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How Much Will Safe Sanitation for all Cost? Evidence from Five Cities

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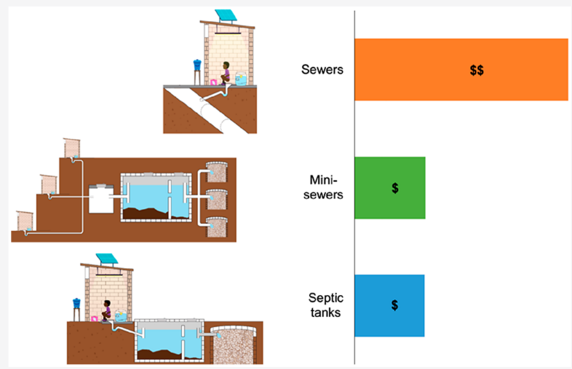
ABSTRACT: Global sustainable development goals call for universal access to safely managed sanitation by 2030. Here, we demonstrate methods to estimate the financial requirements for meeting this commitment in urban settings of low-income countries. Our methods considered two financial requirements: (i) the subsidies needed to bridge the gap between the willingness-to-pay of low-income households and actual market prices of toilets and emptying services and (ii) the amounts needed to expand the municipal waste management infrastructure for unserved populations. We applied our methods in five cities— Kisumu, Malindi, Nakuru in Kenya; Kumasi in Ghana; and Rangpur in Bangladesh and compared three to five sanitation approaches in each city. We collected detailed cost data on the sanitation infrastructure, products, and services from 76 key informants across the five cities, and we surveyed a total of 2381 low-income households to estimate willingness-to-pay. We found that the total financial requirements for achieving universal sanitation in the next 10 years and their breakdown between household subsidies and municipal infrastructure varied greatly between sanitation approaches. Across our study cities, sewerage was the costliest approach (total financial requirements of 16−24 USD/person/year), followed by container-based sanitation (10−17 USD/person/year), onsite sanitation (2−14 USD/person/year), and mini-sewers connecting several toilets to communal septic tanks (3−5 USD/person/year). Further applications of our methods can guide sanitation planning in other cities.



■ INTRODUCTION

Sanitation refers to the management of human excreta and comprises three broad components: collection (in toilets), conveyance (via sewerage or emptying services), and treatment. Inadequate and unsafe sanitation undermines public health, dignity, and economic development.[1−4] Approximately 56% of the urban population in sub-Saharan Africa (229 million people) and 26% in Central-Southern Asia (182 million people) lack access to private, hygienic toilets.[5] Urban sanitation conditions are most concerning in low-income areas (LIAs), which often consist of unplanned settlements with high population densities. Often, toilets in LIAs are shared by five households or more, are poorly maintained, lack privacy, have no amenities for menstrual hygiene management, and are not accessible to persons with reduced mobility.[6−10] Sewerage is minimal in LIAs and toilets are generally built over containment pits, an approach referred to as "onsite sanitation". When pits are full, households commonly employ informal manual emptiers who operate with no protective gear and dispose of the waste in the nearby environment.[11] Municipal treatment facilities rarely meet city needs, and over half of all collected excreta is often disposed in the environment without proper treatment.[12,13]

In adopting the United Nations' 2030 Development Agenda and its sustainable development goals (SDGs), all 193 member states committed to ensuring universal access to safe and equitable sanitation by 2030, paying special attention to the needs of women, children, and those in vulnerable situations: SDG target 6.2.[14] In a 2016 report, the World Bank estimated that meeting this target in all low- and middle-income countries would cost approximately 49 billion USD per year in capital investments alone.[15] The report emphasized that the choice of sanitation technology can have a large influence on these costs and called for more granular analyses at the city

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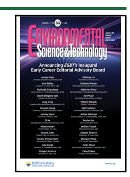

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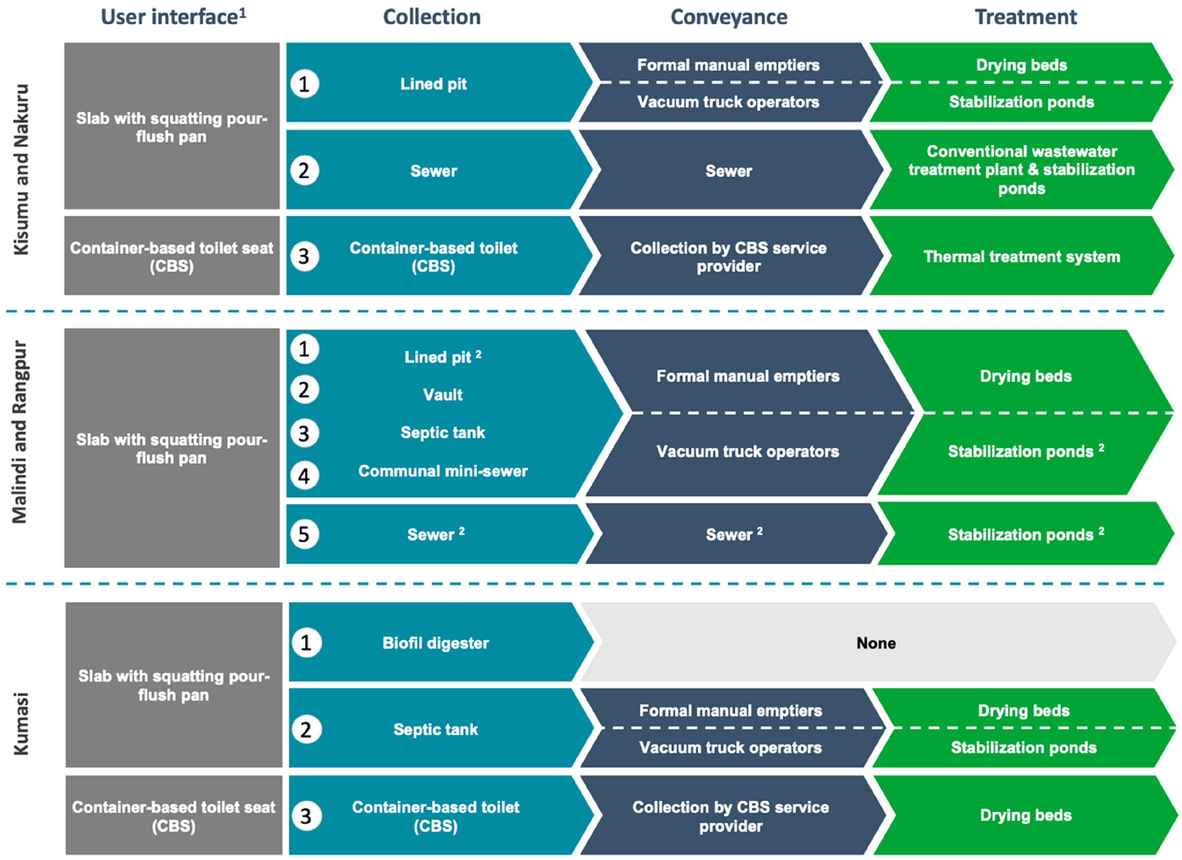

