no significant respondent fatigue. Only 1.6% (n = 218) of surveyed Ghanaian households did not complete all six survey visits, none of which purchased DDs. Only 0.1% (n = 47) of Kenyan households partially completed the survey, of which 6.3% (n = 3) reported purchasing DDs. In Nigeria, 0.02% (n = 8) households partially completed the survey. In both

Table 1. Summary statistics of households consuming DDs, with and without children of diaper wearing age (DWA) in Ghana, Kenya and Nigeria.

	Weighted % of total households surveyed (95% CI) *Number of households*		
	Ghana	**Kenya**	**Nigeria**
Total number of households surveyed	*14,009*	*21,773*	*22,118*
Estimated mean upper age of diaper wearers (see Section 2.4)	0–30 months	0–24 months	0–24 months
Households with at least one child of DWA	**22.1% (21.1, 23.1)** *3416*	**20.6% (19.8, 21.5)** *4869*	**25.5% (24.7, 26.3)** *6009*
Households purchasing DDs	**5.0% (4.4, 5.8)** *533*	**6.4% (5.7, 7.1)** *1147*	**14.0% (13.4, 14.7)** *2825*
Households with child of DWA, purchasing DDs	**4.3% (3.7, 4.9)** *462*	**5.5% (4.9, 6.2)** *1005*	**12.2% (11.6, 12.8)** *2473*
Households with no child of DWA, purchasing DDs	**0.7% (0.06, 0.1)** *71*	**0.9% (0.7, 1.1)** *142*	**1.8% (1.6, 2.1)** *352*

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Kenya and Ghana, there were no missing data for the households that partially completed the survey, thus they were included in the analysis. In Nigeria, the households that partially completed the survey had completely missing data and were excluded from the analysis.

2.1. Household consumption of disposable diapers

Usage of DDs was lowest in Nigeria, where children of DWA used a mean of 59 DDs annually (Table 2). In Kenya usage was greatest, with 433 DDs used annually per child of DWA; Ghanaian children of DWA used 292 DDs annually. Up to three DDs used per day per household was reported in Nigeria, where 97.3% of households used less than one DD per day, per child of DWA. In Kenya, only 53.3% of households used less than one DD per day per child of DWA on average; up to 11 DDs per day were used by a single household.

Estimated annual DD consumption per household in Nigeria (62 DDs) was lower than in Ghana (301 DDs) and Kenya (451 DDs). In Ghana, households purchased 12 to 2232 DDs annually, compared with 12 to 4440 in Kenya and 1 to 1616 in Nigeria. Monthly household DD expenditure in Ghana ranged from US$ 0.12 (GH₵ 0.50) to US$ 38.35 (GH₵ 165.00). Monthly spend on DDs was US$ 0.16 to US$ 65.40 (KES 15.00 to KES 6000.00) in Kenya and US$ 0.02 to US$ 35.00 (₦8.30 to ₦12,500.00) in Nigeria.

Average annual DD expenditure per household was highest in Kenya (US$ 79.81; KES 7322), intermediate for Ghana (US$ 57.48; GH₵ 247.33), and lowest for Nigeria (US$ 16.25; ₦5805.42). Ghanaian households consumed the fewest DDs in total—approximately 116 million/year, equivalent to 4,480 tonnes/year (Table 2). Households in Kenya consumed around 378 million DDs (14,590 tonnes) in a year, similar to Nigeria (ca. 465 million; 17,950 tonnes), despite Nigeria's larger population.

Variations between urban and rural localities (Fig 1) and regionally (S1–S3 Figs and Supporting Information) are apparent. Urban households consistently consume the most DDs across all three countries, highest in Nigeria at 292 million DDs (11,271 tonnes) per year given its large population. In urban Kenya, annual DD consumption (275 million; 10,620 tonnes) was double that in rural settings. Differences between localities were smaller in Ghana: rural households consumed approximately 35.5 million DDs (1,370 tonnes), whilst urban households consumed ca. 80 million (3,100 tonnes).

Table 2. Patterns of disposable diaper consumption in Ghana, Kenya and Nigeria.

	Ghana *(95% CI)*	Kenya *(95% CI)*	Nigeria *(95% CI)*
Households purchasing DDs	*533*	*1147*	*2825*
Estimated national DD consumption per year (in millions)	**116,000,000** *(92,553,461–139,905,867*	**378,000,000** *(274,859,797–480,230,440)*	**465,000,000** *(414,598,929–516,222,867)*
Average number of DDs bought per household per year	**301** *(276, 326)*	**451** *(419, 482)*	**62** *(59, 66)*
Average expenditure on DDs per household per year (USD)	**$57.48** *($52.49, $62.47)*	**$79.81** *($74.24, $85.39)*	**$16.25** *($15.40, $17.11)*
Annual household DD expenditure: range (USD)	$1.39 - $460.15	$1.96 - $784.80	$0.28 - $420.00
Households purchasing DDs with at least one child of DWA	*462*	*1005*	*2473*
Average number of DDs consumed, per child of DWA per year	**292** *(265, 318)*	**433** *(401, 465)*	**59** *(56, 62)*
Estimated number of DDs used during child's diapering period	**730**	**866**	**118**
Maximum reported number of DDs used daily, per child of DWA	**6** DDs/day/child	**11** DDs/day/child	**3** DDs/day/child
Households which annually use <1 DD a day, per child of DWA *(weighted percentage)*	**73.8%**	**53.3%**	**97.3%**

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2.2. National waste generation from disposable diaper consumption

