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Generation and Management of Faecal Sludge Quantities and Potential for Resource Recovery in Phnom Penh, Cambodia

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At the current rate of progress, there will probably still be 2.8 billion people world-wide without safely managed sanitation by 2030. To incentivise and increase implementation of sustainable faecal sludge management (FSM), especially in low and middle-income countries like Cambodia, human waste must be regarded as a resource. However, planning data, e.g. on the quantities, composition and fate of faecal sludge after leaving households, are inadequate and lack accuracy. The aim of this study was to provide baseline data for effective FSM planning by sanitation stakeholders in Phnom Penh. This was done by quantifying sludge volumes generated, transport logistics and resource recovery potential to incentivise sustainable management. Interviews were conducted with users and emptying and transportation contractors, together with collection of technical data about on-site sanitation systems. Geographical coordinates of household sampling locations and disposal sites were also mapped. The results revealed that Cheung Ek and Kob Srov wetlands are the main recipients of faecal sludge collected in Phnom Penh with the amount of 18,800 m^3 and 13,700 m^3 annually, respectively. The analysis showed that faecal sludge in Phnom Penh contains valuable resources such as nitrogen (6 tons), phosphorus (13 tons) and energy (148-165 GWh) annually, but in-depth investigations of appropriate treatment options for resource recovery are required. Detailed documentation of the location of potential recoverable resources from faecal sludge would assist decision-makers in developing action plans for sustainable FSM in Phnom Penh and similar cities.

Keywords: faecal sludge management (FSM), geographic information system (GIS), nutrient recovery, onsite sanitation, sanitation service chain, spatial analysis

INTRODUCTION

Nearly half the world's population lacks access to safely managed sanitation services. Meeting the goal of universal access to safely managed sanitation services by 2030 will require at least a four-fold increase in current rates of progress, depending on the national context (WHO and UNICEF, 2021). This implies that there will likely still be 2.8 billion people world-wide without safely managed sanitation services by 2030 (WHO and UNICEF, 2017). Safely managed sanitation is defined as the use of improved human waste facilities with safe disposal *in situ* or off-site transportation and treatment (Borja et al., 2019; Chandana and Rao, 2022). In many low-income cities, the majority of faecal sludge collected in on-site sanitation technologies, such as pit latrines, is not safely managed (Hafford et al., 2018). Studies in 12 cities have shown that only 37% have safely managed sanitation and that faecal sludge ends up in the immediate urban environment, posing risks to humans and the environment (Peal et al., 2015; Hafford et al., 2018). Environmental impacts from excess nutrients include eutrophication and algal blooms in surface waters, altering the ecosystem functions (Andersson et al., 2016; Singh et al., 2017). This means that increasing the sanitation coverage by expanding the number of toilets cannot be the only solution to controlling waterborne disease and achieving United Nations Sustainable Development Goal 6 (UN SDG) target 6.2 (Strande et al., 2014; Chandana and Rao, 2022). Increasing toilet coverage would reduce open defecation, but is not a stand-alone solution to achieving safely managed sanitation. Rather, solutions and funding are needed to maintain the functionality of the entire faecal sludge management service chain. Appropriate faecal sludge collection and transportation is one of the major future challenges for low-and middle-income countries and efficient Faecal Sludge Management (FSM) is a pressing need (Chandana and Rao, 2021).

There is a misconception that on-site sanitation systems are simpler to manage than centrally based systems, resulting in adequate funding often not being allocated (Strande et al., 2018). Likewise, effective and proper FSM requires attention to the entire service chain (Boot and Scott, 2008; Strande et al., 2014), components of which include collection, transportation, treatment and safe end-uses or disposal (Klingel et al., 2002) and resource recovery (Zewde et al., 2021). In addition to considering all these components, for effective and sustainable FSM at city scale, data on the qualities and quantities of faecal sludge generated are required (Boot and Scott, 2008). However, accurate estimation of the qualities and quantities of faecal sludge on a city-wide level is complicated and such data are often lacking (Strande et al., 2018; Chandana and Rao, 2022). Faecal sludge characteristics differ widely by region, between cities, districts and households, and by source, for instance public and private toilet sludge (Appiah-Effah et al., 2014b; Gudda et al., 2017). Furthermore, there are variations in the characteristics of faecal sludge due to socio-economic status of source households, types of on-site sanitation technologies and collection system (Chandana and Rao, 2022). Selection of appropriate treatment technology is difficult due to these wide ranges of characteristics and unknown stabilisation status of collected faecal sludge (Dodane et al., 2012; Bassan et al., 2013; Appiah-Effah et al., 2014a). Reliable estimates of the qualities and quantities of faecal sludge are important when designing treatment, to avoid over- or under-dimensioned infrastructure. Inadequately sized or non-existent primary treatment and management solutions impact treatment plant operations and pose a direct risk to public health (Strande et al., 2018). For instance, Phnom Penh, the capital city of Cambodia, has no treatment facility in place to receive and treat faecal sludge. Only 22% of on-site sanitation users in the city report emptying their sludge container and only 12% of emptied sludge reaches authorised disposal sites (Peal et al., 2015), while the rest is probably discharged directly into open canals, the sewerage system or surrounding lakes (PPCH, 2021).

Treated faecal sludge is a potential source of fuel (Hafford et al., 2018) and a soil amendment for crop production (Zewde et al., 2021), benefits that could offset the upfront costs of treatment (Hafford et al., 2018; Zewde et al., 2021). Indeed, there is an on-going paradigm shift from viewing human excreta as a waste to seeing it as a resource (Andersson et al., 2016). High value of the recoverable product from faecal sludge could serve as an incentive for appropriate faecal sludge management (Diener et al., 2014), while improving access to sanitation and renewable agricultural inputs (Echevarria et al., 2021). Different types of faecal sludge treatment products could be recovered as resources, such as energy, animal food, building materials, nutrients and water (Schoebitz et al., 2016). Faecal sludge is currently attracting attention as a potentially valuable resource for two reasons. First, it has high potential for generation of biogas, and therefore energy. Second, the digested sludge has good potential to be recycled and re-used as a fertiliser on agricultural land (Yin et al., 2016). However, accurate estimation of the resources contained in sludge is needed to prove the potential benefit to sanitation planners. Information on the quantities and flows of sludge after removal from households is lacking for Phnom Penh and for other similar cities world-wide.