Figure 1. List of sanitation approaches considered in the five study cities. [1]In addition to the user interface, all toilet options also included a durable superstructure with a door lock, lighting, a handrail, a sanitary pad receptacle, and a handwashing station. For CBS, we assumed that the service would include the lease of such a superstructure.[2] We did not consider lined pits, sewers, and stabilization ponds in Rangpur. In Malindi, we considered sewers in the municipal expense estimates, but we did not elicit household WTP for this sanitation approach.

level to guide planning and investment decisions. The body of literature on city-level sanitation costs is growing, but a recent review found that few studies comprehensively report on all cost categories (capital, operating, and capital maintenance expenditures) and on all components of the sanitation value chain (collection, conveyance, and treatment).[16] Prior studies have typically compared per-person costs of different sanitation technologies but have not estimated what it would cost for specific cities to achieve universal access to safe sanitation.[17−20] Additionally, few studies have distinguished household costs (typically for collection and conveyance) from municipal costs (typically for treatment),[16] although understanding this breakdown is important for assessing the feasibility of specific sanitation approaches and for selecting adequate financing strategies.

While households traditionally bear a large portion of water and sanitation investments,[21] it is important to note that willingness-to-pay (WTP) for sanitation is often low among low-income households. Prior studies have investigated demand among poor households for a range of sanitation products and services, including latrine slabs,[22,23] onsite sanitation facilities,[24,25] connections to sewer networks,[26,27] professional pit emptying services,[28,29] and container-based sanitation (CBS).[30,31] These studies have consistently found that WTP among low-income households is well under the market prices of sanitation products and services. Similarly, the 2016 World Bank report warned that safe sanitation services are likely unaffordable to the urban poor.[15] These findings indicate that it is important to explicitly consider household subsidies when assessing the costs of achieving universal urban sanitation, which, in turn, calls for methodologies to estimate the magnitudes of the subsidies required.

In this study, we estimated the financial requirements for achieving adequate and equitable sanitation for all by 2030 in five cities: Kisumu (Kenya), Nakuru (Kenya), Malindi (Kenya), Kumasi (Ghana), and Rangpur (Bangladesh). We note that the study analyzed the financial requirements for addressing existing gaps in sanitation services. It is therefore not an analysis of city-wide costs, that is, we do not report here on the costs of existing infrastructure nor on the expenses that households can bear but rather focus on expenses that remain to be financed. To make our estimates of financial requirements more actionable, we specified them according to the primary cost-bearer: households or municipality. We hope that this breakdown can provide useful insights for decision makers as it indicates the level at which financing should be targeted. Using this lens, we compared the financial implications of different sanitation approaches such as sewerage, onsite sanitation, and CBS. Our results demonstrate that the sanitation approach selected has a large influence both on the overall financial requirements and on the breakdown between household subsidies and municipal infrastructure. More broadly, our methodology provides a framework for replicating this analysis in other cities to guide urban planning.

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Financial requirements to reach universal sanitation by 2030	=	Financial requirements at ***household level***	+	Financial requirements to upgrade ***municipal infrastructure***
		Expenses that households would normally cover (e.g., toilet facilities, sewer connection and fee, emptying services) but that low-income households may not be able/willing to pay in full.		*New municipal infrastructure (e.g., sewers, treatment facilities) required to manage the waste of the currently unserved population and whose costs are not typically recovered through customer payments (at current market prices).*
APPROACH AND ASSUMPTIONS: ➢ *Population considered* ➢ *Cost components*		• Only consider low-income households who do not currently have adequate toilets and emptying. • The rest (i.e., middle/high income households and those who already have adequate sanitation) are able to afford sanitation or continue to afford it. • Consider CAPEX for toilet construction and OPEX for emptying/CBS.		• Consider all households currently without safely-managed conveyance and treatment. • Consider new CAPEX required as a one-time expense at the start of the period. Subtract salvage value of long-term assets at the end of the 10-year period, assuming linear depreciation. • Consider capital maintenance expenditure (CapManEx) for new assets, approximated as CAPEX divided by asset lifetime. • Consider OPEX of new assets, but subtract the portion recovered via customer payments (e.g., sewer fees).

EQUATIONS

$$CAPEX = NPV_{10\ years}\left(\frac{N_{LIA\ hhs\ without\ adequate\ toilets}}{R} * Subsidy_{per\ toilet}\right)$$

$$OPEX = NPV_{10\ years}\left(\frac{N_{LIA\ hhs\ without\ adequate\ emptying}}{R * f} * Subsidy_{per\ emptying\ job}\right)$$

$$Subsidy = Market\ price\ - WTP_{percentile}$$

$$Net\ CAPEX = NPV_{10\ years}\left(CAPEX_{\substack{accounted\\ in\ Year\ 1}} - \frac{(L-10) * CAPEX}{L}_{\substack{accounted\\ in\ Year\ 10}}\right)$$

$$CapManEx \approx NPV_{10\ years}\left(\frac{CAPEX}{L}\right)$$

$$Net\ OPEX = NPV_{10\ years}(OPEX) - NPV_{10\ years}(Sewer\ fees)$$

Figure 2. Conceptual approach and equations used to estimate the financial requirements for achieving universal sanitation by 2030. NPV: net present value of expenses over the 10-year period. Assumes a discount rate equal to the real interest rate. *R*: number of households sharing one toilet. Assumed to be 3, except in sensitivity analysis. *f*: emptying frequency, dependent on the toilet type as specified in Table S1. Note that $R \times f$ is constant, therefore changing *R* does not affect OPEX. $WTP_{percentile}$: selected percentile of stated willingness-to-pay. Assumed to be the 20th percentile (except in sensitivity analysis), that is, the amount that 80% of households stated being willing to pay. *L*: lifetime of municipal assets, specified in Table S5.