Most waste from DDs in Ghana nationally is generated by households with managed formal waste collection in place (Fig 2). Five times fewer DDs are consumed by households disposing of their waste using an unmanaged method (ca. 19 million DDs; 730 tonnes) than those using a safer method of disposal (ca. 100 million DDs; 3,860 tonnes). Ghanaians disposing of waste

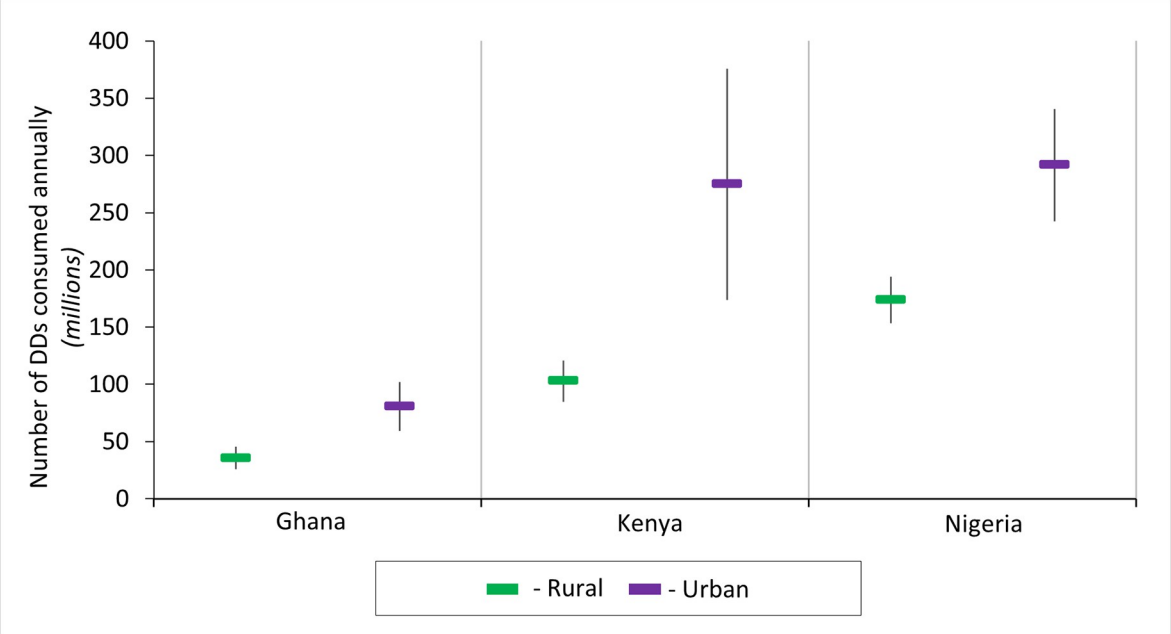

Fig 1. Estimated annual national DD consumption in Ghana (2016/17), Kenya (2015/16) and Nigeria (2018/19), by locality. Vertical bars show 95% confidence intervals, accounting for survey sample design.

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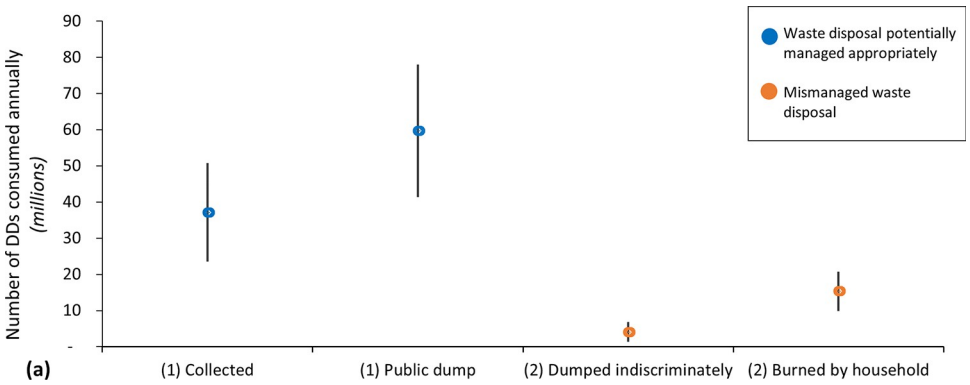

Fig 2. Total annual DD consumption nationally by solid waste disposal method in Ghana (2016/17) (vertical lines indicate 95% confidence intervals; (1): waste disposal potentially managed appropriately; (2): unmanaged waste disposal).

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using a managed system used around 37 million DDs per year (1,430 tonnes), those using public dumps consumed about 60 million (2,310 tonnes).

The proportions of households consuming DDs which do not use managed waste systems are greater in both Kenya (Fig 3) and Nigeria (Fig 4). In Kenya, 1.25 times more DDs were consumed annually by households using an unmanaged method than those whose waste is collected. Nigerian households using unmanaged waste disposal methods used 1.58 times more diapers annually than those using safely managed methods.

In Ghana, households who indiscriminately dump their waste consumed relatively few DDs annually (ca. 4 million), whereas indiscriminate dumping accounted for much higher numbers of DDs in Kenya (101 million; 3,900 tonnes) and Nigeria (123.5 million; 4,790 tonnes). Annually, around 89 million DDs (3,440 tonnes) were disposed of by Nigerian households via an unauthorised refuse heap. Of those who burn their waste, five times the number of DDs were consumed annually by Kenyans (ca. 87 million; 3,360 tonnes) than Ghanaians (ca. 15million; 579 tonnes). Among Nigerian households, 72 million DDs (2,780 tonnes) were consumed by households who either burned their waste or disposed of it within their compound or farm.