Efficient waste collection and transportation could be a cost-saving option for municipalities (Kinobe et al., 2015), but setting up resource recovery systems from FSM requires planning and efficient logistics within the service chain. Application of spatial Geographic Information System (GIS) tools can facilitate logistics planning by reducing the number of trips and travel distance, thereby decreasing fuel consumption and vehicle emissions and providing cost savings in overall sanitation provision (Schoebitz et al., 2017). Using GIS tools for optimisation of faecal sludge collection and transportation at city-wide scale can thus provide opportunities to increase sustainable management of faecal sludge. GIS-based methods are applicable everywhere, but there is a need for local data inputs (Schoebitz et al., 2017). Moreover, there is often no baseline information, e.g. on the overall sanitation landscape, faecal sludge generation rates and faecal sludge transportation pathways (from source to final disposal), to support sanitation stakeholders in efficient planning and decision making for sustainable FSM.

The overall aims of this study were to provide baseline data for effective FSM planning to sanitation stakeholders in Phnom Penh

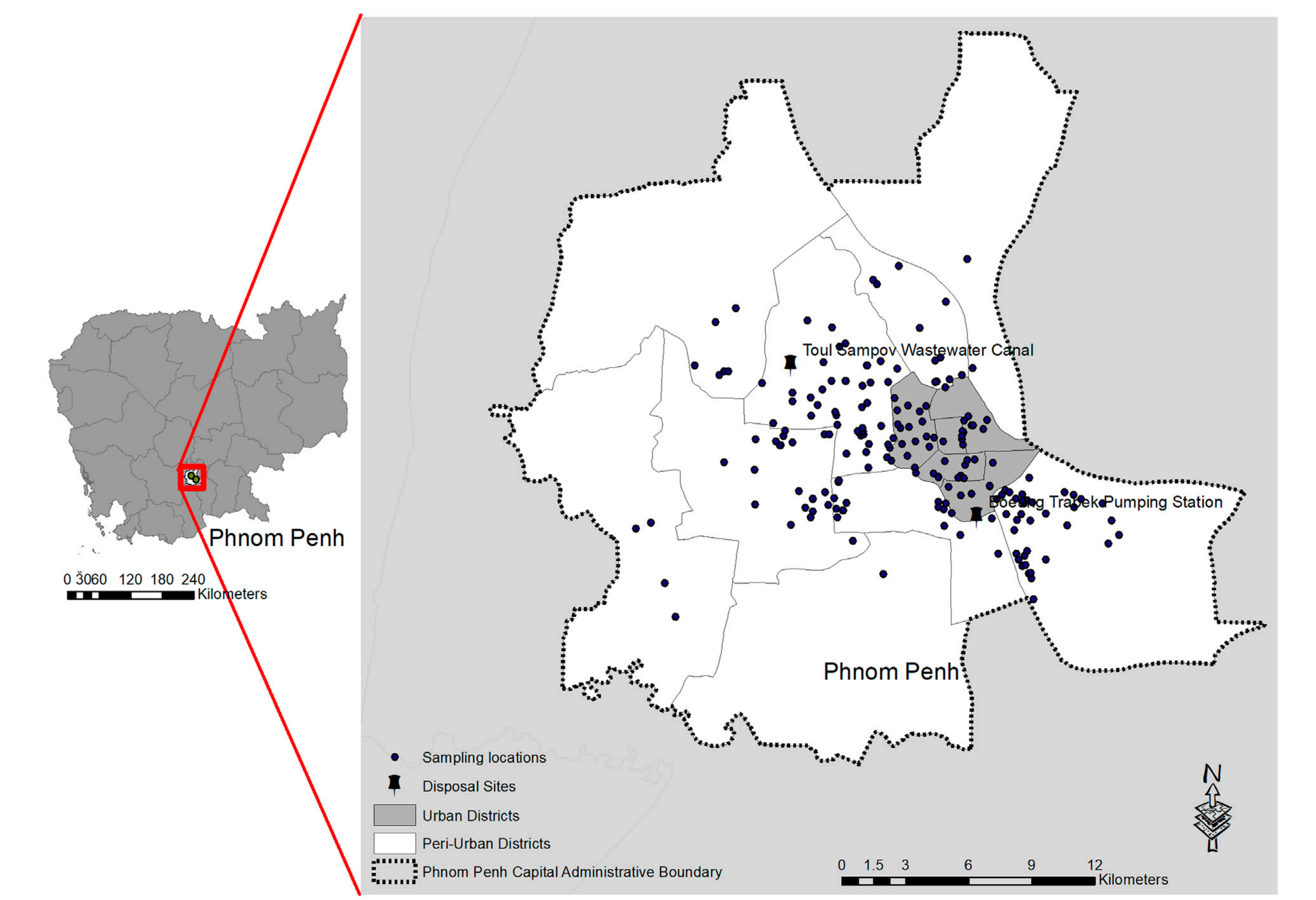

FIGURE 1 | Map showing the areas in Phnom Penh where data collection was conducted. The black dots indicate the locations of households surveyed about their sanitation management practices.

and to identify resource recovery potential in order to incentivise sustainable FSM. Specific objectives were to: 1) map FSM practices by households in Phnom Penh; 2) identify where faecal sludge is disposed of within neighbourhoods and the environment; 3) quantify faecal sludge production from household on-site sanitation systems (excreta generation rate, faecal sludge generation rate, faecal sludge collected and faecal sludge discharged); and 4) estimate the amounts of potential resources (nitrogen, phosphorus, energy) that could be recovered from faecal sludge and within the sanitation service chain.

METHODS

Data were collected through a literature review, surveys of householders in Phnom Penh, interviews with vacuum truck drivers and manual sludge tank emptying operatives, and field observations. The protocols employed in the study were approved by the National Ethics Committee for Health Research, Ministry of Health, Cambodia. The following section provides detailed information on the study area, data collection methods employed and data analysis performed in this study.