■ MATERIALS AND METHODS

Study Sites and Sanitation Approaches. We selected five cities for this study—Kisumu, Malindi, and Nakuru in Kenya, Kumasi in Ghana, and Rangpur in Bangladesh based on two primary criteria: (i) the presence of programs administered by Water and Sanitation for the Urban Poor (WSUP), the international nongovernmental organization that supported this research and (ii) status as secondary population centers (as opposed to the largest metropolis).

In each city, we conducted stakeholder interviews and focus-group discussions to select at least three of the following sanitation approaches, based on the appropriateness for the local context: (i) sewerage, (ii) mini-sewers connecting three toilets to a communal septic tank, (iii) CBS, a service that leases portable self-contained toilets to households and collects the accumulated fecal waste every few days, and (iv) onsite sanitation relying on different types of underground containment, such as lined pits, septic tanks, vaults, and biofil digesters (Figures 1 and S1). Biofil digestion is a technology developed in Ghana that separates liquids from solids and relies upon aerobic composting to degrade fecal waste.[32] With respect to containment structures, we defined designs, dimensions, and construction materials reflecting standard practices in each city (Table S1). We assumed that a toilet would be shared by three households[33] and have a durable superstructure with a door lock, lighting, a handrail, a sanitary pad receptacle, and a handwashing station, all features of safe, adequate, and equitable toilets.[34] With respect to conveyance, we considered two types of service providers for the removal of fecal waste from underground containment structures: vacuum truck operators (VTOs) and formal, professionalized manual emptiers, such as those emerging in cities of Kenya.[35,36] Formal manual emptiers wear personal protective equipment such as overalls, gloves, gumboots, and masks and use dedicated tools such as long-handled steel buckets, Gulpers and Rammers,[37] or diesel pumps (Figure S1). We selected treatment facilities based on the existing or planned infrastructure in each city, which included conventional wastewater treatment plants, waste stabilization ponds, drying beds, and thermal treatment systems[38] (Figure 1). Text S1 provides additional details on sanitation options.

Conceptual Approach to Costing. Our approach to estimate the financial requirements for achieving universal sanitation in a city by 2030 is summarized in Figure 2. We considered two components: (i) household-level requirements, defined as the subsidies needed to bridge the gaps between the collection and conveyance expenses that households would normally face (e.g., toilet facilities, sewer connection, and emptying services) and the amounts that low-income households are willing to pay for these products and services and (ii) municipal-level requirements, defined as the amounts needed to build, operate, and maintain new municipal waste management infrastructure (e.g., sewers, treatment plants) required to reach unserved populations. We considered three types of costs: capital expenditures (CapEx), operating expenditures (OpEx), and capital maintenance/rehabilitation expenditures (CapManEx).

To estimate household-level financial requirements, we calculated the difference between household-level costs and the 20th percentile of WTP among LIA households (see detailed methods below). We defined this difference as the required household-level subsidy. We also estimated the number of LIA households without adequate toilets and emptying based on our survey data (see below), demographic reports, and a population growth rate equal to the 2009–2019 average (Table S2). Summary equations are provided in Figure 2. The term "adequate" sanitation refers to an improved[34] toilet located on premises and shared by a maximum of three households[33] and to safe emptying services provided by VTOs or formal manual emptiers. We applied these estimates to calculate the subsidies required in LIAs for toilet construction (CapEx), emptying services (OpEx), and CBS (OpEx) for every month of the next ten years. We then computed their ten-year net present value (NPV) using discount rates equal to the real interest rates (3.8% in Kenya,[39] 6.9% in Ghana,[40] and 3.6% in Bangladesh).[41]

To estimate municipal-level financial requirements, we first calculated the number of households without safely managed conveyance and treatment, both currently and by 2030 (Table S2), using information from the Shit Flow Diagrams published by the Sustainable Sanitation Alliance (SuSanA) for our study cities[42−44] and from our stakeholder interviews. According to the SuSanA definition, "safely managed" refers to services likely to result in a low public-health risk.[45] Then, we estimated the CapEx, OpEx, and CapManEx for the new infrastructure required to serve this population (see detailed methods below). We considered infrastructures such as sewer systems, communal septic tanks, and treatment facilities (detailed list in Table S3). We also included exhauster trucks and pick-up trucks because prior research suggested that private service providers may need to be supported with appropriate vehicles to expand their services to LIAs.[46] We then computed the ten-year NPV of municipal expenses using the same discount rates specified above. Summary equations are provided in Figure 2.

We applied this methodology to all of the scenarios listed in Figure 1 to compare the financial implications of each sanitation approach (see Text S2 for additional details). We also considered a mixed scenario, in which cities would apply an equal mix of the selected approaches. We note that we chose to compute costs over ten years because this is a policy-relevant timeframe for achieving the SDG target. For simplicity, we did not include the cost of capital (i.e., of loans) nor did we include the staffing and logistics costs for delivering household subsidies in LIAs. All costs were expressed in USD, using exchange rates of September 1, 2019 (1 USD = 101.98 KES, 1 USD = 5.46 GHS, 1 USD = 82.87 BDT).[47]

Estimation of Household-Level Costs. Household CApEx captured the costs of materials, labor, and transportation for building a toilet (slab, pour-flush pan, superstructure, containment, piping to sewer line or communal manhole, sewer connection fee). Household OpEx included emptying services, sewerage bill, CBS service fee, cost of water for flushing, and toilet upkeep. We used market prices to estimate these household costs. We triangulated data on prices and bills of quantities from a total of 53 interviews with LIA households, masons, plumbers, hardware stores, formal manual emptiers, VTOs, water utilities, and CBS service providers across the five study cities. We validated these data through comparisons within and between cities as well as with the existing literature. Additional details on OpEx calculations are provided in Text S2.