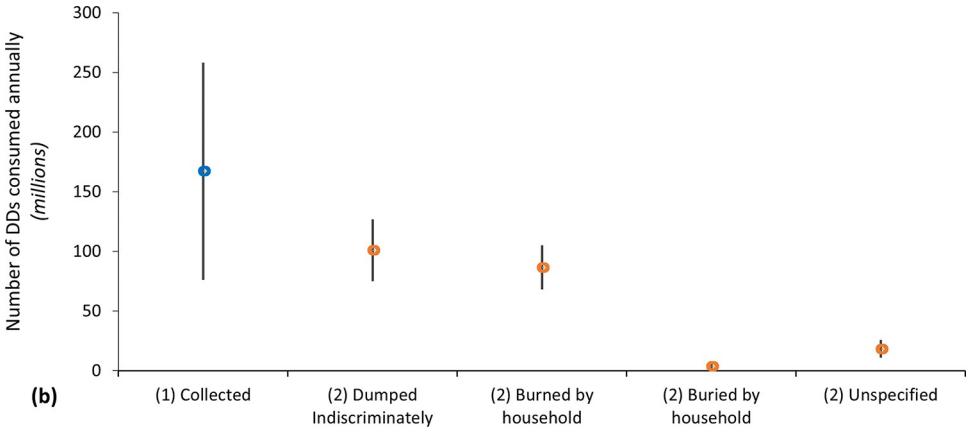

Fig 3. Total annual DD consumption nationally by solid waste disposal method in Kenya (2015/16) (vertical lines indicate 95% confidence intervals; (1): waste disposal potentially managed appropriately; (2): unmanaged waste disposal).

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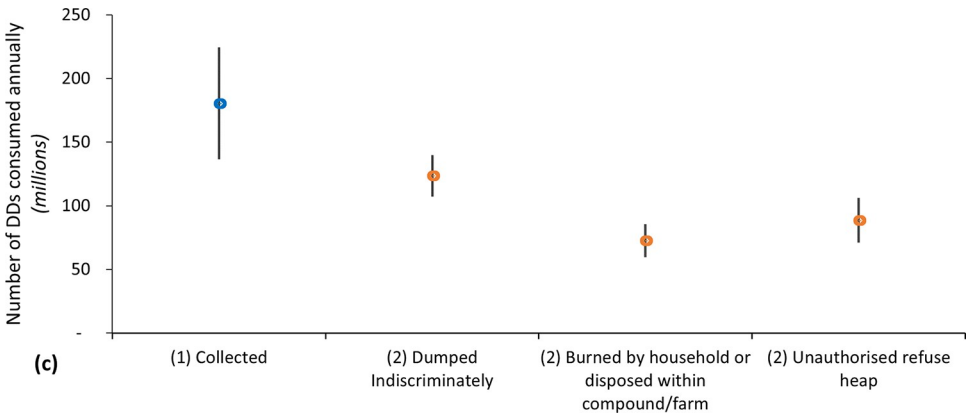

Fig 4. Total annual DD consumption nationally by solid waste disposal method in Nigeria (2018/19) (vertical lines indicate 95% confidence intervals; (1): waste disposal potentially managed appropriately; (2): unmanaged waste disposal).

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2.3. Disposable diaper consumption smoothing in Ghana

Of the households purchasing DDs in Ghana (n = 533), 45.3% of households always bought DDs in single units, whilst 40.9% bought in bulk units (Table 3) and 13.8% purchased DDs in a mixture of single and bulk units.

Welfare quintile is significantly associated with the units DDs are bought in ($\chi(8) = 60.81$, $p = <0.001$). Wealthier households more commonly purchase DDs in bulk units: 62.6% of households in the highest welfare (wealthiest) quintile always bought diapers in bulk units, compared with 16.0% to 34.6% of households in the lowest, lower and middle quintiles. Households in the lower and lowest welfare quintiles were more likely to purchase DDs in singles. Household welfare appeared to have no marked influence on purchasing for households that bought DDs in mixed units.

2.4. Inferring toilet-training age

ROC analysis (Fig 5 and S4 Fig, Supporting Information) systematically cross-tabulated household-reported DD purchases against households whose youngest member was older than a given threshold age. The derived optimal age threshold for predicting household DD purchases was 24 months in Nigeria and Kenya, and 30 months in Ghana. These estimates suggest toilet-training at a higher age in Ghana. Reflecting all age thresholds combined, the AUROC

Table 3. Units of DD purchases by national welfare quintile in Ghana.

Units DDs are bought in across the six survey visits	National Welfare Quintile					
	Lowest	Lower	Middle	Higher	Highest	Total
	Households weighted as percentage of column (n)					
Always bought singles	66.8% (24)	69.3% (54)	54.2% (56)	38.7% (69)	27.3% (35)	45.3% (238)
Always bought in bulk	16.0% (7)	20.8% (19)	34.6% (44)	42.3% (70)	62.6% (79)	40.9% (219)
Mixed single/bulk purchases	17.2% (6)	9.9% (9)	11.3% (16)	10.4% (31)	10.4% (14)	13.8% (76)
Total households purchasing diapers	**100 (37)**	**100 (82)**	**100 (116)**	**100 (170)**	**100 (128)**	**100 (533)**
Total households that did not purchase diapers	*3100*	*2450*	*2265*	*2438*	*3223*	*13,476*