Study Area

Phnom Penh, the capital city of Cambodia (approximately 11°34″N, 104°55″E), is located on the Mekong floodplain, above the confluence of the Mekong, Tonle Sap and Bassac rivers (JICA, 2016). Phnom Penh has undergone rapid development and urbanisation in the past few decades. Recently, the whole city was divided into 14 districts, classified as urban areas (5 districts) and peri-urban areas (9 districts). The total land area of the city is about 679 km^2, with a population of approximately 2 million people in around 500,000 households (NIS, 2020).

Urban areas located in the centre of Phnom Penh are provided with full services in terms of water supply and sanitation (connection to sewerage network). The available network comprises a closed sewer system or an open canal system, depending on the location of the household within the city. Peri-urban areas can be described as adjoining areas, located outside formal urban boundaries and urban jurisdictions, that are in the process of urbanisation. These peri-urban areas can also be described as an interface, i.e., a transition zone or interactive zone, between urban and rural areas (Appiah-Effah et al., 2014b). **Figure 1** shows a map of the study area, including the location of interviews, sampling sites and disposal sites for faecal sludge investigated in this study.

Phnom Penh still uses a combined drainage system that transports domestic, commercial and industrial wastewater, as well as stormwater flow during storm events. The combined wastewater is pumped into natural wetlands surrounding the city for treatment, before flowing to the final recipient waters (Mekong river and Tonle Sap river). There are two extensive wetlands that play key roles in treating wastewater from the whole city, Cheung Ek to the south of the city and Kob Srov to the north. However, the area of these wetlands is declining, due to the current rapid urbanisation and development in the city, as they are being filled with earth to reclaim land for development purposes (Doyle, 2013). Kob Srov wetland is a sewer entry point for Sen Sok district and high levels of untreated wastewater and faecal sludge are off-loaded into the wetland, accompanied by high levels of pathogens (Min, 2019). The Tonle Sap river is the final recipient of wastewater and faecal sludge from Kob Srov wetland.

Untreated faecal sludge can pose a significant health risk when dumped in the open environment, due to the presence of significant amount of bacteria, viruses and other pathogens (Strande et al., 2014). This is certainly the case in Phnom Penh, where downstream communities living along Tonle Sap are dependent on river water for their livelihoods and for key functions, including cooking and drinking and where river water contains varying levels of pathogens that carry risks of infection and illness (Min, 2019). Cheung Ek wetland, a seasonally inundated area located about 5 km to the south of Phnom Penh, receives around 80% of wastewater from Phnom Penh's urban population and from factories (garment and others). This wetland is also used for aquatic plant and fish production, with harvesting being undertaken throughout the year.

Study Design and Data Collection

Household survey: The household survey was designed to collect demographic information on on-site sewage containment users and to map the entire sanitation service chain, by tracking faecal sludge from source through emptying to the final disposal site. The survey was conducted in the period May-September 2020, and an attempt was made to include representative households in door-to-door data collection using a structured questionnaire. Households were selected based on information received from sewage emptying contractors about households requesting their services. These contractors normally offer two different types of service, either emptying sewage containers when full or de-clogging the containment/drainage network. Desludging is therefore included in both services. A total of 195 households were surveyed, representing both urban and peri-urban areas in Phnom Penh. Sampling was planned to collect proportional numbers of samples for urban and peri-urban areas, based on the local population in these areas. In total, 144 households in peri-urban areas and 51 households in urban areas were interviewed. Since the population in peri-urban versus urban areas in Phnom Penh is approximately 3:1 (NIS, 2020), the household sampling is representative.

The structured questionnaire included a combination of dichotomous, multiple choice and open-ended questions (see **Supplementary Information**). It was developed in English, before being translated into Khmer to simplify the interview sessions by using the local language. The questionnaire covered aspects of the household's socioeconomic profile (including sex, education level, employment status, type of residential building, age of building, access to water), household sanitation practices (sewage container type and size, frequency of faecal sludge emptying, volume emptied) and householders' perceptions of faecal sludge management. A draft questionnaire was pre-tested during 1 week at the beginning of the study and refined based on feedback from this field testing. A few modifications were made before the actual survey conducted. The final questionnaire version took around 20 min to complete and targeted any person in the household between 18 and 70 years old and aware of the sanitation system in the house. In most cases, the study team interviewed the head of the family. All households were allocated an identification code and the geo-coordinates (coordination system WGS 1984) of participating households were recorded using a handheld global positioning device (Garmin GPSMAP 60CSx).

Survey of emptying and transportation contractors: Another structured questionnaire was used for interviewing vacuum and manual sludge emptying contractors (see **Supplementary Information**). The purpose of interviewing contractors providing emptying services was to track the final fate of faecal sludge after removal from households. These interviewees were asked about the quantity of faecal sludge they collected and, where possible, the geo-coordinates (coordination system WGS 1984) of the disposal site of faecal sludge from each household was recorded using a handheld global positioning device (Garmin GPSMAP 60CSx). A specific name was assigned to each disposal site at which sludge was deposited. However, private contractors in Phnom Penh sometimes dump sludge illegally (Peal et al., 2015) and some sludge disposal sites had to be recorded as unknown, since a member of the study team was not allowed to accompany the truck driver to the disposal site in all cases.

Field observation: In addition to the interviews with householders and sewage emptying contractors, the study team observed the work performed by operatives during each emptying event. This allowed observations of the accessibility of the containers, respondents' willingness to have faecal sludge treatment before final disposal, and whether the container emptying operatives used personal protection equipment while they performed the work. The study team also accompanied truck drivers to the disposal site and observed the surroundings at the sites, such as presence of water sources and the possibility of the neighbouring community using the site for swimming or for daily water extraction for general purposes.

Literature review: In addition to primary data collection, secondary data were collected from the literature in order to enable quantification of faecal sludge and resources. Data sources included government reports on population census, published literature on the population served by on-site sanitation in Phnom Penh and published information on average urine and faeces generation rates in the city. Statistical data from the Food and Agriculture Organization (FAO) on the total nutrient content in staple foods consumed by Cambodians

TABLE 1 | Sanitation management practices employed by responding households in peri-urban and urban areas of Phnom Penh. Values in brackets are percentage of the respective total. Values in bold indicate significant difference between peri-urban and urban settings ($p < 0.05$).