To compare the household costs of different sanitation approaches, we computed the ten-year NPV of their combined CApEx and OpEx. For this calculation, we used an annual discount rate of 10%, that is, higher than the real interest rate, reflecting the higher cost of capital for LIA households than for municipalities and governments.[48]

Measurement of LIA Household Willingness-to-Pay. In each city, we conducted a household survey in urban or peri-urban LIAs that met the following criteria: (i) did not consist of government housing or squatters illegally occupying government land; (ii) had a limited number of sewer connections (estimated <20% coverage); and (iii) did not have ongoing sanitation provision programs. We randomly surveyed adults in two categories: (i) homeowners or landlords living on the premises and without adequate sanitation for themselves or all of their tenants or (ii) tenants without access to adequate sanitation (Table S4). A detailed description of surveyed LIAs and sampling procedures is available in Text S3.

We surveyed 679 households in Kisumu, 469 in Nakuru, 422 in Malindi, 401 in Kumasi, and 410 in Rangpur between February and October 2019. In all five cities, the majority of survey respondents were female (60–72%), had received a primary education (62–90%), were married or in a union (54–87%), and had monthly household incomes below 500 USD (98–99%) (Table S5). In all cities but Kumasi, almost all households (93–98%) had access to a toilet in the compound, although it was often unimproved (Nakuru) or shared by more than three households (Kisumu and Malindi). In Kumasi, 75% of respondents did not have a toilet in the compound and instead used public toilets (Table S5).

Our household survey employed the double-bounded dichotomous choice method to measure stated WTP for the selected sanitation facilities and emptying services.[49] Enumerators first asked respondents if they would be willing to pay a randomly established price point (approximately 20, 40, 60, and 80% of market prices). If the respondent answered positively, enumerators then asked the same question for a higher amount. Alternatively, they asked about a lower amount. After these two yes/no questions, enumerators queried the respondents' maximum WTP. This method is often used in the case of hypothetical products/services because the sequence of questions helps respondents think about a relevant price range.[50−52] Enumerators used the graphics in Figure S1 to describe sanitation options and specified that a toilet would be shared by up to three households.

Enumerators provided all participants with verbal and printed details of the study in the local language and obtained informed written consent. The Western Institutional Review Board (WIRB) (Puyallup, WA, USA) determined this study exempt from full ethical review under 45 CFR §46.101(b)(2) of the Federal Common Rule in the USA. We obtained ethical approval for our research from Amref Health Africa (AMREF) (ESRC P493/2018) and the National Commission for Science, Technology, and Innovation (NACOSTI) (NACOSTI/P/19/39980/28701) in Kenya, the Bangladesh Medical Research Council (BMRC) (BMRC/NREC/2016–2019/789) in Bangladesh, and the Council for Scientific and Industrial Research (CSIR) (RPN 004/CSIR-IRB/2018) in Ghana.

Estimation of Municipal Infrastructure Costs. We collected and triangulated municipal cost data from a total of 23 interviews with local authorities, utility engineers, treatment plant operators, NGOs, VTOs, and CBS service providers across the five study cities (see data collection tool in Text S4). To calculate municipal CapEx, we estimated the one-time capital investment required to address infrastructure require-