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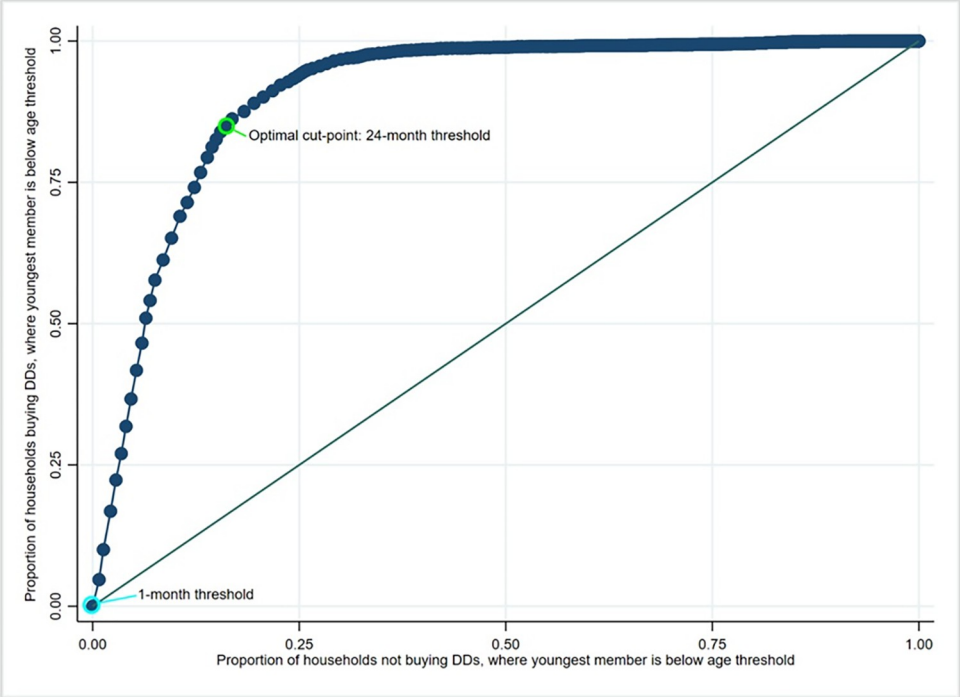

Fig 5. ROC analysis predicting mean toilet-training age in Nigeria from DD purchases and youngest household member's age. (AUROC (area under the ROC curve): 0.906; Empirical optimal cutpoint: 24 months).

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was 0.91 (Nigeria), 0.87 (Ghana), and 0.90 (Kenya), showing excellent performance and overall consistency of DD purchases and household composition (i.e. children reported as household members).

3. Discussion

3.1. Disposable diaper waste: Insights from household expenditure surveys

High DD consumption in LMICs, has previously been reported in local-scale studies in specific cities and via a limited number of national market research surveys [1,17]. Despite their convenience benefits for children's care-givers [5], concern regarding the environmental and public health consequences of unsafe disposal of DDs is clear [27,28] but there have been few attempts to quantify the scale of their use using secondary data. Through the novel application of nationally representative household expenditure survey data, we estimate that annually 960 million DDs are being consumed in Ghana, Kenya and Nigeria (Table 2), mostly in urban areas. Our subnational analysis enables targeting of areas where the environmental effect of DD use is expected to be greatest, notably urban centres in provinces of high DD use (Fig 1 and S1–S3 Figs).

A higher proportion of households (14.0%, almost half of those with children of DWA) in Nigeria report using DDs than in Ghana (5.0%) or Kenya (6.4%) (Table 1). This partly reflects the greater proportion of households with children of DWA in Nigeria compared to Ghana and Kenya (Table 1) and–given lower DD consumption in rural areas—Kenya's more rural population (Section 5.2). Otherwise, it is unclear why reported DD use is greater in Nigeria. Surveys in Gweru city, Zimbabwe [29], and of low-income households in Nairobi County, Kenya [30] have reported 60.7% and 86% of households using DD respectively, confirming localised high levels of urban DD nappy use in SSA.

Since DD usage per child of DWA (Table 2) in Nigeria is considerably lower than either Ghana and Kenya or published estimates from LMIC literature, our study may under-estimate Nigerian DD usage. Reported daily DD use varies with 0.3, 2, 6 and 8 DDs per child per day in India [31], Philippines [31], South Korea [9] and Kenya [30], respectively. This study indicates a maximum daily DD consumption of 3 to 11 DDs/child/day across Ghana, Kenya and Nigeria (Table 2). However, in Ghana, Kenya and Nigeria over half the diaper-wearing population used less than one DD per day per child (Table 2). Thus, household-level consumption appears complex and varied. DDs used during a child's diapering period (Table 2 and S4 Table, Supporting Information) appear markedly lower (118 to 866) than the 4,000 to 7,000 DDs reported for high income countries [1,2]. Compared with the GLSS7 [32] and KHBS [33] which use a one-month recall period, the NLSS uses a longer 12-month recall period [34]. Reporting and recall error in consumption surveys are well documented [35]. A longer recall period increases respondent cognitive demand and resultant memory lapse, potentially leading to under-estimation of reported DD consumption in Nigeria via the NLSS [36].

We estimate 514 million DDs are consumed annually by households in Ghana, Kenya and Nigeria lacking solid waste disposal services (Fig 2, Fig 3 and Fig 4). In Kenya and Nigeria, two thirds of all DDs are consumed by households using unmanaged methods of waste disposal (Fig 3 and Fig 4). In Ghana, most DDs are consumed by households with waste collection services or facilities. Thus, most Nigerian and Kenyan DD consumption takes place in households lacking waste services, in contrast to Ghana where the opposite occurs. This reflects much lower waste collection service coverage and higher proportions of urban slum-dwellers in both countries relative to Ghana (Section 5.2). Without safe disposal of child faeces, exposure to faecal pathogens may increase, especially among young children [7] Alongside blocking of storm drains causing localised flooding [10] and related impacts [11]. With 229 million DDs being dumped indiscriminately (Fig 2, Fig 3 and Fig 4), we highlight the considerable environmental risk associated with DD waste [11,18,37]. We note that 445 million DDs are consumed by households whose waste may be managed appropriately (Fig 2, Fig 3 and Fig 4); despite the benefits of waste systems and services, DDs remain challenging in terms of disposal or recycling [9], especially when considering householders' willingness to use alternative methods such as DD collection centres [27]. Although Kenya's president promised free DD for 3 months via a mother-child benefit package in 2022 [38], this announcement occurred after KIHBS survey implementation in 2015–16. Similarly, NGO or social enterprise-led initiatives to promote cloth diapers [39] remain small-scale in the study countries, so our study's DD consumption estimates are unlikely to be substantially affected by such policies.