Variable	Total n = 195 (%)	Peri-Urban n = 144 (%)	Urban n = 51 (%)	p-value
Type of containment system				
Cesspit	181 (92.8)	135 (93.7)	46 (90.2)	0.527
Septic tank	14 (7.2)	9 (6.3)	5 (9.8)	0.527
Connection to drainage network				
Yes	138 (70.8)	90 (62.5)	48 (94.1)	**<0.001**
No	57 (29.2)	54 (37.5)	3 (5.9)	**<0.001**
Toilet type				
Auto flush	94 (48.2)	66 (45.9)	28 (54.9)	0.341
Pour flush	77 (39.5)	65 (9.0)	12 (21.6)	**0.010**
Both	24 (12.3)	13 (45.1)	11 (23.5)	**0.036**
Water-tight container				
Yes	92 (47.2)	58 (40.3)	34 (66.7)	**0.002**
No	103 (52.8)	86 (59.7)	17 (33.3)	**0.002**
Only blackwater				
Yes	36 (18.5)	30 (20.8)	6 (11.8)	0.220
No	159 (81.5)	114 (79.2)	45 (88.2)	0.220
Age of toilet/container				
<3	32 (17.8)	25 (18.5)	7 (15.6)	0.821
3–10	72 (40.0)	63 (46.7)	9 (20.0)	**0.002**
11–20	58 (32.2)	40 (29.6)	18 (40)	0.269
>20	18 (10.0)	7 (5.2)	11 (24.4)	**<0.001**
Reason for emptying				
Clogged	111 (56.9)	76 (52.8)	35 (68.6)	0.071
Filled	68 (34.9)	60 (41.7)	8 (15.7)	**0.001**
Other	16 (8.2)	8 (5.5)	8 (15.7)	**0.035**

were used to calculate the nutrient content in combined excreta and in faecal sludge.

Data Analysis

Statistical analysis: Microsoft Excel 2010 and R software version 4.0.4 were used for data handling and analysis. Descriptive statistics were calculated, such as proportion test and Chi-square test/ Fisher's exact test (where the number of samples (n) broke the rule of thumb that n (1-p) >10. Samples must be taken for household data to reveal socio-economic status in relation to sanitation practices at household level, especially as regards FSM. p-values <0.05 were considered statistically significant.

Spatial analysis of faecal sludge disposal sites: Geo-coordinate data on households and sludge disposal sites were processed using Microsoft Excel 2010. The distance from each household to its sludge disposal site was calculated using ArcMap 10.8. The drainage network system serving households within the coverage area was used to identify the final disposal site (recipient waters) for faecal sludge. The linear distance calculation method was used to estimate the distance between source household and final sludge disposal site. Three transport zones (4, 9 and 14 km) were added to the map to assess the distance between the two main disposal sites and the households from which the faecal sludge was obtained.

Faecal sludge quantification: The sludge collection method developed by (Strande et al., 2014) was used to quantify the amount of faecal sludge handled throughout the entire sanitation service chain. Based on population data for 2020, the amounts were quantified at six different stages of the chain, using a modified approach taken from Strande et al. (2018). The parameters determined at these stages were excreta generation rate (Q_1), faecal sludge generation rate (Q_2), faecal sludge accumulation rate (Q_3), amount of faecal sludge emptied (Q_4), amount of faecal sludge collected and delivered to Boeung Trabek pumping station (Cheung Ek wetland) (Q_5), and amount of faecal sludge collected and delivered to Prek Pnov open canal (Kob Srov wetland) (Q_6).

Q_1 was calculated as:

$$\text{Excreta produced } Q_1\,(\text{L/year}) = P_{(\text{served})} \text{x} \left(Q_{(\text{urine})} + Q_{(\text{faeces})}\right) \tag{1}$$

where $P_{(served)}$ is the population served by on-site sanitation in Phnom Penh; $Q_{(urine)}$ is urine generation rate, which was set at 1.42 L/cap/day (Rose et al., 2015); and $Q_{(faeces)}$ is estimated faecal generation rate, set at 0.236 L/cap/day for low-income countries (Strande et al., 2018).

Q_2 was calculated as:

$$\text{Faecal sludge produced } Q_2\,(\text{L/year}) = Q_1 + \text{Total container inflow}_{(\text{septic tank +pit latrine})} \tag{2}$$

where:

$$\text{total container inflow}_{(\text{septic tank+pit latrine})} = P_{(\text{served})} \text{ x } C_w \tag{3}$$

and C_w is the quantity of water inflow to the container (septic tank and cesspit). Key assumptions made were 1) that water inflow is similar for septic tanks and latrines, 2) that type of container does not influence faecal sludge characteristics (based on Eliyan et al. (2022)); and 3) that water and excreta are the only substances entering the container, since water is used for anal cleansing and households predominantly have a piped water connection, while the small proportion of the population that use toilet tissue for wiping usually dispose of it in trash bins with other types of solid waste. According to Koppelaar et al. (2018), an average of 58.6 L/cap/day of water enter the sewage container (C_w) in developing countries.

Q_3 was calculated as:

$$\text{Faecal sludge accumulation } Q_3\,(\text{L/cap/year}) = \frac{Emptied\ volume}{Number\ of\ users.Emptying\ frequency} \tag{4}$$

The input values used for calculating Q_3, i.e., emptied volume, number of users and emptying frequency, were the average value for each category based on the household questionnaire and triangulated with data from the container emptying contractors.

The amount of faecal sludge emptied (Q_4) was calculated based on observations during each emptying event. All faecal sludge in the container was removed and only a small amount of water was sprayed to clean the container, so it was assumed that faecal sludge emptied (Q_4) was equal to faecal accumulation rate (Q_3). The analysis covered only faecal sludge collected by mechanical emptying contractors.