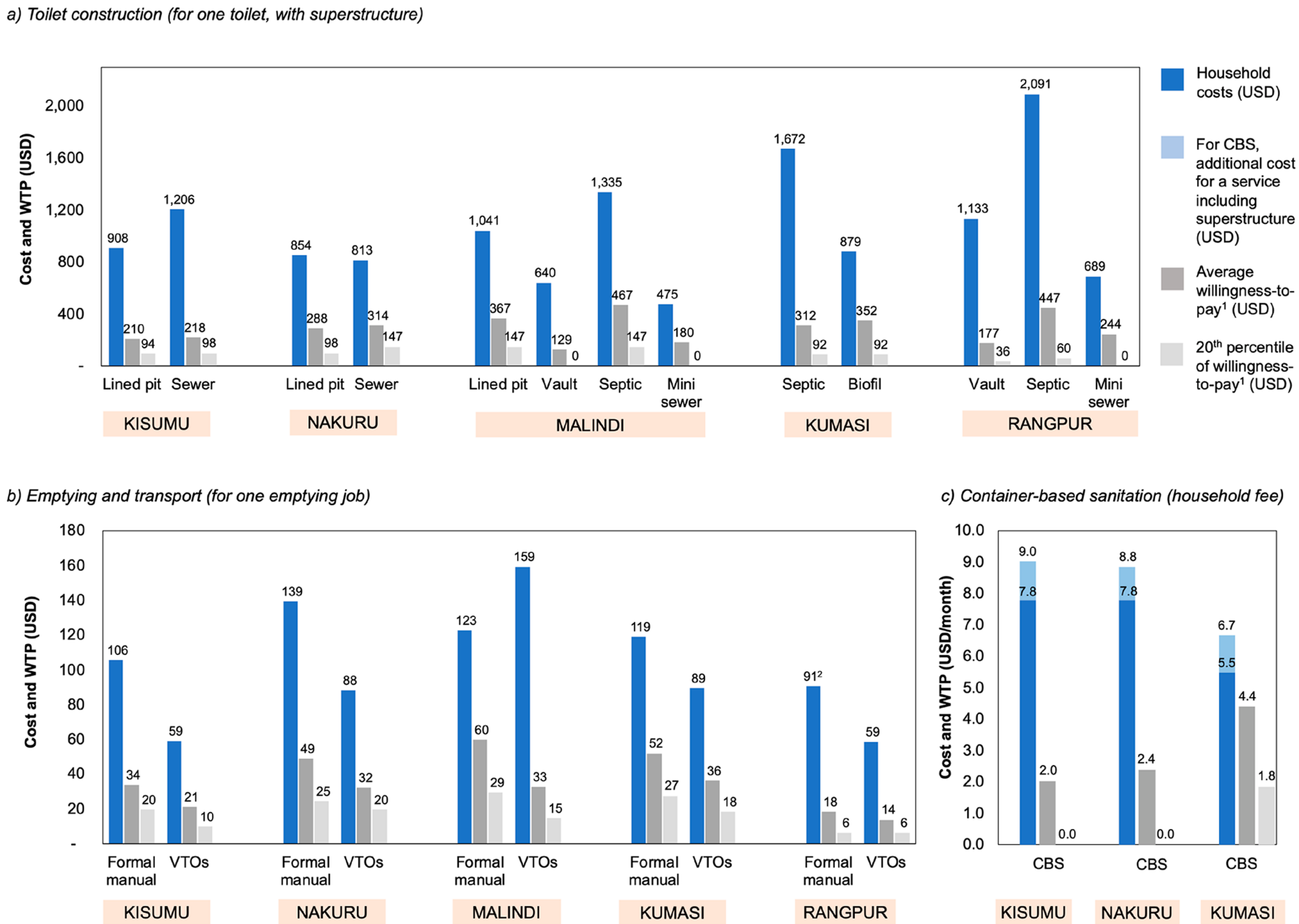

Figure 3. Comparisons of household costs and willingness-to-pay for (a) toilet construction, (b) emptying and transport services, and (c) container-based sanitation (CBS).[1] On panel a, we report the WTP of LIA landlords and homeowners; on panel b, the WTP of any LIA household (landlord, homeowner, or tenant) responsible for emptying expenses; and on panel c, the WTP of all LIA households (landlords, homeowners, and tenants).[2] Formal manual emptiers services do not yet exist in Rangpur. We thus estimated the cost of these hypothetical services using findings from other cities.

ments for the next ten years (thus, we did not include prior CapEx investments). CapEx included the construction of sewerage networks (pipes, inspection chambers, pumping stations), the construction or expansion of treatment facilities and drying beds (including the purchase of land), the purchase of new vehicles for emptying service providers to expand to LIAs (exhauster trucks, pick-up trucks, tractors), and the construction of communal septic tanks for the mini-sewer approach (Table S3). Plausible lifetimes for these infrastructure assets are specified in Table S3. To account for the fact that some assets had a lifetime longer than the study timeframe (10 years), we subtracted their salvage value at the end of the study period assuming a linear depreciation. We approximated CapManEx as a fixed annual cost equivalent to CapEx divided by lifetime.[53] OpEx included labor, electricity, trainings, vaccinations, consumables, routine maintenance, and overhead required to operate sewerage networks and treatment facilities. OpEx also included protective gear and marketing for safe emptying services, as these expenses were not covered in current consumer prices. To calculate OpEx, we first estimated the costs of operating all infrastructure (existing and new), and then subtracted current costs to obtain incremental OpEx. We assumed that OpEx would increase over time, first to serve the existing population within five years and then to keep up with population growth. In scenarios involving sewers, we subtracted sewer fees paid by users to only capture the OpEx borne by the municipality. Additionally, we assumed that CApEx and OpEx were proportional to the populations served.

RESULTS

Household-Level Costs. CApEx amounts for building a complete one-door toilet (containment, user interface, and superstructure) ranged from 475 USD (toilet connected to mini-sewer in Malindi) to 2091 USD (toilet connected to septic tank in Rangpur) (Figure 3a). The variation was largely driven by the differences in containment costs, which, on average, were lowest for mini-sewers followed by biofil digesters, vaults, lined pits, sewer connections, and septic tanks (Table S6). Superstructure costs (356–429 USD) and user interface costs (73–134 USD) were relatively uniform. On average, materials represented 69% of CApEx (range: 56–79%), labor 25% (range: 13–33%), and transportation 4% (range: 1–7%). This breakdown was consistent across countries and toilet options (Table S6).

Household costs for emptying and transport by VTOs ranged from 59 USD to 159 USD per job, and services performed by formal manual operators varied between 91 USD

