Research Paper

Factors influencing physicochemical characteristics of faecal sludge in Phnom Penh, Cambodia

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ABSTRACT

Comprehensive knowledge of faecal sludge characteristics is needed for sludge management planning, but it is lacking for the city of Phnom Penh, Cambodia. Thus, this study characterised physicochemical properties of faecal sludge from households in Phnom Penh and related these to sludge containment unit type, unit age, connectedness to the urban drainage network, type of wastewater captured, watertight containment units, number of users, and emptying practices. In total, 194 faecal sludge samples collected during containment unit emptying were analysed for physicochemical parameters. Information on containment units was collected in a survey of emptiers and users. Mean values of faecal sludge chemical parameters were found to be slightly lower than previously reported values for low-/middle-income countries, whereas physicochemical properties were within similar ranges. The main factor influencing organic matter content in faecal sludge was containment unit connection to the urban drainage network, whereas emptying practice and capture of only blackwater affected nutrient levels. The concentrations of nutrients and organic pollutants greatly exceeded Cambodian discharge standards for wastewater. This causes environmental impacts, so treatment is needed before discharge. The faecal sludge characteristics and influencing factors identified here can serve as a baseline for sanitation stakeholders planning faecal sludge management systems in Phnom Penh and similar cities.

Key words: blackwater, cesspit, low-income country, onsite sanitation, pollutant loading, septic tank

HIGHLIGHTS

- Physicochemical properties of faecal sludge in Phnom Penh far exceeded Cambodia wastewater discharge standards.
- Adding water during emptying and collection of only blackwater could be used as predictors of nutrient loads in faecal sludge.
- Connectedness to the urban drainage network could serve as a predictor of organic loading from faecal sludge.

INTRODUCTION

Onsite sanitation systems worldwide currently serve around 2.8 billion people in urban areas in low- and middle-income countries (WHO & UNICEF 2017), but this number is expected to double by 2030 (Strande 2014). Faecal sludge is produced and contained in different onsite sanitation facilities, such as septic tanks and pit latrines (Strande 2014). The conventional centralised wastewater (sanitation) treatment system is not the most suitable and appropriate solution in low- and middle-income countries due to its high investment and running cost (Polprasert & Koottatep 2017). The promotion of onsite sanitation systems instead could significantly increase sanitation coverage and reduce the proportion of people practising open defaecation. The United Nations Sustainable Development Goals under target 6.2 include safely managed sanitation as one of the indicators of goal number 6. This refers to faecal sludge management beyond the provision of toilets (Rao et al. 2017). Globally, only 39% of the population has access to safely managed sanitation. In Cambodia, 88% of the urban population has access to basic sanitation only, and the complete lack of safely managed sanitation has been reported (WHO & UNICEF 2017).

Treatment is a crucial step for faecal sludge management to alleviate the associated environmental and health risks and recover valuable resources from the sludge (Tayler 2018). Faecal sludge generally contains high concentrations of nutrients and organic matter that can be recovered for reuse in crop production (Changara *et al.* 2018) and energy generation (Diener *et al.* 2014). However, the generation rate and chemical and physical composition of faeces vary widely, making it difficult to select and apply appropriate treatment technologies (Rose *et al.* 2015). Multiple factors influence faecal sludge qualities, including technical, environmental, cultural, and socio-economic factors (Niwagaba *et al.* 2014; Krueger *et al.* 2021). Several studies have characterised the physical and chemical properties of faecal sludge in spatial and temporal terms (Bassan *et al.* 2013; Gudda *et al.* 2017; Strande *et al.* 2018; Ahmed *et al.* 2019). The properties of public and private toilet sludge differ widely by the region and between cities, districts, and households (Appiah-Effah *et al.* 2014; Gudda *et al.* 2017). The optimum choice of treatment technology depends on faecal sludge characteristics and treatment objectives (Koné & Strauss 2004). Therefore, a comprehensive understanding of faecal sludge qualities is necessary before selecting any treatment or designing a faecal sludge treatment plant (Ahmed *et al.* 2019). Furthermore, evaluating faecal sludge qualities in a specific local context is very important when developing faecal sludge management plans on a city-wide scale (Strande *et al.* 2018).