Faecal sludge collected and delivered to Cheung Ek wetland (Q_5) was estimated as the amount of sludge collected from household containers and delivered to the authorised disposal site. According to Peal et al. (2015), Boeung Trabek pumping station is the only authorised disposal site for Phnom Penh. Therefore Q_5 was determined based on data collected from the interviews with container emptying contractors on whether they discharge the sludge they collect at Boeung Trabek pumping station or directly into Cheung Ek wetland. Q_6 was defined similarly as the amount of faecal sludge collected from households and discharged into Toul Sampov wastewater canal or Kob Srov wetland, based on response from contractors during interviews and on field observations. Toul Sampov canal, which is located to the north of the city (see **Figure 1**), is 5 km long and carries wastewater from the Sen Sok area to Kob Srov wetland.

Resources quantification: Resources can be described as the amount of nutrients and energy that could be recovered from faecal sludge. According to FAO (2019), the total protein content in food consumed by the Cambodian population is 65.53 g/cap/day and the protein content in vegetable products consumed is 46.81 g/cap/day. The total amounts of the macronutrients nitrogen (N) and phosphorus (P) in faecal sludge in Phnom Penh were calculated using **Eqs. 5** and **6**, respectively (Jönsson et al., 2004) and considering the fact that only 22% of on-site sanitation users report employing a contractor to empty their sewage container (Frenoux et al., 2011).

$$\text{Content of nitrogen (N)} = 0.13\,x \text{ Total food protein} \tag{5}$$

$$\text{Content of phosphorus (P)} = 0.011x\,(\text{Total food protein} + \text{vegetable food protein}) \tag{6}$$

The nutrient resource in faecal sludge was also calculated based on concentration of total nitrogen (N_{tot}) and total phosphorus (P_{tot}) in faecal sludge according to (Eliyan et al., 2022).

The potential for energy generation from faecal sludge was estimated based on Ahmed et al. (2019), who concluded that the energy potential in faecal sludge lies within the range 16.39–18.31 MJ/kg at a sludge density of 1,001 kg/m^3 (Radford and Sugden, 2014).

RESULTS

Results are presented below for FSM throughout the entire service chain, from source (households) to the final disposal site, divided into five parts: demography of respondents; sanitation management practices by households in Phnom Penh; current disposal sites for faecal sludge removed by vacuum operators; faecal sludge quantities; and resources contained in faecal sludge flows through current pathways.

Demography of Respondents

There was no statistical correlation between demographics of the respondents and geographical locations (see **Supplementary Table S1**).

Sanitation Management Practices

Two types of on-site sewage containment system are used in Phnom Penh, cesspits and septic tanks, According to our survey of households, cesspits dominate, serving up to 92.8% of the population, a trend seen in both urban and peri-urban areas. Around 95% of urban households reported having their sludge container connected to the sewer network, while only 62.5% of households in peri-urban areas reported have a direct connection (p < 0.001). Concerning the sanitation management practices performed

TABLE 2 | Summary statistics on final disposal sites of faecal sludge on Phnom Penh (*N* = number of samples, SD = standard deviation).

Disposal Site	N	% Of Total	Min Transport Distance (km)	Max Transport Distance (km)	Mean Transport Distance (km)	SD (km)
Cheung Ek wetland	63	57.8	0.00	13.9	4.34	2.78
Kob Srov wetland	46	42.2	0.00	12.7	3.87	2.89
Total	109	100				

by respondents, type of containment system and type of wastewater received by the system (only blackwater or not) were found to be unaffected by location in urban or peri-urban areas in Phnom Penh (**Table 1**). However, the age of the sewage container differed significantly with the geographical location of the household. The containers at houses in peri-urban areas of the city tended to be newer, reflecting the fact that the city is developing and expanding outwards. Mechanical emptying services is the only preferred method for households in Phnom Penh when their containments were full or clogged. No evidence of manual emptying practices was found. According to the observation by the study team during data collection, none of pit emptiers used personal protective equipment during emptying events. Hence, it might potentially pose risks to their health.

Faecal Sludge Disposal Sites

There is no faecal sludge treatment facility in Phnom Penh and Boeung Trabek pumping station is the only authorised sewage disposal site (Peal et al., 2015; JICA, 2016). The disposal sites identified in this study included public manholes near the households where faecal sludge was collected, fields around the Kob Srov area, Toul Sampov wastewater canal, a smaller canal (1 km) connected to Toul Sampov wastewater canal, and Boeung Trabek pumping station (Cheung Ek wetland). The survey also revealed that Cheung Ek wetland is the main disposal site (receiving 54.1% of all sludge collected), followed by the small canal and Toul Sampov wastewater canal itself (34.5%). Toul Sampov canal receives wastewater from the Sen Sok area, which flows onwards by gravity to Kob Srov wetland, with the Tonle Sap river being the final receiving reservoir. The remaining 11.4% of collected faecal sludge goes to open fields in the Kob Srov area and public manholes near source households. Since those two main disposal sites are pumping stations, there is limited risk for spillage and spread of faecal matter to local people living around those areas.

Wherever faecal sludge is disposed of within the drainage network, it ends up in one of the two main receiving wetlands, namely Cheung Ek and Kob Srov. The results obtained in this study indicated that Cheung Ek wetland is the main faecal sludge disposal site for container-emptying contractors (57.8%), while Kob Srov receives 42.2% of all sludge collected from household sewage containers by mechanical emptiers (**Table 2**). The mean travel distance from source households to Cheung Ek was found to be 4.34 km, while that from source households to Kob Srov was around 3.87 km. The shortest estimated distance observed was 0 km, in cases where the faecal sludge removed from a household's containment system was disposed of in a manhole located in front of the household. This only occurred for households with drainage network coverage.

The linear distance from source (extraction household) to each disposal site was used to estimate the travel distance for discharging emptied faecal sludge from households in Phnom Penh. Three zones were created around the two main disposal sites, to group travel distances for emptying events. The resulting map revealed that most travel distances for emptying faecal sludge fell within the first and second zones, with few distances within the third outer zone (**Figure 2**). This reflects the current practice of contractors, who prefer not to travel long distances to discharge collected sludge when there is an opportunity to dispose of it somewhere that could reduce their travel distance, thereby saving transportation time and fuel costs.