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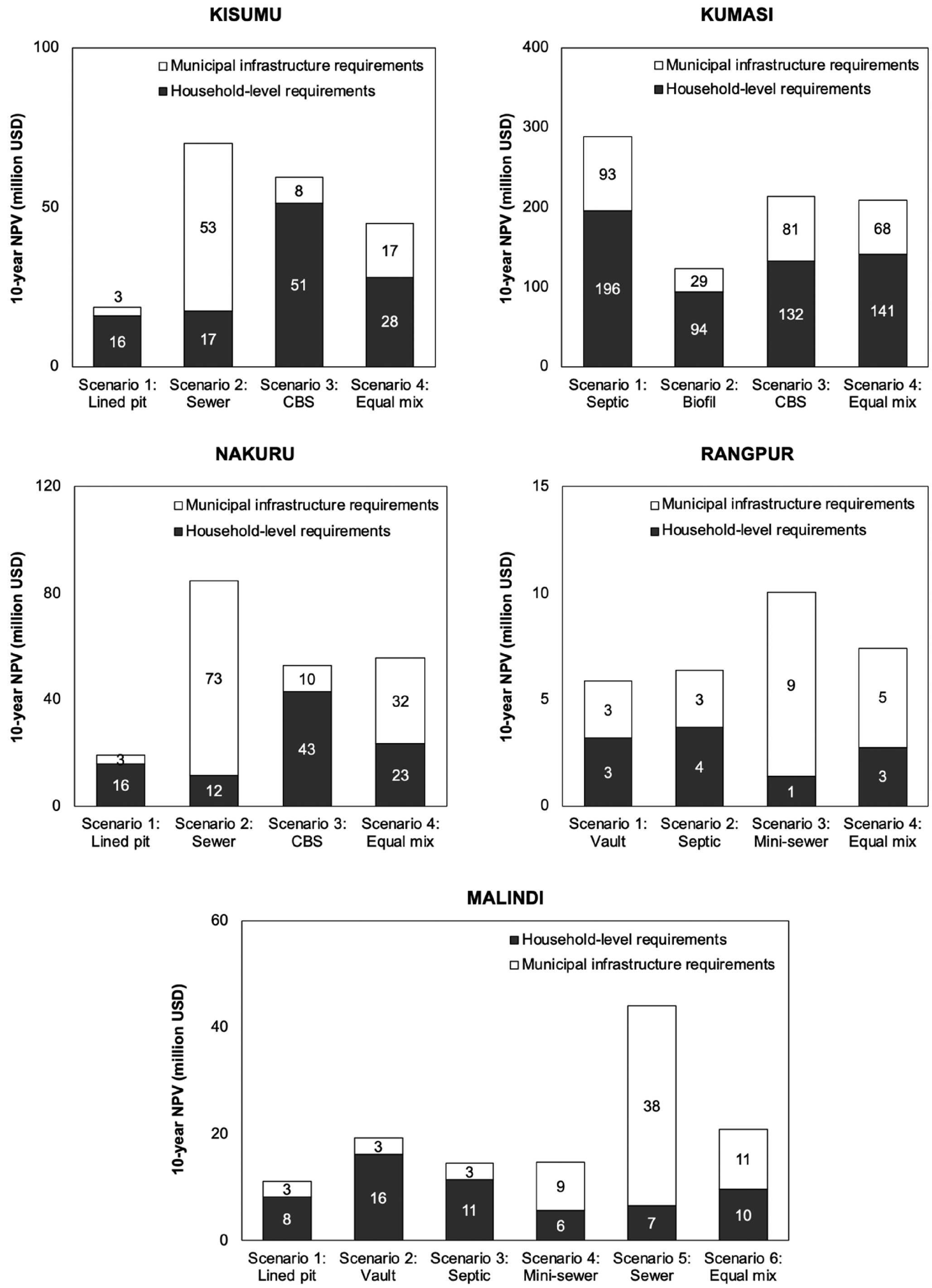

Figure 4. Estimated financial requirements[1] for achieving universal access to adequate, safely managed sanitation by 2030 for each study city and for different scenarios.[1] In our conceptual framework (Figure 2), the total financial requirements were comprised of: (i) household-level requirements or household subsidies and (ii) municipal infrastructure requirements.

and 139 USD (Figure 3b). VTO services were cheaper than formal manual emptiers in all cities except Malindi, where a lack of competition in the VTO market likely inflated prices.[6−10]

The monthly household fees required for CBS service providers to recover operational expenses (capital depreciation, labor for waste collection, and management) when operating at full capacity were 7.8 USD/month/household in Kisumu and Nakuru and 5.5 USD/month/household in Kumasi (Figure 3c). Incorporating the lease of a superstructure in the service raised the breakeven fees to 8.8−9.0 USD/month/household (27 USD/month/toilet) in Kisumu and Nakuru and 6.7 USD/month/household (20 USD/month/toilet) in Kumasi (Figure 3c).

Ten-year household costs (NPV) of adequate sanitation ranged from 816 to 3142 USD per toilet. They were lowest for toilets connected to mini-sewers (816−872 USD per toilet), followed by biofil digesters (1105 USD per toilet), lined pits (1118−1233 USD per toilet), sewerage (1253−1616 USD per toilet), CBS (1551−2101 USD per toilet), septic tanks (1775−

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2229 USD per toilet), and vaults (1796–3142 USD per toilet) (Figure S2, Table S6).

Willingness-to-Pay of LIA Households. Among home-owners and landlords living in LIAs of our five study cities, the average stated WTP for full toilet construction, including user interface, underground containment, and superstructure, ranged from 129 USD to 467 USD, with an average of 285 USD across toilet options and cities (Figure 3a). The proportion of survey respondents willing to pay market prices for toilet construction was consistently less than 10% (Table S7). The 20th percentile of WTP for toilet construction (i.e., the amount that at least 80% of respondents were willing to pay) ranged from 0 to 147 USD (Figure 3a). The resulting subsidy estimates were lowest for toilets connected to mini-sewers (475–689 USD per toilet), followed by biofil digesters (788 USD per toilet), lined pits (756–894 USD per toilet), vaults (640–1097 USD per toilet), sewerage (666–1108 USD per toilet), and septic tanks (1188–2031 USD per toilet) (Table S7).

The average stated WTP for emptying underground containment structures ranged from 14 USD to 60 USD, with an average of 35 USD across service types and cities (Figure 3b). Similarly, less than 10% of respondents were willing to pay full market prices (Table S7). The 20th percentile of WTP for emptying services ranged from 6 USD to 29 USD (Figure 3b), resulting in subsidy estimates of 84–115 USD per job for formal manual emptying and 49–145 USD per job for VTOs (Table S7).

In the case of CBS services, the average WTP ranged from approximately 2 USD/month in Nakuru and Kisumu (20th percentile: 0 USD/month) to 4 USD/month in Kumasi (20th percentile: 1.8 USD/month) (Figure 3c). The higher WTP for CBS in Kumasi was likely because CBS offers a more salient improvement in this city, where the majority of LIA households do not currently have a toilet on premises (Table S5) and instead have to pay 5–10 USD per month to use public toilets.[54] In contrast, in Kisumu and Nakuru over 90% of LIA residents already have some form of sanitation in their compound (Table S5). The resulting subsidy estimates for CBS were thus approximately 9 USD/month/household in Nakuru and Kisumu and 4.8 USD/month/household in Kumasi (Table S7). Example demand curves are presented in Figure S3.