Data on the physical, chemical, and biological properties of faecal sludge are generally scarce for Cambodia. A previous study characterising faecal sludge in Phnom Penh focused on only a few parameters, such as pH, turbidity, and total solids (TS; Frenoux *et al.* 2011). Other studies, for example, by Peal *et al.* (2015) and Chomnan (2018), were based on secondary data complemented by stakeholder interviews. Peal *et al.* (2015) concluded that none of the faecal sludge in Phnom Penh is safely managed. The more recent study by Chomnan (2018) found that 41% of excreta in Phnom Penh are safely managed, but that the overall regulatory and institutional aspects of faecal sludge management in Cambodia are still inadequate. There is a lack of regulatory enforcement for each component of faecal sludge management service in the country. However, no actual field sampling and characterisation of faecal sludge have been carried out; hence, there are limited valid documented data on faecal sludge characteristics and management in Cambodia.

The main aims of this study were to characterise the physical and chemical properties of faecal sludge in Phnom Penh and to identify sources of variation in faecal sludge composition. Specific objectives were to investigate whether sludge characteristics are related to variations in the demographic and technical conditions affecting excreta containment units and to identify critical design parameters and baseline data on local conditions needed for planning appropriate faecal sludge management in the city.

METHODS

Demographic and technical data on onsite sanitation systems in Phnom Penh that might influence faecal sludge characteristics were analysed. Faecal sludge samples were collected from households and questionnaires were administered with users of the system and tank/pit emptiers. Details of the questionnaires used with service providers and users, the sampling plan, the analytical procedure, and statistical analysis are described in more detail in the following sections.

Study area

Phnom Penh, the capital and largest city in Cambodia, is located at about 11°34″N and 104°55″E on the floodplain of the Mekong, above the confluence of the Mekong, Tonle Sap, and Bassac rivers. The city has an administrative area of 679 km^2, stretching over 14 districts (five urban districts and nine peri-urban districts), with a total population of 2.28 million and a population density of 3,360/km^2, representing approximately 500,000 households (NIS 2020).

Only 24% of residents in Phnom Penh have toilets directly connected to a combined sewer network. The majority (61%) rely on onsite sanitation with a toilet connected to the urban drainage network (Frenoux *et al.* 2011; Frenoux & Tsitsikalis 2015). Any type of containment unit can be connected to the drainage network if the household is located within the drainage coverage area. The connection to the urban drainage network allows containment units to discharge free-flowing blackwater and other types of wastewater, such as stormwater, to the drainage system. The sewerage system in Phnom Penh is a combined system that collects both wastewater and stormwater (Frenoux *et al.* 2011) in a closed sewer network or an open canal system depending on the location of the household.

Septic tanks and pits are the standard sanitation technologies and are used in most urban areas of Cambodia. Septic tanks are generally sealed at the bottom to prevent infiltration of liquid into the environment and have an average volume of 2–3 m^3 (Chowdhry & Kone 2012). The following two types of septic tank are used in Phnom Penh: brick and plastic tanks. The septic tanks made of bricks are rectangular and are built using a mixture of cement and water as mortar (Figure 1). Each tank

Figure 1 | Typical (a) circular and (b) rectangular cesspits and (c) imported plastic and (d) rectangular brick septic tanks used by households in Phnom Penh. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/washdev.2021.193.

consists of two or three chambers, with the first chamber receiving everything from the toilet. The supernatant then flows to the next chamber. The supernatant from the last chamber can flow freely to the urban drainage network if it is located within the drainage coverage area. Septic tanks made from plastic are normally imported from Thailand or China. Circular or rectangular cesspits, another onsite sanitation technology, are also commonly used in the city. The circular type is made by assembling two to six pre-cast concrete rings. The rectangular system is similar to a septic tank, but has only one chamber (Figure 1). Residents in Phnom Penh commonly use both auto-flush and pour-flush toilets. Since piped water distribution has almost a full coverage, householders use water for anal cleansing/washing, whereas tissue paper is only used by a small proportion of the population.

Faecal sludge management in Phnom Penh is classified as poor, as it has no framework governing legal and institutional aspects and almost no services (Peal *et al.* 2015; Chomnan 2018). The quality of containment units is not monitored and can vary widely. Faecal sludge management in the city primarily consists of faecal sludge collection and dumping in the wetland, a practice followed by private mechanical extraction and transportation operators (Frenoux & Tsitsikalis 2015). In 2011, there were 19 private companies with 31 vacuum trucks in total to operate the desludging service in the city (Frenoux *et al.* 2011). The charge for emptying a containment unit ranges from 30 to 100 USD (JICA 2016). There is no licensing requirement for providing such sludge emptying and transportation services. There is a lack of faecal sludge disposal sites in Phnom Penh (Frenoux & Tsitsikalis 2015; JICA 2016).