Faecal Sludge Quantities

Estimation of excreta production (Q_1) and faecal sludge generation (Q_2) was based on secondary data taken from the literature, based on Strande et al. (2014) as indicated in data analysis section. The production rate of excreta in Phnom Penh was taken to be 604 L/cap/year for all types of containment system, based on findings (Eliyan et al., 2022) that type of containment system does not influence the characteristics of faecal sludge. The faecal sludge generation rate (Q_2) was estimated to be 21,993 L/cap/year. Based on the primary data collected in the study, faecal sludge accumulation (Q_3) was estimated to occur at a rate of 106 L/cap/year for all types of containment system. This was only around half the value reported previously for the city of Kampala in Uganda (Strande et al., 2018). However, an earlier study conducted in 12 Asia and Africa cities found faecal sludge accumulation rates varying from 35.6 to 959 L/cap/year (Chowdhry and Kone, 2012). The accumulation rates in Phnom Penh are at the lower end of that reported range, possibly because containment systems in Phnom Penh are usually connected to the sewerage network, which allows daily overflow of supernatant from the sludge container to the drain network. In addition, many of the household containment systems in the city are not watertight, which allows the liquid portion of wastewater in the container to drain out to surrounding soil. According to our calculations, the total amount of faecal sludge emptied (Q_4), and thus collected (Q_5), was 32,500 m^3/year (**Table 3**).

Our calculations showed that around 52.5% (18,800 m^3/year) of total faecal sludge emptied from household containment systems during the study period was taken to Cheung Ek

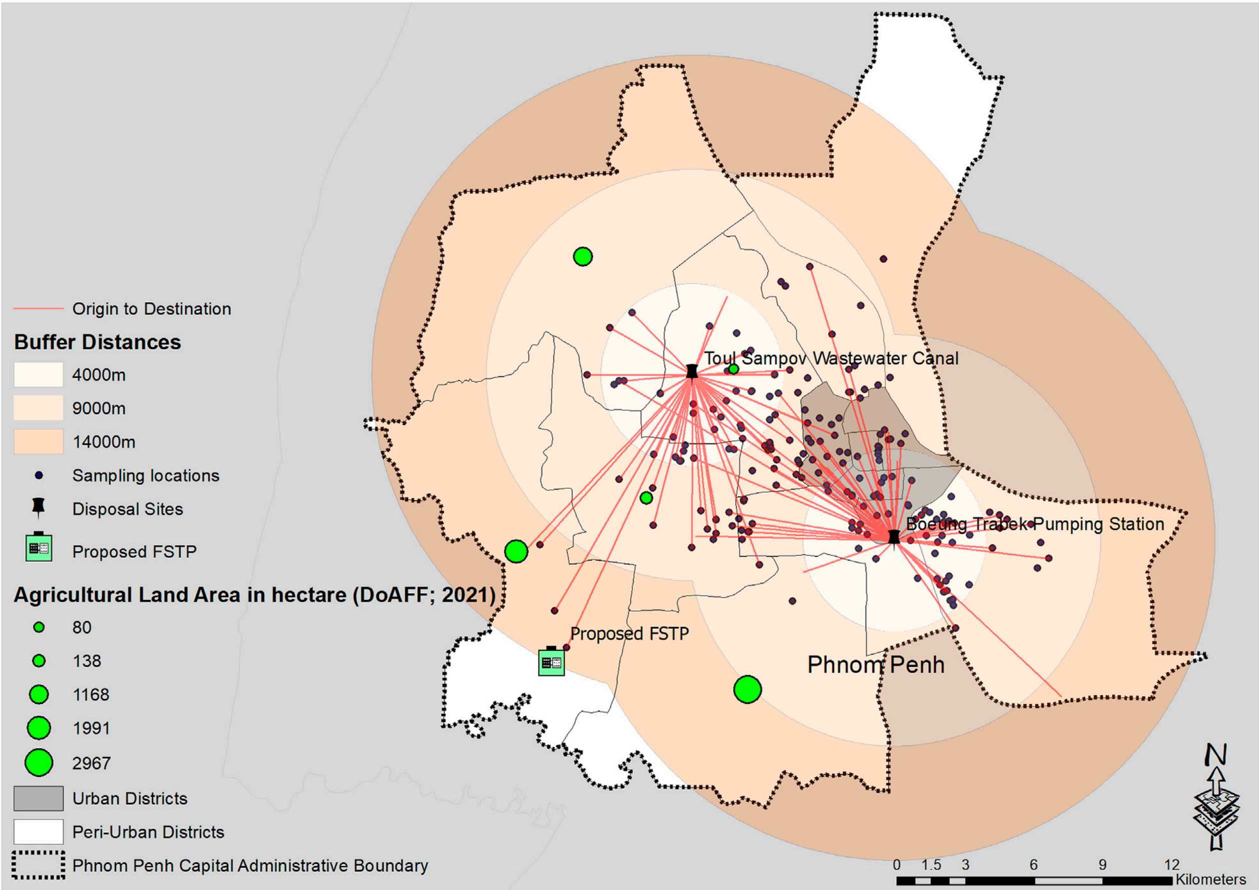

FIGURE 2 | Transport distance zones (within 4, 9 and 14 km) around Toul Sampov wastewater canal and Boeung Trabek pumping station, the two main final disposal sites of faecal sludge in Phnom Penh identified in the study.

TABLE 3 | Faecal sludge quantities at different stages along the on-site sanitation service chain for households in Phnom Penh.

Faecal Sludge Quantification as	Amount (L/cap/year)	Total Quantity (m^3/year)
Excreta produced (Q_1)	604	1,380,000
Faecal sludge produced (Q_2)	21,990	50,190,000
Faecal sludge accumulation (Q_3)	106	32,500
Total faecal sludge emptied (Q_4)	106	32,500
Total faecal sludge collected (Q_5)		32,500
Faecal sludge collected, delivered to Cheung Ek wetland (Q_{5a})	-	18,800
Faecal sludge collected, delivered to Kob Srov wetland (Q_{5b})	-	13,700

wetland and 42.2% (13,700 m^3/year) was discharged in the Kob Srov catchment.