Estimates of Financial Requirements. Based on our survey data and demographic information, we estimated that the number of LIA households who would require subsidies to gain access to adequate sanitation by 2030 was approximately 61,000 in Kisumu, 56,000 in Nakuru, 24,000 in Malindi, 400,000 in Kumasi, and 6000 in Rangpur (Table S2). Assuming that three households share one toilet, these household numbers translate into subsidy requirements of 16–51 million USD in Kisumu, 12–43 million USD in Nakuru, 6–16 million USD in Malindi, 94–196 million USD in Kumasi, and 1–4 million USD in Rangpur over the next ten years, depending on the sanitation approach selected (Figure 4). If instead five households shared one toilet, our sensitivity analysis showed that the required household subsidies would reduce by 26% on average (Table S8), and if we assumed one household per toilet, the required household subsidies would increase by 129% on average (Table S8). If we calculated the unit subsidy amount using the median WTP instead of the 20th percentile of WTP, the required household subsidies would reduce by 20% on average; in contrast, a full subsidy equal to household costs (i.e., assuming zero WTP) would raise the total requirements by 14% on average (Table S8).

The overall population (not limited to LIAs) requiring safely managed conveyance and treatment by 2030 was approximately 88,000 households in Kisumu and Nakuru, 46,000 in Malindi, 530,000 in Kumasi, and 73,000 in Rangpur (Table S2). Municipal infrastructure expenses required to serve this population are also presented in Figure 4. Our estimates varied widely based on the sanitation approach selected. For example, if Kisumu, Nakuru, and Malindi address their sanitation needs by constructing sewerage, municipal infrastructure costs would range from 38–73 million USD. If these cities instead invest in onsite sanitation or CBS, the municipal infrastructure costs would only amount to 3–10 million USD (Figure 4). In these scenarios, municipal expenditures are primarily required for building and operating fecal sludge treatment facilities. In contrast, sewerage requires substantial underground infrastructure (sewer mains, manholes, and pumping stations) as well as large-capacity treatment plants to handle the comparatively higher volumes of wastewater, resulting in higher costs. In Kumasi, we estimated comparable municipal infrastructure costs for CBS or septic tanks (81–93 million USD) and lower costs for biofil digesters (29 million USD) (Figure 4). In Rangpur, municipal infrastructure costs would range between 3 and 9 million USD (Figure 4). CapEx accounted for the majority of estimated municipal infrastructure costs (56% on average), while CapManEx and OpEx represented smaller contributions (20–24% on average) (Table S9).

Across cities, these estimates translated into overall financial requirements of 16–24 USD/person/year for scenarios relying on sewerage, 3–5 USD/person/year for mini-sewers, 2–14 USD/person/year for onsite sanitation, and 10–17 USD/person/year for CBS (Figure S4).

DISCUSSION

Adequate Sanitation is Not Affordable to all Urban Residents. The cost of building an adequate toilet with a superstructure in our five study cities was 1057 USD on average (range: 475 USD—2091 USD). In comparison, almost all surveyed LIA households reported monthly incomes under 500 USD. Further, in all cities but Rangpur over half of the surveyed households reported monthly incomes under 100 USD (Table S5). Other studies have also reported that average incomes are approximately 100 USD per month in urban LIAs of the three study countries.[55−57] Building an adequate toilet in these cities, therefore, requires five to twenty months of household income, which probably contributes to the low stated demand at market prices (0–9% across toilet options, Table S7). Given the high cost of toilet construction relative to income levels, it is important to recognize that demand creation alone (marketing, sensitization) will likely not suffice to improve access to adequate toilets in LIAs. Furthermore, strategies for distributing household costs over time (loans, installments, and subscriptions) may not be sufficient either: even when considered over a ten-year period, adequate sanitation represents 4–13% of the approximate median LIA household income (Figure S2), often above the 5% affordability benchmark recommended by the UN General Assembly for water and sanitation expenses.[58] As a result, while loans or instalments may be appropriate strategies for the wealthier fraction of LIA residents, adequate sanitation will

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likely not be accessible to the majority without household subsidies, independent of the technology option.

The methods described in this study enable estimating the overall subsidy requirements for different sanitation approaches in a given city. In Kisumu and Nakuru, we found that onsite sanitation and sewerage would require comparable amounts of household subsidies, whereas CBS would require threefold higher amounts (Figure 4). This is because our estimated household costs for CBS were comparatively higher (Figure S2) and also because LIA residents had a lower WTP for this approach. In Malindi and Rangpur, subsidy requirements were lower for mini-sewers than for more traditional onsite sanitation approaches (Figure 4), due to markedly lower household costs (Figure S2); for mini-sewers, we assumed that the construction of communal septic tanks was the responsibility of the municipality, as reflected in higher municipal infrastructure costs. In summary, the technology options proposed to address insufficient access to adequate sanitation in urban LIAs can have a tangible impact on the volume of household subsidies that local governments will have to administer and manage. This is an important consideration as administering targeted household subsidies is potentially difficult, requiring a large number of small transactions, good management information systems, and extensive verification processes.[59,60] Capturing these implementation costs was outside the scope of this study and will require additional research. More broadly, future work should examine the most cost-effective ways to administer sanitation subsidies at scale. Recent research on subsidies for emptying services in Kisumu, for example, showed the importance of identifying appropriate coordinating organizations.[46]

Choosing the Appropriate Sanitation Approach. The total financial requirements for achieving safely managed sanitation in each study city by 2030, which include both household subsidies and expenses for new municipal infrastructure, also varied widely depending on the sanitation approach selected. Scenarios relying on sewerage were the costliest (total financial requirements of 16−24 USD/person/year across cities), while scenarios relying on onsite sanitation such as lined pits, septic tanks, vaults, and biofil digesters (2−14 USD/person/year across cities and options) and CBS (10−17 USD/person/year across cities) were less expensive. These estimates are consistent with other studies that also found that sewerage was more expensive than other sanitation approaches. For example, in Dakar, Senegal, the cost of the existing sewer system is approximately 55 USD/person/year, while existing onsite sanitation systems cost 12 USD/person/year.[18] Another analysis estimated that the costs of sewers ranged from 19 to 59 USD/person/year compared to 8−15 USD/person/year for simplified sewers and 6−24 USD/person/year for septic tanks.[61] In addition, we note that the net cost of onsite sanitation and CBS may further decrease if revenue is generated from waste reuse, which was not included in our analysis. For example, CBS waste can be processed to produce compost, fuel briquettes, or animal feed worth 150−400 USD per ton,[62] which could largely offset the cost of treatment.[63] Despite its higher cost, local governments may view sewerage as the gold standard or as the most convenient and modern approach;[13] for example, the government of Kenya envisions increasing access to sewerage in urban areas to 80% by 2030.[64] However, our results add to the existing body of evidence showing that sewerage is the costliest approach to achieve sanitation targets, which demands re-evaluating historical preferences.