Sampling procedures

In this study, 34 emptying and transportation operators were identified as operating in the city. They were contacted via telephone and asked whether they would assist in faecal sludge sampling, of which seven emptying and transportation operators agreed to participate. These participating emptying and transportation operators contacted the study team when a household required emptying services and allowed the research team to participate in the emptying event. Sampling was conducted between late May and mid-September 2020, with 194 faecal sludge samples collected immediately after emptying events by vacuum trucks at different locations within Phnom Penh (Figure 2). The number of samples collected was based on the number of emptying events required by households in Phnom Penh during the sampling period. This study collected 148 samples from the nine peri-urban areas and 46 samples from the five urban areas. Since the population ratio in peri-urban areas vs urban areas in the city is approximately 3:1, the sampling is representative. Grab samples were taken from the discharge valve of the vacuum truck, since it was impossible to open the upper side of the truck. It was also not practical to implement the recommended composite sampling (Koottatep *et al.* 2021), as the sampling team was not permitted to follow the trucks to the disposal sites nor to sample multiple times during emptying. Temperature, pH, conductivity, and dissolved oxygen (DO) of the collected sludge were measured onsite. Samples were collected in 500-mL polypropylene bottles, placed in an icebox, and transported to the laboratory at the Department of Environmental Science, Royal University of Phnom Penh, for further analysis within the recommended sample handling and storage period (APHA 2017).
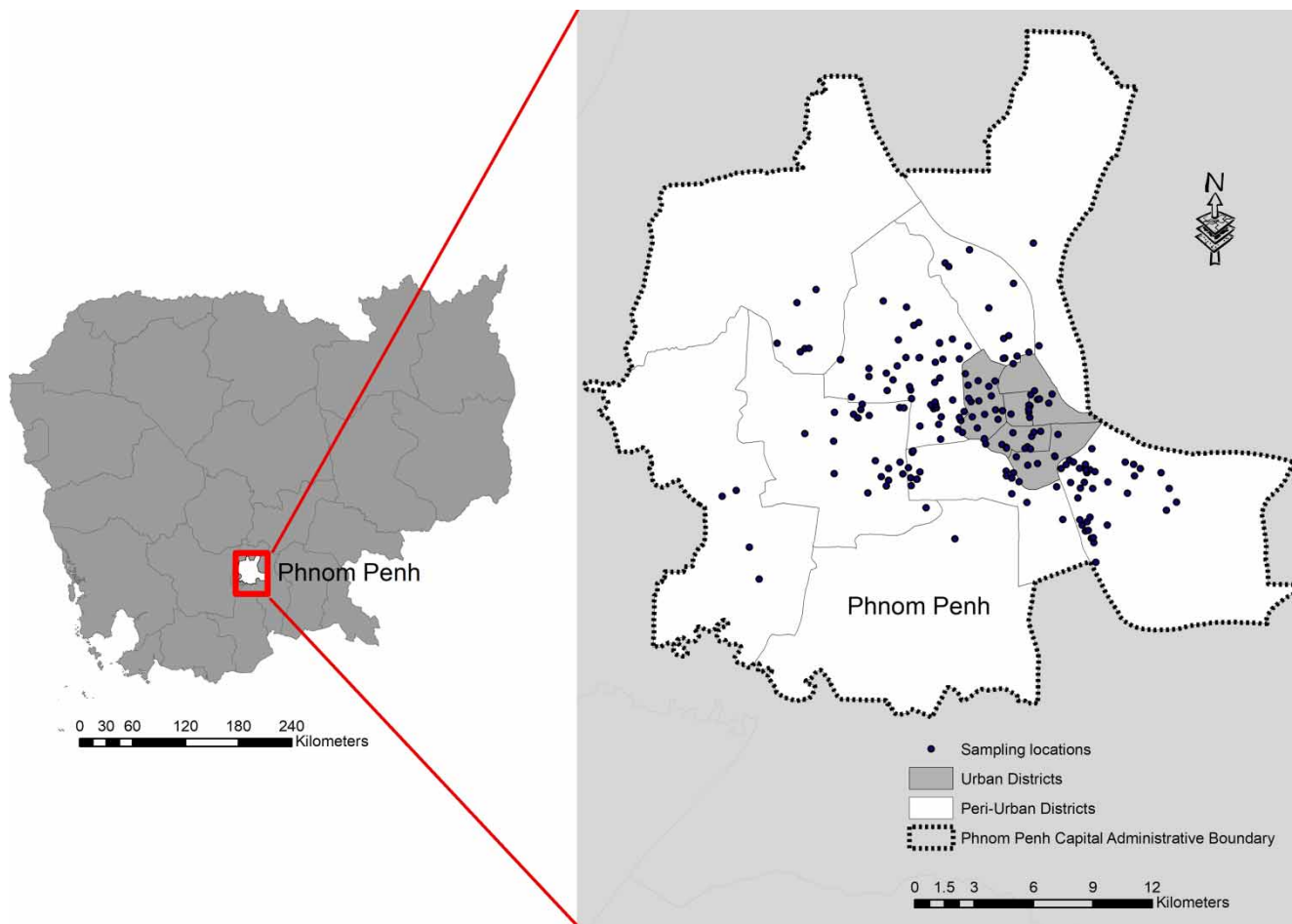

Figure 2 | The study area map of the city Phnom Penh and sampling locations of the 194 samples, where demographic, environment, and technical data were collected during sampling.