ROC analysis (Fig 5) suggested toilet-training age was between 24 and 30 months in the three study countries, lower than a median age of 36.8 months reported in the US [25] as part of a global trend towards later toilet training [24]. One of the few African toilet-training studies [40] found that most Nigerian children achieved continence by 12 months, lower than both developed country estimates and our estimates from household surveys. The cultural or socio-economic drivers of lower toilet-training age are unclear [40], but such behaviour would reduce the public health and environmental impacts of DD consumption among households lacking waste services.

3.2. Plausibility of reported household DD consumption

DD consumption patterns were plausible in relation to household socio-economic status and household demographic composition. Firstly, consumption-smoothing is evident among households purchasing DD in Ghana: wealthier households more consistently purchase DDs in higher-priced bulk units than poorer households (Table 3). Low-income households in

Ghana are smoothing their consumption [41]; by purchasing DDs in more affordable single units as they reduce the financial risk of purchasing in bulk units [42]. This "*Kadogo* economy" [43] (Kiswahili for 'small') involves repackaging and resale of commodities into their smallest divisible units, reflecting the needs of customers.

Secondly, DD purchases were plausible in relation to diaper-wearing age. When estimating toilet-training age by comparing reported nappy purchases with the minimum age of any household member, the mean age of 24 months in Nigeria (Fig 5) and Kenya (S5 Fig, Supporting Information) was similar to 23 months reported in Iran [44]. Evidence on toilet-training in Africa is limited, though in Nigeria toilet-training is initiated as young as ≤12 months and takes 1–6 months [40]. Social and cultural influences affect the age of toilet-training [45,46]; in HICs, this often starts from 18–21 months, with dryness achieved by 35 months [47]. The age of toilet-training has increased over recent decades, possibly due to greater DD use [25]. Our findings are consistent with prior studies of toilet-training and highlight the opportunity to use expenditure surveys to infer nappy-related behaviours of public health interest.

3.3. Transferability and scalability of methodology

Our analysis extends previous studies using household expenditure surveys to quantify unmanaged plastics from consumption of packaged water consumption [48] and cooking oil [49], and to understand DD consumption patterns and their related impacts in LMICs. Household micro-data from expenditure surveys facilitates in-depth and transparent analysis of DD consumption, whilst accounting for sample design [48]. Pre-existing household survey data, as opposed to data from retailers or the private sector, are particularly valuable. Government-collected data may be perceived as more credible and provide greater leverage for policy advocacy [50]. Ability to assess unmanaged DD waste could underpin targeting of regulatory policy concerning DDs and suitable waste management. DD purchases are explicitly included in several household expenditure surveys, e.g. a sub-group of West African LMICs which included DDs alongside other AHPs [51] (S5 and S6 Tables and S6 Fig, Supporting Information). Our methodology could readily be applied to these countries, but not necessarily elsewhere, suggesting the resultant estimates are analogous to a Tier II SDG indicator (i.e. one implementable from existing data, but for less than 50% of global population [52]). The method could also be applied to historic and future expenditure surveys, enabling time-series monitoring of DD consumption and waste management.

This analysis could also be transferred to other consumer products that cause waste management problems, for instance menstrual related AHPs [53]. However, to enable this, expenditure survey data need to include a single commodity code specific to a product of waste management concern. Internationally, the number and nature of commodity codes used for products vary, reflecting local context and a given survey's purpose [54]. The transferability of our methodology is also dependent on assumptions concerning unit costs. In this analysis, where the unit cost of a DD was not reported in Kenya and Nigeria, we relied on market research (section 5.4). The reporting of standard and non-standard measurement units for DD purchases made analysis more complex in Ghana but was highly valuable in enabling the assessment of consumption-smoothing. This element of our analysis is only transferable to contexts where surveys capture measurement units and quantities of purchases.

3.4. Methodological limitations

Alongside potential recall bias [36] and telescoping [55] due to the temporal specificity of survey questions [see Section 4.1], prestige errors may also lead to over-reporting of consumption for socially desirable commodities [56]. Non-exhaustive, online market research was used to

calculate DD unit costs in Kenya and Nigeria, which predominantly included large retail outlets and branded DDs. The inclusion of non-branded, cheaper DDs, likely preferred by lower income households, was limited. Similarly, the number of single DDs in non-standard bulk purchases is uncertain. Supplementary fieldwork could enable more robust unit price estimation and enable the creation of a conversion table, transferring non-standard to standard units [49]. In each country, our cross-sectional study estimated DD waste generation only for a single period with the most recent, available household expenditure survey. However, time series of survey-based sanitation indicators sometimes contain outliers [57], which arise from survey harmonisation or implementation issues. Thus, indicators derived from a single survey can be misleading. To address this, future studies could analyse DD consumption in expenditure surveys over several years using established time series techniques used for SDG indicators [57,58]. However, suitable survey data would only be available for a few SSA countries such as Ghana.