Municipalities may not make decisions based on costs alone. Factors such as public health benefits, operational complexity, household preferences, and water availability are also important considerations. The available evidence suggests that sewerage may lead to higher diarrhea reductions than onsite sanitation, although this finding is likely confounded by higher sanitation coverage in studies evaluating sewerage.[65] Additionally, onsite sanitation combined with fecal sludge management puts more responsibility on households and private service providers and, therefore, requires sophisticated verification and enforcement. For example, cities in the Philippines and Japan that have implemented large-scale onsite sanitation have also established strong regulatory environments such as building codes for septic tanks, mandatory scheduled desludging, and household inspection visits.[66,67] Household preferences are another important consideration, not only politically but also because uptake and usage are key determinants of the cost-effectiveness of sanitation.[68]

Our analysis found that scenarios involving mini-sewers connected to a communal septic tank were the least costly (3−5 USD/person/year). Where local conditions are favorable (water availability, space), governments should therefore consider this approach seriously when elaborating their master plans, as this semi-decentralized solution also offers user-friendliness comparable to sewerage and opportunities to simplify the oversight of fecal sludge management. For example, because all communal septic tanks would be built and registered with the municipality, it would be easier to implement building codes and scheduled desludging than in the case of private, fully decentralized underground containments.

Financing Universal Sanitation Goals. Our estimates of the financial requirements for achieving sanitation goals (2−24 USD/person/year across cities and sanitation approaches, Figure S4) were generally lower than the World Bank's previous estimates of 24−26 USD/person/year across low and lower-middle income countries.[15] Nevertheless, independent of the sanitation approach selected, the expenditures needed over the next ten years are substantial: 19−70 million USD in Kisumu, 19−85 million USD in Nakuru, 11−44 million USD in Malindi, 122−289 million USD in Kumasi, and 6−10 million USD in Rangpur (Figure 4). These costs likely exceed available budgets. For example, Kisumu's 2018−2022 development plan budgeted less than 200,000 USD per year for urban sanitation, which is approximately tenfold lower than our annual estimates to achieve sanitation targets by 2030.[69] Strategic financing approaches are therefore needed to achieve universal safely managed sanitation.[70]

The methodology developed here provided a breakdown of financial requirements according to the cost bearer (households or municipality), which may allow urban planners anticipating and identifying the right strategies to deliver financing at the appropriate level. For example, result-based funding[71] may be appropriate to address financial requirements at the household level, while traditional government loans may be more suitable to finance municipal infrastructure.

Limitations. Our study had a number of limitations. First, our estimates of the required household subsidies were based on stated willingness-to-pay surveys, which are prone to courtesy bias and anchoring.[51] Other research has found that revealed WTP (as measured by actual purchases) can be lower than stated WTP, especially for expenses that are large relative to incomes.[72,73] As a result, actual subsidy requirements could be higher than our current estimates (which we addressed in our sensitivity analysis in Table S8). Second, our survey also had a large proportion of female respondents, who may not be always the primary decision maker. Third, unlike the data we collected on household costs, our data for municipal infrastructure costs often relied on information provided by local authorities and were more difficult to verify. Fourth, we assumed municipal CapEx to be a one-time payment. Considering the cost of capital in the case of loans would have increased our cost estimates. Fifth, capturing implementation costs (staffing, logistics) for delivering subsidies at scale in LIAs was beyond the scope of this study; however, future plans to achieve universal sanitation at the city level should seek to estimate these costs, which would certainly result in higher effective OpEx. Sixth, our analysis estimated the financial requirements for cities to achieve a universal coverage of "adequate" sanitation facilities (improved, on premises, and shared by a maximum of three households) and "safely managed" conveyance and treatment (as defined by SuSanA[45]). Achieving universal safely managed sanitation as defined by the UNICEF/WHO Joint Monitoring Programme (which requires that toilet facilities are not shared between households)[74] would require higher levels of household subsidies than reported here (+129% on average, Table S8). Lastly, we acknowledge that our criteria for city selection were driven by the funder's (WSUP) programmatic priorities. Collecting representative WTP information in larger metropolitan areas (such as Nairobi, Accra, or Dhaka) would have been more complex because of the larger numbers and wider geographic spread of LIAs in these cities. Nevertheless, the general approach outlined here to estimate financial requirements for universal sanitation are broadly applicable across contexts, independent of the city size.

Finally, there is room to refine our estimates by considering the spatial distributions of population density, topography, water availability, land tenure, and available infrastructure. Spatial heterogeneity may lead to opportunities to optimize costs by applying different sanitation approaches to different parts of the city. For example, sewerage may be preferable in densely populated areas with piped water access, especially if the local topography allows for gravity flow sewers, or in areas immediately adjacent to middle/high income neighborhoods where a sewer system is already present. In less dense sections of the city that are accessible to vacuum trucks, mini-sewers connecting three toilets to a communal septic tank and requiring emptying every two years will be more cost-effective. CBS will be the most cost-effective in areas where high customer penetration can be achieved, for example areas with a high density of tenants with no sanitation facilities on the premises.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.0c06348.

> Detailed descriptions of sanitation approaches; methods for calculating household OPEX; details on the scenarios considered for achieving universal sanitation; survey locations and sampling protocol; data collection tool for municipal infrastructure costs; figures depicting sanitation approaches, ten-year household costs, household demand curves, and annual per-capita financial requirements to achieve universal sanitation; tables presenting dimensions of toilet facilities, sanitation needs in study cities, municipal cost items considered, sampling information for the household survey, socio-economic characteristics of survey respondents, detailed household costs, household WTP, sensitivity analyses on required household subsidies, and detailed municipal costs (PDF)

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Notes

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