Questionnaire and checklist

A questionnaire was used to collect demographic and technical information about the containment systems and their users, once a faecal sludge sample had been collected from each household. The questions covered: containment unit type (cesspit or septic tank); watertight containment (yes or no); containment unit connected to the drainage system (yes or no); water added during emptying (yes or no); only blackwater (yes or no); origin category (single-household or multi-occupancy house); and containment system age in years since installation (3–10, 10–20, and >20 years). Connection to drainage facilities refers to a connection to the closed sewer network or an open canal, and the authors did not differentiate between these two types of networks in this study. Different types of wastewater are generated by domestic sources, such as blackwater (excreta, flushwater, and anal cleansing water) and greywater (kitchen and bathing wastewater). In this paper, only blackwater containment refers to containment units that capture only wastewater from toilets. The origin category reflected the different number of users of the containment unit, grouped into three sub-groups (<10, 10–50, and >50 people), to detect a significant difference between different numbers of users. A checklist was also developed to collect technical data about the containment system from pit emptiers. The questionnaire used with householders and the checklist used with pit emptiers are included in the Supplementary Material.

Analytical methods

The parameters such as pH, DO, temperature, and conductivity of faecal sludge were measured onsite using a HORIBA-U-52G multi-parameter water meter. The *in situ* parameters were determined immediately after collecting the samples from outlet of the truck. The HORIBA-U-52G meter was also regularly calibrated to ensure the accurate measurement. TS, volatile solid (VS), total suspended solids (TSS), volatile suspended solids (VSS), and biochemical oxygen demand (BOD) were analysed in the laboratory following standard methods (APHA 2017). Gravimetric, ignition, oven drying, ignition, and spectrophotometer method 2540B, 2540E, 2540D, 2540F, and 5210B, respectively, were used to analyse TS, VS, TSS, VSS, and BOD, respectively. Ion chromatography was used for phosphate (PO_4-P) analysis. Hach Lange standard tests were used to analyse total phosphorus (TP), ammonia nitrogen (NH_4-N), and total nitrogen (TN), following the manufacturer's instructions (Bassan *et al.* 2016; APHA 2017). The analysis was conducted within 24 h of sampling for BOD and 48 h for TS, VS, TSS, VSS, and PO_4-P. The samples were preserved for the analysis of TP, NH_4-N, and TN. Sample handling and storage for those analyses followed the Standard Method for the Examination of Water and Wastewater (APHA 2017). The results are expressed as the mean value of duplicate analyses of each sample for all parameters.

Statistical analysis

The Microsoft Excel 2010 and R software version 4.0.4 were used for data computation and analysis. Descriptive statistics were employed to assess faecal sludge characteristics across all samples, regardless of the type of containment system. Nine faecal sludge chemical parameters (PO_4-P, NH_4-N, TP, TN, BOD, TS, VS, TSS, and VSS) were chosen to conduct hypothesis testing with the containment data (categorical explanatory variables) collected via the questionnaire. They were selected because they are critical design parameters for faecal sludge treatment plants to respond to treatment objectives to reduce oxygen demand and suspended solid content in wastewater (Tayler 2018). TS content is also commonly used in designing treatment technologies for sludge, such as drying beds (Niwagaba *et al.* 2014). To assess differences in faecal sludge characteristics between each categorical explanatory variable, a general linear model (lm model in R, car package) with each categorical explanatory variable was used. To determine which categorical variables exerted the greatest influence on each faecal sludge parameter, a general linear model with all categorical explanatory variables (lm model in R, car package) was used. Faecal sludge characteristics were log-transformed to achieve normal distribution of the residuals. The values of $p < 0.05$ were considered statistically significant.