Expenditure surveys only enquire about the main waste disposal method, so unmanaged DD waste estimates may not reflect waste separation practices and secondary disposal methods [49]. Harmonised classifications of waste disposal methods were not present across the surveys. Regrouping waste categories to allow for inter-country comparison could affect the robustness of estimates of DD waste. More granular response categories for private, government or community-run waste collection would enable quantification of different sectors' contributions to managing DD waste. Furthermore, bulk purchases of DDs often entail additional secondary packaging that we have not considered in our estimations.

3.5. Practical applications, recommendations for policy and future work

Our methodology enables quantification of DD waste generation without extensive and costly dedicated data collection. We provide a mechanism for producing vital evidence for policy concerning child faeces disposal as solid waste and for prioritising solid waste management systems. Such estimates can also be used to advocate for accelerated DD product development and waste management strategies. Multi-country studies are especially valuable when holding multinational corporations accountable and providing evidence on their environmental impact in multiple locations. Our methodology could be especially valuable if used within the United Nations Environment Programme's plastic waste hot-spotting framework for action to reduce plastic pollution [59]. This framework identifies five types of waste hotspot that can be targeted for action: 'orphan' polymers; sector hotspots (industrial, agricultural or domestic); waste management stages where waste enters the environment; geographic hotspots; and application or product hotspots [59]. Example targeted actions include redesign of products constituting application hotspots through extended producer responsibility and waste collection system investments to address geographic hotspots [59]. Since DDs contain plastics such as their polypropylene top-sheets, they constitute a potential application hotspot in the domestic sector, as recognised in a recent national plastic waste hot-spotting implementation for Kenya [60]. Reducing mismanaged DD waste is likely to require both greater waste collection service coverage and engagement with manufacturers to support DD product redesign through extended producer responsibility [4]. Additionally, it may require greater investment in market surveillance and product regulation, given reported import of unregulated DD brands into Ghana especially [61].

Methods could be enhanced using spatial analysis to identify geographic DD waste hotspots. The Living Standards Measurement Study has started to collect GPS coordinates in some household surveys [62]. If expenditure surveys included coordinate information, gridded surfaces of unmanaged DDs could be spatially linked to datasets such as HydroSHEDs [63] to

identify river catchments at risk from DD contamination, similar to contamination risk studies for wastewater treatment [64]. There is evidence of DD consumption smoothing (Table 3) and number of DDs used reportedly declines with child age [65]. Thus, in future studies, there would be scope to explore child age, household socio-economic status and other covariates associated with household-level variation in DD expenditure.

To advance our analysis, harmonisation of expenditure survey waste disposal classifications, recall periods, and reporting DD purchases, would be valuable. International harmonisation of survey questions is especially pertinent in ensuring meaningful monitoring of progress towards the SDGs [66]. If all expenditure surveys included details on single and bulk DD consumption (e.g. GLSS7), more consistent international comparison would be possible. Consumption-smoothing and the presence of a "Kadogo economy" could then be explored in other contexts. Additionally, if the number of single DDs in a bulk unit were reported in all cases, we could more robustly estimate DD consumption and improve estimation of unmanaged DD waste.

Finally, estimates of DD consumption, resultant unmanaged waste, and related underlying assumptions need to be corroborated using evidence from primary observations. In the interim, findings could be triangulated with other data sources, including global DD trade data [67], retail sector records on DD sales and regulator records of waste composition [49]. These datasets could also be combined with bespoke household surveys to enhance the evidence on DD use and waste in LMICs.

4. Conclusion

Household expenditure surveys provide an opportunity for quantifying DD use and associated unmanaged waste. Our analysis in Ghana, Kenya and Nigeria shows DD use in LMICs is significantly lower than in HICs. Despite this, we estimate that much consumption takes place in households lacking waste services, presenting a health risk and environmental threat. Consumption patterns in relation to household socio-economic status and household composition are credible and consistent with published evidence on toilet-training and consumption-smoothing. Moving forward, there is considerable potential to exploit the methodology, including in different contexts and for other products increasingly consumed by households lacking waste collection services. Household expenditure surveys could also be used to construct international monitoring indicators indicating DD consumption among households lacking waste services. These would be value in advocating for accelerated DD product innovation and in targeting areas with high DD consumption, but low waste service coverage.

5. Methods

5.1. Data audit and study country selection

To identify suitable household surveys, we audited household expenditure and consumption surveys with available micro-data, reviewing metadata from the Institute for Health Metrics and Evaluation [68], the World Bank Microdata Library [69] and the International Household Survey Network [70]. For inclusion in our study, surveys had to be conducted in LMICs within SSA, i.e. where progress on SDG6 and SDG11 is lagging most [71] and have accessible micro-data with records of both household DD purchases and waste disposal methods. Of the 48 LMICs in SSA [72], 17 had household survey data with DD consumption details. Of these, 15 also had information on waste disposal methods available. Data were accessible for 13 of these countries.

Ghana had a survey question that concerned total expenditure and quantity of DDs purchased (S6 Table, Supporting Information). Kenya, Nigeria and Malawi had a survey question

concerning DD that only recorded total expenditure. The remaining eight countries meeting selection criteria and with accessible data grouped DD consumption with other absorbent hygiene products (AHP) and only reported total expenditure. Ghana, Kenya and Nigeria were thus selected, for which methods have been used for other recent studies of household consumption and waste management [48, 49].

5.2. Study countries

Ghana had a population of 33 million in 2021 [73]. Of the 19 million urban dwellers, 29% live in slum households [74]. Only 13% of Ghanaians use a basic sanitation service, 18% practice open defecation and 11% use unimproved sanitation facilities [75]. Some 40% of mothers dispose of their youngest (<5yrs) child's stools safely [76].