Estimation of Resources Content in Excreta and Faecal Sludge

Potential resources assessed in this study were the amount of nitrogen, phosphorus and energy contained in faecal sludge. Based on FAO protein consumption data and resulting N and P in excreta (**Eqs. 5** and **6**), it is estimated that each individual excretes around 3.12 kg N and 0.45 kg P per year (**Table 4**), the total amount of nitrogen theoretically present in excreta (urine plus faeces) was thus estimated to be 955 tons/year, while the amount that could potentially be extracted from faecal sludge was only 6 tons/year (Jönsson et al., 2004). Thus, according to these findings faecal sludge in Phnom Penh contains less than 1% of total nitrogen excreted by humans. Nitrogen in wastewater is mostly found in the water-soluble form as ammonia and follow the liquid fraction into the sewer network or into the ground due to non-watertight containers.

TABLE 4 | Estimated amounts of resources (total nitrogen (N_{tot}) and total phosphorus (P_{tot})) contained in excreta (urine + faeces) and in faecal sludge generated annually in Phnom Penh and discharged to Cheung Ek wetland and Kob Srov wetland.

Resource	Generation rate[a] (kg/cap/year)	Amount in excreta[b] (kg/year)	Amount in Faecal sludge[c] (kg/year)
Total nitrogen in excreta	3.12	955,500	-
N_{tot} in faecal sludge	-	-	6,100
N_{tot} to Cheung Ek	-	552,000	3,530
N_{tot} to Kob Srov	-	403,000	2,580
Total phosphorus in excreta	0.45	137,000	
P_{tot} in faecal sludge			12,980
P_{tot} to Cheung Ek	-	79,600	7,500
P_{tot} to Kob Srov	-	58,200	5,480

[a]*__Equations 5__ and __6__.*

[b]*The number of population used for this calculation was 306,238, represented the population used onsite sanitation with experiences of emptying their containments (Frenoux et al., 2011; Peal et al., 2015; NIS, 2020).*

[c]*The concentration of total nitrogen and total phosphrus were 188 mg/L and 400 mg/L, respectively (Eliyan et al., 2022). Note that it is Q_4 x concentration.*

The results for phosphorus showed that a larger fraction, around 9%, remains in faecal sludge (**Table 4**), presumably because phosphorus tends to precipitate as metal phosphate and attach to solid particles in sludge and is less water-soluble than nitrogen. However, a high proportion of both nutrients (nitrogen and phosphorus) remains in the liquid wastewater fraction, which with improved wastewater treatment could be captured and treated as part of achieving the UN SDG goal 6, under target 6.2 and 6.3, as well as meeting the Cambodian wastewater discharge standard (RGC 2017; RGC, 2021) and to avoid environmental impacts. In conclusion, around 6 tons of nitrogen and 13 tons of phosphorus could be recovered from faecal sludge annually.

Potential energy generation was calculated based on the total faecal emptied annually (Q_4). Based on energy potential from Ahmed et al. (2019), the estimated amount of potential energy that could be captured from faecal sludge annually was within the range 532,571–594,959GJ, or 148-165 GWh.

DISCUSSION

The baseline data obtained in this study can support sanitation stakeholders in future decision-making for more sustainable FSM, while the logistical data obtained, such as volumes of sludge generated and travel distance from source to disposal site, are critical for planning FSM at city-wide scale. The study also indicated that recovery of resources (plant nutrients, energy) from faecal sludge could potentially be an incentive for FSM in the long run.

Factors such as household connection to the city's sewerage network and age of sewage containment systems were found to differ significantly between geographical areas of Phnom Penh, particularly between urban and peri-urban areas. It emerged that urban area generally had full drainage coverage, while some parts of peri-urban area still had limited access to the sewerage network due to slow development in the city's wastewater management sector. Data on the age of the containment systems and toilets in the households surveyed indicated that there are more new households in peri-urban settings, since in most cases houses and toilet are built at the same time. The city is developing and expanding rapidly, while wastewater management services have not kept pace with the rate of development.

Different factors were found to lead to indiscriminate disposal of faecal sludge at sites other than at the official designated site, Cheung Ek wetland. One such factor was related to cost and travel distance between households and Cheung Ek wetland. The unofficial cost of 2.50 USD per truck and km travel distance between Cheung Ek wetland and the next household served by the truck. Frenoux et al. (2011) found that reducing the travel distance from extraction household to faecal sludge disposal site, by dumping sludge at an unauthorised site closer to the household, would enable truck drivers to increase their income by up to 10%, through faster turn-around and potential cost savings on transport. The largest company among the sludge-emptying contractors surveyed in this study owns around seven trucks and pays monthly discharge fees at Cheung Ek wetland, so it is most likely that faecal sludge extracted by this company is discharged at the official site. Other survey responses indicated that the truck drivers would prefer not to travel more than 9 km between source household and sludge disposal site, for reasons of turn-around speed and transport distance. This supports findings by Frenoux et al. (2011) that the shorter the travel distance to sludge disposal, the more savings the contractor can make, e.g. by only travelling within 4 km distance to disposal site, they could save up to 10% of their extraction income. Travel distance and traffic congestion are also the main business constraints identified by operators (PPCH, 2021). The first faecal sludge management strategy for Phnom Penh Capital Administration (2035) pointed out the need to build up to four treatment plants to treat faecal sludge for the whole city. The location for the first treatment plant has been established as Kamboul district, in one of the peri-urban areas of Phnom Penh (PPCH, 2021). This site lies around 20 km from the two main sludge disposal sites identified in this study, which is rather far for transporting sludge from households located in the centre of the city and likely poses a risk of indiscriminate dumping still happening to some extent.