RESULTS AND DISCUSSION

Physicochemical characteristics of faecal sludge

Results on faecal sludge characteristics of all samples, septic tanks, and cesspit samples are presented in Table 1 and Supplementary Table S1. The measured faecal sludge characteristics were found to be highly variable and unevenly distributed, which is consistent with other studies (Gold *et al.* 2018; Strande *et al.* 2018; Krueger *et al.* 2021; Ward *et al.* 2021). Both mean and median values are included in Table 1 and Supplementary Material, Table S1, since faecal sludge qualities were not normally distributed. The standard deviation was often almost as high as the mean value, which is in

Table 1 | Summary statistics on sludge qualities for all samples and the summary of the mean values of faecal sludge characteristics from different studies

Parameter	Summary statistics from this study							Mean value from other studies					
	Minimum	Maximum	Lower quartile	Upper quartile	Median	Mean	Standard deviation	Public toilet[a]	Private toilet[a]	Pit latrine[b]	Lined pit[c]	Unlined pit[c]	Septic tank[b]
pH	5.03	8.80	6.90	7.46	7.16	7.13	0.55	7.58	7.66	–	7.20	7.70	–
Conductivity (mS/cm)	0.21	4.92	0.97	1.63	1.21	1.44	0.84	10,900	5,340	–	17,300	12,500	–
Temperature (°C)	28.3	35.7	30.8	32.8	31.7	31.8	1.36	25.3	26.5	–	22.8	22.9	–
DO (mg/L)	0.29	2.96	0.37	0.52	0.44	0.52	0.37	0.8	0.76	–	–	–	–
BOD (mg/L)	111	8,600	613	2,100	1,110	1,710	1,640	4,310	3,990	2,130	–	–	1,450
TS (g/L)	1.32	134	10.3	42.2	24.5	30.8	25.9	–	–	13.3	51.4	177	8.98
VS (g/L)	0.73	52.8	5.86	22.1	13.9	15.4	11.6	0.84	0.73	64[d]	–	–	74[d]
TSS (g/L)	0.99	179	6.99	34.5	18.6	25.3	24.8	20.3	7.85	10.9	–	–	7.07
VSS (g/L)	0.29	59.1	3.91	18.6	10.6	13.0	11.2	–	–	–	–	–	–
PO_4-P (mg/L)	1.27	153	10.7	27.0	18.0	26.1	26.4	236	199	–	–	–	–
TP (mg/L)	72.8	1,930	259	686	400	503	338	111	89.5	–	–	–	–
NH_4-N (mg/L)	16.4	668	101	204	140	180	125	1,950	1,320	–	–	–	–
TN (mg/L)	51.2	657	138	288	188	219	111	1,550	1,280	–	–	–	–

For abbreviations, see the text.
[a]Ahmed *et al.* (2019).
[b]Bassan *et al.* (2013).
[c]Semiyaga *et al.* (2017).
[d]Units (% SS).

accordance with findings in Kampala, Uganda, and Hanoi, Vietnam (Strande *et al.* 2018), Nairobi, Kenya (Junglen *et al.* 2020), and Sircilla, India (Prasad *et al.* 2021). Physicochemical parameters such as temperature, pH, and conductivity showed small standard deviation, in agreement with findings in a study in Hanoi and Kampala (Englund *et al.* 2020). Faecal sludge characteristics showed a slightly lower range than most reported values, whereas temperature, pH, conductivity, and DO were within the range of previously reported values (Table 1). The concentrations of all parameters studied were within the similar ranges for both septic tank and cesspit containment systems.

The mean and median values of the physical and chemical properties were slightly lower than the values reported in the literature (Bassan *et al.* 2013; Appiah-Effah *et al.* 2014; Semiyaga *et al.* 2017; Prasad *et al.* 2021; Ward *et al.* 2021) but were within the range identified in studies in Kampala (Strande *et al.* 2018), Vietnam (Gold *et al.* 2018), and selected cities in developing countries (Koné & Strauss 2004). Strande *et al.* (2018) found that households with access to a piped water connection seem to have slightly diluted faecal sludge, resulting in lower TS concentration. It is also the case for Phnom Penh. Almost all the samples taken were from connection to piped water households. Sample collection was performed differently in previous studies and the present study, which can potentially explain some of the differences between studies. For example, Semiyaga *et al.* (2017) collected faecal sludge directly from the pit latrine, whereas in this study faecal sludge grab samples were collected from the truck discharge valve after emptying of the sludge containment unit. This sampling procedure could be another reason for highly variable sludge characteristics.

The lower TS fractions found in this study reflect the high dilution of the sludge and can be linked to challenges for handling and transport to treatment plants. The highly diluted sludge will also require effective dewatering. Dewaterability characteristics of faecal sludge influence the entire faecal sludge management chain (Semiyaga *et al.* 2017). The high BOD level indicates that this faecal sludge is less stabilised and still has high biodegradability potential (Ahmed *et al.* 2019). This would require a significant amount of oxygen by microorganisms to degrade the organic matter content in faecal sludge. The application of biological treatment would be appropriate to handle faecal sludge in Phnom Penh. However, the high ammonia inhibits algal growth and impairs plant growth in wetland treatment systems (Koné & Strauss 2004). Alternatively, the present levels of nutrients in faecal sludge indicate the potential for agricultural application as a fertiliser.