Kenya had a population of 53 million in 2021; 28% reside in urban areas [72]. Of these, 46% live in slum households lacking formal waste or sanitation infrastructure [16]. Nationally, 33% of households have basic sanitation; 33% use unimproved facilities and 9% practice open defecation [75]. Some 83% of mothers dispose of their youngest child's (<2yrs) stools by burying, or via a toilet or latrine with 7% via household solid waste disposal [77].

Of Nigeria's population of 213 million in 2021 [73] and 53% are urban. Those living in slums account for 53% of the urban population [74]. One in ten urban and 29% of rural households use an unimproved sanitation facility [75]. Overall, 19% of the population practice open defecation and 31% use a safely managed sanitation service [75]. Around 30% of <2-year olds' faeces are disposed of with household waste; 57% of mothers dispose of their youngest child's (<5yrs) stools safely [78].

Nigeria has a greater proportion of population living in poverty (earning below $2.15/day) at 30.9% than Kenya (29.4%) or Ghana (25.3%) [79]. Similarly, Nigeria's illiterate adult population is higher (38.0%) than that in Ghana (19.6%) and Kenya (17.1%) [80]. Solid waste collection is lower among Nigerian (14.4%) [34] and Kenyan households (22.0%) [81] than those in Ghana (33.4%) [82]. Comparable national waste management statistics are unavailable for the three countries [23].

5.3. Data sources

Data from the 2016–2017 Ghanaian Living Standards Survey (GLSS7), 2015–2016 Kenyan Integrated Household Budget Survey (KHBS) and 2018–2019 Nigerian Living Standards Survey (NLSS) were used. All surveys included information on household demographic and socio-economic information, and methods of waste collection.

The three surveys were designed to be nationally and regionally representative. The GLSS7 was conducted from October 2016 to October 2017 and employed a two-stage stratified sampling design, with 1000 enumeration areas (EAs) selected to form the primary sampling units (PSU). Probability proportional to population size sampling was used to select the PSUs from Ghana's then 10 administrative regions. Fifteen households from each PSU were selected, resulting in a total sample size of 15,000 households [32]. The response rate was 93.9% with a final sample of 14,009 households.

The KHBS also used a two-stage stratified sampling design. Data collection was from September 2015 to August 2016. From 92 sampling strata, 2400 clusters were selected in the first stage, with 10 households selected per cluster in the second stage. Overall, 24,000 households were sampled, 90.7% responded, with a final sample of 21,773 [33].

The NLSS provides representative estimates for Nigeria's 36 states and Abuja, the Federal Capital Territory, from which sixty EAs were selected. Within each EA, 10 households were randomly selected. Data collection took place for 12 months from September 2018. Civil

unrest affected fieldwork in Borno state [34]. Where possible, these were replaced with EAs from the same state and sector, though the Borno sample is not considered representative. Overall, 22,587 households were sampled, and the response rate was 98%; 22,118 fully completed the survey and a further 8 households partially completed the survey, resulting in a final sample of 22,126 [34].

This secondary data analysis study received ethical approval from the ethics committee of the Faculty of Environmental and Life Sciences, University of Southampton, UK (ref: 74037; approval, 26/07/2022). The household surveys analysed obtained verbal consent of respondents.

5.4. Estimating household consumption of disposable diapers

In the GLSS7, DD expenditure, units and quantities purchased were recorded via six separate visits, five days apart over 31 days. Analyses of respondent fatigue was assessed via a logistic regression which tested for significant differences in reporting of DD consumption per visit. DD expenditure was reported as the total value of single DD and bulk quantities (sets, packets, dozens and bundles), purchased since the previous visit. Bulk quantities were converted to single DDs, and all six household visits summed.

NLSS and KHBS respondents both report expenditure on DDs over a recall period. For the NLSS, total spend over the previous 12 months is reported; the KHBS uses a one-month period. For both surveys, total expenditure was used to calculate the number of single DDs bought, based on the unit price. The average unit cost was calculated using market research.

5.4.1. Calculating disposable diaper unit costs. Using the GLSS7, the average unit cost of a DD was based on the reported unit price and the calculated unit price for 12 DDs. The median unit price per DD, including instances where more than one DD was purchased, was USD $0.16 (GH¢ 0.7) (n = 705; inter-quartile range GHC 0.5 to 0.8). The median unit cost of a DD in a 'dozen' bulk purchase was USD $0.23 (GH¢ 1) (n = 8; inter-quartile range GHC 1 to 1.2).

Linear regression indicated no significant differences in the price per DD between dozen and single purchases reported in the GLSS7 (S1 Box, Supporting Information). Thus, the pooled average unit cost per DD (USD $0.21; GH¢ 0.89) was used to estimate the number of DDs consumed based on reported expenditure.

The GLSS7-derived unit cost of a DD (S7 Table, Supporting Information) was crosschecked with online research. Leading brands and manufacturers of DDs (S8 Table, Supporting Information) were identified via searches of DD-related literature [10,83]. Internet searches using terms such as 'diaper brands sub-Saharan Africa' (plus narrowing down by country) and of supermarket websites, blogs and newspaper articles were undertaken.

Internet market research included retail prices for DD sold by major Ghanian retailers, as of 16th August 2022, adjusted to 2016/17 prices using the consumer price index for the median GLSS7 survey month (April 2017) [84]. DD unit prices were USD $0.14 to $1.37 (GH¢ 0.59-GH¢ 5.88). Package sizes varied from 8 to 200 DDs. There were fewer larger DDs per packet and at higher unit cost. Overall, the GLSS7 DD prices were relatively low but within the price range identified by market research. The single or dozen DD prices reported in the GLSS7 are thus realistic.