The faecal sludge generation rate was found to be quite high compared with the excreta production rate (**Table 3**). The calculation was based on the total generation rate, which included the supernatant that continuously flows into the drainage network for households located within the coverage area. The discrepancy reflects the fact that on-site containment systems in Phnom Penh are either connected to the drainage network, or not, depending on household location, e.g., urban households located within the drainage coverage area are typically connected to the network. The amounts of faecal sludge emptied and disposed of are equal in Phnom Penh, since all mechanical operators (based on our observations during the study period) normally removed all faecal sludge from the containers at each emptying event. With this current practice, more trucks would be needed to transport the required emptied volume to authorised disposal sites. PPCH (2021) found that business activity in the faecal sludge empting and transportation sector in Phnom Penh has increased by at least 5% in the past 8 years, including the number of vacuum trucks and intensification of the service. Greater efficiency in logistics and transportation is needed to cope with the required transportation of collected sludge along the entire service chain, which has been identified as one of the business constraints for sludge collection contractors in the sector (PPCH, 2021). Similarly, a study conducted in informal settlements of Kampala, Uganda, found that three key factors for improving service provision were truck capacity, fuel costs and travel distance (Murungi and van Dijk, 2014). Another issue in Phnom Penh is that the supernatant which flows continuously from household containment systems goes directly to the drainage network and eventually reaches natural recipient wetlands without any treatment. The quality of this supernatant may barely meet the effluent standard for wastewater discharge (RGC, 2017) and it should be collected and treated when planning for safely managed sanitation in Phnom Penh.

The two big natural wetlands in Phnom Penh, Cheung Ek and Kob Srov, play an important role as recipients and in treatment of faecal sludge before final discharge. With the current practice, the nutrients contained in faecal sludge act as pollutants, with environmental implications for the wetlands. For example, high ammonia concentrations inhibit algal growth and impair plant growth in wetland treatment systems (Koné and Strauss, 2004). Excess nutrients could lead to eutrophication and algal blooms in surface water (Andersson et al., 2016; Singh et al., 2017). It is possible to change this pollutant loading into resource recovery, particularly of plant nutrients, as fertiliser plays a key role in crop productivity and food security. The demand for fertiliser in Cambodia increased sharply, by around 210%, between 2002 and 2011 (Vuthy et al., 2014). The present study demonstrated good potential for nutrient recovery from faecal sludge in Phnom Penh and the recovered nutrients could potentially replace commercial fertiliser use in some agricultural applications in Phnom Penh. According to the Cambodian Department of Agriculture, Forestry and Fishery, 6,300 ha of agricultural land in Phnom Penh, located within five of its peri-urban districts, are farmed in the wet season. According to a market study conducted by GRET (2019) the amount of N and P fertiliser used in agricultural applications in Phnom Penh is around 1,460 ton/year. Therefore, the 6 tons of N and 13 tons of P that could be recovered from faecal sludge could replace part of chemical fertiliser use in Phnom Penh, while avoiding logistics costs in transportation and adding more value to the final product from wastewater treatment facilities. It would therefore reduce the total cost of agricultural production, since fertiliser use is the major determining factor in variable costs (Vuthy et al., 2014).

In addition to the nutrients contained in faecal sludge, it is also possible to recover energy for domestic use. For instance, based on the assumption that the average household in Phnom Penh consumes around 1723 kWh/year (Sovanndara, 2002), the amount of energy generated from faecal sludge, if converted into electricity, would be enough to supply 85,900–95,900 households, replacing electricity generated from non-renewable sources or imported.

CONCLUSION

The comprehensive baseline information obtained in this study can be used as input for FSM planning throughout the entire service chain in Phnom Penh. An estimated amount of 32,500 m^3 of faecal sludge is emptied from household containment each year. The results also revealed that the current practice of indiscriminate disposal of faecal sludge will likely cause environmental problems, such as eutrophication, in recipient natural wetlands (Cheung Ek, Kob Srov), which currently act as natural treatment systems. Annually, approximately 18,800 m^3 and 13,700 m^3 of faecal sludge are emptied untreated into Cheung Ek and Kob Srov wetlands respectively. Treatment of faecal sludge before release into the environment is thus crucial to meet the goal of safely managed sanitation in the city. When planning future faecal sludge treatment plants, our results indicate that efficient transportation logistics will be needed to maximise the income level of private contractors, cope with a rising faecal sludge generation rate and improve the cost effectiveness of FSM. In the case of Phnom Penh city, there should be at least two treatment plant nodes, one located in the south and the other in the north of the city. Our study showed that private operators prefer to discharge the sludge they collect within a 9-km zone, a finding that should be taken into account at an early stage when considering possible locations for wastewater treatment plants. Alternatively, setting up several faecal sludge transfer stations at regular intervals could be a solution to avoid long transport distances to wastewater plants for vacuum truck drivers, and thus reduce the likelihood of indiscriminate dumping. The supernatant that currently flows continuously from households' on-site containment systems should also be properly treated as part of the goal to achieve safe sanitation management in Phnom Penh. Depending on plant design, this supernatant could be treated in faecal sludge treatment plants or sent to a combined wastewater treatment plant.

To incentivise contractors and compensate for the operational costs of sludge treatment, resource recovery from faecal sludge treatment products could be considered. This study indicated a possibility for alternative FSM through recovering resources from faecal sludge. Nutrients (6 tons/year of nitrogen and 13 tons/year of phosphorus) and energy (148-165 GWh/year) could be recovered from faecal sludge. This could be used to partly replace chemical fertiliser and imported electricity for agricultural applications and household usage. However, resource recovery alternatives need to be investigated more thoroughly to enable proper planning of sustainable faecal sludge management in Phnom Penh and similar cities world-wide.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

All participating households were informed about the purpose of the study and asked for their voluntary participation. Verbal consent was obtained from each household and documented in the questionnaire. The protocols employed in this study were also approved by the National Ethics Committee for Health Research, Ministry of Health, Cambodia.

AUTHOR CONTRIBUTIONS

CE: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing-original draft, Writing-review and editing. JM: Conceptualization, Investigation, Validation, Methodology, Supervision, Writing-review and editing. CZ: Methodology, Supervision, Writing-review and editing. TK: Methodology, Supervision, Writing-review and editing. KS: Funding acquisition, Methodology, Supervision, Writing-review and editing. BV: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Writing-review and editing.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.869009/full#supplementary-material

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.