Overall, the faecal sludge characteristics identified were significantly higher than the permissible limit for wastewater discharge in Cambodia (RGC 2017). This is similar to findings reported for Kenya (Gudda *et al.* 2017) and Zimbabwe (Changara *et al.* 2018). With the current practices, faecal sludge and wastewater are handled in the same way since the final disposal for both is Chheun Ek wetland. Faecal sludge can be a pollution source and threatens public health if it is not properly handled. As indicated in JICA (2016), there is no existing authorised faecal sludge disposal site in Phnom Penh. The total fee that the households pay includes the disposal fee, as well as a fee to cover travel costs from the source to the disposal site. With this additional cost of disposal fee, it likely increases the possibilities for illegal dumping, given the fact that there is no penalty and enforcement for illegal dumping (Peal *et al.* 2015). Depending on the containment unit size, one trip can be a combination of faecal sludge from single or multiple households. Gudda *et al.* (2017) concluded that the average faecal sludge concentration from pit latrine in Nakura, Kenya, was higher than was safe for treatment in wastewater treatment plants, with an increased likelihood of significant pollution to the ecosystem. This is also the case for Phnom Penh. Most of the faecal sludge collected is dumped indiscriminately in drainage channels or wetlands, which likely overwhelms the performance of the natural wetlands surrounding Phnom Penh. This will ultimately affect the water quality in the Mekong and Tonle Sap rivers. Hence, a proper faecal sludge management solution for Phnom Penh is urgently needed to avoid damaging effects on the environment and public health. If treated properly, faecal sludge could be a valuable resource, for example for fertiliser and biogas production, with its high level of nutrients and organic matter. However, utilising faecal sludge in this way requires the development of cost-effective sanitary management solutions.

Sources of variation in faecal sludge characteristics

The assessment of variables with the greatest influence on each faecal sludge characteristic revealed that two significant explanatory variables ($p < 0.001$) were the predominant sources of the variations in PO_4-P and NH_4-N levels in faecal sludge. They were as follows: adding water during emptying ($p < 0.001$) and type of wastewater captured by the containment system ($p = 0.008$). Connectedness to the city's drainage network ($p = 0.004$) and the type of wastewater captured by the containment unit ($p < 0.001$) significantly influenced the concentration of TP in faecal sludge ($p = 0.006$). Whether the containment unit captured only blackwater or mixed wastewater appeared to have a great influence on the concentration of TN ($p = 0.004$). However, the model failed to indicate significant results ($p = 0.102$) for TN. The concentrations of

BOD ($p = 0.008$), TS ($p = 0.026$), VS ($p = 0.012$), TSS ($p = 0.026$), and VSS ($p = 0.012$) appeared to be impacted by the connectedness to the urban drainage system. Significance in the models was detected for BOD ($p = 0.044$), but not for TS, VS, TSS, and VSS. However, the multiple R^2 and adjusted R^2 values in all models were quite low, indicating that the models did not explain much of the variation in the categorical explanatory variables studied. The highest multiple R^2 (0.330) and adjusted R^2 (0.276) were obtained for the PO$_4$-P level.

In the assessment of differences in each faecal sludge parameter with each explanatory variable, four of the seven variables studied significantly affected at least some of the sludge quality parameters (Table 2). In sludge from watertight containment units (lined) and containment units that were connected to the urban drainage network, BOD, TS, VS, TSS, and VSS were higher than sludge from leaking or unconnected containment units. In addition, containment units connected to the drainage network resulted in significantly lower PO$_4$-P and NH$_4$-N levels compared with units that were not connected to the network. The levels of PO$_4$-P, NH$_4$-N, and TN also differed significantly depending on whether water was added during emptying. Nutrient parameters and BOD of faecal sludge were significantly influenced by whether the containment system captured only blackwater or a mixture of wastewater from a domestic source. The concentrations of nutrients were higher, whereas the BOD level was lower, in sludge from containment units reported to capture only blackwater compared with those that received all types of wastewater. Containment system type, number of users, and containment unit age did not affect the selected chemical properties of faecal sludge (Supplementary Figures S1, S6, and S7). The following section gives insights into each variable and how they affected faecal sludge parameters.