For the NLSS and KHBS, the unit cost per DD could not be calculated using the survey data, so the market price was estimated. The average DD unit cost for all available brands, package sizes and DD sizes was calculated using major online retailers (S9 and S10 Tables, Supporting Information). Prices were as reported online on 25th October 2022 for Kenya and 24th November 2022 for Nigeria. Prices were adjusted to 2015/16 for Kenya and 2018/2019 for

Nigeria, using the consumer price index for the median survey months (Kenya: February 2015; Nigeria: March 2019) [85,86]. The average DD unit cost in Kenya was USD $0.18 (KES 16.22) and USD $0.26 (₦ 92.85) in Nigeria.

For Ghana and Kenya, annual DD consumption rates were estimated from the one-month survey recall period. The survey design was accounted for using the *svy* commands in Stata [87], to generate regional, urban, rural, and national estimates of consumption rates and total DD consumed with 95% confidence intervals. A mean diaper weight of 38.6g used for DD life cycle assessment by the UK Environment Agency [22] was used to convert numbers of DD used to kg of waste.

5.5. Inferring Toilet-Training Age and Number of Children Using Diapers

Using household DD purchases, we inferred the age at which toilet-training took place. Receiver Operating Curve (ROC) analysis was used to assess the relationship between the age (months) of the youngest household member and DD purchases. The Stata utility *cutpt* [88] identified the optimal age threshold for predicting household diaper purchases via the Euclidean method [89], calculating Area Under the ROC (AUROC) as a predictive performance measure.

The number of DD wearers per household was calculated using each survey's household roster. Children were classified as diaper-wearing age (DWA) at $\geq$30 months for Ghana, and $\geq$24 months for Kenya and Nigeria.

5.6. Exploration of consumption smoothing

Consumption smoothing was only feasible for Ghana where the GLSS7 reported the unit in which DDs were purchased. The unit of DD purchases across each of the six visits was categorised as either a single DD purchase or a bulk purchase. Bulk purchases included bundles, dozens, packet, sets, and pairs. Data were categorised to reflect whether households always bought single or bulk DDs, or a mixture, across the six survey visits.

A finer scale classification was created for households buying a mixture of single and bulk units, i.e. a 50/50 mix of single and bulk units, mainly single, or mainly bulk DDs.

Supporting information

S1 Table. 2016–2017 characteristics of Ghanian households with children of DWA (n = 3416), households purchasing DDs (n = 533) and households with a child of DWA that are purchasing DDs (n = 462).
(DOCX)

S2 Table. 2015–2016 characteristics of Kenyan households with children of DWA (n = 4869), households purchasing DDs (n = 1147) and households with a child of DWA that are purchasing DDs (n = 1005).
(DOCX)

S3 Table. 2018–2019 characteristics of Nigerian households with children of DWA (n = 6009), households purchasing DDs (n = 2825) and households with a child of DWA that are purchasing DDs (n = 2473).
(DOCX)

S4 Table. Estimation of mean DDs consumed during a child's diapering period for all three study countries.
(DOCX)

S5 Table. Data scenarios of household consumption surveys reporting DD expenditure.
(DOCX)

S6 Table. Available household income and expenditure surveys, with details of related disposable diaper and waste survey questions.
(DOCX)

S7 Table. August 2022 average and median unit cost per DD from a bulk packet in Ghana, for all DD sizes, converted to April 2017 prices.
(DOCX)

S8 Table. Leading DD brands and manufacturers in SSA.
(DOCX)

S9 Table. October 2022 average and median unit cost per DD from a bulk packet in Kenya, for all DD sizes, converted to February 2015 prices.
(DOCX)

S10 Table. November 2022 average and median unit cost per DD from a bulk packet in Nigeria, for all DD sizes, converted to March 2019 prices.
(DOCX)

S1 Fig. Estimated number of DDs consumed annually by region in Ghana (2016/17), with 95% confidence intervals.
(DOCX)

S2 Fig. Estimated number of DDs consumed annually by region in Kenya (2015/16), with 95% confidence intervals.
(DOCX)

S3 Fig. Estimated number of DDs consumed annually by region in Nigeria (2018/19), with 95% confidence intervals.
(DOCX)

S4 Fig. ROC analysis for prediction of toilet-training age in Ghana, based on household DD purchases and age (in months) of the youngest household member (AUROC (area under the ROC): 0.8705; Empirical optimal cutpoint: 1171).
(DOCX)

S5 Fig. ROC analysis for prediction of toilet-training age in Kenya, based on household DD purchases and age (in months) of the youngest household member (AUROC (area under the ROC): 0.8964; Empirical optimal cutpoint: 1285).
(DOCX)

S6 Fig. Coverage of household surveys (2015–2020) across LMICs in SSA that report DD consumption, with survey question details.
(DOCX)

S1 Box. Linear regression, with survey weights, of price per DD for purchases of single or dozen units by households reporting in the GLSS7.
(DOCX)

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Author Contributions

Conceptualization: Allan G. Hill, Joseph Okotto-Okotto, Lorna G. Okotto, Jim A. Wright.

Formal analysis: Mair L. H. Thomas-Possee, Jim A. Wright.

Funding acquisition: Peter J. Shaw, Joseph Okotto-Okotto, Lorna G. Okotto, Mawuli Dzodzomenyo, Jim A. Wright.

Investigation: Mair L. H. Thomas-Possee, Robert E. S. Bain, Jim A. Wright.

Project administration: Jim A. Wright.

Visualization: Mair L. H. Thomas-Possee, Jim A. Wright.

Writing – original draft: Mair L. H. Thomas-Possee, Jim A. Wright.

Writing – review & editing: Peter J. Shaw, Robert E. S. Bain, Allan G. Hill, Joseph Okotto-Okotto, Lorna G. Okotto, Mawuli Dzodzomenyo.

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