Containment type

None of the parameters studied differed significantly between septic tank and cesspit containment (Supplementary Figure S1). Almost all parameters had similar concentration levels between technologies. This agrees with findings in a study conducted in Durban, South Africa, by Krueger et al. (2021). They found no evidence of different median VS levels between different sanitation technologies, such as ventilated improved pit, urine-diverting toilet, and septic tank. However, it slightly contradicts the findings by Strande et al. (2018) and Prasad et al. (2021). In the study by Prasad et al. (2021), the type of containment system affected TS, VS, and chemical oxygen demand (COD) concentrations in faecal sludge in Sircilla, India. In the study by Strande et al. (2018) in Kampala, faecal sludge in a septic tank containment system had a higher water content (lower TS) than sludge in a pit latrine due to the prevalence of toilet flushing. Krueger et al. (2021) detected significantly higher TS, but not VS and nitrogen content, in ventilated improved pit latrine and urine-diverting dry toilet sludge than in septic tank sludge in Durban, South Africa. This difference was due to flushed and mechanical emptying of the septic tank, whereas manual dry emptying was applied for the ventilated improved pit latrine and urine-diverting dry toilet.

The local sub-decree on construction permits in Phnom Penh (legal document required for a new building) specifically requires septic tank installation for new households, but no standard drawings, laws, or regulations on operation and maintenance of the tanks are included in the sub-decree (JICA 2016). Institutionally, there is no technical standard and monitoring process available to certify and control the quality of sanitation facilities built at the household level in Cambodia (Frenoux & Tsitsikalis 2015). Therefore, there is no regular emptying schedule and emptying services are mainly employed only due to full

Table 2 | p-values for the F-test of general linear models of faecal sludge parameters with each categorical explanatory variable

Variables compared	PO$_4$-P	NH$_4$-N	TP	TN	BOD	TS	VS	TSS	VSS
Septic tank vs cesspit	0.278	0.398	0.899	0.809	0.278	0.845	0.713	0.927	0.697
Lined vs unlined containment unit	0.266	0.900	0.329	0.098	**0.039**	**0.029**	**0.008**	**0.022**	**0.006**
Connected vs not connected to urban drainage network	**<0.001**	**0.002**	0.199	0.786	**<0.001**	**0.002**	**<0.001**	**0.002**	**<0.001**
Water added vs no water added	**<0.001**	**<0.001**	0.674	**0.042**	0.712	0.117	0.255	0.127	0.381
Only blackwater vs mixture of wastewaters	**<0.001**	**<0.001**	**0.022**	**0.002**	**0.026**	0.784	0.680	0.789	0.620
Number of users (<10, 10–50, >50 people)	0.517	0.579	0.417	0.786	0.249	0.888	0.999	0.954	0.840
Containment unit age (3–10, 10–20, >20 years)	0.395	0.468	0.636	0.967	0.686	0.939	0.992	0.895	0.953

Bolded values indicate a significant difference in hypothesis testing ($p<0.05$). For abbreviations, see the text.

or clogged tanks. Irregular emptying may lead to poor performance of the containment system and may result in similar pollutant levels in whatever type of onsite sanitation system is used by households.

Watertight containment

The concentrations of BOD, TS, VS, TSS, and VSS were higher in sludge from watertight than from leaking containment units (Supplementary Figure S2). However, no significant difference was found for nutrient levels (NH$_4$-N, TN, PO$_4$-P, and TP) (Supplementary Figure S3). This result partially agrees with Semiyaga et al. (2017) who found that faecal sludge from lined and unlined pits in Kampala, Uganda, showed significant differences for all physicochemical characteristics (including TS and VS), but not pH and temperature. However, Strande et al. (2018) did not find any significant difference in TS regardless of whether the containment unit was watertight or not. Actual underground conditions are likely to affect the TS level. It is also the case that underground conditions vary between cities. Some forms of the nutrients are water-soluble and water leaking out from unlined containments could carry some nutrients with it, whereas solids will remain in the containment unit. Therefore, nutrient levels in sludge can be expected to be lower if the containment unit is unlined. The fact that this study did not find significantly lower nutrient levels is likely due to high variability of faecal sludge, resulting in part from the sampling strategy.

Connected to the urban drainage network

Regardless of the type of containment unit used by the household, the urban drainage network in Phnom Penh is available to all those who reside within the network coverage area. In this paper, 'connected to the drainage network' refers to any containment unit with a free-flowing outlet connected to the public drain network. The BOD, TS, VS, TSS, and VSS concentrations were significantly higher when the containment unit was connected to the drainage network, as shown in Supplementary Figure S4. This was expected, since the supernatant keeps flowing out of the containment unit to the drains, leaving more viscous sludge remaining in the containment unit. However, we found significantly lower NH$_4$-N and PO$_4$-P concentrations in sludge from households with their containment unit connected to the drainage system, presumably because these water-soluble nutrients were continuously washed out to the drain with supernatant. In contrast, no significant difference was found for TN and TP concentrations (Supplementary Figure S5).

Water added during emptying events

According to the interviews with the pit emptier, water was only used to facilitate the faecal sludge pumping process and cleaning at the very end of the emptying operation. Water was also needed in a high-pressure gauge to overcome clogging problems and the volume used was estimated by the pit emptiers, according to interviews. The amount of water added varied based on the viscosity of the faecal sludge in the containment unit. According to the study teams' observations during the sampling campaign, in containment units with sludge with higher organic matter content, the sludge was watered down to a similar viscosity as for other sludge without water added. Hence, all faecal sludge when emptied had about the same viscosity, to make it possible to pump it out from the containment units, leading to similar BOD and solid concentrations. However, due to the dilution effect, the sludge collected from the containment units where water was added during emptying had significantly lower concentrations of NH$_4$-N, PO$_4$-P, and TN compared with those units where water was not added (Supplementary Figure S6). Nevertheless, significant differences in nutrient concentrations were found, despite the fact that the exact amount of water added was not known. There was no impact on the other parameters studied (Supplementary Figure S7).

Only blackwater

Some households had separate containment units to capture different types of wastewater, i.e. separate collection of blackwater, whereas others had a single containment to collect all types of wastewater. As expected, nutrient concentrations in faecal sludge were significantly higher when the containment unit was reported to capture only blackwater (Supplementary Figure S8). This is because a majority of nutrients are found in excreta. Even if detergents may contain some phosphorus, the levels of P in detergent are generally lower than what is in excreta (Jonsson et al. 2005). The concentration of organic matter, such as BOD, was lower when the containment unit stored only blackwater. This could be explained by the containment unit capturing a mixture of wastewater, including kitchen wastewater, which could possibly contain a higher degradable fraction, for example, fats, and contribute to a higher concentration of BOD. Other parameters were not significantly different between containment units that collected only blackwater and those that collected all kinds of wastewater (Supplementary Figure S9).

Number of users

The number of users of the containment unit did not significantly impact any of the faecal sludge parameters (Supplementary Figure S10). This corroborates findings in India by Prasad et al. (2021), who concluded that faecal sludge quality does not differ significantly with number of faecal sludge containment unit users.

Containment unit age

There was no significant difference between containment unit age and faecal sludge qualities (Supplementary Figure S11). In contrast, the study in Sircilla by Prasad et al. (2021) found that the older the age of the containment unit, the higher the concentrations of TS, VS, and COD in the sludge. The lack of effect in Phnom Penh may be because all faecal sludge was continuously pumped out from the containment unit at each emptying event and there was no ageing sludge residue left after each event. Additionally, some emptying events happened because of clogging problems and hence all faecal sludge was pumped out. Some containment units appeared to be emptied before they were full, which raises questions regarding the performance of the system. It appears that faecal sludge containment systems can perform similarly, regardless of their type or age, if they are maintained as they are in Phnom Penh, with total emptying of the contents at regular intervals.

CONCLUSIONS

This study is the first comprehensive investigation of faecal sludge qualities in Phnom Penh. The results showed that concentrations of many faecal sludge parameters, such as nutrients and organic matter, are at the lower end of the range reported for other similar cities worldwide, but still higher than the permissible Cambodian discharge levels. This indicates that faecal sludge in Phnom Penh is a pollution source and that treatment is needed before discharging it to the natural environment to reduce potential health and environmental consequences.

The three predictors with the strongest influence on faecal sludge characteristics were as follows: the addition of water during emptying, connection to the urban drainage network, and the type of wastewater captured by the household containment system (mixed wastewater or only blackwater). These parameters could be used as predictors to estimate organic matter and nutrient content in faecal sludge, as they are critical inputs for designing faecal sludge treatment plants. Age of the containment system did not show any correlation to faecal sludge composition, indicating that the management of the system with full emptying and the interval of emptying are more important than the system's age.

The composition of faecal sludge in Phnom Penh varied, but within the range reported for other similar cities on average. A general linear model including all sludge variables studied here could be applied in future studies, since it would give a more reliable assessment of factors influencing faecal sludge characteristics. The faecal sludge characteristics and influencing factors identified in this study can serve as baseline data for sanitation stakeholders planning faecal sludge management in Phnom Penh or cities with similar sanitation contexts.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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